UNIVERSITY OF SOUTHERN QUEENSLAND
AUSTRALIA

All-electric LNG a viable alternative to conventional gas turbine driven LNG plant

Dissertation submitted by

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For the award of

Engineering Doctorate

2014

ABSTRACT

The world demand for natural gas which is at an increasing trend has rekindled interest in the production and transportation of Liquefied Natural Gas (LNG) from resource rich areas in Africa, Middle East, Far East, Australia and Russia to customers in Europe, Americas, China and India. The challenges for the future are to produce and transport gas in a cost effective manner to be competitive in the market place.

Gas is beginning to play an increasingly important role in energy scenario of the world economy. The easiest ways of getting gas to the market is by pipe lines. However to reach markets far and wide across oceans, gas needs to be converted and transported in liquid form. Competitive pressure and search for economies of scale is driving up the size of LNG facilities and hence the capital requirement of each link of the value chain. Interdependent financing of the various links of the value chain, while maintaining their economic viability, is the challenge that sponsors need to address. The industry is potentially a high risk business due to uncertainty associated with the characteristics of the industry, which calls for high level of investment in an environment of volatility of the price and political and economic changes in the world market.

LNG production facilities are becoming larger and larger than ever before to take advantage of economies of scale. These massive plants not only have created new challenges in design, procurement and construction and environment but will create new challenges in operation and maintenance. Innovative technologies and first of a kind equipment applications with a rigorous technology development and a stringent testing plans ensure that the facility will achieve a long term reliable operation. Conventional LNG plants use Gas Turbine as main drivers for refrigerant compressors. To this effect All-Electric LNG has a potential to provide an alternative offer a life cycle advantage over the convention. Hence it would be worthwhile to study the pros and cons and prospects offered by this new technology from an overall life cycle perspective for future of LNG projects. This research is an endeavours in this direction.

Certificate of Dissertation:

I certify that the idea, collection of data and information, analysis, results and conclusions reported in this dissertation are my own work except when otherwise specified. I further certify that this work is original and has not been previously submitted for another award except where otherwise acknowledged.

Endorsement

Bharatendu Deo **Date**

Dr. David Thorpe,
Principal Supervisor **Date**

Mr. Trevor Drysdale,
Associate Supervisor **Date**

Acknowledgement:

This research has been completed with assistance of a number of people. I wished to express my gratitude to those who helped and inspired me throughout my candidature.

Firstly, I must thank my Principal Supervisor Dr. David Thorpe, who has been a constant source of guidance throughout the journey since last four and a half years. His advises and comments have helped in making the necessary changes required to complete my work. I also would like to extend my thanks to my Associated Supervisor Mr. Trevor Drysdale for his support and advice during my work.

I should also acknowledge Ms. Juanita Ryan for all her administrative assistances throughout the project work.

I thank my family especially my late father and late elder brother and my mother who has always been a source of inspiration for me with their sense of duty and indomitable spirit.

I also sincerely thank my mother for her love affection and never say die attitude to carry forward in face of all odds; my wife, Ashima, who has patiently took care of the home and handled the children when I was busy working; my children Vidhisha and Aryavardhan for their patience when I was busy with my work; and I further thank all my sisters and brother without whose help I would not have reached this stage of my accomplishment.

Last but not the least I thank all those colleagues who extended their support during my work.

Table of Content:

List of Table:

List of Figures:

List of Abbreviations and symbols:

ABB: Asea Brown Boveri
AC: Alternating Current
APCI: Air Products chemical Inc.
AVRs: Automatic Voltage Regulators
BAT: Best Available Technology
BGT: Big Green Train
BTPO: Build The Project Organization
Btu: British Thermal Unit
CAPEX: Capital Expenditures
CCGT: Combined Cycle Gas Turbine power plant
CCS: Carbon Capture and Storage
CMMS: Computer Maintenance Management System
CNG: Compressed Natural Gas
CO_2: Carbon Dioxide
CSI: Current Source Inverters
dBA: Decibel Absolute
DC: Direct Current
DCS: Distributed Control Systems
D-Drive: Direct (Gas Turbine) Drive
DLN: Dry Low NO_x
ECA: Export Credit Agency
EIA: Environmental Impact Assessment
E-LNG: Electrical LNG
EMC: Electro Magnetic Compatibility
EMT: Electromagnetic Transient
EPC: Engineering, Procurement and Construction
EPCM: Engineering Procurement, Construction and Management
EPCC: Engineering, Procurement, Construction, and Commissioning
ETA: Event Tree Analysis
FEED: Front End Engineering and Design
FMEA: Failure Mode and Effects Analysis
FMECA: Failure Modes, Effects and Criticality Analysis
F.O.B.: Free On Board
FPRS: Full Pressure Re-start
FPSO: Floating Production Storage and Offloading
FTA: Fault Tree Analysis
GHG: Green House Gas
GSPA: Gas Sales Purchase Agreements
GT: Gas turbine
GTL: Gas To Liquid
GTO: Gate Turn Off Thyristor
H_2S: Hydrogen Sulphide (Acid gas)
HAZOP: Hazard and Operability Study
HP: Horse Power
HSE: Health, Safety and Environment

HRA: Human Reliability Analysis
HRSG: Heat Recovery Steam Generator
IEGT- Injection Enhanced Gate Thyristor;
IGBT: Insulated Gate Bipolar Transistor
IGCT- Integrated Gate Commutated Thyristor;
IOC: International Oil Companies
ITP: Inspection Test Plan ()
JSR: Joint Safety Review
LCA: Life Cycle Assessment
LCC: Life Cycle Costing
LCI: Load Commutated Inverter
LNG: Liquefied Natural Gas
LPG: Liquefied Petroleum Gas
LSTK: Lump Sum Turnkey
LTSA: Long Term Services Agreement
LV: Low Voltage
MAEX: Maintenance Expenditure
MAINTEX: Maintenance Expenditure
MAP: Mechanical Acceptance Package
MCC: Motor Control Center
MDR: Manufacturer's Data Repot
MMBTU: Million Metric British Thermal Units
mm SCM: Million Metric Standard Cubic Meter
MTBF: Meantime between failures
MTBM: Mean Time Between Maintenance
MTPA: Million Tons Per Annum
MMTPA: Million Metric Tons Per Annum
MTTF: Mean Time To Failure
MTTR: Mean Time To Repair
MVAR: Mega Volt Ampere Reactive
MW: Mega Watt
NO_x: Nitrogen Oxide compounds
NOC: National Oil Companies
NPC: Neutral Point Clamped
NPV: Net Present Value
OPEX: Operating Expenditure
PDC: Product Development Center
PLC: Programmable Logic controller
PMI: Positive Material Identification
PMS: Power Management System
PPM: Parts per million
PRI: Political Risk Insurance
PSC: Production Sharing Contract
PTR: Project Technical Review
PWM: Pulse Width Modulation
QRA: Quantitative Risk Analysis
RAM: Reliability, Availability and Maintainability

RCDA: Reliability Centered Design Analysis
RCM: Reliability Centered Maintenance
RM&D: Remote Monitoring and Diagnosis
RMS: Root Mean Square
ROI: Return On investment
SCF: Standard Cubic Feet
SCR: Silicon Controlled Rectifier
SGCT- Symmetrical Gate Commutated Thyristor;
SHE: Safety, Health and Environment
SIMOPS: Simultaneous Operations
SO_x: Sulphur Oxides
SPC: Special Purpose Company
SPV: Special Purpose Vehicle
SR: Safety Review
SSTI: Sub-synchronous Torsional Interaction
TDS: Technology Development Stage
THD: Total Harmonic Distortion
TIC: Total Installation
TM-GE: Toshiba Mitsubishi Electric- General Electric
T.P.A: Tons Per Annum
TQMS: Technology Qualification Management System
TQP: Technology Qualification Process
TSR: Torsional Stress Relay
UPS: Uninterruptible Power Supply
VFD: Variable Frequency Drive
VSDS: Variable Speed Drive Systems
VSI: Voltage Source Inverters
X/R ratio: Reactance to Resistance Ratio
λ = Constant Failure Rate
t = Number of hours in a year.
μ = Constant Maintenance Rate

CHAPTER 1

Introduction

1.1 Natural gas:

Natural gas is the world's third largest source of primary energy after coal and oil. Since the early 1970s, world's proven and recoverable reserves of natural gas have been increasing steadily. The bulk of the natural gas reserves are located in Russia, the Middle East and Australia. There are various mode of transportation available for gas produced. Natural gas is distributed to the consumer either by pressurized pipeline distribution or as Liquefied Natural Gas (LNG), which is carried internationally by LNG tankers. Transportation is very important for gas business as reserves are often located at quite a distance from the main markets. In Russian, Europe and North America pipelines is the primary means of transport of the gas and for which there is a well-developed gas grid. Where it involves long distance transportation, and if it needs to be cross-continental across deep oceans, transporting gas in its liquid state is economical and this enables it to be transported by purpose built cryogenic LNG tankers.

1.2 What is LNG:

Natural gas is an abundant fossil fuel composed primarily of methane (90%), along with hydrocarbons such as ethane, propane, butane, and other inert gases such as nitrogen and is found deep inside the earth crust. It is taken out of earth by drilling deep wells on onshore or offshore locations. When natural gas especially methane (CH_4) is cooled to a temperature of approximately -162°C (-259°F) at atmospheric pressure it condenses to a liquid called Liquefied Natural Gas (LNG) (The Internal group of LNG importers, 2009). So LNG is natural gas (methane) in a liquid form. LNG is odorless, colourless, non-toxic and non-corrosive. One volume of this liquid takes up about 1/600th the volume of natural gas. Specific gravity of LNG is about 45% that of water (The Internal group of LNG importers, 2009). When vaporized and mixed with air it burns only in concentrations between 5% (Lower Explosive Limit) to 15% (Higher Explosive Limit). To liquefy natural gas, impurities that would freeze at low temperature, such as water and carbon dioxide, and other materials like sulphur compounds and heavier hydrocarbons are removed (The internal group of LNG importers, 2009). The gas is then cooled at atmospheric pressure to condense methane to liquid form, which is then stored or transported at atmospheric pressure. The liquefaction allows natural gas to be transported more efficiently over long distances where pipelines do not exist.

1.3 LNG Industry and its future:

The need to transport gas long distances across oceans led to the development of the international LNG trade which began in 1954. Its success led to the first shipments, which was made on a trial basis in the early 1960s between the US and the UK, while 1964 saw the start of the first commercial-scale LNG project to ship LNG from Algeria to the UK This was followed by ventures between Algeria and France in 1965, and Alaska and Japan in 1969 (Bosma and Nagelvoort, 2008). The LNG trades actually developed in the 1970s, as much larger projects were planned in that era, to exploit economies of scale in liquefaction and to meet the increasing demand (Deo and Mangala, 2002). The demand for gas did fluctuate on the whole based on the strength of soaring demands from Japan, Korea and Taiwan; new capacities were built, especially in Middle East and Australia. Globalization, the emergence of a robust marketplace, the fluidity of supply and demand, and the increased understanding of energy as a commodity have produced a mature and sophisticated LNG industry. Favourable supply/demand fundamentals, compelling new technologies, and the recognition of LNG as a viable supply source are fueling rapid growth in the sector (Ernst and Young, 2013). There is a conscious shift worldwide from oil towards natural gas, which is a cleaner, and a cheaper source of energy. With surging demand for natural gas across countries, supply restrictions and impracticality of cross-country and cross continent pipelines through deep oceans, there was no option but to supplement natural gas requirement through imports of liquefied natural gas (LNG). Demand for energy in North America, Europe and emerging markets in China and India is increasing (International Energy Agency, 2012). Liquefied natural gas (LNG) offers an excellent option helping to meet energy demand growth. LNG provides a flexible and economical alternative for delivering remote gas reserves to expanding markets across the globe. Worldwide gas demand is climbing, largely because of the combined impacts of deregulation and the development of high-efficiency combined-cycle gas turbine technology that makes natural gas increasingly the fuel source of choice in power generation. LNG also had a premium value as a clean fuel. Along with these factors, advances in liquefaction technology have driven significant cost out of the LNG chain to improve the prospects for monetizing these stranded gas reserves (Castel et al, 2012). A stranded gas reserve is found in a natural gas field which has been discovered, but remains unusable for either physical or economic reasons. Figure; 1.1 shows the Global LNG demand in the past and forecast for the future.

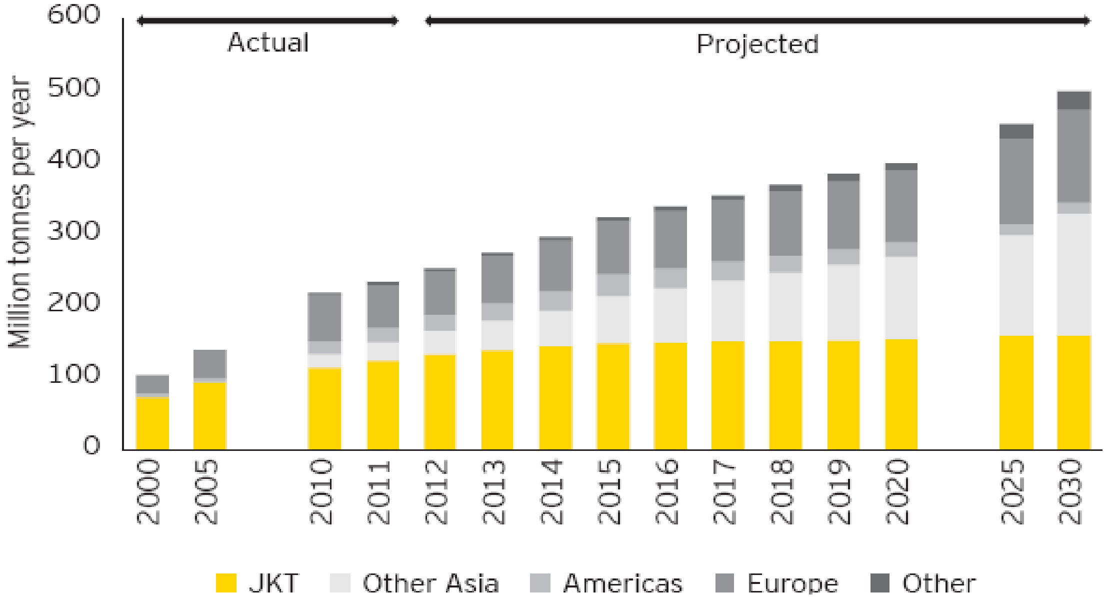


Figure 1.1: Global LNG demand; Source (Ernst and Young, 2013)

1.4 Uses of LNG:

Most LNG that is traded internationally is used to fuel electric power plants (Siemens, 2008). LNG is also used for the purpose of heating. Growing needs for electricity around the world has increased demand many folds, making it one of the fastest growing energy sources in the world. Once delivered, LNG is stored in insulated tanks so that it can be vaporized and distributed as natural gas to the customers. In addition to use of LNG in power plants to generate electricity and for the purpose of heating, it is emerging as an alternative motor fuel to diesel.

1.5 LNG Process:

There are steps that explain the process of liquefying natural gas and ultimately delivering it to customers – this process is often referred to as the LNG "Value Chain" (Palmer, 2012). Figure 1.2 demonstrates the LNG liquefaction process (Palmer, 2012).
Step 1: Extraction– Natural gas is extracted from deep inside the earth by drilling process either on offshore or onshore drilling wells and piped to onshore LNG plants.
Step 2- Inlet receiving and Condensate removal- The gas is received at the onshore facility. The liquid hydrocarbon (condensate) associated in gas is removed at this stage
Step 3: Acid gas removal- Acid gas (H_2S) is removed and sent to the sulphur recovery unit for extraction of sulphur. Carbon dioxide is also removed.
Step 4: Dehydration- The gas is purified before being cooled because impurities found in raw gas would freeze at low temperatures. The gas is dehydrated as the water vapour will freeze at the liquefaction temperature of LNG.
Step 5: Mercury removal- Mercury compounds are removed at this stage

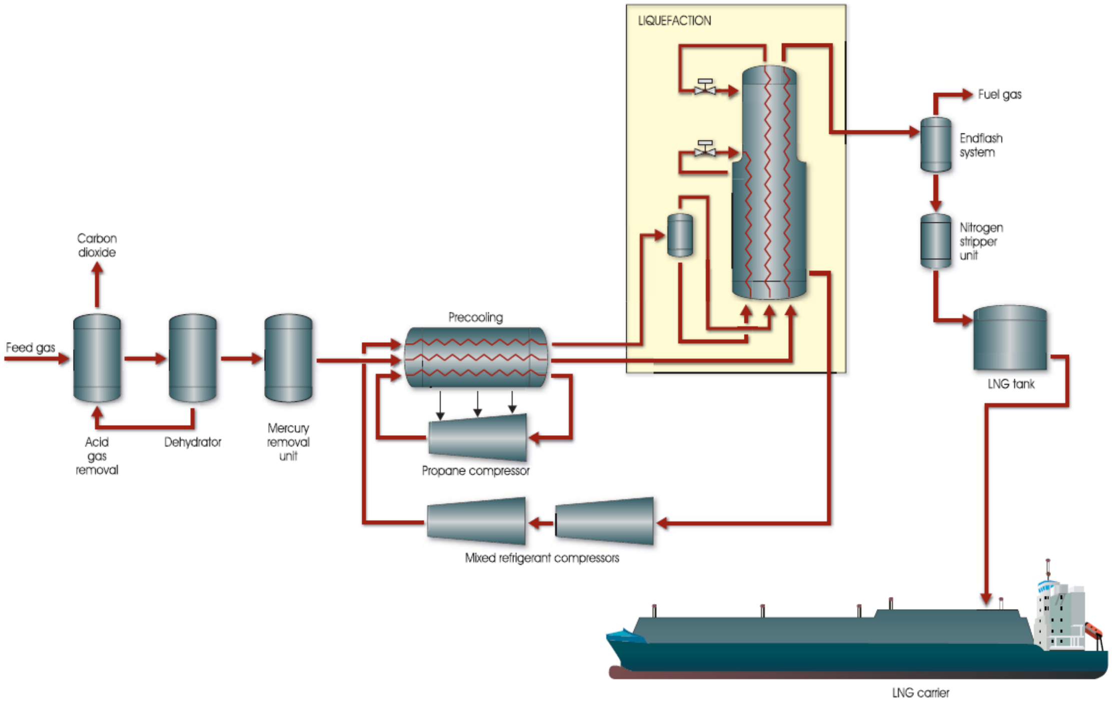


Figure-1.2: LNG Liquefaction process; Source (Buzzini, 2012)

Step 6: Pre-cooling- Once the gas is cleaned, the gas is pre-cooled at this stage using refrigerant. In large units propane is used as a pre-cooling refrigerant.

Step 7: Refrigeration/Liquefaction–The gas is chilled in successively colder heat exchanger that uses propane, ethylene, and methane as refrigerants. A mixture or combinations of refrigerant are used at this stage. LNG is produced at this stage and then sent to storage tanks.

Step 8: Sub-cooling- Sometimes sub-cooling is required for larger units before LNG is sent to the storage and Nitrogen is used for sub-cooling so as to increase production.

Step 9: Storage– LNG is stored in double-walled tanks at atmospheric pressure. These tanks are specially designed and cooled to contain liquefied gas until it is loaded on to tankers.

Step 10: Loading- From the storage tank LNG is loaded on to special purpose, custom built cryogenic ships.

Step 11: Shipping– LNG is shipped from the LNG Plant to a Regasification Terminal via tankers with specially designed tankers.

Step 12: Storage– LNG is stored in special design double-walled tanks at atmospheric pressure till it is sent for consumption.

Step 13: Re-gasification– LNG is extracted from the tanks, pressurized and re-gasified using heat exchangers to be sent over pipes.

Step 14: Customer Delivery– After LNG is returned to its gaseous state, the natural gas is treated in a number of ways, including metering and odorizing, and then fed into a transmission network for distribution to customers.

1.6 Alternative Fuels to LNG:

LNG’s growth has largely been fueled by a need for a clean fuel. However, there are certain other fuels that are alternative sources of energy as a clean fuel. On the other hand there are many others, which are in developmental stage and are expected to become cost effective in future (Deo and Mangala, 2002)

a) LPG: (Liquefied Petroleum Gas)

LPG is mostly made up of a mixture of propane and similar hydrocarbon gases. These hydrocarbons are gases at room temperature, but turn to liquid when they are compressed. LPG is stored in special tanks that keep it under pressure, so it stays as liquid. LPG is used in homes for heating, cooking, hot water and other energy needs. LPG costs less than gasoline for the same amount of energy. LPG fueled engines pollute less than gasoline and diesel engines.

b) CNG: (Compressed Natural Gas)

Compressed natural gas (CNG) is compressed into high-pressure fuel cylinders. Many automakers around the world are developing vehicles to run on compressed natural gas because of its clean burning nature and because it pollutes less than petroleum, gasoline and diesel. Cars, vans, buses and small trucks generally use natural gas in the form of CNG.

c) Hydrogen:

One of the most interesting and in some ways promising, alternative transportation fuels is hydrogen. While only experimental vehicles are operating on this fuel now, the potential for this unique energy source is excellent (Energyquest, 2002). It is easy to produce through electrolysis, simply splitting water (H_20) into oxygen and hydrogen by using electricity. Because hydrogen burns nearly pollution free, it has been looked at as the ultimate clean fuel. Being a non-carbon fuel, the exhaust is free of carbon dioxide, which is a greenhouse gas. Hydrogen's clean burning characteristics may, one day, make it a popular transportation fuel.

d) Liquid from coal:

Like oil and natural gas, coal is a non-renewable, fossil fuel formed in the earth from what was once living plants. Being a solid, coal is not easy to use for most transportation fuel needs. However, there are ways to make gasoline, diesel fuel, methanol, and other chemicals from coal (Energyquest, 2002).

e) Bio-diesel:

It is vegetable oil that is bio-degradable; hence it is much less harmful to the environment, if spilled. This process makes vegetable oil and animal fat into esterified oil, which can be used as diesel fuel, or mixed with regular diesel fuel. Oil produced from jatropha and castor seeds are getting popularity as bio-diesel (Energyquest, 2002).

f) Ethanol and Methanol:

Both ethanol and methanol are now used as transportation fuels and will likely play an increasingly important role in the future. Ethanol is generally made from corn or from biomass, which includes agricultural crops and waste, plant material left from logging, and trash including cellulose. Methanol can be made from various biomass resources like wood, as well as from coal.

g) Gas to Liquids:

Natural gas can be converted into liquid hydrocarbon products, called ‘gas to liquids’. The products are virtually free of nitrogen and sulphur giving them excellent combustion properties. Gas to liquids technologies provide opportunities to create value from otherwise stranded natural gas resources and will play an important role in the coming years. The liquids products are cheaper to transport than gas, and will therefore be competitive across a greater range of market (Deo and Mangala, 2002).

1.7 Purpose of the Study:

The purpose of the project is to explore various aspects of life cycle of major project from ‘cradle to grave’ and the challenges faced from conceptualization up to project completion, operation and finally till the facility is dismantled. The purpose of choosing this topic is that it has relevance to the LNG industry in which I am working and especially to my company, which is the largest LNG producer in the world and also involved in marketing LNG and it's by products. This study will help enhance my understanding on various challenges encountered in building and operating large capital intensive infrastructure project from an engineering management perspective. As 'All Electric' LNG is a concept that is yet to catch up with the imagination of the LNG developers, it is an interesting and challenging subject to research. I intended to carry out detailed investigations on various aspects such as engineering, technical, environmental, contractual and operational perspective to understand the spectrum of issues that are encountered while building and operating large capital intensive projects. This research will help improve insight into key management and technical theories and practices and application to a real life plant environment. This study helped in broadening and deepening my knowledge base on dynamics of technological innovation, qualification, application and management of various risks and challenges faced in managing large assets. There is a perception gas between conventional gas turbine driven LNG plants are the "All Electric driven LNG". This study will also endeavour to bridge the gap and investigate whether "All Electric" can be a viable alternative to the convention.

1.8 A conventional Gas turbine driven LNG:

A concept of a contemporary LNG driver-compressor strings are shown here in Figure 1.3. A number of large size compressors are used in the LNG plant in pre-cooling, refrigeration and sub-cooling (liquefaction) cycles. Here the Propane compressors. Mixed refrigerant compressors and Nitrogen compressors are driven by large gas turbine drivers, which constitute by far the largest loads in the LNG plant.

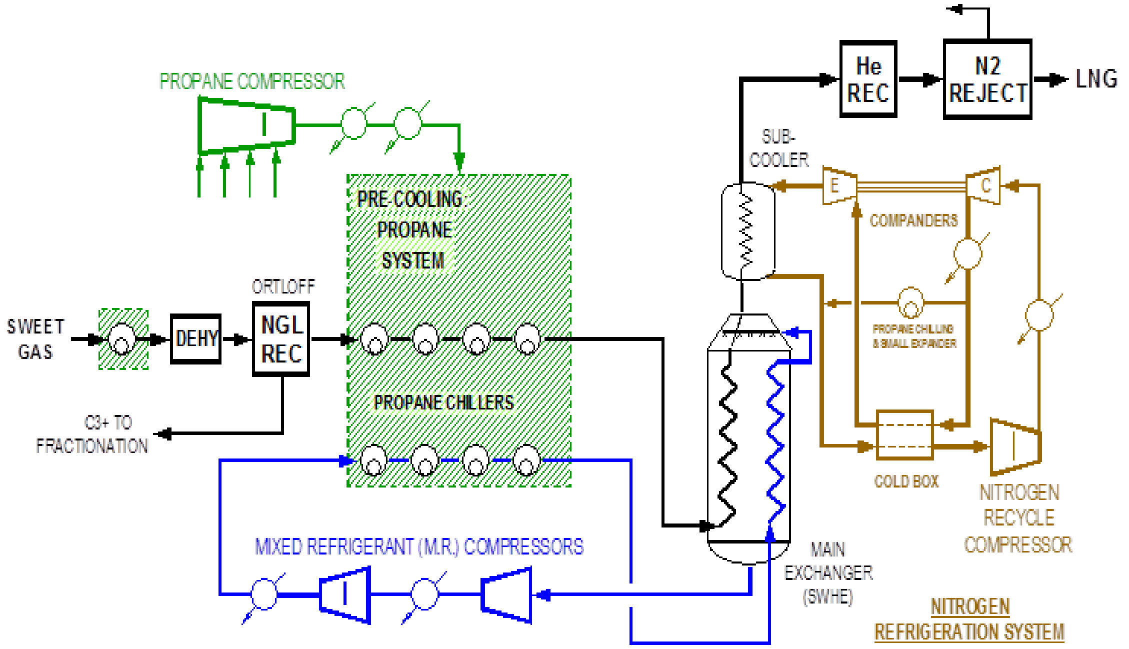


Figure 1.3 Conceptual drawing of LNG process; Source: Perez et al (2009)

The turbine-compressor string has to be started from stand still by a small electric starter motor and brought up to a certain speed when gas turbine is fired, which gradually takes up the entire compression load. Then the starter motor runs idle. Gas turbine's output is very sensitive to fluctuation of ambient temperature. At higher ambient temperature the air becomes thinner hence the power output of the turbine reduces thereby affecting the compression process adversely. Further, if the process train trips, for the purpose of restarting the string, the compressor has to be de-pressurized by venting the inventory. This not only leads to loss of inventory hence revenue but also increases emission. In modern concept the starter motor size has been increased so that this can start and restart the gas turbine-compressor string, even in fully pressured condition in a process called 'Full Pressure Re-start". This concept is shown in Figure 1.4. During high ambient temperature conditions in summer, the gas turbine capacity goes down. In addition to starting the turbine compressor string this motor can also perform as a helper to add power to the string in summer so as to maintain flat production. Starting a large electric motor 'direct on line' leads to sizeable voltage drop due to large motor inrush current, which may lead to power system instability. Hence a Variable Frequency Drive (VFD) is used to soft-start the large motors-gas turbine-compressor string slowly so as to limit the inrush current in starting. The VFD slowly builds up the speed of the string and at a certain speed fuel is introduced and the gas turbine is fired. It then picks up the load slowly and the VFD load is reduced.

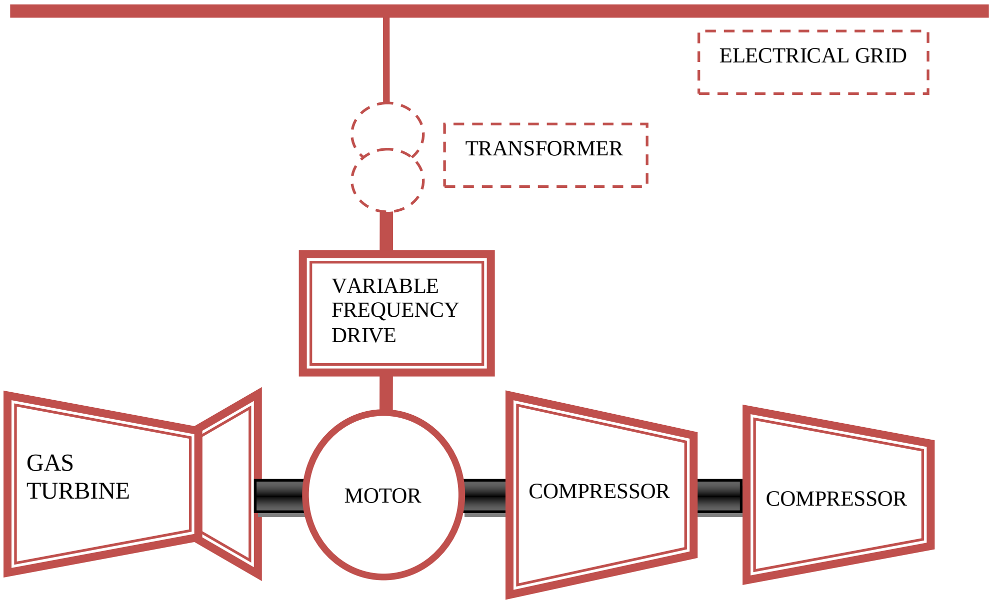


Figure 1.4: A Conventional Gas Turbine-Compressor string with Variable Frequency Drive (VFD) starter/ helper motor (Concept- Qatargas 2 project doc. 2006)

1.9 An 'All Electric LNG' concept:

As discussed earlier, gas turbine itself is not inherently self-starting hence an electric motor is used to start it. This motor also helps to 'full pressure restart' the string following a trip, without flaring the inventory or refrigerant. Further in summer when gas turbine performance is adversely affected due to high temperature the motor can also perform as a helper to maintain a steady production. There are many other life cycle issues with gas turbine such as lower availability, higher maintenance, high level of emission, noise and safety issues etc. which will be discussed in details later.

The ‘All Electric’ concept is based on increasing the size of the VFD driven starter/ helper motor, used in large gas turbine compressor string, so as to replace the gas turbine and assume the complete responsibility of the driver of the compressor load. The idea behind this study is whether this concept of replacement of the gas turbine with a VFD driven electric motor is a viable option.

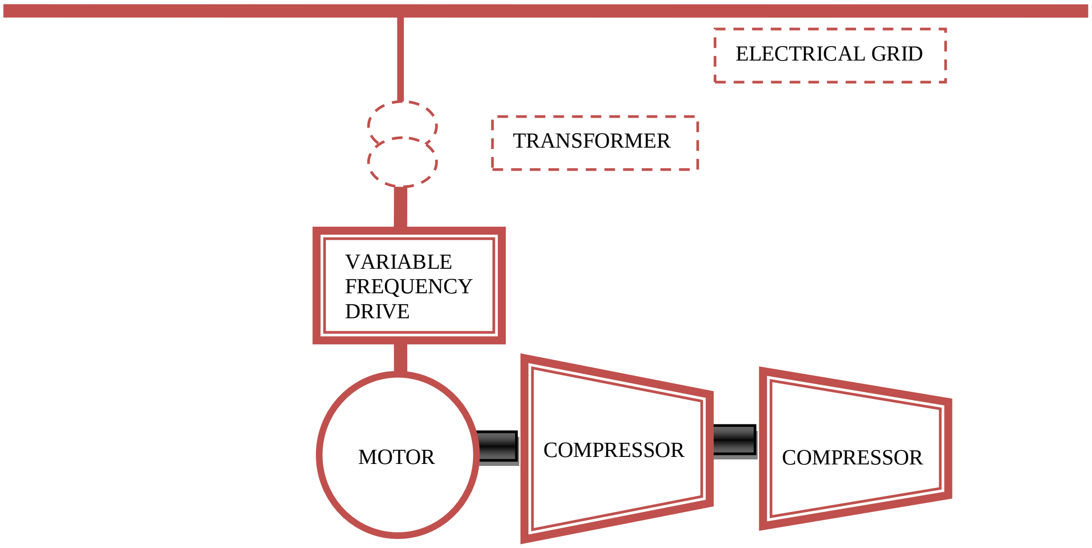


Figure 1.5: An ‘All Electric’ Variable Frequency Drive (VFD) Motor driven Compressor (Concept: ABB, 2005, Siemens, 2006; Devold, 2006; Kleiner, 2005)

1.10 Project learning objectives:

- To make useful original contribution to the existing knowledge on alternative LNG production technology and understand the challenges faced in building and operating large infrastructure projects.
- To make a systematic and coherent analysis in order to facilitate understanding of engineering management issues. To conduct original and intensive study to find solutions to pressing and complex engineering management problems, research current and new approaches to effectively manage change and leverage technological innovations.
- To develop a deep insight into dynamics of LNG Industry and finding out linkages with other such similar projects elsewhere.
- To explore the challenges faced in life cycle management issue of large projects, especially from an engineering management stand point from ‘cradle to grave’.

- To broaden knowledge of the socio-economic implications and long-term sustainability associated with major engineering decisions and technology innovations while adopting new engineering processes or technologies.
- To disseminate newly acquired knowledge and new concepts and ideas to a larger interested audience, in publications and through participation in scholarly and professional societies.
- To advance knowledge and skills to conceptualize, formulate, analyze, and solve complex engineering problems with multiple interrelated variables, both deterministic and probabilistic. Such problems may cross the boundaries of various engineering disciplines and involve social, economic, and sustainability factors.
- To advance knowledge and understanding of the concepts and application of good management practices to deal effectively with change and innovations and their socio-economic impact.
- To bring insight into the factors affecting project planning engineering, procurement, construction, commissioning, operation and maintenance from an engineering management perspective for the entire LNG value chain.
- To delve into economic, social and technological implication of the LNG Projects and also associated safety, environment, quality and cost implication from a life cycle perspective.
- To explore factors affecting world LNG expansion strategy and the bearing of new technology in reducing specific cost by improving Net Present Value (NPV).
- To bridge the gap between perception and reality and investigate whether “All Electric” can be a viable alternative to the conventional gas turbine driven LNG.

1.11 Summary of outline of Chapters:

The **‘Introduction’** chapter deals with natural gas, LNG and their uses. It also describes how it is processed, stored and transported. The alternative sources of energy to LNG are also described in brief. Natural gas Liquefaction processes using gas turbines as process compressor driver and introduction to Electric drive concept has also been discussed in a brief. The key elements and major processes to be considered to start large capital intensive engineering ventures have been discussed in **‘Literature review’** chapter. The treatment of risk, availability, reliability, maintainability, capability, thermal efficiency, and effectiveness has been discussed. Subsequently, technology qualification management process for adopting a new technology has been discussed in detail. The benefit and importance of sustainability adopted in life cycle process has been analyzed. A success of any venture which depends on life cycle cost, profitability and Net Present Value (NPV) has been analyzed. The criteria for selection of drivers for LNG process have been discussed and hypothesis built. **‘Methodology chapter’** deals in the processes and method by which data has been sourced, collected and analyzed. In addition to desk research, questionnaire method and interviewing method, various mathematical and statistical analyses have been utilized to analyze and summarize the data. The life cycle management related to Financial, Contractual, Environmental, Commercial, Procurement and Logistical, Safety, Human Resources, Quality, Construction, Testing, Commissioning, Operation, Maintenance aspects have been described with respect to all electric option has been discussed in chapter entitled **‘Life**

Cycle Management Challenges'. When an alternative is suggested to a well-established practice the advantages and disadvantages of the alternatives vis-e-vis the standards need to be discussed. This has been done in 'Gas **Turbine Vs Electric drives, a comparison'**, in which various aspects of both the options have been compared extensively. All-electric option as a driver for LNG compressor offers a number of advantages but also has many challenges both technical and otherwise. '**Technical Challenges of Electric Drives'** chapter deals with all the technical and reliability challenges of all-electric concept. All electric is relatively new concept which offers many advantages about which some case studies have been produced by various concerned entities. I have analyzed some of the **'Case studies'**, carried out by principals, contractors and vendors, which throw light into various advantages of the "all electric" option. Some of the cost data from the case studies has been utilized in building the life cycle cost benefit model. In the '**Life cycle cost benefit analysis'** studies, the overall cost and benefit of the electric option and uses Net Present Value method and Sensitivity analyses has been utilized to demonstrate economic advantages of 'all electric' concept. In **'Questionnaire and interview discussion'** chapter, questionnaire survey and interview with knowledgeable persons is discussed in details and new insights and perception of experienced personnel has been analyzed. '**Summary and further research'** chapter summarizes the research and gives recommendations. It also identifies areas where further research has to be conducted.

1.12 Study objective:

To study as to whether an 'All Electric LNG' plant can be a viable alternative to a conventional gas turbine driven LNG plant from a life cycle perspective.

CHAPTER 2

Literature Review

2.1 Introduction:

Liquefied natural gas is playing an ever increasingly role in the world energy scene. The combination of higher natural gas price and rising demand is encouraging the producers to monetize their gas reserve. As regards the world LNG supply/demand balance, the combination of the increase in new LNG supplies and the current economic slow-down will introduce new dynamics into Global LNG markets for the future. As the oil and gas industry's capital expenditures have soared in the recent years, capital project execution and operation of assets becomes an important topic of discussion among the producer, distributors, financers, consumers and EPC (Engineering, Procurement and Construction) contractors alike (Luan &Wray 2007). Increase in complexity, increase in the scale of the project in demanding environment, aggressive performance expectations and financial expectations are bringing in a quantum shift from the older approaches. These major projects present unique physical, technical, environmental and political challenges. This can impede the ability to manage this significant wave of capital investments and secure the world's energy future. The lack of predictability in delivering projects includes CAPEX (Capital Expenditure) overruns, late project completions, overly optimistic recoverable reserve estimates, etc.(Luan, Wray 2007).There are many factors which can affect the schedule and cost for building major infrastructure facility. Large LNG projects typically involves state-owned enterprises and international oil and gas companies comprising the upstream and liquefaction components and credit-worthy off takers such as electric and gas utilities making up the downstream component. Consequently, both upstream and downstream sponsors have sought to integrate themselves throughout the entire LNG value chain in an effort not only to share value throughout the chain, but also to internalize and spread the risks and lower the overall risk profile (LNG journal, October 2005). Some of the key elements that determine the success of the projects need not be over emphasized. In order to develop a liquefaction facility for the 21st century, a few key elements are necessary to place a new project on the LNG world map **(**Kotzot et al. 2007). These elements are discussed in the following section.

2.2 Key elements for placing a new project:

a) **Having the right location:** Distance of the site location from the offshore wells and from the port is quite important. Cost of site preparation will vary significantly with the soil conditions and location and on the plant size. A second factor is location as regards to its geographical position to reach various LNG markets. A key advantage is through technologies which can drastically reduce the unit operating costs to reach markets both east and west (Kotzot et al. 2007).

- **Accessing markets:** The access to various markets by a successful marketing team cannot be over emphasized. To commercialize resources it is needed to find viable gas markets. The effort should be to access traditional LNG markets in Japan, Korea and China and develop new opportunities in Europe and in India.

b) **Having the right partners:** Most major projects involve complex commercial arrangements across numerous companies and shareholders. In this situation, making quick decisions can be challenging and project schedule can be delayed by slow responses from joint venture partners (McKenna et al 2006). While joint venture partners for contractors' can help mitigate risks, however a number of interfaces challenges needed to be resolved because of distinction in the cultural background, work culture, approach to the jobs and interface handling. Complex dealings and conflict of interest between parties may delay decision making. Sometimes the various parties work in cocooned environment with restricted information exchange **(**Kotzot et al. 2007).

c) **Having the right financial plan:** As the global market for LNG has developed, financing has always required careful planning and is becoming increasingly complex. The financing cost includes the interest on equity and debt on capital expenditure, as well as the operating capital necessary for the initial phases of the project until LNG revenues will cover operating costs and other repayment obligations. Various aspects of financing that need to be considered include project rate of return, long-term demand, political and regulatory stability, production covered by take-or-pay arrangements, risk allocation among the sponsors, creditworthiness of the buyers and the availability of security or guarantees. (Kotzot et al 2007).

d) **Having Stable Political & Business Environment:** Having a stable political and business environment engenders large scale investment. Host governments frequently require that international partners use local suppliers with whom oil and gas companies do not have an established track record for material and services. The decision making mechanisms of the host governments are often unclear and the interference can lead to significant schedule delays (McKenna et al 2007).
   - **Managing relationship between NOCs and IOCs:** The world is witnessing a greater role for International Oil Companies (IOCs) with more LNG developments. Relationships between National Oil Companies (NOC) and International Oil Companies (IOC) have changed over the past twenty years as NOCs have allowed increased participation and involvement of IOCs in the development of LNG project structures. IOCs can bring project and process management skills, risk sharing and understanding, political risk overview, access to market, access to alternative LNG supply, human resource support, finance, technology and support for development of the local market to LNG project chain (Ledesma, 2007).

e) **Cost related issues:**
   - **Contract and cost escalation:** Owners continue to offer lump sum contracts while contractors manage most of the project risk alone. To reduce and spread the risk exposure in large projects the contractors show preference to joint

venture. It introduces some degree of complication when the joint venture partners are geographically diversely located, have different cultural and linguistic background and have different corporate culture. This can be problematic, since megaprojects put particular stain on labour availability and delivery of long lead items (McKenna et al 2006). Lump Sum Turnkey (LSTK) contracts mean that contractors have had to bear some of the financial load of cost escalation and materials shortages. The contactors favour moving towards time and material charges cost-plus contracts rather than lump sum contacts for high risk projects, which push the financial risks back onto project sponsors, often adding additional complexity and time to final decision-making by sponsors (OECD/IEA/ 2008).

- **Lowering costs thorough technology**: Cost reduction throughout the value chain is a major contributor towards success in the LNG business. Working out a series of scale and technology initiatives have contributed to holding cost well below industry benchmarks. The application of large train LNG technology, "Design One, Build Multiple" strategy state-of-the-art turbines, compressors and heat exchangers with greater efficiencies have delivered a significant competitive advantage (EM Energy project doc. 2005).
- **Material Related Cost:** Material costs can vary substantially from historical norms depending on the technical requirements of the project and the condition of the materials market during the procurement effort. As the number of equipment items increases, the total cost of material also increases, which is a primary concern to build large facilities. The proportion of material cost to total plant cost will affect comparisons of specific cost among LNG projects as the material market has outpaced economy of scale benefits over recent years (Kotzot et al, 2007).
- **Capital cost:** The difficult part is to define what is "right" in order to achieve the lowest cost and shortest schedule. "Lowest cost" is the most crucial driving factor in every project. Although Life Cycle Cost is often cited as a criterion in plant design, it seldom becomes more influential than lowest capital cost (Kotzot et al 2007). The specific cost of an LNG plant has become a metric to compare projects against each other. This dollar per ton per year number, referred to as "dollars per ton", is frequently cited in technical and commercial literature. Standardizing design when possible and a focus on technological innovation when replicating technology can reduce project cost. However when there is a step change in size, complexities and technology content standardization may be difficult to achieve.
- **Value of Replication:** There are various benefits for replicating the design and construction and implementing lessons learnt of an existing project. The other benefits are reduced capital costs, reduction in execution time, enhanced safety, completion, quality performance and quicker facility availability. The success of the RasGas expansion Project and lessons from the value of replication have served as a springboard for even larger LNG expansions in Qatar. Both RasGas3 and sister Qatargas companies built six of the world's largest LNG trains while employing the same contracting and replication strategies that have been tested and proven by the RasGas expansion projects (Khoo et al, 2007).

f) **Competition among contractors:** New LNG projects are facing a limited pool of contractors capable of building new plants. High commodity costs for construction materials, intense competition for skilled labor and project delays are becoming the norm, rather than the exception. To counter constraints in the Engineering, Procurement and Construction (EPC) contracting business, including a shortage of capacity in many areas and rising prices, a contracting strategy should foster competition, while retaining control over the areas where proprietary technology is involved. To deliver the project safely, on time and to budget, and at the right quality a 'One Project, One Team' ethos on the project should be followed encouraging all involved to work together in a cooperative fashion(Brown, 2009). In Qatar, unanticipated requirements or delays in awarding smaller contracts at Qatargas and RasGas allowed cost increases, which postponed the start-up by at least six months, and had a domino effect on the other projects down the line (Kotzot et al 2007).

g) **Supply value chain:** Traditional LNG models have an upstream investor group comprising state-owned enterprises and international oil and gas companies selling to a downstream credit-worthy off-taker. With the evolution of the LNG industry, upstream participants are getting interested in downstream investments and vice versa. A fully integrated ownership allows the project sponsors to internalize risks, increase commercial flexibility and value chain integration. Projects are constrained in raising capital unless they are part of a fully integrated value chain: from upstream, liquefaction, shipping, re-gasification, and even to off take and marketing. The challenge for sponsors and lenders is to connect the links with interdependent financing and investment commitments and commercial relationships, while still preserving each link's economic viability, collateral, and the ability to tap separate pools of capital (LNG Focus, 2005).

h) **Managing Technical Risk:** Building a large project tries to take advantage of economy of scale with a step change from the past, while maintaining an acceptable level of risk. The risk of using new technology and new equipment should be properly assessed and mitigated. A structured approach to risk management during the maturation of project elements with attention given to both technology integration and technology qualification activities is required. In Qatargas2 project a number of new step-out technologies implemented presented a major challenge in itself requiring a very rigorous and structured approach to ensure the design, construction, installation and operations (Khoo et al 2009). Introduction of new technology adds to project complexity and can be problematic (McKenna et al 2006). Technology Qualification Management System (TQMS) is a key to systematically determine the suitability of all new critical equipment and processes. (Thompson et al, 2004).

i) **Human resources angle to project success:** Success of any large project has a human resources angle to it and depends on the team and leadership. Some of the key elements towards the success of Engineering and a Project organization largely depend on mobilizing the staff and sharing the vision of the project, establishing proper communication between them, organizing a strong Project Implementation

Team and helping in removal of organizational barriers in the system (Luan, Wray 2007).

- **Short supply of technical talent:** There is a challenge for the LNG industry to attract, develop and retain talent for reasons such as job insecurity from single project mentality, perception by youngsters that oil and gas is a sunset industry, lack of formal career path for the project staff after completion of the project and lifestyle issue, since most activities take place in remote locations putting hardship on families. Hence engineers are not opting oil and gas as a career option (McKeena et al 2006).
- **Having the right people:** A major contributor to the success of a project is the cost of labour, availability of quality labour force which is both plant size and location dependent, and varies significantly based on project location (Kotzot et al 2007). The labour rate and labour productivity factor and a more expensive location significantly change the contribution of labor to the metric for specific cost. With labor costs accounting for up to 50% of the cost of construction which is quite significant, the impact of labor has to be considered separately from the cost of equipment (Ledesma 2007). While industry is aggressively managing material costs, labor is the largest variable. For example, as might be expected, in the United States material and labor are the major components in construction (Herron, 2008).
- **Building the Producing Organization:** When building large Greenfield and Brownfield projects the operating organization has to look into building a permanent organization, which takes over the facility from the project organization and operate it successfully for the rest of the period of the life of the facility. A producing organization is required to ensure completion and integration of the projects into operating organization and make sure that the organization is prepared to assume ownership and operatorship of the new facilities and achieve production, safety, and availability goals when completed. Road Map or execution plan have to be created so as to identify, plan, schedule, steward and execute the tasks to ensure readiness for operations consistent with the project schedule. The task is to identify and work key interfaces necessary to achieve operational readiness (Qatargas, BTPO 2006).
- **Handling resistance to change:** A major obstacle to implementing a new project delivery is the sheer inertia within the organization. People are accustomed to developing, planning, and exploiting opportunities in a particular way. The firm, as well as its entire supporting infrastructure, may be organized to sustain the old way of planning and executing projects (Luan & Wray 2007). To establish a sense of urgency, management should call for action and communicate the risk involved in not achieving the goal. This will instill promptness in action among the project personnel.

2.3 Major Processes of Large Capital Intensive Ventures:

2.3.1 Finance:

The challenges of financing massive infrastructure projects with billions of dollars of investments require independent commercial and financial evaluation and structuring of various sources of capital. Consortiums are formed in order to share and spread the risk. In general project funding begins with consideration of three key elements such as the main risks and the risk owners, the project structure and who provides the money (Deloitte Resource News, 2005). Project financing is a type financing of a particular economic unit where a lender is initially satisfied to look to the cash flow as the source of repayment of the loan and the assets as the collateral of the loan (Gajameragedara et al 2008). Project finance is usually based on single special purpose company's asset's cash flow. A fundamental concept inherent in all project finance deals is the structuring of future cash flows to meet the debt obligations of the project. As such, a project must demonstrate its ability to service debt, even under adverse circumstances, before lenders become comfortable with the deal (White and Case 2004). The recovery of the debt is dependent on the performance of the project. By this mechanism the borrower transfers some of the project risk to the lender which is normally reflected in a higher financing cost. However all cost can be more than offset by significant risk mitigation, expanded debt capacity and better management due to enhanced transparency of the project(White and Case 2004).In project finance the bank finances a Special Purpose Vehicle (SPV) that will build and operate a project and the SPV has off-take contract with an end user.

2.3.2 Commercial:

The commercial risk of LNG plants entails balancing the capital and operating cost with the projects' expected cash flow generated by the LNG production. Over past decades, liquefaction of natural gas has matured to become an economically viable as well as a technically and commercially proven scheme for shipping natural gas from remote production locations to distant consumers. Reducing the specific cost of LNG by up-scaling liquefaction trains and increasing their productivity through innovative technologies is a recognized industrial trend. The size, production and monetization of the gas resource are the biggest commercial challenges in developing LNG projects due to the uncertainties associated with the quality and deliverability of the gas and the economy of scale required for a liquefaction plant. LNG projects are designed and driven by economy of scale and environmental concerns of the host country related to gas flaring. Most commercial issues associated with an LNG plant are resolved on the same basis as a plant by the project sponsors, suppliers, contractors and host government and trade-offs required to make the project viable (Chiu, 2006).

2.3.3 Contracts:

Determining the correct form of contract can have a great effect on the cost and risk associated with a major project. Proper front-end definition work can identify the stakeholders' expectations, project priorities and critical success factors early on. This information is a must in order to correctly identify the proper contract strategy and structure required to meet the project objectives. Failing to meet the project objectives of safety, cost and schedule stems from misunderstanding the objectives of the project from the conceptual stage and therefore often leads to improper selection of the contract type (Agnitsch et al, 2001).The cost of construction varies inversely with the amount of business risk the owners and financers are willing to accept. The less business risk the owner wishes to assume, the higher the cost of construction. This follows the “risk-reward” motto for business (Prodigy, 2006). The two most common types of contacts in a LNG project are EPC (Engineering Procurement and Construction) “turn-key” and EPCM (Engineering Procurement, Construction and Management). Each of these methods has variations that can be adapted to each project as needed (Prodigy 2006).

2.3.4 Environment:

It is widely believed that the greatest contribution to be made to slow the pace of global warming is to reduce the use of carbon rich fossil fuels which is related to the human demand for energy and subsequent release of carbon into the atmosphere. Dashwood (2010) adds that “rising greenhouse gas emissions pose a significant risk to society and ecosystems” and that “many emissions were energy related.” Natural gas is a much better fuel than liquid hydrocarbons in terms of emissions. If Propane is used instead of Natural Gas (Methane) the emissions are 15% higher and the use of Fuel Oil increases the emissions by more than 50%. This is due to the ratio of hydrogen to carbon that is much lower in heavy hydrocarbons than in methane (Rabeau et al, 2007).Total life cycle greenhouse gas emissions from the use of LNG, spanning the complete LNG chain from production through to consumption, are markedly lower per unit of energy than traditional fossil fuels such as coal or fuel oil. The available options for reducing greenhouse gas emissions in each LNG segment will ultimately determine which technologies are economically sound for a particular project in the LNG chain (Chiu 2003).Not only can LNG production reduce the flaring and venting of associated gas from oil production, thus reducing the greenhouse gas emissions, but also the re-gasified fuel can be used in a combined cycle gas turbine (CCGT) power plant to increase efficiency. Greenhouse gas emissions are quantified in the form of carbon dioxide equivalent emissions and recommendations are made for process and technology improvements.

2.3.5 Procurement and logistics:

Procurement involves purchasing, subcontracting, field materials functions, and all related activities. Sourcing of the materials and services is done from financially sound, reputable organizations with proven performance track record. Proper planning and documentation of procurement activities with adequate resources assigned to manage the processes and deliveries is vital to meet all project schedule requirements. Procuring a comprehensive power-to-compression solution from a single point of responsibility offers a host of benefits for end customers and EPCs alike. A single point of contact can lead to significant reduction of interfaces, simplifying project management and communications, reducing engineering, erection and commissioning time and costs (Siemens, 2005).

2.3.6 Safety:

Safety Health and Environment (SHE) philosophy is based on the belief that all incidents can be prevented and demonstrated by giving SHE the highest priority and implementing adequate measures. The overall goal of Safety, Health, Environmental and Security philosophy is to protect the health and safety of persons, equipment and the environment. An effort to foster a culture that understands and recognizes hazards and takes proactive and pre-emptive actions to eliminate all hazards is the need for every project. OHSAS 18001 Occupational Health and Safety Zone provides information, guidance, resources and recommendations to help organizations address the requirements to manage health and safety more effectively. It helps minimize risk to employees, improves an existing Occupational Health and Safety management system and demonstrates diligence and gains assurance (*The Health and Safety & OHSAS Guide*; 2013). Meyers et al (2007) opine that while recent projects teach important new lessons regarding LNG safety and reliability, every stakeholder in each LNG project must identify risks throughout its chain, evaluate and quantify under various likely scenarios, develop mitigation measures to reduce the risk to an acceptable level, and, finally, make business decisions based on the best available assessment of all interrelated risks.

2.3.7 Quality:

Basic quality requirements for projects are defined by the International Standard such as ISO 9001 in accordance with international best practices. ISO 9001:2008 specifies requirements for a quality management system where an organization needs to demonstrate its ability to consistently provide product that meets customer and applicable statutory and regulatory requirements, and aims to enhance customer satisfaction through the effective application of the system, including processes for continual improvement of the system and the assurance of conformity to customer and applicable statutory and regulatory requirements(*ISO-9000*, 2013).A stricter regime of quality control and verification, both through internal training and external certification, can help improve quality record even in the face of future competitive cost pressures, new players, and inexperienced new employees. The demand for highly skilled employees outstrips the supply across the energy industry, nowhere more so than for contractors with LNG experience and capabilities. On three recent occasions, suppliers have delivered cryogenic equipment with substandard welding quality. One of these incidents caused a leak with subsequent ignition and explosion – the infamous Skikda accident. The two others were detected, and the consequences were limited to serious project delays. The difference may have been a simple matter of personnel that were better trained to recognize risks, and managers that were willing to take action (Meyers et al, 2007). This signifies the importance of quality in infrastructure projects.

2.3.8 Human Resources:

Planning and executing large, high risk, capital projects means that the organizations have to create and maintain their project delivery systems. It is a major challenge to develop and implement a robust project management processes to support high capital expenditure projects. The major obstacle to implementing a new project delivery system or project management processes is the sheer inertia within the existing organization. The firm, as well as its entire supporting infrastructure, is organized to sustain the old way of planning and executing projects. The systemic challenges include all systems associated with human resources, management information, business processes and support staff that apply an organizational and behavioral change model for overall success. Success of any large project has a human resources angle to it and depends on the team and leadership (Luan and Wray, 2009).

2.3.9 Operation:

With an ongoing industry trend towards larger train sizes, and more emphasis placed on higher energy efficiency and lower greenhouse gas (GHG) emissions, the use of a technology that helps in ease of operation, reduces the operating expenditure to help the bottom line success. To that effect large electric motors to drive the compressors becomes of increasing interest (Kleiner et al 2005). The flexibility of operation also should include operation under varying climatic, gas compounds, density, volume flow rates and pressure levels. Achieving high levels of efficiency and availability will translate directly in an increased production output and an improved product quality (ABB, 2009).

2.3.10 Maintenance:

Maintenance is intended to achieve a maximum overall availability of the plant facilities at a minimal cost while ensuring safe operating conditions. This is achieved by internal control, coordination and efficiency and effectiveness by minimizing facility down time so as to achieve optimum equipment performance by minimizing maintenance costs in balancing direct and indirect costs. In today’s competitive market Asset Management is very essential for all enterprises, especially for asset intensive industries like Liquefied Natural Gas (LNG). Best Asset Management practices would be the premier tools for customer satisfaction, budget control, and firm’s edge over its competitors. The basic philosophy of maintenance of major process, rotating equipment and instrumentation should be predictive as opposed to reactive (Qatargas Maintenance documents, 2010). To accomplish this objective several asset management tools such as the Machinery Management System, Instrument Management System etc. can be included in the project design. These systems shall be networked to make the asset management diagnostics available remotely to maintenance personnel.

2.4 Project Execution:

Execution of the work to design, construct, install and start-up follows a discipline and orderly management approach outlines a Feasibility Study, followed by the pre-Front End Engineering Design, appropriate management reviews and completion of the Front End Engineering Design, EPC (Engineering Procurement and Construction), bidding and award of contract for execution of facilities, mechanical acceptance followed by commissioning and handover (Qatargas project documentations, 2005). The important elements of project execution have been discussed below (Qatargas project documentations, 2005):

- **Design and Engineering:** During design and engineering, specifications, standards and regulations need to be complied within consideration of operability, accessibility,
  maintainability and constructability by taking in to account start up, shutdown and upset conditions.

- **Equipment and Equipment Sparing:** Special attention need to be given to standardization and interchangeability of equipment, noise level and maintainability and consequence of failure of a single component or auxiliary component by adequate sparing. Equipment needs provisions for safe maintenance actions.

- **Human Factors:** Human Factor principles for safe and operable equipment be incorporated into the facility design. The guidelines require adequate access, egress, ease of operation, ease of maintenance and accessibility andfuture growth.

- **Project Management Team organization:** Project Manageent Team ensures performance in accordance with the requirements of the project, fully adapted to each specific phase of the work and resourced to complete the work in scheduled time.

- **Teambuilding Program:** Teambuilding session are held to develop a high-performing team working environment. Team building workshops are held at key project milestones and phases of the project.

- **Cost Effectiveness and Design Enhancements:** The opportunities for potential improvements of the facilities should be evaluated and an economic analysis should be condcuted for cost savings and cost effectiveness.

- **Information Security:** Tight security should be maintained for all sensitive documentation and other information to minimize any opportunities for individuals/organizations to obtain information without specific authorization.

- **Training of Personnel:** A training program need to be developed in accordance with the requirementsso as to make the personnel ready to operate and maintain the plant.

- **Management of Changes in the work:** Although the general effort is to minimize changes, design deveopment and other changes occurs during project, hence a management of change procedure should be developed and implemeneted with adequate risk assessments as required for various changes.

- **Interface Management;** It is required to establish for coordination for sharing of data and information for tie in among the various subprojects and other external operating plants for which an interface management has to be adopted.

2.5 Project Controls:

The Project Controls Plan which includes a standard project controls systems and procedures, reflecting minimum requirements to address key controls activities including: Planning and Scheduling, Progress Monitoring System, Cost Control and Estimating, and Accounting Procedure, Close Out Report and Change control is required to be developed and implemented. Planning and scheduling should meet the Project Completion Milestones including an appropriate level of detail in recognition of interfaces and coordination with other entities. Systems should be capable of producing a comprehensive range of reporting options to provide timely and concise decision-making information. Actual progress, showing start and finish dates, should be monitored against these schedules on an ongoing basis and available for formal distribution, to support the progress (Qatargas project documentations, 2005).Liquidated damages are payable in case performance guarantees are not met. It should guarantee the quantity of product defined with respect to the required input to the specifications. As soon as possible after the startup at a stage of running in steady conditions and the feedstock has reached its operating specification, a test run is undertaken in order to verify the performance guarantees for capacity and quality at their maximum operating conditions. If any guarantee is again not met, contractor shall have the option to pay liquidated damages in lieu of undertaking modifications due to performance deficiencies. If any LNG train fails to achieve an agreed auto-consumption level, the contractor has to pay liquidated damages as applicable (Qatargas project documentations, 2005). After completion of the work a project closeout report is produced, which summarizes the technical scope, project schedule, and cost of the activities. This report should incorporate overall summaries at the end of the work. It should further include a lessons learned report that covers engineering, procurement and construction. Lessons learned should focus on recommended strategies, plans, procedures and tasks that should be modified to enhance the execution success of the subsequent project (Qatargas project documentations, 2005).

2.6 Risk Identification/Allocation/Mitigation:

Risks affecting organizations can have consequences in terms of economic performance and professional reputation, as well as environmental, safety and societal outcomes. Therefore, managing risk effectively helps organizations to perform well in an environment full of uncertainty.ISO31000:2009, (Risk management) – Principles and guidelines, provides principles, framework and a process for managing risk. Using ISO 31000 (ISO 31000, 2013) can help organizations increase the likelihood of achieving objectives, improve the identification of opportunities and threats and effectively allocate and use resources for risk treatment. The success parameters for any project are in timely completion, within the specific budget and with requisite performance or technical requirement. Large-scale project are exposed to uncertain environment because of factors such as planning and design complexities, presence of various interest groups, resources availability, climatic conditions and economic and political environment and statutory regulations etc. The first task in management of a project is to acceptance of the fact of existence of risk and creation of a framework for risk identification and management(Holding et al, 2007).Established project management practice starts with proper project definition and forward planning followed by careful management of costs, time and resources during the design, engineering and construction, implementation and operational phases so as to extract maximum economic value from the investment by minimizing risk of failure to comply with the project objectives. Through the correct assessment and quantification of risk the appropriate mitigation strategy can be applied from the Transfer, Take, Terminate or Treat the associated risk. Project Value can be destroyed by unmitigated risk impact and the process should address this possible consequence in the context of probabilistic analysis of the Schedule, Estimate and Project Economics (Holding et al, 2007). Risk Management is the systematic and structured process of identifying, analysing and managing risks in order to maximize project value. In other words risk is the identification and recognition of uncertainty which can have either positive (opportunity) or negative (threat) implications, and in some cases both. The process involves an examination of the likelihood or probability of a risk happening and the associated consequences if it does occur. Risk Management minimizes the probability and consequences of adverse events and ensures those risks accepted by the project have been allowed adequate contingency in the budget if they were to occur (Holding et al, 2007).The key steps in this management process are a) Risk identification b) Risk evaluation c) Risk mitigation d) Review and closure(Qatargas project documents, 2005).

2.7 Risk Register:

A key output of the risk management process is the Risk Register. It is a live document that captures key information about risks and their mitigating actions and is the key management tool for communication and tracking of risks/actions. Identified risks are captured and recorded on a Risk Register which allows priorities to be set and identified mitigating actions to be tracked until closure (Qatargas project documentations, 2005).

2.8 Risk Management Methods:

Risk management is an increasingly important business driver and stakeholders have become much more concerned about risk. Risk may be a driver of strategic decisions, it may be a cause of uncertainty in the organisation or it may simply be embedded in the activities of the organisation. An enterprise-wide approach to risk management enables an organisation to consider the potential impact of all types of risks on all processes, activities, stakeholders, products and services. Implementing a comprehensive approach will result in an organisation benefiting from what is often referred to as the 'upside of risk' (http://theirm.org/documents/SARM_FINAL.pdf, 2013).

a) Ishikawa diagram:

Ishikawa diagrams also called fishbone diagrams, or cause-and-effect diagrams that show the causes of a specific event. Common uses of the Ishikawa diagram are to identify potential factors causing an overall effect. Causes are usually grouped into major categories to identify these sources of variation. When there is a problem, it's important to explore all of the things that could cause it, before starting to think about a solution. That way the problem can be solved completely. It is a Cause and Effect Analysis with this diagram-based technique, that consider all possible causes of a problem.

A fishbone diagram helps identify the cause and effect relationship that exists in every system. The head of the fishbone diagram is the effect; the bones (typically six) in the fishbone diagram are the generic causes behind every effect. Kaouru Ishikawa (1915-1989), a renowned Japanese engineer, identified the generic causes in the fishbone diagram as the six Ms: Machines, Manpower (people), Methods (Processes), Mother Nature (Environment), Money and Measurement (The Fishbone diagram and The Reverse Fishbone Diagram Conceptswww.processexcellencenetwork.com, 2013).

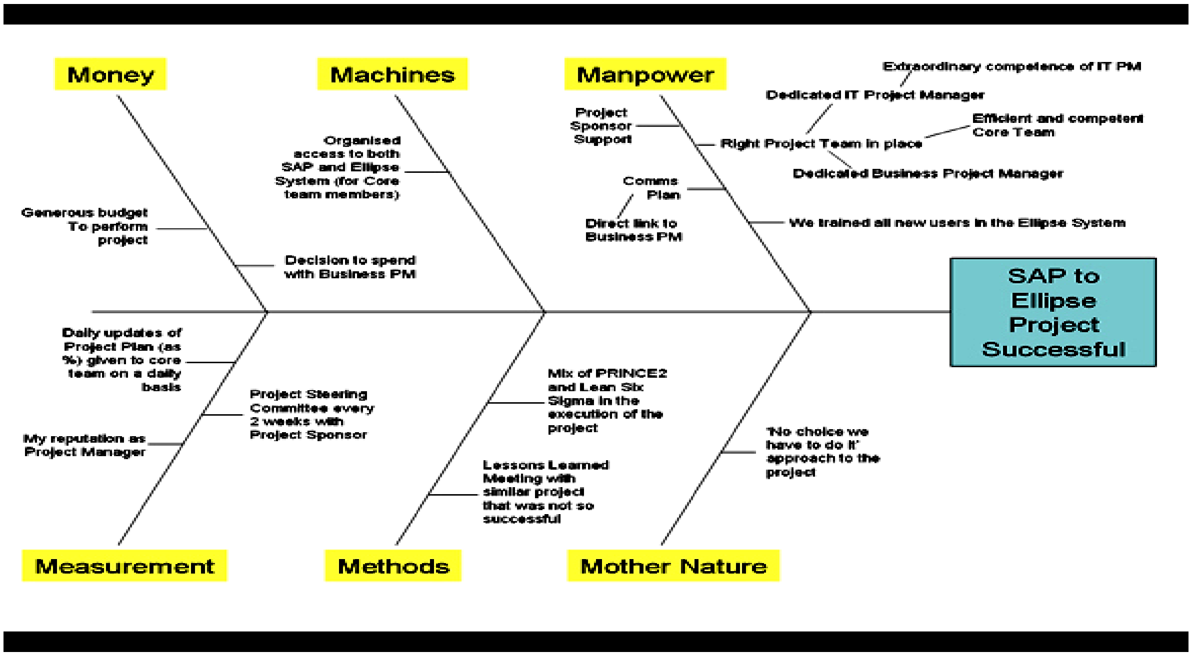


Figure 2.1 Ishikawa diagram: (Ref-*The Fishbone Diagram and the Reverse Fishbone Diagram Concepts*; www.processexcellencenetwork.com, 2013)

b) Five whys:

The ‘5 Whys’ is a method of asking questions ‘why’ several times to explore the cause/effect relationships underlying a particular problem. The ‘5-Whys’ is a simple problem-solving technique that helps to get to the root cause of a problem quickly in a simple, easy to learn and apply method (Qatargas document, 2010).

c) Fault tree:

Fault Tree Analysis attempts to model and analyze failure processes is basically composed of logic diagrams that display the state of the system and is constructed using graphical design techniques. Typically failure rates are derived from substantiated historical data such as mean time between failure of the components, unit, subsystem or function. It also helps identify corrective actions to correct or mitigate problems (Qatargas project document, 2010).

d) Root Cause Analysis:

Root Cause Analysis implies the conducting of a full-blown analysis that identifies the Physical, Human and Latent Root Causes of how any undesirable event occurred. The analysis may include safety incidents, quality defects, customer complaints, administrative problems and the similar events. Root Cause Analysis is applicable to many more than just mechanical situations (Qatargas project document, 2010).

e) Failure Mode and Effects Analysis (FMEA):

A FMEA is an inductive analytical technique used to identify hazards in complex process systems. A failure mode is an event that causes a functional failure and a failure effect describes what happens when the failure mode occurs, which should be analyzed in sufficient details for it to be possible to select a suitable failure management policy (Moubray, 1992).An FMEA involves a tabulation of potential failure modes of various components of a system and the effects of these failures on the overall system. It also includes an estimate of consequences resulting from the failures. The traditional Failure Mode & Effect Analysis (FMEA) is commonly used in many industries to identify and address design deficiencies in the early stages of a development (Judd et al, 2007).

2.9 Value Engineering:

Value engineering can be defined as an organized effort directed at analyzing designed building features, systems, equipment, and material selections for the purpose of achieving essential functions at the lowest life cycle cost consistent with required performance, quality, reliability, and safety (*U.S General Services administration*, 2013).Value engineering is a systematic and organized approach to promote substitution of materials and methods with less expensive alternatives, without sacrificing functionality(www.investopedia.com, 2013). From the point of view of the LNG production facilities, the concern is in developing a low cost and technically sound process solution with desired plant reliability, availability, maintainability. Again, the conflict between the desire to reduce project cost and the evaluation of production and delivery risks requires an understanding in order to achieve a compromise on the cost-benefit ratio of a particular project. It is recommended that these value engineering should include all the possible contributors to cost effectiveness, such as owners, contractors, vendors, process licensors, etc. The growth of LNG train size is the result of technical teams attempting to achieve the lowest unit cost of LNG production. At the same time, these larger capacity single trains are in many cases able to satisfy the typical market size contracts that the commercial teams are developing. As a result, the LNG business has started to see the appearance of single train projects, both grass roots and expansions, with similar capacity/availability as some of the existing multiple trains projects. (Durr et al, 2001).Another concept that has been proposed is to build “small” LNG plants, to avoid all the problems associated with larger projects. This concept does not seem to be economic except for example, if the small plants are close to the market thus reducing the cost of LNG shipping, then the higher unit cost of LNG production associated with small plants may still be economic, when looking at the project as a whole. Another possible situation is where there is very significant step out technology or infrastructure that would lower the cost of production (Durr et al, 2001).Increased competition in the LNG market results in downward pressure on LNG prices. The response is a push for cost savings in all aspects of the LNG chain, namely gas production, liquefaction, shipping, re-gasification and pipelining. Many of the proposed cost reduction measurements are based on economy of scale, integration of facilities, modularization, and reduction in spare equipment and use of larger ships with alternative propulsion systems(Durr et al, 2001). Hence Value engineering should therefore be used to aid selection of the best solution.

2.10 Availability, Reliability, Maintainability, Capability:

For a project in process industry, it is always desired to have the lowest life cycle cost. However, the traditional approach considers the capital cost, operation cost etc. except the cost related to the process reliability and availability. Once the design is fixed, it may be later discovered that the system does not provide the sufficient reliability and availability. However, it may be very expensive to change the design at this time. This reality drives a proper Reliability, Availability and Maintainability (RAM) studies upfront, simultaneously with the design, so as to avoid any major changes in order to maintain production with a reduced down time during the life of the plant. To understand the relation between reliability, availability and maintainability is very critical for integrating RAM study into process synthesis (Yin et al 2009). The elements of the effectiveness equation provide insight into how things work in a continuous processing plant and clues to where corrective action may be helpful. In all cases, alternatives should be considered, based on life cycle costs, for ranking the high cost of problem so the important issues can be identified for corrective action (Barringer, 1997).

a) Reliability:

Reliability deals with reducing the frequency of failures over a time interval and is a measure of the probability for failure-free operation during a given interval. In other word, it is a measure of success for a failure free operation (Barringer, 1997). Reliability is defined to be the probability that a component or system will perform a required function for a given period of time when used under stated operating conditions. Mean Time To Failure (MTTF) and Mean Time Between Maintenance (MTBM) are two of reliability measurements (Yin et al, 2009).If the time (t) over which a system must operate and the underlying distributions of failures for its constituent elements are known, then the system reliability can be calculated by taking the integral from‘t’ to infinity, as shown in the following equation (DOA, 2007)

$$R(t) = \int_t^{\infty} f(t)\, dt$$

Reliability: $R(t) = e^{(-t/MTBF)} = e^{(-\lambda t)}$ (Yin et al 2009)

(Where λ is constant failure rate and MTBF is Mean Time Between Failure and 't' is the number of hours in a year.)
MTBF measures the time between system failures for a given mission time, to achieve high reliability, a long MTBF is required which increases productive capability while requiring fewer spare parts and less manpower for maintenance activities which results in lower costs (Barringer, 1997). It is closely related to downtime due to corrective maintenance. To the user of a product, reliability is measured by a long, failure free, operation. Long periods of failure free interruptions results in increased productive capability (Barringer, 1997).

b) Availability:

Availability deals with the duration of up-time for operations and is a measure of how often the system is alive and well. It is often expressed as:

Availability= (Up time)/(Up time + downtime) (Yin et al, 2009)

Up time refers to a capability to perform a task and downtime refers to not being able to perform the task. As availability grows, the capacity for making money increases because the equipment is in-service a larger percent of time (Barringer, 1997). Jaimeson (1998) defines availability as the net annual production divided by the design daily production multiplied by the number of days in a year. The plant availability is closely related to the plant downtime, which is the sum of the preventive maintenance and corrective maintenance hours. Very frequent preventive maintenance will cause the operation to lose profit through reduced product throughput. Insufficient preventive maintenance will cause the process to suffer unscheduled breakdowns, needing corrective maintenance. The trade-off is an optimal Preventive Maintenance (PM) interval exists at the point where the availability is the highest with efficient utilization of maintenance resource.

c) Maintainability:

Maintainability deals with duration of maintenance outages or 'how long' it takes to achieve, with ease and speed. The key figure of merit for maintainability is often the mean time to repair (MTTR) and a limit for the maximum repair time based on the total down time for maintenance including: diagnosis, trouble shooting, tear-down, removal/replacement, active repair time, verification testing that the repair is adequate, delays for logistic movements, and administrative maintenance delays.

$$\text{Maintainability } M(t) = 1- e^{(-t/MTTR)} = 1 - e^{(-\mu t);}$$

Here μ stands for constant maintenance rate and MTTR is the mean time to repair. High availability (high up-time), high reliability (few failures) and high maintainability (predictable and short maintenance times) tend toward highly effective systems if capability is also maintained a high levels (Barringer 1997).

d) Capability:

Capability deals with productive output and is a measure of how well the production activity is performed compared to the datum. This index measures the systems capability to perform the intended function on a system basis. Often the term is the synonymous with productivity which is the product of efficiency multiplied by utilization. **Efficiency** measures the productive work output versus the work input. **Utilization** is the ratio of time spent on productive efforts to the total time consumed or available (Barringer 1997).

Capability= Efficiency x Utilization

e) Effectiveness:

Effectiveness is defined by an equation as a judging the opportunity for producing the intended results and how well the product or process satisfies end user demands and to find areas for improvement. Higher effectiveness is generally better than lower effectiveness. Effectiveness is generally a measure of value received (Barringer 1997).

Effectiveness = availability * reliability * maintainability * capability

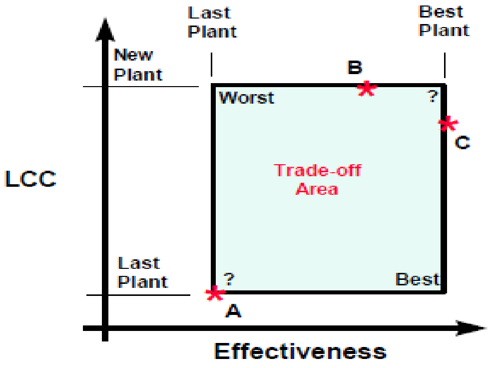
The effectiveness equation is the product of: (Barringer 1997)

- The equipment/ system will be available to perform its duty (Availability),
- It will operate for a given time without failure (Reliability),
- It is repaired without excessive lost maintenance time (Maintainability),
- It can perform its intended production according to the standard (Capability).

f) System effectiveness equations (Effectiveness/LCC):

System effectiveness equations are helpful for understanding benchmarks, past, present, and future status as shown in for understanding the trade-off. Referring to the figure below the lower right hand corner brings much joy and happiness often described as “bang for the buck” (Weisz, 1996). The upper left hand corner brings much grief. The remaining two corners raise questions about worth and value (Barringer, 1997). The major and unarguable economic issue is finding a system effectiveness value which gives lowest long term cost of ownership using lifecycle costs (LCC) for the value received.

System effectiveness = Effectiveness/LCC (Barringer, 1997).



Parameter	A Last Plant	B New Plant	C Best Plant
Availability	0.95	0.95	0.98
Reliability	0.3	0.4	0.6
Maintainability	0.7	0.7	0.7
Capability	0.7	0.8	0.6
Effectiveness	0.14	0.22	0.25
LCC	80	100	95

Figure 2.2 System Effectiveness Example Source (Barringer, 1997).

In the above example shown, although the plant C has a lower capability because of its higher availability and reliability and a lower Life Cycle Cost (LCC) has a better effectiveness that Plant B. The elements of the effectiveness equation provide information about how things work in a continuous processing plant and where corrective action may be particularly helpful. In all cases, alternatives should be considered, based on life cycle costs, for ranking the high cost of problems so the important issues can be identified for corrective action (Barringer, 1997).

g) **Thermal efficiency:**

Thermal efficiency of a LNG facility is defined as the total energy that can be sold from the facility divided by the total energy that is delivered to the facility. Thermal efficiency is an important benchmark that is used to compare various liquefaction technologies. Higher thermal efficiency can significantly lower lifecycle operating costs and improve plant economics. LNG operators can greatly improve profitability by focusing on plant thermal efficiency (Meher-Homji et al 2008). The thermal efficiency of a LNG facility depends on factors such as gas composition, inlet pressure and temperature, compressor driver selection, the use of waste heat recovery and self-generation versus purchased power. A common consideration in evaluating competing LNG technologies is the difference in thermal efficiency. When evaluating the benefits of achieving a high thermal efficiency with a specific LNG plant design, a true accounting of all of the energy being consumed in the process must be considered. Turndown capabilities of an LNG process also need to be considered when thermal efficiency and lifecycle comparisons are being made. The efficiency of a LNG process is dependent on two most significant factors; efficiency of heat exchange and the turbo-machinery efficiency. The turbo-machinery efficiency depends on the compressor and turbine efficiencies (Meher Homji et al, 2008). Keeping the compressor efficiency constant if the driver efficiency is improved by replacing the gas turbine by a more efficient driver such a Variable Frequency Drive (VFD) electrical motor system with a much higher efficiency the overall LNG process efficiency can be improved.

2.11 Technology Qualification Management:

Technology provides organizations with the opportunity to transact business more efficiently and effectively. It is changing at a faster pace, which has significant implications on conducting new project work. In an era where the new technology development is the order of the day the question that needs to be asked is how a technological change affects the way we conduct business to achieve a corporate bottom line success (Frame, 1994). Increasingly challenging projects increase the likelihood that new technology will be required. In order to make advances in technology, it is necessary to develop and execute a risk management plan to ensure that technology advances are correctly executed with minimum risk. When evaluating the risk for new technology prototypes it has to be determined as to what extent the technology is new, i.e. how different it is from something that is proven and how many years of proven experience in similar service. The key to successful risk management is to first identify all the project risks in three categories: design, execution, and prototype or unproven technology. Once the risks are identified, the relative importance of each risk is determined by estimating the cost of eliminating or substantially reducing each risk item (Durr et al, 2001). A structured approach to risk management during the maturation of the project has to be undertaken, with considerable attention given to both technology integration and technology qualification activities for critical processes and equipment. Technology Qualification Management System Process has to be employed to systematically determine the suitability of all new critical equipment and processes. While challenging from the standpoint of financing, technical and project execution considerations, all key issues need to have been addressed and the pathway for a successful project to be clearly defined (Thompson et al 2003). Pinkerton (2003) believes that Technology Qualification Management System is the process of analyzing available technologies in assessing the comparative value of alternative technologies in relations to ventures undertaken. This process not only identifies and addresses the knowledge and technology gaps that may exists and must be overcome but also assist in pointing out the risk involved in such frequently overlooked factors such as potential early obsolescence and insufficient knowledgeable resources both in-house and outsources.

Risk= f (probability or likelihood of occurrence x consequence of occurrence)

To reach an agreement and optimize the cost of the project and its ability to finance it is necessary to provide a quantitative risk assessment of all proposed cost reduction measurements. The risk is defined as the consequence of not achieving the required production as a result of a given upset condition directly related to the proposed cost reduction scheme. Technology Qualification Management is the process of providing the evidence that a technology will function within specific operational limits with a specified level of confidence. Consequence of an event can be quantified in monetary units as per above formula or in lost production days, which are always convertible to monetary units. These additional requirements can be justified and the resultant increase in capital costs accepted based on ease of operation, safety, risk aversion, increased production and the like. The issue is not one of trimming specifications but one of understanding all their consequences and insuring they will meet the project objective (Durr et al, 2001).Since the large investments incurred and success of the project hinges on these technologies, a very rigorous and structured approach need to be developed for the introduction of new technologies, from project inception through all the stages of project execution and in to operations (Khoo, 2009). This formalized technology qualification process is a systematic method for analyzing cost, schedule, risk, reliability and a process of supporting integration of new technology into projects. Technology Qualification is a tool to qualify or move “emerging technologies” to a deployment-ready state (Chaplin,2009). In order to manage the implementation; these technologies can be divided into three categories, new to the industry, new to the company, and significant step outs in size (Khoo et al, 2009). Improved technology will play an increasingly important role in achieving the corporate bottom line. A structured approach maximizes the chances of success of deploying new technology. A Successful Technology Qualification Process provides a tool to efficiently assess the readiness of new technologies to be used to assess both internal and external technologies by a scalable process for technology qualification (Chaplin, 2009). It helps in technology deployment with an increased level of confidence through a better understanding of the risks and probability of success. A multi-disciplinary, cross-company team supported by participation will help in assuring alignment of stakeholder. Working in close partnership with critical vendors, extensive and elaborate modeling and testing programs and a comprehensive review to assess potential issues and mitigation actions is required.

2.11.1 Technology Qualification Process (TQP):

As the analysis progresses the process should be documented. Pinkerton (2003) outlines the following steps to be followed in new technology qualification process. A statement of objective laying out the parameters for the analysis has to be followed by a list of potentially viable sources that comply with the statement of objectives. An examination of previous qualifications and application and pilot plant testing should be conducted. Complete review of safety and environmental issues to be done to ensure that process or equipment confirm to regulations. Financial comparisons factors including initial cost of equipment, operating and maintenance considerations including compatibility with the existing work force have to be studied. The licensing and legal ramification of acquiring anyone of the alternative technologies with long rage corporate strategies has to be analyzed. Chaplin (2009) suggests the fowling Technology development Process workflow(Figure 2.3) and Technology Development Stage (TDS) Table (Table 2.1). Qualification process is a necessary first step in the deployment of new technology. The Technology Development Process (TDP) may take several iterations of the Process cycle to reach the desired Technology Development Stage (TDS).

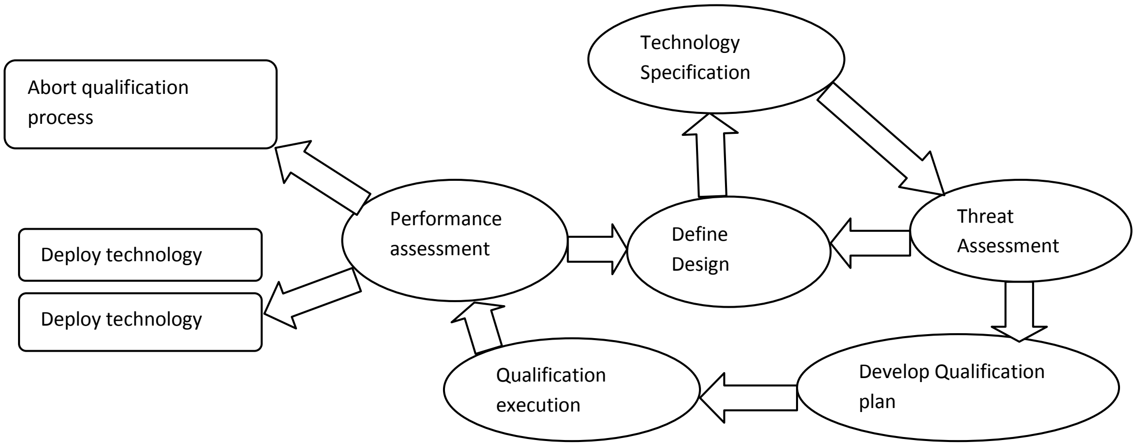


Figure 2.3 Technology development Process workflow: Source Chaplin (2009)

The key is to minimizing significant step-outs in technology, leveraging previous experience in similar project execution, keeping a close oversight during engineering design, manufacturing and testing, ensuring an adequate design margins, implementing an extensive audit program and a comprehensive testing program, ensuring advanced manufacturing technology and a rigorous vendor qualification and ensuring online maintenance capability(Khoo et al 2009).

TDS		Name	Description
Strategic research	1	Initiation	Basic principles observed and reported
	2	Concept	Technology concept and/or application formulated
	3	Proof of concept	Analytical and environment critical functions and/or characteristics proof of concept
Technology development	4	Integration	Component and/or bench configured and sub-system validation in laboratory environment
	5	Demonstration	Component and/or bench configured and sub-system validation in real world environment
	6	Prototype	System or sub-system model or prototype demonstration in a relevant environment
	7	Pre-production	System prototype or system demonstration in the intended operating condition and environment
Application	8	Production	Actual system completed and qualified through tests and demonstration in realistic operating environment
	9	Field proven	Actual system(s) proven through successful field operation@Chevron U.S.A Inc alright reserved

Table 2.1: Technology Development Stage, (Source Chaplin, 2009)

2.12 Sustainability:

Sustainability in general refers to the property of being sustainable and a sustainable development is a progress that meets the needs of the present without compromising the ability of the future generation to meet their future needs. The benefits are reducing operating and maintenance cost, enhanced productivity, improve safety, environment quality and reduce greenhouse emission and by this increase overall profit (Gulati, 2013). A sustainable company in industry considers not only business development and profit, but also environmental protection and social responsibility. However, stakeholders are now demanding proof of the “overall sustainability performance” of operational initiatives such as undertaken projects or technological innovations. Brent et al (2004) have outlined the drivers that need to be incorporated into the business process for sustainability. This involves incorporation of sustainability as a core business process by pressure from regulating authority as a license to operate. Investors also push the organization to incorporate sustainability to demonstrate good corporate governance. International trade agreement also insists on sustainability practice for license to sell the product. Last but not the least the business process is aligned with and supported by the responsibility and care principle of corporate social responsibility.

To assess the sustainability of such operational initiatives in industry, Brent et al (2004) suggest following measures to understand the extent operational initiatives are aligned with the principles of sustainable development:

- The interaction of life cycles from an industry perspective must be addressed.
- A framework of sustainable development criteria, relevant for operational initiatives in industry, must be defined.
- Two types of sustainable development indicators namely, the environmental and social dimensions of sustainability must be followed.

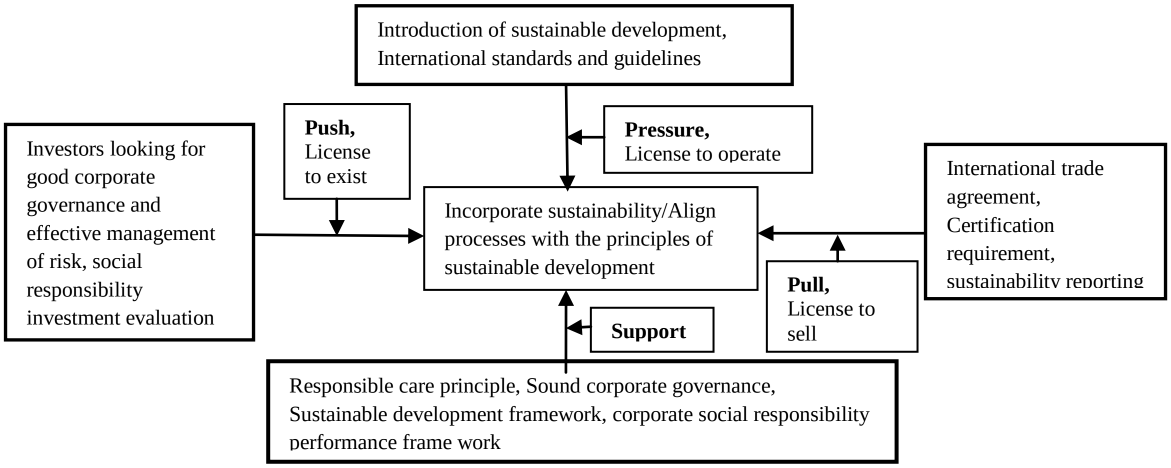


Figure 2.4: Drivers to incorporate sustainability into business Ref- Brent et al, 2004

In order to assess sustainability performances in industry, a framework of appropriate criteria and associated indicators has to be defined. A number of current integrated frameworks, need to be reviewed to determine the relevant aspects or criteria that should be considered when assessing industry sustainability. From a business perspective, the inclusion or consideration of social aspects in sustainability practices is marginal compared to the environment and economic dimensions. Certain social impacts are more important in certain phases, while it has been evident that stakeholder participation is crucial in all life cycle phases (Brent et al 2004).

2.12.1 Environmental Impact Assessment (EIA):

EIA (Environmental Impact Assessment) assesses the potential impacts of a proposed activity on the environment. It describes the impacts, and documents ways to avoid, minimize or mitigate potential negative impacts of a project. The ISO 14000 family addresses various aspects of environmental management. It provides practical tools for companies and organizations looking to identify and control their environmental impact and constantly improve their environmental performance (ISO-14000, 2013). An EIA is a process designed to contribute pertinent environmental information to project decision making. The assessment attempts to predict or measure the environmental effects of the project and rank their environmental significance, apart from identifying methods to prevent or minimize those effects. Long and Short-Term potential impacts are identified for the design, construction, operation, maintenance, decommissioning and abandonment of the project (Qatargas project documents, 2006).

2.13 Life cycle process and interactions:

A prerequisite for aligning operational initiatives, such as undertaken projects or technological innovations, with the principles of sustainable development is a clear understanding of the various life cycles that are involved and the interactions between these life cycles. Three distinct life cycles can be distinguished, namely: project life cycle, asset or process life cycle and the product life cycle.

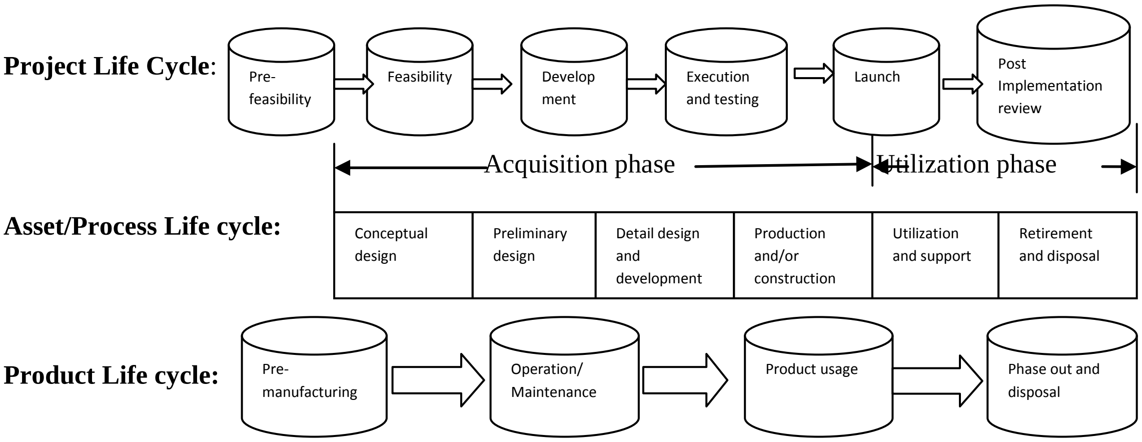


Figure 2.5: Interaction between the project, asset and product life cycles (Brent et al 2004).

A project in this context is viewed as a vehicle to implement a capital investment in a new or improved asset or technology. Each of these life cycles consists of various phases (Figure2.5) and nevertheless interacts, for example: the product and asset life cycles interact, while the asset and the project life cycle also interact (Figure 2.6 and 2.7).

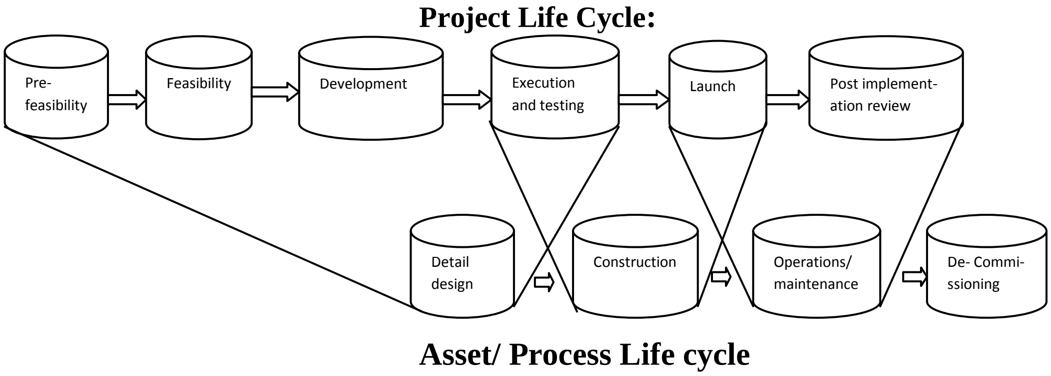


Figure 2.6: Interaction between the project and asset life cycles(Brent et al 2004)

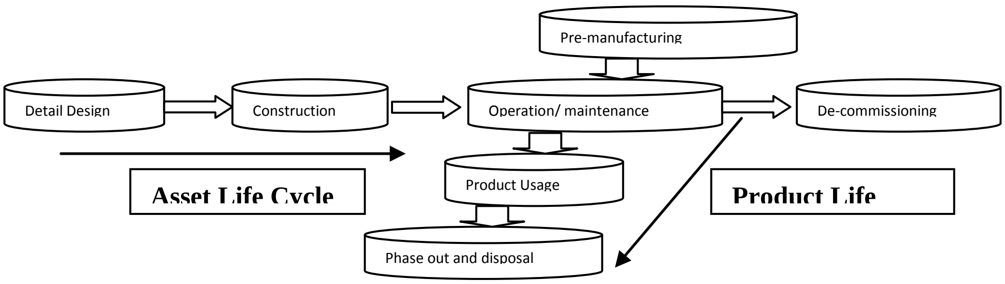


Figure 2.7: Interaction between the asset and product life cycles (Brent et al 2004)

If the sustainability of a project or technology is assessed, the impacts or consequences of the assets and products associated with the project or technology must be included in the assessment (Brent et al 2004).

2.13.1 Whole Life Cycle costing:

Whole life cycle costing approach, based on cost of ownership rather than capital cost, to design, procurement, construction and facilities management is delivering major benefits. Recent initiatives whole life costs in order to prepare detailed financial and risk management plans for projects. Performance and durability of components are inadequately considered and maintenance and operating costs rarely forecast. However, for every unit of capital cost, several units are spent on maintenance, staffing, opportunity loss and environmental consequences. Savings in whole life costs can thus be dramatic over the operating life of the asset benefiting both the clients and the supply chain (Meyers et al, 2004).

2.14 Life Cycle Cost and Profitability Analysis vs. Capital Cost:

Life Cycle Cost, or the total cost of ownership, is an economic index widely used today to aid in the analysis and selection among different project designs or process alternatives. Life Cycle Cost is not an index of profitability. It does not measure income and compare it to cost as profitability does, but looks only at total cost. Estimates of project’s profitability are the basis for a project approval if it satisfies the precondition of adequate returns (Durr et al 2001). Profitability is expressed in different ways i.e. as time to recover the investment, as return on investment, as net present value at a chosen fixed rate of return etc. Life Cycle Cost is expressed only on a monetary basis (Durr et al 2001). Since Life Cycle Cost is applied for a given period of time, all deferred costs are converted to net present value (NPV) for comparison purposes. A typical profitability analysis uses the discounted cash flow rate of return criteria, which includes all cash flows (in and out flows) over the entire life of the project, and adjusts them normally to the start-up time. The calculation required for the cash flows of the project is equivalent to the calculation of the Life Cycle Cost. This is normally defined as the sum, throughout the lifetime of the plant, of the capital expenditures (CAPEX), operating expenditures (OPEX); maintenance expenditures (MAINTEX). The calculation of the NPV assumes a rate of inflation and/or price increase and compensates with the required capital interest rate. Although, both economic criteria, profitability and Life Cycle Cost, complement each other, they are used for different purposes. In general, it can be said that while profitability is mainly a concern of high-level management, Life Cycle Cost is a concept used for making engineering decisions between alternative options or tradeoff studies during design, operation, and maintenance of the plant facilities (Durr et al 2001). A major consideration in the Life Cycle Cost and/or profitability analysis is the effect that schedule reduction has on the economics of the project. This is due not only to their sensitivity to interest rates, escalation costs, etc. but also to the project viability, often based on a window of market opportunity. As such, the speed to the market is a key element between the technical and commercial teams. Hence, the technical design must have the project execution schedule as one of the primary considerations in the technical design. It is important when comparing Life Cycle Costs that all cost throughout the defined life span of the plant be considered. Thus, Life Cycle Cost should include direct and indirect cost, maintenance and operational cost, service reliability and its effect on overall production. A structured methodology should be followed to obtain the necessary information in order to make informed decisions. In this regard, the use of a reliability/availability/ maintainability (RAM) model is of paramount importance to be able to quantify proposed changes in terms of availability and product deliverability. Another advantage of the Life Cycle Cost analysis is that it often helps to identify where data deficiencies are reducing the accuracy of the analysis and costing money. There is always the tendency by the contractor to reduce the scope and its initial capital cost in order to provide the lowest lump sum bid. However, this may be at odds with the owners desire to reduce lifecycle cost. Hence in the bidding process, the owner should be very clear about his evaluation criteria. It should be emphasized that since profitability is a long term concept it can only be determined after a long period of time of operation (Durr et al 2001). Profitability calculation for future projects are only estimates and short term profitability should be reviewed very carefully. In order to improve the overall performance of the project, successful operation in the first few years is paramount. Hence, an analysis of this aspect of the economics is essential in the proper selection of the technical solutions (Jamieson, 1998).

2.15 Life cycle evaluation:

Capital cost is not the only driver in project economics and capital cost reduction cannot be an objective all by itself. Capital cost must be balanced with fuel costs, maintenance costs, and plant reliability. Safety and environmental issues are also of paramount importance. The full impacts of capital cost decisions must be analyzed overall aspects of the project and over its entire life. Total cost of ownership or life cycle cost evaluation is common terms for this kind of assessment. Unless reliability and availability issues are addressed properly and maintenance costs evaluated thoroughly it is easy to reach wrong conclusions. Furthermore recommendations based on simple payback evaluations or even net present value economics can be wrong unless proper consideration is given to tax and financing issues (Jamieson, 1998).

2.16 Criteria for selection of a compressor driver:

Most of the processes in the chemical, oil and gas industries are complex and are exposed to the harshest environmental conditions. These conditions put a high demand on the process equipment. Achieving high levels of efficiency and availability will translate directly in an increased production output and an improved product quality (ABB, 2009). Before selecting the main drivers for the large compressors used in the process plant, the following factors needs to be considered (Meher-Homji, 2011).

- **Driver Power Capability-** The power developed by the driver must be appropriate for the worst case situation taking into account the highest ambient temperature, and a level of performance degradation over the life.

- **Reliability and Availability Experience –**The viability of the LNG Plant is highly dependent on availability of the refrigeration equipment. The reliability takes into account forced outages, while the availability parameter includes scheduled and planned maintenance schedules including the force ones.

- **Capital Cost –** The competitiveness and viability of a LNG project is very sensitive to the installed cost**.** The capital cost of power generation must be considered as the selection of driver type will impact power generation requirements.

- **Technical Issues**– These include the operating speed of the driver, speed variability, starting torque capability and controllability and rotor-dynamics considerations.

- **LNG Plant Thermal Efficiency Considerations**- With the increased emphasis on limiting global warming, and as fuel costs increase, the issue of overall thermal efficiency is important consideration without sacrificing reliability and availability. LNG technologies should be compared based on thermal efficiency and economic and environmental merits.

- **Operation at part load conditions:** As the temperature changes during the day it impacts the performance of the gas turbines and the operator needs to continually adjust plant parameters to achieve optimal performance which impacts overall thermal efficiency of the gas turbine and the plant and lifecycle costs. The turbo machinery efficiency depends on the compressor and gas turbine efficiencies. Compressor driver plays an important role in the thermal efficiency, greenhouse gas emissions, and flexibility under various operating conditions. Where high fuel costs are expected, the selection of a high efficiency driver becomes a strong criterion in the lifecycle cost evaluation.

- **Effects of site conditions on driver performance (Meher-Homji, 2011):** It is important to understand the effects of site conditions on gas turbine performance as they directly will impact the LNG production rate. Site conditions such as ambient temperature, altitude (atmospheric pressure), Inlet filter pressure losses; exhaust system pressure losses, ambient humidity effects and influence in changes in fuel heating value are some of the factors that directly affect the gas turbine output.

- **Improved control and flexibility of processes:** Outputs of oil and gas fields can vary greatly in their compounds, density, volume flow rates and pressure levels. This imposes varying operating conditions on process equipment, which means that compressors and pumps, which must exhibit a high degree of flexibility, cannot always be operated at their optimum design point.

- **Reduced faring:** The drive need to be considered that can restart the compressor after a trip with fully pressurized condition without have to flare the inventory which lead to loss of revenue and increase emission.

- **Multiple start an restarts:** The drive which gives a flexibility to start several time without being have to wait for thermodynamic stress consideration.

- **Least time to start and load:** The drive that gives the flexibility to load quickly without thermodynamic stress concerns.

- **Life cycle benefits:** The drive system which offers a life cycle benefit should be considered. Generally the efforts of project are centered on reducing the CAPEX, whereas for life cycle benefits both CAPEX and OPEX should be considered.

2.17 Conclusion:

In order to achieve successful outcome of any project there are various aspects that need to be looked into. Every project is unique in itself as far as the challenges faced, resolutions achieved and lessons learnt. A conventional approach to project management is to establish an adequate relationship among all the phases of the project, forecast project achievement for building confidence in the team, make decision on the basis of available data base, provide adequate information for effective management to enable to achieve corporate bottom line(Fink and Beaty, 2001). Risk analysis is important to make objective decision for completing the project in time, within the budget and within the requisite specification in line with the project objectives and organizational policy. These are some of the factors that drive the decision about the new project and affect the amount and type of investments. Taking short cuts in making economic analysis may lead to inappropriate decisions.LNG business remains a highly capital intensive, technologically sophisticated, long-term business, needing long-term planning and continuing cooperation between the project host country, sellers and buyers (Troner 2001). In the coming years, there is a huge market growth potential for LNG. To that effect a Technology Qualification Management Process is essential to formally assess technology and make high quality risk-based decisions regarding deployment of new technology in to a new project based on life cycle benefits. This process should be applied to qualify conventional, step out, scale up or new technology. The above discussion about literature review delves into literatures related to successful completion of large projects and the factors that need to be looked into from an Engineering Management perspective.

2.18 Hypothesis Building:

The hypothesis of the study has been built in three steps. In the first step alternative option to the conventional compressor drivers have been discussed. The next step identifies the gap in research between the convention and the proposed alternative. The final step the hypothesis is built.

2.18.1 Alternative theory:

When given to decide an alternative technology to the convention the bottom line is that it is either better or worse. The decision on the project depends on value of the project cost and receipts, interest rates, possible returns, tax regulations, available financing risk and reward etc. As per Fink and Beaty (2001) the investment decision to choose between alternative technology depends on ability to borrow money, relative risk between alternative, possibility to capitalize tax benefits, timing of the costs and revenue based on schedule completion, ability to shift investments to a more attractive alternative and ability to maintain and operated the equipment cost effectively. The technological innovations and improvements are changing the LNG business today. By lowering costs and increasing flexibility, these changes will have dramatic impact on the development of the LNG business, with important consequences. Rising environmental concerns are growing world concerns. Hence a technology that provides a lesser environmental impact will certainly will have to be considered for future LNG development. Further, the section 2.17has discussed various criteria for selection of a compressor driver for LNG process. In theory moderately large Variable Frequency Drive (VFD) motor systems which are used as starter/ helper motor for the large gas turbine compressor strings have the potential to be used as a main driver to the compressors and fulfill the future requirement of LNG process driver better than the conventional gas turbine drivers.

2.18.2 Need for research, knowledge gap and research contribution:

No major substantial study has been done so far to research whether a VFD Electrical motor system hitherto referred to as “All-Electric Drive” system can be used as a main driver for the major compressors in the LNG plant by completely replacing the mechanical gas turbine drives. Further, the constraints and hurdles for an All-Electric drive concept has not yet been thoroughly dealt with. A detailed research needs to be carried out to bridge this gap so that a viable alternative to the conventional gas turbine driver can be identified. Further, there is a need for a study to determine why it not preferred as an option in present LNG development and bridge the gap in knowledge and understanding. The purpose of the project is to explore various aspects of engineering management and will do a detail investigation on the challenges faced on a major project from a life cycle perspective and from engineering management stand point. As ‘All Electric’ LNG is a concept that is yet to catch up with the imagination of the LNG developers, is it will be an interesting and challenging subject to research and find whether it is a better alternative to conventional gas turbine driven LNG project. A detailed investigation on engineering, technical, environmental, contractual and operational perspective will be carried out to understand the issues that are encountered while building and operating large capital intensive projects. This research will contribute towards improved insight into key management and technical theories and practices and application to a real life plant environment. This study will also contribute towards broadening and deepening knowledge base on dynamics of technological innovation, qualification, application and management of various risks and challenges faced in managing large assets. The life cycle advantages of an “All Electric LNG” over a “Gas turbine driven LNG” have to be thoroughly researched. The technological challenges of All-electric concept need to be identified along with area of further research and development. This will help future researchers to concentrate on critical areas which are responsible for reducing the reliability concerns of an All-electric concept.

2.18.3 Hypothesis:

Almost all the LNG project the main drivers of compressors are gas turbines. Considering the constraints of the gas turbine as a main driver it is pertinent to look into other technologies that may provide and life cycle advantage over the gas turbines. Hence, the hypothesis is going to test as to whether an “All-electric LNG is a viable alternative to the gas turbine driven LNG from life cycle perspective”.

CHAPTER 3

Methodology

3.1 Introduction:

Gas turbines have been mainly used for driving process compressors in LNG (Liquefied Natural Gas) operations for a long time. In gas compression stations there is extensive use of electrical motors. However, in the field of LNG there are not many references of use of electrical Variable Frequency Drives (VFD) motor system exclusively used for driving large compressors in the LNG trains. However, they have been used in applications of the pumps or compressors for smaller capacity. Recently larger VFDs up to 45MW capacity have been utilized in the LNG to start and help Gas turbine compressor strings. Hence it will be interesting to study as to whether electrical VFD motor system can be upsized to successfully drive large compressors in LNG process Trains by replacing the gas turbines completely and whether there are any life cycle advantages to this concept. Being an electrical engineer with a considerable work experience in LNG industry, I intended to use both my engineering and management credentials to pursue a study on ‘All Electric LNG’. The method adopted for this research comprises of theoretical analysis, quantitative and qualitative research with considerable overlap in the contents. Theoretical Analysis which is primarily concerned with "Theory Building" forms the common foundation for the remainder of the project (Swatman, 1998). In addition to the case study approach, which is classified as being qualitative, are a number of other approaches which are considered to be quantitative such as descriptive, correlational, and comparative studies etc. Qualitative approaches rely on the use of a small number of cases. Quantitative approaches on the other hand, rely on a large number of cases for undertaking statistical analysis (George &Bennett, 2005).According to Hoffman (2009) the strongest means of drawing inferences from case studies is the use of a combination of within-case analysis and cross-case comparisons within a single study or research program. This study used considerable desk research combined with case studies approach, questionnaire survey, statistical and mathematical analysis. A questionnaire survey has been carried out to gather ideas and opinions of the industry experts on the subject. A statistical analysis of maintenance data using Meridium Software has been carried out to analyze the reliability of the VFD system to find out areas that need further improvement. Goal of this section of the Method chapter is to describe why and how the particular unit of analysis was selected. This prepares the reader for what is to follow and provides a framework within which to incorporate the material. As per Johnston (2012) the ‘Methodology chapter’ is a good starting point to explain how the study was carried out in a logical order. This chapter describes the process of the study to help understand and appreciate the links among the research problem, the method, and the results. The following discussion is based on guidelines suggested by Narasimhan (2006).

3.1.1 Assumptions:

A number of case studies have been analyzed in my approach and a number of secondary data have been utilized from these case studies to build the life cycle cost/ benefit analysis. The assumption is that the data available in the public domain is credible, reliable, dependable, transferable and current. The cost benefit calculation uses extrapolated data collected from these case studies and the correctness of the results depend on the reliability of these data.

3.1.2 Limitations:

Financial and statistical data have been collected from published article available in the public domain. There is a limitation of use of other data that may be available, which are credible and recent but which may be considered proprietary and sensitive. While proprietary, classified and sensitive data may have been able to give a more accurate cost benefit data, such data have been avoided largely because of potential limitations and restriction on its use. A minor error could have crept in to the calculation because of the above reason, but that would not change the final outcome of the study as the 60% to 70% of the additional income in ‘All Electric ‘ option is based on additional online-stream days of operation which forms the bulk of the income. Minor change to the other cost saving may have a small change in the overall net income.

3.1.2.1 Limitations of data/ information:

The research used both qualitative and quantitative approaches. Research quality is heavily dependent on the individual skills of the researcher and more easily influenced by the researcher's personal biases and idiosyncrasies. Secondary research is research already published, and is the cheapest form of research because the data already exists for acquisition. Secondary research can be split into internal and external research. It is easy to find and collect secondary data. However, one needs to be aware of the limitations the data may have and the problems that could arise if these limitations are ignored. Secondary data can be general and vague and may not really help with decision making. The information and data may not be accurate. The source of the data must always be checked. At times the data presented maybe old and out of date. The sample used to generate the secondary data maybe small. Gathering and processing data can be very expensive. As the All Electric LNG still on a conceptual stage there is lack of enough information hence one has to rely on available data from secondary sources. There are often time and resources constraints. The value of any research findings depend critically on the accuracy of the data collected. The data collected from the OEM may be representing vested interest and may have any bias. Data quality and reliability can be compromised if the data obtained from above sources. There is also the issue of legal and ethical constraints of using confidential data. There is also a possibility that data is collected from sources that do not have sufficient in depth knowledge about the subject.

3.1.3 Delimitations:

Delimitations imply limitations to a research design that has been imposed deliberately. The research study has been carried out on an onshore LNG project. Although the concept can be expanded to an offshore LNG plant or FPSO(Floating Production Storage and Offloading) installation and compressor stations, the cost and benefit calculations has to be carried out specifically for such cases as the variables might be different.

3.1.4 Originality:

No major full scale research studies have been carried out on electric VFD drives being used for a LNG project replacing the gas turbine drives for compressor application in my knowledge except some case studies and paper presentation in conferences. Hence this study has originality both in its approach and outcome.

3.1.5: Period of study:

The period of study is from 2009 to 2013 during which all the data have been sourced, gathered and analyses and conclusion drawn.

3.1.6 Approach:

In the introduction chapter (Chapter 1), I have introduced the readers on Liquefied Natural Gas and its use. The use of gas turbines in LNG production has been discussed and concept of all-electric LNG has been introduced. The literature review chapter (Chapter 2) supports the project and forms the basis of the project objective. A study in Engineering Management is not complete without delving deep into the various challenges of Engineering Management of large capital intensive ventures. The chapter 'Life cycle management challenges of large projects' (Chapter 4) discusses various issues related to Financial, Commercial, Contractual, Procurement and Logistical, Safety, Human Resources, Environmental, Engineering, Construction, Commissioning, Startup, Operation and Maintenance aspects specific to LNG projects. The subsequent chapter (Chapter 5) discusses the various advantages and disadvantages of Gas turbine driven LNG project and All-Electric driven LNG project and makes a critical comparison of the pros and cons of either systems. Being a step out technology, the all-electric concept has its own share of technical challenges. Major technical challenges and mitigation measures are discussed in the chapter (Chapter 6) entitled "Technical challenges of All-Electric Concept". In this chapter the reliability and availability of large VFD system operating for a starter/ helper function has been analyzed using SAP which is used as a CMMS (Computer Maintenance Management System) Software function and Meridium software, which is one of the Reliability analysis software to compare design versus actual figures and areas of further improvements have been identified. Moving on the next chapter a number of "Case studies" (Chapter 7) conducted by renowned stakeholders and major players in LNG business such as Shell Global Solutions, Shell Development (Australia), Foster Wheeler, Conoco Philips, Total, ABB Process Automation Oil and Gas, Bechtel Corporation, CFAST consortium (comprising Chiyoda, Foster Wheeler, ABB and Stolt), TOTAL, TMEIC GE (Toshiba Mitsubishi/ General Electric), Kellogg Brown and Root have been analyzed and discussed. Some of the case studies are in the main text and some of them have been incorporated in to Appendix B. Based on the information and data collected, a "Life cycle cost benefit analysis" model (Chapter 8) has been built to demonstrate the economic advantages of All-Electric LNG. I have generated calculations for an annual saving for a 7.8MTPA (Million Tons Per Annum) LNG plant, which is the largest size of single LNG Train built so far, for an all-electric over a gas turbine drive option. Further, I have made use of Net Present value (NPV) and Sensitive Analysis for various discount rates, plant sizes and LNG unit prices to strengthen and support the hypothesis. I have also carried out a questionnaire survey to gather ideas and opinions of experienced personnel in the LNG field to get an all-round perspective. Subsequently, the questionnaire survey results have been discussed in the subsequent chapter (Chapter 9) entitled "Questionnaire Survey Discussions". The last chapter (Chapter 10) entitled "Conclusion and further research" has summarized the entire study and has discussed areas of further research.

3.1.7 Rationale behind this approach:

Designing a research study comprises three general framework elements. Firstly, the philosophical assumptions and theoretical perspectives need to be established. Secondly, the general procedures of the research, i.e. its strategies of inquiry are set. Finally, detailed procedures of data collection, analysis, and reporting are determined (Koivisto, 2008). The above approach makes proper use of all these three steps to build analyze and conclude the study.

3.1.8 Validation of the hypothesis:

A validation plan for the hypothesis using studies, modeling and simulation etc. has been discussed below.

a) Scope :

The entire hypothesis that an "All-Electric LNG is a viable alternative to the gas turbine driven LNG from life cycle perspective" is being validated during the study. The idea of the study came to my mind while working in the project, from 2004 to 2009, to build a 2x7.8MTPA (Million Tons Per Annum) LNG plant driven by General Electric Frame 9 gas turbine-compressor strings being started and helped by large VFD driven motors (60 MW short time and 45 MW long time rating) functioning as starter/helper/generator. I thought of studying the possibility of upsizing the VFD motor system to take up the full compressor load and replace the gas turbine altogether. I had a very faint idea that the system may work from informal discussions with some colleagues, manufacturers and contractors. There has been no major research carried out in this field to my knowledge and I had to device my own original approach to this study. The overall philosophy approach was to use a combination of Theoretical, Quantitative and Qualitative approach with data sourced from internet, company intranet, LNG Seminars, paper presentations, Case studies, discussion with experienced and knowledgeable personnel in the industry, construction and commissioning test results and available maintenance data.

b) Other approaches considered/ discarded:

Initially my idea was not to go for the questionnaire approach. The reason being there is not much information available on all–electric LNG as only one operational plant, ‘Snohvit LNG’ operated by Statoil in Norway, based on all electric technology was commissioned a few years back. Since the subject is highly technical the response base is very much limited to LNG personnel with experienced only. Further, based on the novelty of the technology a limited number of people have knowledge about All-Electric LNG. Nevertheless, I decided to go ahead and conduct a questionnaire survey to get the present level of awareness of the industry professionals and to gather any new perspective that may spring from the survey. The response rate to the survey was 50% as many of the respondent decline to comment as they thought they did not have enough knowledge to make a fair judgment. Nonetheless, I received some interesting observations and got some new perspectives. I have discussed these ideas in my study in the “Questionnaire survey discussion” and “Summary” chapters.

c) Negative or counter-intuitive results:

During the course of study, I made a statistical analysis of the reliability of the VFD of the Qatargas major expansion Trains used as starter/helper for the gas turbine-compressor string. Contrary to the claim of the manufacture the reliability of the IGBT (Insulated Gate Bipolar Transistor) cells has been lower and also the availability of the VFD threads was lower than the designed value. This is discussed in details in the chapter entitled “Technical challenges of all electric concepts”. Further research should go into improving the reliability of the cells and also reliability of the cell by-pass contactor so that redundancy features can be fully realized to improve the reliability and availability of the VFD motor system.

d) Instances where hypothesis breaks down:

The all-electric motor system needs a large combined cycle power plant to supply the large motors. The power generation and distribution system has to be constructed for a high reliability and a low electricity generation cost. Imposition of penalty on emission is another area which will support an All-Electric concept as it has potential of reduced CO_2. There are other conditions that do not support the hypothesis, which are discussed below.

a. Low reliability of the VFD motor system will be counter-productive to the hypothesis.
b. Low reliability and low stability of electrical power generation and distribution during system disturbance does not support this hypothesis.
c. Low gas price to electricity price ratio, which may of course change over time, means a higher electricity price, leads to a much lower marginal cost benefit.
d. Major routine inspection requirement for static equipment reduces the available additional stream days. If the routine inspection can be delayed by non-intrusive inspection that will support the all-electric concept.

e. Lack of confidence of financiers to fund a new technology and stick to time tested gas turbine system although it has a lower availability and efficiency.
f. If loss of additional stream days is not considered as a production loss but a temporary opportunity loss which can be compensated at a later day.
g. The entire business strategy is built around gas turbine by factoring in the loss of a few days of production in a year due to routine maintenance of the gas turbine.

3.2 Source of Data and information:

a. Internet:

Internet is an excellent and a vast source of information on natural gas. There is access to various journals and websites that proved to be valuable sources of information and greatly facilitated the research work.

b. Intranet:

Company's intranet is a large data base of information. The share point is a location where a plethora of information is stored. As an employee of the company I had access to test and maintenance data which was made good use of to study the reliability of the VFD-motor system. Project documentations were also utilized to gather information on the gas turbines and VFDs.

c. LNG Seminars, paper presentations:

Seminars and workshops and forums on Natural Gas are held throughout the world every year. Papers presented during the seminars also provided vital pieces of information to help the study work.

d. Case studies:

Several case studies have been carried out by eminent players from the LNG industry from the clients, EPC contractors, financial entities and research bodies. These studies were analyzed to get a wider view point and an all-round perspective. There were arguments both in favour and against the All-Electric system which made interesting reading. This information has also helped in building my Life cycle cost benefit analysis.

e. Experienced and Knowledgeable personnel of the industry:

By questionnaire survey approach and personal interview approach it was possible to gather various perspectives from knowledgeable and experienced industry professionals.

f. Test results:

Various test data gathered during the manufacturing, construction, commissioning of the gas turbine and VFD system stood in good stead during the study process.

g. Maintenance data:

Qatargas 2 utilizes an electrical motor system with VFDs of 45MW (60MW short term) as starter/ helper motor on the main gas turbine-compressor string for the pre-cooling, refrigeration and sub-cooling circuits. The compressor string is mainly powered by the gas turbines. On the basis of my experience and involvement on manufacturing, testing, commissioning and maintenance of the VFD system and the gas turbine driven compression system, I have gained considerable exposure and gathered some useful information about the VFD driven motor system. I made use of the wealth of data from my project and maintenance experience, which was brought to good use to advance my study.

3.3 Tools and Measures:

This section describes the particular measures employed and how they measured the variables specified in the research questions and hypotheses. Questionnaires are not the only type of data collection instrument as behavioral observations, extended interviews, and archival data all constitute valid sources of data for dissertation research (Sage, 2007). Potential problems of relying on archival data are missing, incomplete, or compromised data. This can take the form of an insufficient sample size, the absence of information on important variables that were not included in the original data collection, or the reliance on flawed or out of date measures (Sage, 2007).

- Peer Review or Debriefing:

Many qualitative researchers make use of peers or colleagues to play the role of devil's advocate, asking tough questions about data collection, data analysis, and data interpretation to keep the researcher honest. The other role of the peer reviewer is to provide professional support (Sage, 2007). I had assistance of some of the peers in analyzing and interpreting the data for reliability analysis of Qatargas VFD motor system.

- Sampling:

Strauss and Corbin (1998) stressed that several forms of sampling are appropriate at various stages of the study. Data collection should be stopped when the results start to become redundant is the key determinant of sample size (Sage, 2007). It is important to collect sufficient data to represent the breadth and depth without becoming overwhelmed. During collection of data from case studies and collecting information from published articles, the above points had been kept in mind.

- Criteria of Adequacy and Appropriateness of Data:

Adequacy pertains to the amount of data collected in a qualitative study. Adequacy is achieved when enough data has been obtained so that the previously collected data are confirmed and understood. Appropriateness means that information has been sampled and chosen purposefully rather than randomly to meet the theoretical needs of the study (Sage, 2007). To that end multiple sources of data have been obtained to provide adequacy, appropriateness and confirmation of the emerging model.

- **The Audit Trail**:

An audit trail refers to keeping a meticulous record of the process of the study so that others can recapture steps and reach the same conclusions. An audit trail includes not only the raw data but also evidence of how the data were reduced, analyzed, and synthesized, as well as process notes that reflect the ongoing inner thoughts, hunches, and reactions of the researcher. This critical self-reflection component illuminates the researcher’s potential biases and assumptions and how they might affect the research process (Sage, 2007). A complete record of all the information accessed has been stored and all the questionnaire survey responses and interview notes have been stored for further reference if required in future and for the purpose of personal privacy.

- **Triangulation:**

Soliciting data from multiple and different sources as a means of cross-checking and corroborating evidence and illuminating a theme or a theory is known as triangulation. The different sources may include additional participants, other methodologies, or previously conducted studies (Sage, 2007). This method has been adopted in cross checking of evidence between several case studies and published articles in journals and presented papers.

3.3.1 Desk Research:

Many text books and technical handbooks have been referred to further understand the theory and practice of gas turbines and Variable Frequency Drive motor system. I have researched various periodicals, journals and magazines for valuable information. I made a good use of my earlier research works, paper presentations at seminars and thesis in the field of Sub-synchronous Torsional Interaction (SSTI), Harmonics and Electrical Resonance phenomenon. There are many journals and magazines which publish papers on studies and discussion about VFD system, which helped provide very useful insight in to the subject.

3.3.2 Questionnaires:

A questionnaire method was one of the many research methods utilized to gather information. The idea was to collect qualitative data on the respondent’s perception and understanding on the subject matter.

3.3.3 Interview:

Individual interview is one of the methods that has been adopted to gather information

The intent was to interview experienced, knowledgeable and relevant people who by virtue of their responsibilities in handling various processes in LNG industry have in-depth knowledge and who could provide an insight to critically analyze the processes and give new perspective to the study.

3.3.4: Statistical and Data analysis software:

There is a general concern about the reliability of the power electronics in the VFD. SAP software was made use of to gather failure data of the VFDs used in Qatargas Trains 4, 5, 6 and 7. Qatargas uses a 45MW VFD motor system with perfect harmony technology using IGBT (Insulated Gate Bipolar Transistor) devices with Pulse-width modulation principle to function as starter/ helper to the gas turbine compressor strings. This has a potential to be upsized to run as a main drive for the compressors replacing the gas turbine completely in an ‘All-Electric’ concept. Further, Meridium software was used to carry out a Reliability Analysis of the VFD threads and IGBT cell devices, by using MTBF (Meantime between Failures) plot of the dominant failure modes to determine the MTBF of the cell and thread failures and tried to understand what the reliability issues related to VFD are and how they can be mitigated.

3.4 Data analysis:

This section provides a detailed description of the exact steps taken for systematic and coherent analysis of data so as to draw inference. The steps taken in analysis are presented below.

3.4.1 Challenges in Engineering Management:

There are various challenges to engineering management with respect to large capital investment. The asset-intensive nature of these businesses creates various challenges that needs advance planning and execution to tackle them from conceptualization to retirement. LNG industry faces multiple challenges, with a heavy investment on equipment and plant facilities, the need to increase return on investment, reduce costs, increase productivity, and growth in the business. The life cycle challenges in LNG business are discussed in detail and are specific to All-Electric LNG.

3.4.2: Comparative study:

The constant comparative method implies that the researcher continues to build and test the completeness of a theory by reaching across participants to determine how the findings apply to cases that appear to be exceptions to the rule. By deliberately searching for these “deviant” cases, it becomes possible to test a provisional hypothesis and amend it to incorporate new and different data (Sage, 2007). The advantages and disadvantages of both gas turbine and All-Electric option have been thoroughly studied and their attributes compared from a life cycle perspective to test the hypothesis.

3.4.3: Technical challenges of the new concept:

Both gas turbine and the All-Electric option have their own shares of technical challenges. The technical challenges of gas turbine driven LNG are well understood and mitigated as it has a large experience base and time tested profile. Various specific technical challenges to be faced in technology qualification, manufacturing, testing, commissioning and maintenance of an all-electric system for a LNG Train have been analyzed in details and mitigation measures discussed. This study also identifies areas of further research.

3.4.4: Statistical analysis:

Reliability of VFD driven motor system is analyzed by statistical analysis tools and issues were identified so that further studies can be done to improve these shortcomings. I have gathered data from Computerized Maintenance Management System (CMMS) software (SAP) on failure data of Qatargas Variable Frequency Drives and by using Merdium software (Reliability Analytics) I have calculated the Mean Time Between Failure (MTBF) and Reliability percentage and compared it with the design values. By using Pareto analysis I have analyzed the major sources of unreliability of the VFD system.

3.4.5: Case Studies Analysis:

A number of case studies carried out by various eminent industry stakeholders were analyzed. Some of the case studies have been included in the main text and the rest have been included in the Appendix B. The data from the case studies have been utilized to build a model to create a life cycle cost benefit analysis.

3.4.6: Life Cycle cost benefit analysis:

By using data and information collected, a Life cycle cost benefit analysis model for a 7.8MTPA LNG train, which is the largest single Train size built so far, driven by an All-Electric System has been built and compared with that of a gas turbine driven plant. Additional income per year has been calculated for the All-Electric case and a Net Present Value (NPV) calculation for the future additional cash flow for 25 years of operation has been calculated to test the hypothesis. Further, sensitivity analyses have been carried out for different unit prices, plant sizes and discount rates to further corroborate the hypothesis.

3.4.7: Questionnaire survey and interview result analysis:

Quantitative data may be useful in measuring attitudes across a large sample. However, Grounded Theory Methodology (GTM) offers a powerful methodological framework if the aim of the study is to learn about individuals’ perceptions (Gorra, 2008). The characteristics of this methodology is based on real life experiences, valuing participants' perspectives, based on an interactive process between researcher and respondents and relying on people's words (Gorra,2008). The questionnaire survey and interviews were conducted to gather the perception of the industry experts on electric LNG. The discussion chapter deals with the results of this endeavour and also helps identify new insights.

3.4.8: Conclusion and Further research:

The entire research has been summarized to support the hypothesis and issues that need further research have been identified. New insights which were identified during the questionnaire survey and interview process are further discussed and some of them have been included for further research section. The figure shows the methodological inter-relationship between the Theoretical, Quantitative and Qualitative analysis have been depicted.

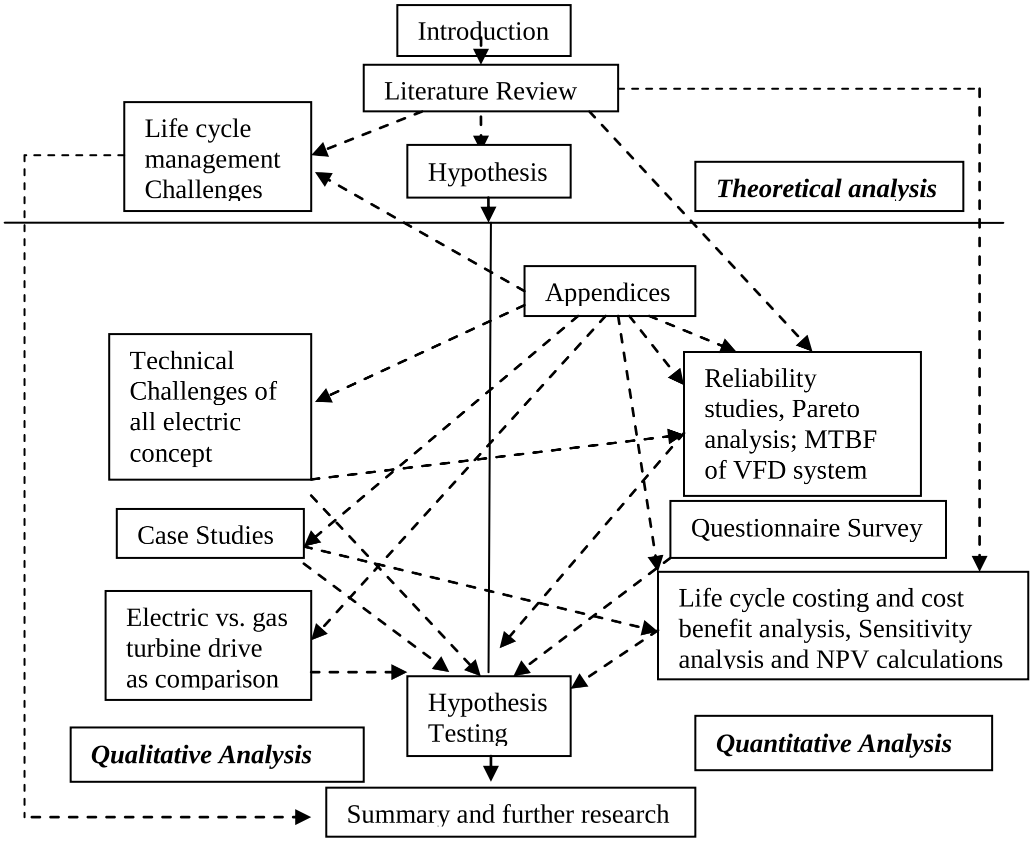


Figure 3.1: Methodological Inter-relationship; (Concept from Swatman, 1998)

Further the various steps and process of the research the various analytical tools and the procedures for testing the hypothesis has been shown.

3.5 Validity and Reliability of the study:

Validity and reliability generally describe the quality of the research. There are different types of errors that reduce the quality of the research. Lack of proper responses, weaknesses in study instruments, sampling methods, and treatment of the data can cause systematic and/or casual errors in the final result (Koivisto, 2008). Validity and reliability of the research is related to its ability to give non-random results. Insufficient reliability usually arises from random errors, but systematic errors may also affect reliability (Koivisto, 2008). One of the bases of collection of cost data was from case studies. The life cycle cost benefit analysis model has been built on information collected from these case studies. The cost saving by improved efficiency, maintenance cost saving, reduction in emissions and reduction in circulation loss which constitute about 30-40% of the cost saving per year has been extrapolated from data collected from these case studies. Errors in these data may introduce some inaccuracies in the life cycle cost calculation, and Net present Value (NPV) calculation. In spite of the above, the hypothesis will still be correct based on the fact that about 60-70% of the cost saving is because of production due to additional on-stream days in all-electric LNG option against gas turbine driven LNG plant.

The questionnaire survey has been limited to knowledgeable and experiences personnel in the LNG business. The questionnaires were selected so that the technical terms and conditions are understandable to the experienced personnel. A common disadvantage of research is subjectivity (Koivisto, 2008). Since the concept of All-Electric is new, some amount of subjectivity might have crept in to the answers to the questions. One weakness of the survey method is that different respondents can understand the questions differently. Furthermore, they may understand them differently to what the researcher meant. This divergence can be due to difficult statements or unknown terms (Koivisto, 2008).Random errors arise from the sample size and the study instruments, as well as from all the factors that are impossible to control in the test situation in a questionnaire survey (Koivisto, 2008). One of the reasons for the questionnaire survey was to get the opinion of the respondent on All-Electric LNG and the other was to get any new insight into the investigation process. The result of the questionnaire process has been overwhelmingly in support of ‘All-Electric” option. Any error due to divergence and sampling size etc. as described above in the questionnaire process could have introduced minor error into the final result but the result would still be in favour of all-electric option.

3.6 Chapters:

a) Introduction: (Chapter 1)

The introductory chapter talks about natural gas, LNG and their uses. It also describes how it is processed stores and transported. The alternative sources of energy to LNG are also described in brief. Moving on, the natural gas processes where gas turbine is utilized as a driver for running process compressors has been discussed. Later the concept of Electric drive for process compressor for LNG production has been discussed.

b) Literature review: (Chapter 2)

This important chapter starts with discussion of various key elements that need to be considered to start a large new project having considerable investment. Then it delves into major processes involved in large capital intensive engineering ventures. Risk identification/allocation/mitigation, which is made use of during all the important stages of the project, has been discussed. The effectiveness of a venture can be judged by factors such as availability, reliability, maintainability, capability, thermal efficiency and effectiveness equation, which have been discussed in details in this chapter. The risks and challenges encountered in adopting a new technology can never be over-emphasized. Subsequently, the new technology qualification management process has been discussed in details. The benefit of adopting sustainability in life cycle process has been analyzed. A success of any venture depends on its life cycle cost, profitability and Net Present Value. The theory behind these important elements has been discussed in details. The criteria for selection of compressor drivers for LNG process have been outlined. In the subsequent step the theory and gap in research has been identified and the hypothesis has been built.

c) Methodology: (Chapter 3)

Methodology chapter deals in the processes and method by which data has been sourced, collected and analyzed. In addition to desk research, questionnaire method and interviewing method, various mathematical and statistical analyses have been utilized to analyze and summarize the data.

d) Life Cycle Challenges: (Chapter 4)

The management of engineering ventures is fraught with many challenges. The challenges related to Financial, Contractual, Environmental, Commercial, Procurement and Logistical, Safety, Human Resources, Quality, Construction, Testing, Commissioning, Operation, Maintenance aspects have been discussed in detail with respect to all electric option.

e) Gas Turbine Vs Electric drives, a comparison: (Chapter 5)

When an alternative suggestion is made to a well-established process the advantages and disadvantages of the alternatives vis-e-vis the standards needs to be compared. This is precisely what has been done in this chapter, in which various aspects of both the options have been compared extensively.

f) Case Studies: (Chapter 6)

The All-Electric is relatively new concept which offers many advantages about which some case studies have been produced. Some of these studies that have relevance to the topic of research and have relevance to both All-Electric option and conventional gas turbine drives have been analyzed.

g) Technical challenges of electric drives: (Chapter 7)

Although an Electric option as a driver offers a plethora of advantages it is not devoid of challenges both technical and otherwise. This chapter deals with all the technical and reliability challenges of this concept. In this aspect reliability issues of Qatargas major expansion train starter/ helper VFD motor system have been analyzed. Studying technical issues related to this system can provide areas in which further research can be done to improve reliability and availability, before considering the VFD as the main driver in LNG compression processes.

h) Life cycle analysis: (Chapter 8)

For the all-electric concept the electrical power can be generated inside the facility by a combined cycle captive power plant or purchased from an outside utility company. Depending on whether it is produced or purchased the CAPEX (Capital Expenditure) and OPEX (Operating Expenditure) is going to greatly vary. If the power is produced internally one has the advantage of better control of the source but the CAPEX is much higher. The life cycle analysis studies the overall cost and benefit of the electric option and uses Net Present Value method and Sensitivity analysis to demonstrate economic advantages of ‘All-Electric’ concept over the gas turbine option.

i) Questionnaire and interview discussion:

A structured questionnaire approach limited to twenty questions has been adapted to touch a wider section of respondent and get their ideas. While designing the questions, particular care has been taken so that the questionnaire is not very lengthy, easily understandable and can be completed without much time, so that the participants do not lose interest and focus. The questions were devoid of unambiguous language, jargons, personal questions and double headings or leading questions (Deo and Mangala, 2002). Questionnaire process has some limitations as the questions are asked from the view point of the interviewer rather than what are the import issues as felt by the interviewee. Hence, the last question was left open for the respondents to write their comments on the subject. Questionnaire and Interview exercise care has been taken so that and the confidentiality and anonymity of the information collected is maintained. Personnel from various different disciplines have been involved so as to get an all-round perspective without any bias. The questions were open-ended in order to get the interviewee’s point of view on the subject matter with the purpose to engage without directing. An open discussion is a useful source for gathering information supplementing desk research and questionnaire survey. It was a challenge to get people to spare quality spare time from their very busy schedule. However, some interviews were conducted to gather valuable insights. The sample of interviewees was random. Although the interview itself was quite loosely structured, flexible and free flowing, some questions were prepared in advance to gather useful and important information.

j) Conclusion and further research:

This chapter summarizes the research and gives recommendations. It also identifies areas where further research has to be conducted.

3.7: Conclusion:

This Chapter has explained the structure of the present research project, pointing out the nature of the research process and the effort to present material in a logical and structured manner. In this chapter, I have attempted to describe the effort in an engineering management standpoint, analyzing how each individual component of the process was chosen and how they fit together to form the whole. The Chapter also provides a justification for the research methods in some detail and explains both strategy and manner in which the process was implemented. This chapter also outlines arrangement and contents of the all the chapters in the study report. This study utilizes Theoretical, Qualitative and a Quantitative method. The relationships between the methods and approaches have been summarized in Figure 3.1.

CHAPTER 4:

Lifecycle Management Challenges

4.1 Introduction:

Decisions on new asset acquisition, construction, commissioning, operation and maintenance needs careful monitoring and management, while the challenge and focus of the different segments can be quite different. The asset-intensive nature of these business efforts creates various challenges. It takes a lot of advance planning and execution to tackle the challenges from acquisition to retirement. LNG industry faces multiple challenges, with a heavy investment on equipment and plant facilities, the need to increase return on investment, reduce costs, increase productivity and grow the business. Asset optimization takes concerted planning, integrated management and fact-based decisions. From acquisition to operations and maintenance through retirement, the way infrastructure assets are monitored, deployed, and maintained has a critical bearing on the success of any operation (Edwards, 2009). Huge capital investments in equipment and infrastructure present major financial and operating challenges for the energy business. The study is not complete if the challenges faced in each segment of the life cycle of a major investment in the LNG business are not thoroughly analyzed. Some of the main Life Cycle management challenges are discussed in this chapter. Some other important challenges such as Procurement and Logistics Challenges, Quality Challenges, Safety Challenges, Human Resources Challenges, Construction, Commissioning and Completion/ Turnover/ Startup and acceptance challenges are further discussed in Appendix E.

4.2 Financial challenges:

The Liquefied Natural Gas (LNG) industry's expansion has increased the challenges for sponsors to finance what are amongst the most capital intensive projects in the world. Whether any LNG financing is successful depends on its fit with sponsors' objectives (White, 2005). The trend of the day is that upstream sponsors are moving down the value chain and investing in shipping and terminals and in turn the off-takers are taking equity stakes in the upstream and liquefaction elements. Value chain integration creates unique challenges which requires expert commercial and financial structuring that will not only safeguard each individual project's commercial viability and collateral, but also ensure that every value chain segment is able to fully tap the different pools of finance necessary to fund these capital intensive endeavours (Newendorp et al 2005). Investment decisions are based on project analysis and the results of the evaluation depends on the validity and reliability of the assumptions used, which consider the strategic implication, environmental implication and also enhancement of company's bottom line. (Gajameragedara et al 2008).

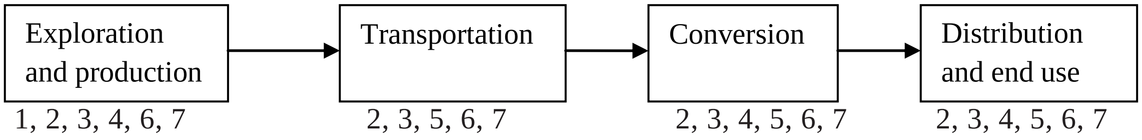
A Special Purpose Company (SPC) which owns the entire project asset; works with construction contracts and provides services or buys gas dealings with other SPCs.

The operating costs are met first, and then the principal and interest payments on loan are made and only then are the dividends to the shareholders paid. In this way, isolated from all outside obligations of the project sponsors, the SPC concept enables a significant decrease in participant risk. Apart from this all the SPCs are usually bound by mutual gas supply and delivery contracts, which mitigate delivery and volume risk (Deloitte Resource News, 2005).

4.2.1 Risk of LNG:

Large projects need big capital expenditure requirements, which increase the challenge of locating sources of debt. Capital markets have not played a large role in LNG financing partly due to the nature of the industry and the perceived risks. LNG off take volume commitments such as long-term Gas Sales Purchase Agreements (GSPA) needs to satisfy lenders for the entire volume of liquids production. Shipping and market access need also to be seriously addressed. In addition, condensate and gas liquids which are also produced along with LNG also contribute to a very substantial percentage of the developer’s revenue and profitability stream and risk diversification element which also need to be considered (Deloitte Resource News, 2005). Each link in the value chain of the projects offers different market and political risk profiles. At the same time, solid integration, whether through ownership or contractually, can lower risk to lenders and provide more flexibility for borrowers (Newendorp et al 2005).

Gajameragedara and Bommer (2008) define four distinct stages of the project namely Exploration and Production; Transportation; Conversion and Distribution and End use. The risks can be broadly divided into Geologic; Engineering; Market; Commodity Price; Capacity price; Financial and Political risks. The investment decisions depend on the result of assessing the risk.



(Risks: 1-Geologic; 2-Engineering; 3- Market; 4- Commodity Price; 5-Capacity price; 6-Financial; 7- Political)

Figure 4.1: Investment Decisions, (Gajameragedara and Bommer (2008)

The above figure shows the various risks that may have to be evaluated at each stage of the LNG value chain. Some of the types of risks are common more than one stage. Careful evaluation of these risks is required to preserve the bankability of each segment and minimize direct competition for debt funding among segments in an integrated value chain. Commercial structuring must be tailored to generate market risk profiles appropriate for different lender groups (Newendorp et al 2005).

4.2.2 Reassurance:

Various different market access options through shipping and re-gasification and marketing capabilities available to sponsors and off-takers provide greater reassurance to lenders to the liquefaction project. Newendorp et al (2005) state that in most upstream and liquefaction projects located in the developing world, export credit agency (ECA) participation is sought to improve the credit profile of the project by insulating commercial lenders for Political Risk Insurance (PRI). Even in low political risk countries, ECAs can play a significant role because of the need for increased debt capacity.

4.2.3 Efficiencies of scale/ Scale-up and value chain integration:

Value chain integration and project scale-up also present significant financial structuring challenges. To improve the project competitive position, the sponsors size up each component of the value chain. Further, lenders are more comfortable if there is advantage of sharing facilities from previous successful operation. There are also additional assurances if the sponsors demonstrate that the new facility will be operated and maintained to highest industry standards on the basis of previous track record of successfully and professionally operating existing operations. Fully integrated value chains and an integrated project sponsorship approach from upstream, liquefaction, shipping, re-gasification, and even to off-take and marketing are closely associated with key characteristics of a rapidly changing global LNG business. The challenge for sponsors and lenders is to connect the links with interdependent financing and investment commitments and commercial relationships, while still preserving each link’s economic viability, collateral, and the ability to tap separate pools of capital (Newendorp et al 2005).

4.2.4 Cost elements:

In analyzing the potential cost optimization of a LNG project, one must consider the characteristic of each business chain in order to achieve the highest cost impact items without sacrificing the basic safety, reliability and operability of the whole system. A typical cost share for each LNG business chain is Upstream Development 10%, LNG Plant 40%, LNG Transportation 30% and Receiving & Re-gasification Terminal 20% (Suprapto, 2000). Many of plants achieve an availability factor as high as 97%, which is an impressive record. As the LNG train size is getting larger, the specific costs of a LNG project will tend to be lower and lower. Nowadays, the LNG Buyers will certainly give more attention to a LNG projects that can offer lower LNG cost, shorter contract period at smaller contract quantity, attractive price structure and more flexible sales agreement terms and conditions (Suprapto 2000).

4.2.5 Sales purchase agreement in LNG industry:

In the past nearly all LNG trade have been done through long term Sales and Purchase Agreement (SPAs) with little flexibility in terms of volume or price, because the LNG industry is long term and extremely capital intensive with extended payback period combined with less exposure to spot market risks. However the number of short term contract though small is growing rapidly

(Deloitte Resource News, 2005). Thus the buyer bears the entire volume risk and the sellers take the price risk. In the current LNG business environment, the investment risk is in fact getting better by the availability of alternate sources in addition to the long term Gas Sales and Purchase agreement (GSPA) in terms of spot cargoes.

4.2.6 Financing challenge for All Electric LNG:

LNG being hugely capital intensive involves separate elements of infrastructure that must be in place in order to monetize the gas. The common thread is that to achieve final investment decision and raise the substantial sums of capital required each project will be subject to high degree of scrutiny and risk mitigation (Sousa 2010) The Capital Expenditure (CAPEX) and Operating Expenditures (OPEX) are roughly proportional and thus account for a substantial amount of the total investment. Hence there is major life cycle cost saving that can be realized both in CAPEX and OPEX if these can be reduced in a liquefaction project. As such, a project must demonstrate its ability to service debt, even under adverse circumstances, before lenders become comfortable with the deal. The impact of rising cost results in reduction in profit. Although it is important to reduce the CAPEX which happens only once, more attention should be put on reducing OPEX which occurs throughout the lifetime of the project after it is commissioned. The LNG plant is a major cost element in a LNG business chain and has become the focus of cost optimization in recent years. The cost for a plant can vary drastically when site and technology specific conditions demand different considerations. As a result, it is clear that no two LNG projects are created equal. (Kotzot et al 2009). So the challenge for securing the finance for an All Electric LNG is to convince the lenders that it can provide an edge over the conventional gas turbine driven LNG in terms of better return on investment and lead to lesser environmental damage. The LNG plants are being sized up to reduce the specific cost of production hence it needs to be seen whether all-electric plants can meet the requirement of LNG business.

4.3 Commercial challenges:

There are numerous variables need to be considered for the ultimate success of the project. The commercial variables such as available gas reserves, financing ability, corporate objectives and market penetration must be considered in combination with project related variables such as schedule, capital expenditures and life cycle costs. The objective is to develop strategy that provides the highest rate of return whilst adequate risks management is adopted by the owners.

4.3.1 Host Government consideration:

The contractual relationship for the exploitation of a country’s hydrocarbon resources is generally governed by a Production Sharing Contract (PSC), Concession Agreement, or some other agreement entitling the off taker to a share of the oil and gas discovered and produced. Gas contract terms, always require a longer period to recover the investment than an oil project. The commerciality of a gas depends on the size of the resource, conditions for gas utilization and marketing defined for the life of the field. Local content and employment are major host government considerations in exploiting its natural resources and economic development. The capital investment generally fosters development of domestic use of gas and other lateral industrial developments raising the overall economic development of the area and providing more employment (Chiu, 2006). Greenfield LNG projects have traditionally received tax holidays and other incentives necessary to justify the large capital investment of the sponsors. The host governments generally grant fiscal concessions in addition to providing support, guarantees and assurances to launch a successful project (Chiu, 2006).

4.3.2 Owner's considerations: (Redding et al, 2005)

Rapid commercialization: After making a decision, to invest the interest of the shareholders is to bring the project to commercial operation rapidly so that they are able to monetize the reserve and help the bottom line after taking care of the mandatory obligations. Hence the project schedule is an important parameter for consideration.

Reduced Technology Development Cost and Schedule: In addition to schedule, owners' challenges are to bring down the cost of unit of production by increasing the production train size so as to improve the economy of scale. The new technologies are being implemented to reduce the specific cost and schedule.

Market penetration: LNG brings diversity of supply to importing countries by providing them with a substitute for coal and liquid fuels in power generation. This is creating a challenge for reliable and steady source of supply, which can be achieved by access to multiple forms of energy from various different sources. Lower emissions target and global economic recovery with shift toward cleaner fuels provides opportunities and avenues for market penetration of LNG into hitherto unseen areas.

Reduced commercial Risk: Adopting a standardized approach within the proven range of experience reduces technical risk and provides better prediction over actual operation in future. This lowers risk situation and in turn aids in the marketing effort by ability to demonstrate a consistent LNG supply.

4.3.3 Buyer's consideration: (Chiu, 2006)

Reliability of System: LNG buyers have been large regulated utilities or government owned companies capable of executing long-term take-or-pay contracts. With limited suppliers and receiving terminals scattered around the world security of supply has become almost equally as important as price. While the restructured world gas industry is now more market responsive and the price risk has shifted more to the producer, the need for security of supply has not diminished. The primary concern of a buyer will be the reliability of the system to produce and deliver LNG as contracted (Chiu, 2006).

Resource assurance: Buyers will still seek assurances of sufficient gas resources exist to meet long term contractual obligations. The short-term and spot market has a number of characteristics of a commodity market but in reality these sales only accounts for approximately 12% of the world LNG trade. The spot and short-term market only exist because of surplus capacity in over designed and constructed liquefaction plants (Chiu, 2006).

Free On Board (F.O.B) Limitations: The use of special purpose vessels required for loading is the attractiveness of an F.O.B. trade and the buyer's shipping options. The vessels should be dedicated to the project to enhance the buyer's security of supply and plant off-take. The purchase of "spot cargos" will be limited to the availability of a special purpose vessel for delivery to a buyer within the shipping distance of the projects annual delivery program (Chiu, 2006).

Expanded Force Majeure Terms: Until the LNG facilities have established a proven record of safety and reliability with a new technology, it is anticipated the sponsors ask for force majeure provisions to cover the inherent risk associated with an extension of existing technology (Chiu, 2006).

4.3.4 Lender's primary concerns:

Reliability: Reliability of a LNG plant will be the sponsors and lenders primary concern as to whether the facility generates sufficient revenues to repay the loan. Lost production days due to weather, damaged to equipment, lack of spare parts, etc. can be modeled to determine the impact on a project's revenues. Lenders will need to be satisfied that there are sufficient resources available to the sponsors to produce the revenues required to pay back the loan (Chiu, 2006). So the reliability and availability of the LNG plant will be of prime importance to the lender.

Safety, environmental and other Concerns: Safety of the facility and its ability to resist damage, system failure, gas leak or other unplanned event are major considerations for all parties involved. Quantitative Risk Assessment tools and Monte Carlo simulations can be used to understand the risk and determine its acceptability. Lenders will look at the sponsors experience and reputation in LNG and their ability to execute large multi-billion dollar projects (Chiu, 2006). LNG projects were financed historically on the credit of large, regulated utility companies or state monopoly companies capable of executing long-term, take-or-pay contracts. The security for the loan is the LNG plant rather than the contracts supporting the LNG trade.

Competition from Shale Gas: Gas may be pushed into low price environment because of the increase in production of natural gas and shale gas. Because of shale gas exploration there is a lot of gas now available in US which is one of the main consumers of LNG. The technology of exploitation of shale gas is likely to be transferred to regions of the world which may lead to increase in production and reduction in demand for the LNG. Further competitors in the LNG business will bring gas prices down, that will impact revenues and profits of the producers. The majority of generation in many developing countries like India and China comes from old coal-fired plants, which will eventually be shut down and replaced by the most effective and environment friendly fossil fuel for now: either natural gas or LNG. Hence the demand for LNG will remain high for the foreseeable future. As competition rises the specific cost of production becomes increasingly important parameter (ABB, 2005).

4.3.5 Commercial challenges for All Electric LNG:

The variables to be considered are numerous but from a high-level perspective, commercial variables such as available gas reserves, finance ability, corporate objectives and market penetration must be considered in combination with project related variables such as schedule, capital expenditures, specific cost, life cycle costs, reliability/ availability and impact on environment etc. The objective is to develop a strategy providing the highest rate of return whilst taking full account of the risks that can be managed. From technology and commercial perspectives there is less risk associated with adopting a standardized approach. At the same time incorporating new technology reduces specific cost of production which increases the challenge. So a balance has to be struck to make sure that new technology helps achieving economy of scale by reducing specific cost with a more environmentally friendly approach by identifying and mitigating the risks associated with it (Redding et al, 2005). In the All electric contest, it remains to be seen as to whether the new technology implemented will bring overall commercial benefit.

4.4 Contracts Challenges:

Determining the correct form of contract to pursue can have a great effect on the cost and risk associated with the project. Proper front-end definition work can identify the stakeholders’ expectations, project priorities and critical success factors early on. This information is a must in order to correctly identify the proper contract strategy and structure required to meet these objectives. Failing to meet the project objectives of safety, cost and schedule stems from misunderstanding of the objectives of the project from the conceptual stage and therefore often leads to improper selection of the contract type (Agnitschet et al, 2001). The cost of construction varies with the amount of business risk the owners and financers are willing to accept. The less business risk the owner wishes to assume, the higher the cost of construction (Prodigy 2006). The two most common types of contacts in a LNG project are Engineering Procurement and Construction (EPC) “turn-key” and Engineering, Procurement, Construction and Management (EPCM). This is due to the risk involved in large capital investment in LNG project and because of a limited number of contractors worldwide to execute such contracts. Each of these methods has variations that can be adapted to each project as needed (Prodigy 2006). From the perspective of the Owner, the primary differences are that an EPC is an all-encompassing lump sum contract. There are numerous types of contracts between Owner companies, General Contractors, vendors and Sub-contractors. The variations are basically derivatives of the major three as discussed below (Agnitsch et al 2001).

a) **Fixed Price:** A company is paid a single fixed sum to engineer, procure, construct and commission a project.

b) **Cost Reimbursable:** A contractor is paid on a cost-plus basis such as cost plus a percentage, or cost plus a fixed monthly fee to fully engineer, procure, construct and commission a project.
c) **Unit Rate Contracts:** Similar to cost reimbursable, a company is paid on a per-unit basis for installed product. This type of contract is used most often in the construction phase of a project.

4.4.1 Key Elements of a Contract:

a) Scope Development:

The LNG promoters set the parameters for the overall project as a whole, and anticipate lower costs through careful design of the initial Front End Engineering and Design (FEED) document for bidders. FFED defines the project scope aligned with business objectives and further evaluates technological alternatives, capital budgets, design criteria for use in detailed engineering along with project scheduling and cash flow projections. Owners prepare their FEED plans with the help of a FEED contactor and then accept bids for the entire project with bidders submitting their bids for consideration (Troner et al 2001). It is essential that there is very good definition of the contract scope and changes are avoided lest there is significant cost growth. Technical due diligence need to be completed prior to final award so that any issues that were earlier overlooked could be incorporated. In fact, the design developed during the FEED may have to be independently reviewed by a consultant with considerable project experience (Jamieson, 1998).

b) Competency of the contractor:

The competency of the contractor is an important consideration in selection process as the success of the project is highly dependent on it. The strengths and weaknesses of the participating contractors with respect to LNG experience, record of on time and quality job and a sound financial footing should be considered. Typically, an owner with little construction experience will be more comfortable handing relative control of a project to a contractor than would an owner with more construction management experience (Oylan et al 2007).

c) Control:

Many factors influence and can dictate the relative degree of control the owner wishes over the work. For example, whether the owner would like to exercise considerable control and or it may prefer to offload responsibility and ideally risk to third parties**.** The latter may indicate a preference for more of a “turnkey” arrangement (Oylan et al 2007).

d) Marketplace:

It is often useful to determine the market’s appetite for various forms of agreement and what the current drivers may be that are associated with those forms of contract. Quite apart from how the present marketplace determines the risk aspects of the Design

Engineering, Procurement and Construction contract is how the marketplace understands the tendering process (Oylan et al 2007).

e) Priorities:

Generally the owners' priorities are maintaining budget, schedule, and quality which are reflected in the contracting strategy and terms of the contract. The contract should impose costs or set forth rewards for the contractor depending on whether the goals are achieved. To achieve its goals, a contractor may insist on a high degree of control over its work (Oylan et al 2007).

f) Tolerance for Risk:

The most efficient and effective contract recognizes that the parties' allocation of risks should commensurate with rewards. It is essential that the parties understand their goals and properly coordinate their activities under the contract. The lion's share of risk should be borne by the party most able and willing to manage that risk and such party should be rewarded in a commercially reasonable fashion (Oylan et al 2007).

g) Cost:

The cost of the LNG Projects has increased over the years. Historically, prices dip due to improved technology being implemented. Now, due to contractor demand and material and equipment escalation, the cost of LNG projects has significantly increased (Greer, 2006). However there is significant increase in risk contingencies, particularly West Africa and Middle East with significant premium for EPC (similar to turnkey) lump sum compared to reimbursable/ mixed contracts.

4.4.2 Basic features of an Engineering Procurement and Construction (EPC) contract:

Under an EPC contract a contractor is obliged to deliver to a client a complete facility for a guaranteed price, by a fixed date and under a performance guarantee, who need only to 'turn a key' to start operating the facility. It means the contractor is contracted to provide engineering, procurement and construction services by the owner. EPC contracts are a common form of contract used to undertake construction works by the private sector on large-scale and complex oil and gas projects (DLA Piper, 2011). The EPC contracts have received bad publicity as a result of a number of contractors having incurred heavy losses leading to a number of them reluctant to enter into EPC contracts in certain jurisdictions (Progidy 2006). This problem has been made worse as the insurance market has become more expensive due to significant losses suffered on many projects. The cost risk and control are weighted towards the Contractor. The goal of the owner is to build a cheaper plant and within budget with a fixed price that includes substantial guarantees and warranties along with a single point of responsibility (Jamieson, 1998). This was a very effective way of reducing exposure to start-up delays and production shortfalls from a less proven technology. There are bonuses for additional production, early completion and safety performance during construction. Characteristics of EPC and EPCM contracts are discussed in Appendix C.

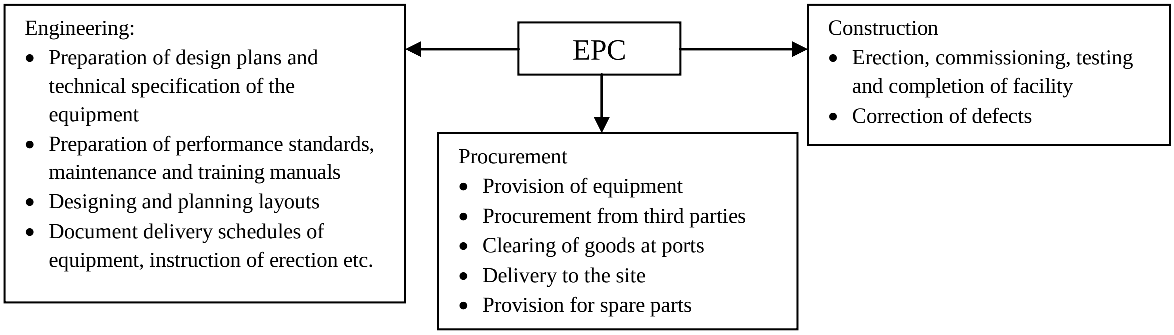


Figure 4.2: Strategy and issues of selection of EPC contractor (Oylan et al, 2007)

4.4.3 Engineering, Procurement and Construction Management (EPCM) Contract:

EPCM (Engineering, Procurement and Construction Management) contract means the contractor is contracted to provide engineering, procurement and construction management services. Other companies are contracted by the Owner directly to provide construction services and they are usually managed by the EPCM contractor on the Owner's behalf. Some projects proponents believe that the EPCM project delivery methods give them greater flexibility and that they have the expertise and experience required to control costs in an EPCM contract (Progidy, 2006). Briefly, the primary difference between EPC (Engineer, Procure, and Construct) and EPCM (Engineer, Procure, Construction, Manage) is that the EPC contractor is paid a lump sum price to deliver a complete facility, with all subcontracts under their name. Conversely, the EPCM contractor is an extension of the contractor, executing all contracts and procurement under the name of the Owner and being compensated on either a lump sum or reimbursable basis to perform engineering and management services. Characteristics of EPCM contract is detailed in Appendix C.

4.4.4: Alliance Contract:

Alliance contracts involve a collaborative process in which it aims to promote openness, trust, risk- and responsibility-sharing and the alignment of interests between clients and contractors. The essence of an alliance contract is more in the process, the foundation of which lies in an approach of co-operation between clients and contractors. Trust instead of distrust is the basis of an alliance contract, although a clear and transparent contract is still needed to support this spirit of trust. Both a legal and a psychological contract are necessary for the logical development of an alliance. Excessive focus on legal leads to mistrust and absence of legal structure leads to way to abuse of trust hence a balance is necessary (Arino and Reuer, 2004). An alliance contract seeks to move away from the traditional “adversarial” approach in which parties are first of all competitors. The focus is on the best arrangement for project delivery rather than on self-interests, typical of traditional contracts (IADC-2008). Difference between alliance contracts and traditional “adversarial” contracts lays in the premise of diversion of capability, intellect, attention and energy away from project construction, which is a source of major inefficiency in traditional contract. This win-lose attitude leads to inefficient allocation of intellectual and professional resources. Traditional forms of contracting cause parties to adopt defensive behaviour, which leads to adversarial relationships and misdirects efforts. Alliance contracting removes the necessity for diversion of effort and seeks an alignment. This alignment makes possible joint management of the risks and the project as a whole, resulting in a more effective process. In an alliance contract parties may agree to share an early-delivery bonus, so that both parties have the same interest: A speedy delivery of the project **(IADC-2008).** An alliance contract is one contract between the owner/financier/commissioner and an alliance of parties who deliver the project or service (lhalliances.org.uk, 2013). An alliance contract is not a very common form. An alliance contract does not solely rest on legal clauses; non-legal considerations such as trust, openness and a collaborative and constructive mentality also play an important role.

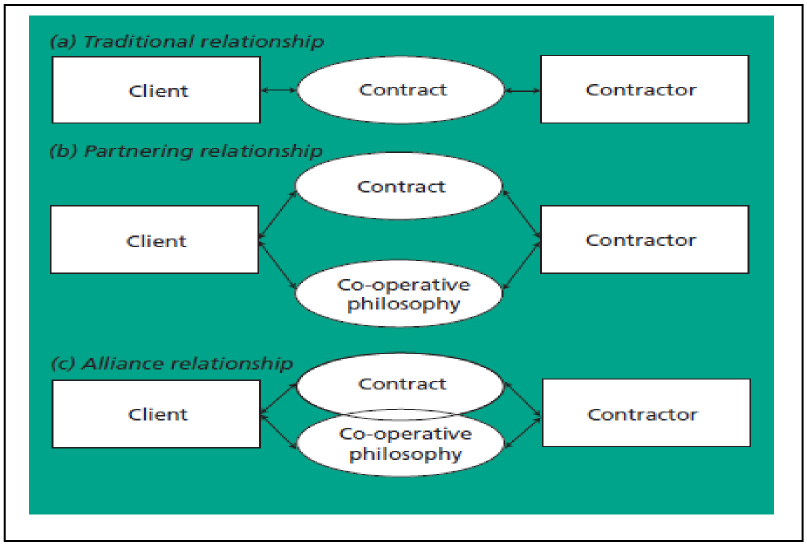


Figure 4.3: Traditional, partnering and alliance contracts (IADC-2008).

If parties share a constructive and collaborative attitude and approach from the beginning, then the best form of contract should automatically follow. A partnering type of contract may run parallel to a traditional contract providing guidelines to the relationship amongst the various partners. Alliance is sometimes seen as an outgrowth of a partnering relationship which results in a legally enforced contract.

4.4.4.1 Advantages of Alliance Contracts:

Alliance contracts can diminish the threat of disputes through a more co-operative approach between principals and contractors, which leads to several following advantages (IADC-2008).

- Most risks remain within the alliance. The contractor can be reimbursed for all direct costs even in the case of delay, negligence, cost overruns or defective design.

- More contractors are likely to bid on projects because of the shared liability exposures and a greater ability to prevent and pass cost increases and delay risks.
- Working in an alliance contract reduces conflict or confusion. There is far less emphasis on legal considerations and more on time and cost obligations.
- Conflict is avoided by defining the nature and the extent of the co-operation at an early stage of the project and by establishing an effective alliance board which, if and when necessary, can intervene as a deadlock breaker
- Alliance contracts tend more toward risk sharing and less toward allocating the risk to one party, which is the logical consequence of co-operating in the early stages.
- A good alliance contract has a major instrument called 'Alliance Board' to promote the spirit of co-operation and amicable dispute resolution and increasing efficiency.
- Frequent communication means that time is often saved in other areas. The client and contractor work much more closely as a team and are far less competitive.

4.4.4.2 Disadvantages of Alliance contact:

The major disadvantages of alliance contract as per (IADC-2008) are as follows:

- An alliance contract cannot function without a true spirit of co-operation and better and frequent communication which might seem to be difficult.
- The time and cost obligations are notably lacking and the emphasis is on the result, e.g. delivery of the project, and less on the road that leads to the result. This brings with it a degree of uncertainty about budgets and delivery dates.
- If a project has an inflexible completion deadline or inflexible budget, then an alliance contract could lead to major problems.
- The organization of an alliance contract can also be much more difficult if more than two parties are involved as an alliance board may easily become unmanageable. Parties may therefore prefer a traditional contract with all the usual certainties.
- Third parties confronted with an existing alliance contract may wish to deal only with either the contractor or the client, not with both.
- Third-party involvement may even lead to a conflict of interests because of obligations deriving from relationships with third parties.

Alliance contracts are by no means the only form of contract for the future. Traditional contracts probably remain the most appropriate form of contract for small-scale, straightforward, short-term jobs. In such cases alliance contracts may be overkill, because they need time, energy and devotion to succeed. Furthermore, not all parties can easily adopt the spirit of trust and co-operation that is essential for an alliance contract to succeed. For large-scale, complex projects which require long-term planning and execution, an alliance contract offers a unique opportunity to work in a cost-efficient manner that can result in a win-win situation for contractor and client. At first sight, the shortcomings of an alliance contract on traditional bankability issues, such as certainty of time and cost, appear critical. Still, banks are more and more coming to terms with the concept of alliance contracts. There is a risk share across all parties and collective ownership of opportunities and responsibilities associated with delivery of the project or service. Any 'gain' or 'pain' is linked with good or poor performance overall and not to the performance of individual parties (lhalliances.org.uk, 2013).

4.4.5 Contract challenges for All Electric LNG:

Failing to meet or exceed the project objectives of safety, cost and schedule typically stems from misunderstanding the objectives of the project from the conceptual stage and therefore often lead to improper selection of the contract type. Personnel, contract structure, authority levels, trust and teamwork are significant factors in achieving the project objectives (Agnitsh et al 2001). Dependent on the level of risk the Owner of a project is willing to accept, budget constraints, and the Owner's organization core competencies, will determine which method is best for their project. EPC contracting tends to be more expensive to the Owner, due to the shift of project risk away from the Owner to the EPC Contractor. On average, a project's cost 10% - 20% more using EPC style of contracting than a project using the EPCM style of contracting (Agnitsh et al 2001). This limited number of experienced suppliers, along with the understandable reluctance of the LNG industry to try new things, has probably contributed to the price increases (Jamieson, 1998). To that effect an All Electric LNG contract price will be more than a conventional LNG project as there are a lot of step out technological changes involved in addition to the large combined cycle power plant that needs to be built, however the due diligence with contractor will be more complex and cumbersome. An alliance contract in an LNG environment can be explored to spread the risk between the owners and contractors.

4.5 Engineering challenges:

4.5.1 Engineering:

4.5.1.1 Front End Engineering Design (FEED):

It is often a general practice to squeeze the front end engineering and fail to provide adequate planning time to fully engineer, design and plan project execution. Front End Engineering and Design comprises a logical progression from capital project selection through capital asset commissioning and operation (Morris, 2009). For a better lifecycle performance the owners have to ensure that more upfront engineering is done. During early project stages, the FEED has to define the project scope aligned with business objectives. In addition to identifying and evaluates technological alternatives it prepares capital budgets, design criteria for use in detailed engineering along with project scheduling and cash flow projections. It also identifies risks, judges importance, ranks and assigns mitigation responsibility within the Owner's organization. This helps the contractor to provide firm costs and schedules while minimizing change orders (Wenninger, 2007). A slightly longer planning window on front-end-engineering and more technical resources application with the right skills will go a long way in significantly improving the final outcome. Advantage of implementing a FEED approach is that it allows and requires early value engineering, constructability reviews and operation and maintenance input before the contractor fixes cost and schedule and make it possible to "freeze" the project scope so that further changes are few (Wenninger, 2007). The other key improvement area is better integration of contractors and service companies into planning process. Technology limits are pushed to utilize and reduce the overall development cost in a lower price environment (Jacobsen, 2009). During each phase of Front End Engineering Design (FEED), sound engineering judgment and industry “best practices” are applied to improve Capital Expenditures (CAPEX) and Operating Expense, (OPEX). There are significant risks when owners fail to provide for the engineering function, by this lacking the ability to define projects at the front end. During later stages, these companies become overly dependent on their detailed design and construction contractors, whom they are ill equipped to manage. Failing to provide for the owner's engineering function can lead to compromised quality, exceeded capital costs and/or extended schedules. According to a recent Business Roundtable study, companies successfully executing Owner's Engineering functions spend 28% less on projects, reduce cycle time to start up by 30%, increase plant capacity by 6% and transform average 15% Return On Investment (ROI) projects into 22+% return (Wenninger, 2007). Companies also face the challenges of complying with safety/environmental regulations apart from the challenges of a new operating frontier with billions of dollars in capital investment. This operating, safety and environmental challenges necessitates utilization of new technology, improvement of asset reliability and reducing operating expenses to life cycle advantage over the competitors (Morris, 2009).

4.5.1.2 Reliability Centered Design Analysis: (RCDA):

Reliability Centered Design Analysis (RCDA) leverages the guiding principles and rules that comprise the Reliability centered Maintenance (RCM) methodology (Morris, 2009). RCDA is a formalized methodology, following a step-by-step process, which lowers the probability and consequence of failure, resulting in the most reliable, safe and environmentally compliant design. RCDA is a process, which can be integrated into project management stages i.e. Front End Engineering and Design (FEED). Funding for Reliability Centered Design Analysis is included in project stage. Direct benefits using Reliability Centered Design Analysis in Front End Engineering and Design are higher availability, reduces risk designs, lower the probability and consequence of failure, focuses on maximizing the reliability of critical components, safer and reliable operations, better quality control and more stable operation (Morris, 2009). It also helps in lowering operating expense (OPEX), optimizing Preventive and Predictive Maintenance programs, emphasizing on condition-based maintenance practices, documents the primary modes of failure and their consequences and optimizes spare parts requirements (Morris, 2009).

4.5.1.3 Detailed engineering process:

Detail design activities are undertaken and project design plan prepared, conforming to the project design requirements and schedules. The Design Plan needs to take care of the personnel involved, list of design Inputs and output, release schedule of design output, the method of revision, updating and control. (QG2 Project design plan, 2005). The schedule and interface that defines the organizational and technical interfaces among different organizations that input into the design process need to be established. Basic design need to follow the general specifications, design specifications, construction specifications, basic design drawings, standard design drawings, the process licensor's design package, the project engineering data and the like. Design output should include design calculations, drawings, specifications, and data sheets with the output meeting the input requirements, including applicable regulations, specifications for purchased products and also gives acceptance criteria for safe and proper operation and maintenance of the plant. Design reviews are conducted to examine and evaluate the design so as to identify any problems, including those in related designs, construction, safety, environmental, operation, maintenance, etc. Process and Instrumentation Diagrams (P&ID), Plot Plans 3-Dimensional model review are conducted by an independent team which reviews the adequacy of design. Design verification is conducted to ensure that the output meets the requirements in accordance with the design criteria. Design validation is to be conducted to confirm that the product satisfies specifications. Design validation is not only the performance tests specified but also to confirm the design by calculation and simulation, etc. at appropriate design stages. Design changes are reviewed and approved by the same organization that performed and approved the original review (QG2 Project design plan, 2005).

4.5.1.4 RAM Analysis:

As a best engineering design practice, Reliability, Availability and Maintainability analysis (RAM) is conducted during the early stages of project design. RAM is a statistical analysis, which quantifies system reliability, availability and maintainability. RAM analysis utilizes failure information from system components in order to develop failure probability distributions. The analysis provides insights particularly the identification of primary contributors and critical events to system unreliability. The results help to consider an alternative design if the primary design fails to meet the expected project deliverables with respect to reliability, availability and maintainability. Additionally the analysis provides assistance in determining operational and maintenance strategies, life cycle cost, equipment operating spares, repair strategies and logistical requirement considerations. Combining the efforts of RAM in conjunction with the principles of Reliability Centered Maintenance (RCM), which deals with routine maintenance and replacement based on reliability improvements, further enhances system reliability and reduces operating expenditure (Morris, 2009).

4.5.1.5 Human factor design:

An extensive use of three dimensional modeling is required during the design development that encompasses the key human factors in the design. This involves the collaboration of project, operations, and contractor personnel and a human factors specialist (Chavez et al 2007).

Adjustment to the Anthropometry of Local Process Workers: Today, anthropometry plays an important role in industrial design, where statistical data about the distribution of body dimensions in the population are used to optimize design. Design and construct of process plants need to accommodate the physical characteristics of the working population with respect to accessibility, exit and clearance of installations (Chavez et al 2007). Other features to be ensured that safety escape routes ensures proper escape routes and provision of an additional alternative means of egress and accessibility to process equipment for maintainable by cranes and other lifting equipment (QG2 project documentation 2005).

4.6 Operational Challenges:

The LNG facility is designed to continuously produce on-specification product over its full range of capability. The plant operability automatically adjusts controls to correct for disturbances caused by changing weather, process or utility conditions so as to be capable of controlling the transients during start-up (hot or cold), normal shutdown, and emergency shutdown. The facilty is normally designed to operate for a 3-year period without a major turnaround to coincide with the gas turbine driver maintenance cycle (ABB, 2009). The probability as well as the consequences of a given type of failure is an important factor in consideration of special features included for continuity of operations. Some of the operational challenges for continuity of operations are discussed below.

4.6.1 Online stream days:

The average one line stream days is dependent on various factors such as preventive maintenance intervals, turnaround time for gas turbine related inspection and additional time for actual maintenance work. Further, the operations is also dependent upon Mean Time Between Failures (MTBF) of various critical rotating equipment especially gas turbines. While planned shutdowns can be delayed, unplanned shutdown can occur resulting in an average 12 lost stream days per year in total capacity (Devold, 2006).

4.6.2 Operational cost:

The other challenge to minimize the operational cost such cost of fuel and running utilities etc. More detailed assessment of opportunities demonstrates that a VFD driven electric motor is significantly less expensive to operate than a gas turbine. (Kleiner et al 2005).

4.6.3 Maintenance cost of Interval between maintenance:

Due to thermal and mechanical stresses and wear parts service & maintenance expenses for Gas Turbine drivers is quite high (Kleiner et al 2005). In case of electrical drive systems the cost is only a fraction. The challenge is to implement a system that is simpler and less failure prone. The scheduled maintenance should be minimized by increased predictive maintenance and also the reduction of spare parts for replacement. Electrical drives can run for periods up to 6 years of continuous operation, and even after that no costly parts need to be replaced (Kleiner et al 2005). The in-operation Mean Time Between Failure (MTBF) of electrical drive system is higher than that of gas turbine with availability of 99.9%. In an all electrical system it has been demonstrated to lower maintenance costs by up to 80% (ARC strategies, October 2000).

4.6.4 Operational safety:

In conventional LNG, gas turbine driven compression combustion equipment are present in the process area. The evolving concept of all-electric LNG plants segregates combustion and convective heat recovery equipment from the high pressure liquid hydrocarbon equipment from process area in to utility area thus eliminating associated risks and can reduce associated insurance costs (Kleiner, 2005).

4.6.5 Thermal Efficiency:

One major challenge of LNG process is reduction of thermal efficiency. Overall refrigeration-system efficiency is about 32% in a traditional mechanical drive solutions, which can be increased to of up to 45%, with a Combined-cycle power plants fed all-electric drive system and also reduce greenhouse-gas emissions by around 30 percent compared to traditional mechanical compressor drives (Kleiner et al 2005). Even including distribution losses the electric drive systems along with the process-steam supply system may reach an overall thermal efficiency of 90 percent (Siemens, 2008). Thus, even in a not fully optimized configuration, where the efficiency of the gas turbine is about 25%, the power generation efficiency is about 47%, but climbs as high as 55% for a combined cycle plant. Therefore, the savings in taxation and consumption of fuel gas at the prevailing market price could add up to as much as third of the system’s CAPEX (Devold et al 2006).

4.6.6 Emissions:

Continuous improvement in environmental performance is becoming increasingly important motivated by the potential to reduce both cost and GHG emissions. In comparison to gas turbine drives which has a much higher emission the potential for E-drive remains noteworthy and significant in the context of future capital investment for emissions reduction.

4.6.7 Performance Deterioration and Recovery:

The area of gas turbine performance deterioration is of great importance to any LNG operation. Total performance loss is attributable to a combination of “recoverable” (by washing) and “non-recoverable” (recoverable only by component replacement or repair) losses. Recoverable performance loss is caused by fouling of airfoil surfaces by airborne contaminants.

4.6.8 Flexibility of operation:

Scaling up of gas turbine drives for LNG may have reached a plateau. Hence there is very little margin of flexibility. Further due to the discrete size of the gas turbines the compressor size is also restricted by gas turbine size. With E-LNG, process and compression-plant size is no longer restricted by available mechanical drives. In these systems, multiple motors with lesser outputs may serve as dedicated compressor drives, improving operational flexibility (Kalyanaraman, 2005).

4.6.9 Ambient temperature consideration:

In gas turbine as the ambient temperature goes up the output goes down as the combustion air becomes thinner. In an all electric system the production remains largely unaffected by ambient temperature (Siemens, 2008).

4.6.10 Capability of successive and cumulative starts:

Quick and controlled starting and re-starting of pressurized compressors minimizes downtimes and eliminates flaring of expensive refrigerant gas (Siemens, 2008). Full power is instantly available over the entire temperature and speed range, and the number of successive and cumulative start-stop and load cycles is generally uncritical (Kleiner et al 2005).

4.6.11 Restart after a trip:

A full shutdown in an LNG plant creates both a safety hazard and a major loss of production. In a gas turbine LNG the gas turbine needs to cool down before it is restarted and the gas needs to be flared for restarting purpose and it takes up to 48 hours to come back on line resulting in lost production, which is not required in All-Electric LNG (Devold et al 2006).

4.6.12 Design flexibility of train sizing:

Gas turbines are generally available in fixed sizes hence does not offer a wider design flexibility in terms of size of trains. This is not the case with all electric LNG as motor can be built to various different sizes as per the design requirement.

4.6.13 Testing:

Lack of performance or malfunctions of subsystems after installation can have grave financial consequences and complete testing of compression systems at the manufacturer’s location is thus normal. To make sure that the gas turbine drives perform to its design, extensive testing has to be carried out at the factory. Later at the site extensive construction and validation testing has to be carried out. The testing duration of the All-Electric Drive is much shorter and less complex.

4.6.14 Optimizing size and accessibility of compressors:

Accessibility can often be arranged providing ready access to the inner bundles, bearings, and seal cartridges of vertically-split compressors, without disturbing the basic alignment of the compressor bodies.

4.7 Environmental challenges:

ISO 14001:2004 and ISO 14004:2004 focus on environmental management systems. The other standards in the family focus on specific environmental aspects such as life cycle analysis, communication and auditing (ISO, 2013). LNG plant contributes to CO2 emissions, which is a greenhouse gas and a prime contributor to global warming. Liquefaction of natural gas produces emissions during the removal of carbon dioxide from inflow gas, fuel used in gas turbines compressors and fuel used by power generation turbines. There are two ways to increase the efficiency and decrease the emissions firstly by improving the process and secondly by improving the efficiency of the production of heat and power (Rabeau et al 2007).

4.7.1 Specific CO_2 emission (Coulson, 2010)

4.7.1.1 CO_2 Emissions from Feed Gas:

Further, improving overall thermal efficiency of the plant reduces the CO_2 emissions in two ways. Firstly, the CO_2 emissions from fuel are reduced, because there is less fuel required, and secondly, the CO_2 emissions is reduced because using less fuel requires less feed gas (Coulson 2010).

4.7.1.2 CO2 Emissions from Fuel gas combustion:

The CO_2emissions from fuel for LNG liquefaction plants are typically in the range 0.24 to 0.32 tonne CO_2/ tonne LNG, which can still be reduced. With optimization of the heat and power balance the fuel consumption and CO_2 emissions from fuel can be reduced by approximately 30% leading to CO_2 emissions from fuel in the range of 0.17 to 0.22 tonne CO_2/ tonne LNG. Assuming capture and export of 90% of the CO_2 from the combustion flue gases, there is potential to reduce the CO_2 emissions from fuel to around 0.02 tonne CO_2/ tonne LNG (Coulson 2010). The refrigeration and gas recovery power requirements can account for up to 90% of the plant fuel gas consumption. Therefore, the selection of combustion efficiency has a direct impact on the overall plant greenhouse gas emissions. The fuel consumption is about 10% of the typical feed gas for LNG production. 39% of the overall CO_2-e emissions estimated for normalized operations occur from power generation (Barnett, 2010).

4.7.2 CO_2 Capture and Storage:

Carbon capture and storage (CCS) system can be employed so that CO_2 can be captured from process, heaters, boiler exhausts and vents. The two major sources of CO_2 emissions in LNG plants are the acid gas removal unit and the flue gas from the gas turbines used for driving refrigerant compressors and electric power generation.

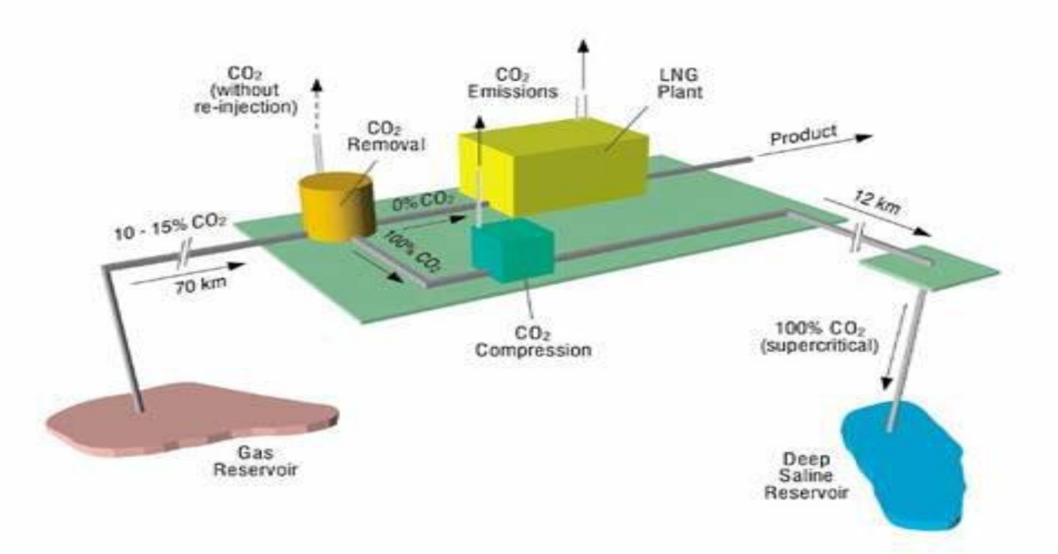


Figure 4.4: CO2 Re-Injection Scheme for Gorgon Gas Development (Barnett, 2010)

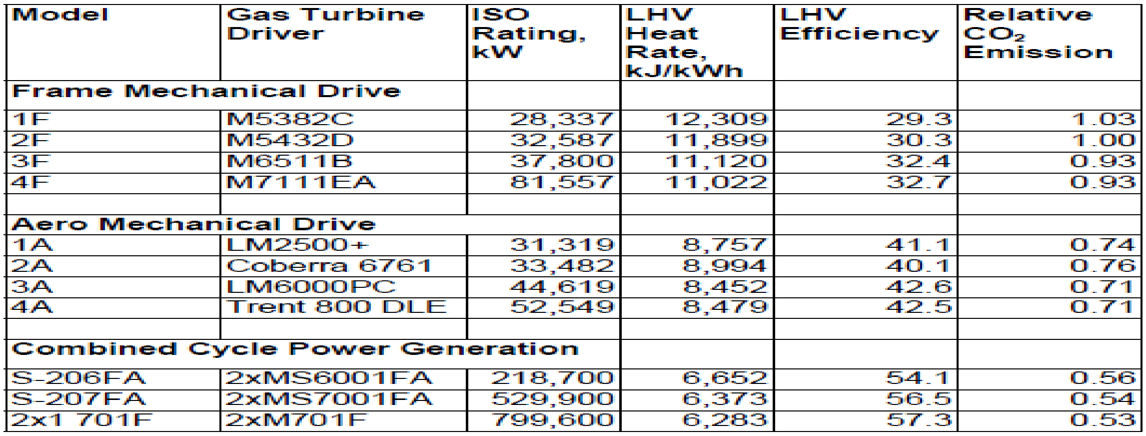
The removal of CO_2 from the feed gas is usually performed using solvent process or other options such as membrane or cryogenic distillation, (Kikawa 2001). The removed CO_2 can be compressed, dehydrated and transported and injected to storage locations such as saline aquifers, depleted reservoirs, where enhanced oil and gas recovery could be employed (Chiu 2003). By this CO_2 emission to the atmosphere can be considerably reduced.

4.7.3 Waste Heat Recovery:

Most new LNG plants use large industrial gas turbines for both power generation and for direct drive of the refrigeration compressors. The use of waste heat recovery units on the gas turbine exhaust, to provide heat for plant heating needs, can reduce the greenhouse gas emissions and fuel consumption in place of using fired heaters. Usually these heating requirements represent around 5% of the total fuel requirements of the LNG plant. Although the capital cost of waste heat recovery systems is generally greater than that of direct fired heating systems, the added cost may be justified by the reduced cost of fuel and emissions (Chiu 2003). Compared to not having any waste recovery incorporation of Heat Recovery Steam Generation (HRSG) CO_2 emissions can been reduced by about15% by using one HRSG per production train and by about 30% by using two HRSG per train (Rabeau et al 2007). This can be achieved by reduction of energy requirement as some of the waste heat could be recovered from the flue gas.

4.7.4 All Electric Drive System:

The entire LNG plant's electric power requirements, both for refrigeration compressor drivers and the balance of the plant can be provided by large generators in either the conventional gas turbine driven LNG plant or the combined cycle plant driven with aero-derivative gas turbines. Large motors could be used to drive refrigeration compressors. Heiersted et al (2003) state that in the Snøhvit LNG Project in Norway, systems involving emission have been compared and selected based on economical robustness in life cycle costs comparisons. The table shown below shows that the relative emission from a combined cycle power plant is much lower than that conventional gas turbine driver for the LNG plant which further demonstrates that with All Electric LNG concept the CO_2 emission can be minimized.



Model	Gas Turbine Driver	ISO Rating, kW	LHV Heat Rate, kJ/kWh	LHV Efficiency	Relative CO_2 Emission
Frame Mechanical Drive					
1F	M5382C	28,337	12,309	29.3	1.03
2F	M5432D	32,587	11,899	30.3	1.00
3F	M6511B	37,800	11,120	32.4	0.93
4F	M7111EA	81,557	11,022	32.7	0.93
Aero Mechanical Drive					
1A	LM2500+	31,319	8,757	41.1	0.74
2A	Coberra 6761	33,482	8,994	40.1	0.76
3A	LM6000PC	44,619	8,452	42.6	0.71
4A	Trent 800 DLE	52,549	8,479	42.5	0.71
Combined Cycle Power Generation					
S-206FA	2xMS6001FA	218,700	6,652	54.1	0.56
S-207FA	2xMS7001FA	529,900	6,373	56.5	0.54
2x1 701F	2xM701F	799,600	6,283	57.3	0.53

Table 4.1: Typical Gas Turbine Performance and relative CO2 Emissions (Chiu 2003)

4.8 Maintenance Challenges:

4.8.1 Gas turbine shutdown intervals:

As the study is focused on main compressor drivers the maintenance challenges is discussed here in that context. Gas Turbine Shutdown intervals are based on equipment requirements such as turbine maintenance for combustion inspection at 12000 hours, hot gas path inspection at 24000 hours and major inspection at 48000 hours along the mandatory inspection schedule of the gas turbines (Qatargas Maintenance Doc, 2006).
The inspection programmes of static equipment are set up according to criticality assessment or statutory practices. Between major six years shutdown, yearly planned shutdowns will be scheduled based on turbine annual requirements.

4.8.2 Long term services agreement for Gas Turbine Maintenance:

Normally due to the criticality and complexity of the main drivers a Long term services agreement (LTSA) is implemented between the operating company and the main supplier of the drivers. This stipulates the provision of the following Parts/services:

4.8.3 Routine maintenance:

Maintenance of regular, preventive or minor nature is performed periodically during Gas Turbines shutdown or during operation to maintain equipment on a day-to-day basis without the need for an outage. All preventive maintenance activities such as checking lubrication, calibrations, minor leak repair, provision of fluids, greases, and resins, cleaning and replacement of operational spare parts, filters, strainer and cartridges, maintenance or replacement of those parts included in the operational spare parts list and other similar preventive, routine or minor work (Qatargas Maintenance Document, 2006).

4.8.4 **Parts**:

The parts include new, repaired, refurbished or upgraded parts, materials, components and other goods furnished etc. Aim is to guarantee the achievement of performance agreed in the LTSA contract in terms of availability. During the life of the contract LTSA will supply and manage a set of mandatory spare parts. Parts will be used for the covered units during Planned, Unplanned and Routine maintenance (Qatargas Maintenance Document, 2006).

4.8.5 Personnel at Site:

In order to achieve and manage the performance agreed in the Contractual Service Agreement the personnel provided by the main supplier cater for Performance Management, for performing planned maintenance on turbine control panels, devices and instruments calibrations and related equipment and performing planned maintenance on turbines and its auxiliaries (Qatargas Maintenance Document, 2006).

4.8.6 **Planned maintenance**:

It is the scheduled periodic inspection, testing, repair and/or replacement of components of a covered unit. Planned maintenance is performed on periodic basis. In case of planned maintenance, following materials and services are supplied.

- Decontamination work necessary for maintenance activities
- Site utilities (compressor air, electricity, lighting, special tools, etc.)
- Fire-fighting equipment and services
- Adequate space for lay down, inspection and repair
- Workshop services for minor machining and fabrication works

4.8.7 Unplanned maintenance:

Maintenance of the covered units required to repair an in-service failure or abnormality of a component, whether discovered during an outage which occurs as a result of a problem or failure, or during inspection or monitoring of a covered unit.

4.8.8 **Remote Monitoring and Diagnosis**:

Data acquired by Remote Monitoring and Diagnosis service system are analyzed by machine experts to determine the condition of the equipment, to help in operating the asset below the alarm levels, to identify anomalous trends and to highlight incipient failures in order to assist the performance has the scope to collect and archive equipment operating data making them available to engineers. Acquired data are transferred to the Remote Monitoring and Diagnosis (RM&D) service center continuously where they are checked by RM&D engineers and used to assess machines status and potential problems or abnormalities (Qatargas Maintenance Document, 2006).

4.8.9 Trend analysis and forecasting:

Data acquiring process and related analyses are designed to evaluate the mechanical health of the equipment. The intention of the remote service is to detect potential problems before an equipment shutdown occurs. If necessary, maintenance or repair action are suggested quickly thus minimizing the extent of repair and avoiding potential collateral damage.

4.8.10 Availability:

Availability guarantee is effective after the maintenance start date. It is calculated for each train based on the operating assumption.

4.8.11 Scheduled Maintenance for Large compressor turbines:

The mandatory inspection schedule of the gas turbines is as follows (Qatargas Maintenance Document, 2006).

Combustion inspection: 12000 hrs.
Hot gas path inspection- 24000 hrs.
Major inspection: 48000 hrs.

4.8.12 Emergency Shut-Down (Trip):

If an ESD occurs due to a failure on the covered units, a ‘Trip report’ is issued for further analysis. It is quite evident from the above that the gas turbine needs very extensive maintenance routine with considerable routine downtime for regular planned maintenance activities so as to improve system availability and reliability. By incorporation of All-Electric LNG it is believed that the down time can be considerably reduced hence improve the system availability and availability. Further the Long Term Services Agreement (LTSA) for gas turbine can be very cumbersome and very expensive affair which can be avoided by adopting an All-Electric LNG option where LTSA is less expensive.

4.9 Conclusion:

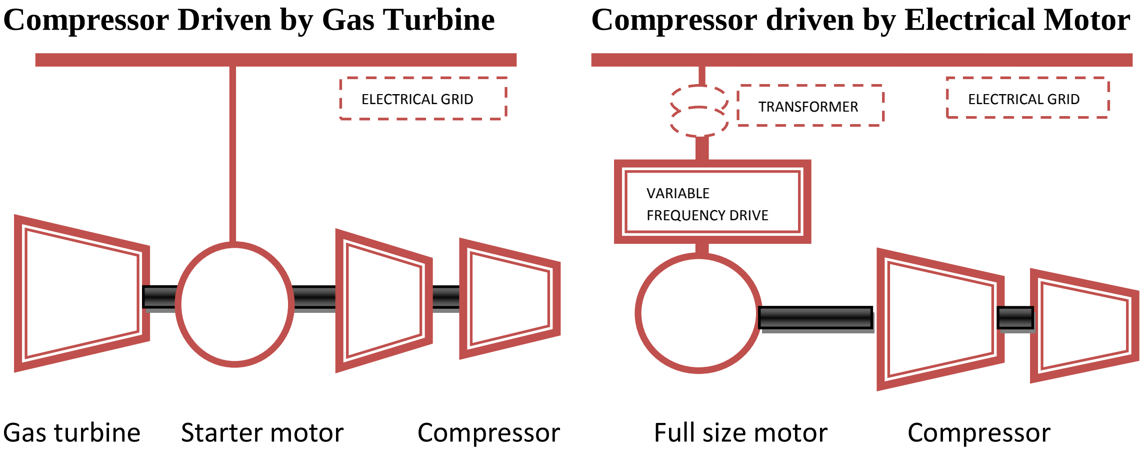
Every stage of the asset lifecycle, from long-range capital planning, procurement, construction to capitalization, operations, maintenance, and eventual disposal is filled with numerous challenges. The decisions to face these challenges must be based on full consideration of business functional requirements and economic and technical feasibility in order to produce an effective result (Life cycle management manual, 2009). Before carrying out a detail analysis and comparison between the gas turbine drive and the all-electric drive technology it is imperative to know the challenges faced during the entire life cycle processed.

CHAPTER 5

Electric vs. Gas Turbine Drives

5.1 Introduction:

In a conventional plant gas turbine is used as a main driver for compression. A small motor is provided to start the string from stand still and bring it up to a certain speed before gas turbine is fired and gradually takes up the entire compression load. During normal operation the starter motor runs idle. If the process train trips, it has to be de-pressurized by venting the inventory for the purpose of restating the string the compressor. In modern concept the motor size has been increased so that it can restart the gas turbine string in fully pressured condition in a process called ‘Full Pressure Re-Start” (FPRS). In addition to FPRS the motor can also perform a function of a helper to add power to the string during high ambient temperature condition to maintain flat production. Starting a large motor, direct on line, leads to sizeable voltage drop due to large inrush current that may cause power system instability. Hence a Variable Frequency Drive (VFD), which can provide both starting and FPRS function. It starts the string slowly so as to limit the inrush current in starting. In an electric driven compressor string the function of the gas turbine is fully taken over by the VFD driven electrical motor system, which provide all the functions for operating the compressor.



Compressor Driven by Gas Turbine

Compressor driven by Electrical Motor

Figure 5.1: Comparison Gas Turbine and Electrical Driven Compressors (Qatargas 2 and Siemens, 2008)

5.2 Advantages of Gas Turbine as a compressor driver:

Before going into the detail of comparison between the gas turbine and the all-electric LNG it is essential to discuss the advantages of the gas turbine compressor drives.

a) ***Long LNG experience:*** Gas turbine has long years of service experience being the LNG industries dependable workhorse for about four decades.

b) ***Robust and sturdy:*** It is a robust, sturdy and simple machine to operate.

c) ***Lower risk as no step out:*** Since this technology has been there since a long time it has a lower risk of design construction, testing and operation. Since there is no step out technology involved, it is considered low risk

d) ***No large power requirement:*** It requires a small amount of power for starting and do not need large complex power station to be built.

e) ***Proven Reliability:*** Although it has a lower availability because of routine time consuming and costly maintenance regime, the reliability of the machine is quite high. Integrated approach to design, engineering, manufacturing and testing ensures that the machines are of high quality and performance (General Electric, 2006).

f) ***Full load String test up to 130MW:*** Proven capability exists to string test the gas turbine and compressor in the manufacturer's facility up to 130MW (General Electric, 2006) by which all the shortcomings can be identified and fixed before the machine is transported to site.

g) ***Confidence of Lenders, financiers and stakeholders:*** Because of the long years of dependable service, all the stakeholders are quite confident in its performance.

h) ***Global Service:*** Dependable global service network is available for gas turbine in terms of personnel and spare parts.

i) ***Rigorous testing regime:*** It has established improved performance and reliability (General Electric, 2006).

5.3 Gas Turbine and Electric Drive comparison:

The use of electric motors as compressor drivers is gaining increasing interest in the LNG industry. Systems may also be considered which uses combinations of electric motor and gas turbine drive for the refrigeration compressors. All gas turbines, by nature of their physics and design, have inherent limitations when compared to equivalent electric motors. These limitations do not apply to electric motor variable speed drivers of equivalent rating & performance and this is the key to considering electric motor compressor drivers as a viable alternative for new installations. The limitation of gas turbine with respect to electric motor is discussed here in detail.

5.3.1 Availability, Reliability and Maintainability:

There is increasing interest by some in the LNG marketplace for using electric motor drivers instead of using gas turbine drivers. This interest has a potential for higher plant availability and lower compressor driver life cycle costs. Plant availability can be higher than the 96%. The higher plant availability derives from the fact that the motors require minimal maintenance and can be kept operational for six years at a time (Martinez, et al 2005).Apart from a smoother process and energy savings, electronic speed control also results in less maintenance because there is less mechanical stress on the machines, bearings and shafts. This prolongs operational life and keeps downtime to a minimum. The low starting current because of the use of VFD also reduces the mechanical and thermal stress on the machine and the adverse influence of starting surges on the power system. All these factors contribute to high reliability and maximum availability of a plant (ABB, 2009).

Online stream days: While planned shutdowns can be delayed, occurrence of unplanned shutdown can result in an average 12 lost stream days per year in total capacity (Devold, 2006).In Snohvit LNG Electric motors, provided with variable speed features, driving the refrigeration compressors, are parts of significant ‘Best Available Technology (BAT)’. For the Snøhvit design, the availability of the all-electric concept is approximately ten on-line-stream days more per year than for a mechanical drive, industrial heavy-duty based concept, with gas and steam turbines (Heiersted et al, 2003).

5.3.2 Train size restriction:

The gas turbines come in fixed sizes hence the LNG production Trains. However, depending on the desired capacity and the maximum electric motor size, many different configurations are possible. A train can produce up to 8 MTPA using electric motors up to 65 MW in size (Roberts et al, 2004).This is the driving force behind the enormous increase in the number of electric drives being installed in oil and gas industries for compressor applications (ABB, 2009).Gas turbines are available only type-tested standardized products of fixed sizes with given output ratings. Electric drive systems are custom engineered for the application on hand, allowing the compressor to be optimized in capacity and speed for the process on hand, and not being limited by a given Gas Turbine rating (Kleiner et al, 2005).Liquefaction capacities from 7-10 MTPA can be achieved, with the specific arrangement depending upon the maximum motor size considered proven.

5.3.3 Starting limitations:

The gas turbine is not inherently self-starting. LNG plants using gas turbine as prime driver of the compressor string use a smaller size motor to shaft power start the string from stand still and achieve a certain speed before which the combustion can start and the turbine can take over. If the string has to be restarted after a trip either the pressurized inventory or refrigerant has to be flared or a much larger motor is required for pressurized start. Since a large motor takes a large inrush current at starting leading to large voltage dip which could lead to power system instability, a VFD driven electric motors is considered as this helps the string to be started in a controlled manner limiting the current inrush. Full-pressurized re-starting capability of the string in case of a trip allows starting without depressurizing refrigeration loops around compressors, which eliminates flaring refrigerant and also significantly reduces starting times and hence improves availability. The same motor is also utilized as a helper to maintain flat LNG production when the gas turbine output reduces in summer because of high ambient temperature. This starter/helper drives can be upsized to fully rated variable speed drive systems to substitute the gas turbine entirely (Kleiner, 2005).

5.3.4 Multiple starting and stopping Restrictions:

Gas turbine once tripped has to be cooled slowly since the shaft is at very high temperature and immediate stopping leads to bowing of the shaft. Hence the shaft has to be rolled slowly up to six hours to slowly cool it before it is brought to stand still. During the operation the lubrication oil has to be constantly supplied so as not to damage the bearings. For the above two operations, emergency electrical power provision has to be made, especially if the trip is because of electrical blackout condition. Further restarting and loading of the gas turbine takes several hours so as not to put the shaft under undue thermal stress. Hence there is both starting and stopping restriction for gas turbines. In Electrical drive system the motor can be started and stopped multiple times and there is no need of slow roll or emergency lube oil requirement hence no emergency power system required. The variable speed drive does not draw more than rated current from the power system during starting, and is thus not thermally and/or mechanically stressed beyond its rated duty. Full power is instantly available over the entire temperature & speed range, and the number of successive and cumulative start-stop and load cycles is generally uncritical due to slow controlled starting (Kleiner et al, 2005).The above mentioned advantages are not there in gas turbine drives. A full shutdown in an LNG plant creates both a safety hazard and a major loss of production. It takes up to 48 hours to come back on line resulting in lost production. In a gas turbine LNG the gas turbine needs to cool down before it is restarted and the gas needs to be flared for restarting purpose which is not required in all-electric LNG (Devold et al, 2006). With an electric motor driven compression system, quick and controlled starting and re-starting of a pressurized compressor minimizes downtime and eliminates the potential for flaring large quantities of expensive refrigerant constituents. Once shut down, planned or unscheduled, re-starting is less time consuming (Kleiner et al, 2005).

5.3.5 Full Pressure Restart:

On most gas turbine mechanical drive applications the centrifugal compressor usually start-up unloaded or a very low pressure. The turbine string is started up by a relatively small starter motor. Then the turbine is fuel fired and it picks up speed. After it reaches the minimum continuous speed after which the compressors are loaded. In an LNG plant this depressurized starting method results in loss of refrigerant to depressurize refrigeration loops after any plant shutdown with increased flaring and increased plant downtime (approximately 8 hours required to complete plant start-up). Electronically controlled starting torque of the VFD is always sufficient to start even a fully loaded compressor, a valuable asset in case of process trips because the compressor circuit does not have to be depressurized resulting in no flaring or loss of refrigerant and the cryogenic process elements do not warm up (ABB, 2009). Quick and controlled starting and re-starting of pressurized compressors minimizes downtimes and eliminates flaring of expensive refrigerant gas (Siemens, 2008).A pressurized starting capability with the help of VFD can help increasing plant availability by greatly reducing starting times. Service can typically be restored within a short time because the drive can always restart the fully loaded compressors.

5.3.6 Performance Deterioration:

The area of gas turbine performance deterioration is of great importance to any LNG operation. Total performance loss is attributable to a combination of "recoverable" (by washing) and "non-recoverable" (recoverable only by component replacement or repair) losses. Recoverable performance loss is caused by fouling of airfoil surfaces by airborne contaminants. Periodic washing of the gas turbine, by on-line wash and crank-soak wash recovers 98% to 100% of these losses (Sheldrake, 2003). The objective of on-line washing is to increase the time interval between crank washes. A critical factor in any LNG operation is the life cycle cost that is impacted in part by the maintenance cycle and engine availability (Meher-Homji et al 2007).Electric drive systems do not require de-rating.

5.3.6.1 Dirty engine losses:

Consideration should be given to the fact that engines become contaminated with the combustion deposits, the lubrication oil becomes less efficient, blades erode and lose their thermodynamic efficiency and air filters become less efficient due to the presence of filtered particles. These effects combine to reduce the output of the machine. A rule-of-thumb figure for de-rating a gas turbine for dirty engine operation is 5% of its capacity (Sheldrake, 2003). This depends upon the type of fuel, the type of engine, the environment and how long the engine operates between clean-up maintenance periods (Sheldrake, 2003).

5.3.6.2 Fuel composition and heating value losses:

The chemical composition and quality of the fuel will to some extent influence the power output. However, it is usually the case that more or less fuel has to be supplied by the fuel control valve for a given throughput of combustion air. Hence it is usually possible to obtain the declared normal rating from the machine, but attention has to be given to the supply of the fuel. In extreme cases the profile of the fuel control valve may require modification so that adequate feedback control is maintained over the full range of power output (Sheldrake, 2003).

5.3.6.3 Silencer, filter and ducting losses:

The amount of silencing and filtering of the inlet combustion air depends upon the site environment and the operational considerations. Site environmental conditions may be particularly bad, e.g. deserts where sand storms are frequent; offshore where rain storms are frequent and long lasting. The more filtering that is required, the more will be the pressure loss across the filters, both during clean and dirty operation. This pressure drop causes a loss of power output from the machine. The amount of inlet and exhaust noise silencing will depend upon, how many machines will be in one group and total noise level permitted by standards. It is then necessary to allow a de-rating factor for the pressure drop that will occur due to long runs of ducting. With a reasonable degree of silencing a rule-of-thumb de-rating factor would be 98%. The following de-rating factors should be used in the estimation of the continuous site rating for the complete machine (Sheldrake, 2003).

- ISO to a higher site ambient temperature, typically 0.5 to 0.8% per every^{0}C rise.

- Dirty engine losses and the ageing of the gas turbine, assume 5%.
- Fuel composition and heating value losses, discuss with the manufacturer.
- Silencer, filter and ducting losses, assume 2 to 5%.
- Gearbox loss, typically 1 to 2%.
- Generator electromechanical inefficiency, typically 2 to 4%.
- Auxiliary loads connected to the generator, typically 1 to 5%.

5.3.7 Speed control range restriction:

Being a mechanical drive a gas turbine has a limited speed variation capability by controlling the inlet guide vane and firing rate. With the use of a Variable Frequency Devices, the speed of each compressor can be optimized not only to achieve maximum compressor aerodynamic efficiency at a design point but also at the warm and cold ambient temperature extremes and as per process requirement (ABB, 2009).In addition, compressor speeds can be suitably changed to optimize for target production with smaller train capacity while remaining insensitive to swings in ambient temperature (Chart Energy & Chemicals Group, 2013). Apart from a smoother process and energy savings, electronic speed control also results in less maintenance because there is less mechanical stress on the machines, bearings and shafts (ABB, 2009).The VFD enables the strings to vary speed required to optimize LNG production by increasing or decreasing the speed as per process requirement. Since the efficiency is more or less same for the entire speed range.

5.3.8 Emissions:

Continuous improvement in environmental performance is becoming increasingly important motivated by the potential to reduce both cost and greenhouse gas emissions. In comparison to gas turbine drives which has a much higher emission the potential for zero emissions in the LNG supply chain, and this advantage for Electric drive remains noteworthy and significant in the context of future capital investment for emissions reduction. Use of “carbon tax” is typical to decide the appropriate compromise between minimum cost, minimum greenhouse gases and also reduce greenhouse gas emissions by around 30 percent in electrical drives compared to traditional mechanical compressor drives (Kleiner et al 2005).

5.3.9 Schedules of installation:

The schedule with gas turbine installation and testing is quite expansive. Typically, E-LNG schemes provide significant time benefits. Faster string test programs, modular motor-drive systems, and shorter installation times offer the potential for months of schedule reduction and a substantial decrease in related costs (Siemens, 2008). Motor delivery times are shorter than that of a gas turbine driver.

5.3.10 Testing:

No extensive testing such as gas turbine required.LNG plants are mostly located in remote areas and in extreme climate zones. The gas turbine testing is extensively discussed in Appendix D. Hence complete testing of the compression systems at the manufacturer's location is thus normal to avoid financial consequences due to lack of performance or malfunctions of subsystems after installation. To make sure that the electrical drive system performs as specified prior to this full-load test at the compressor manufacturer's test facility, they can be load-tested as well in the motor factory at or near full load & speed. To verify that quality standards and customer requirements a drive can be subjected to thorough testing modern test facilities. Routine tests and functional tests can be performed in accordance with international standards. Combined test with the complete drive system, including transformer, converter and motor can be performed with or without load to verify functionality as well as the load performance to confirm the design data and verify performance values as well as reduce installation and commissioning time on site. With two or more identical drive systems on order at the same time, they can be tested in the so-called back-to-back mode, i.e. one unit operates as motor, the other one as generator and loaded (Kleiner et al 2005).

5.3.11 Ambient temperature consideration:

In gas turbine as the ambient temperature goes up the output goes down as the combustion air becomes thinner as shown in Figure 5.2. In an all-electric system the production remains largely unaffected by ambient temperature (Siemens, 2008). Full power is instantly available upon issuing the 'Start' command, regardless of the ambient and motor temperature, and the number of successive starts is also unlimited: (Kleiner et al 2005). Decoupling of plant production and ambient temperature is possible with electric drives as typical gas turbines lose approximately 0.33% of their output for every one degree F increase in ambient temperature (Martinez, et al 2005).

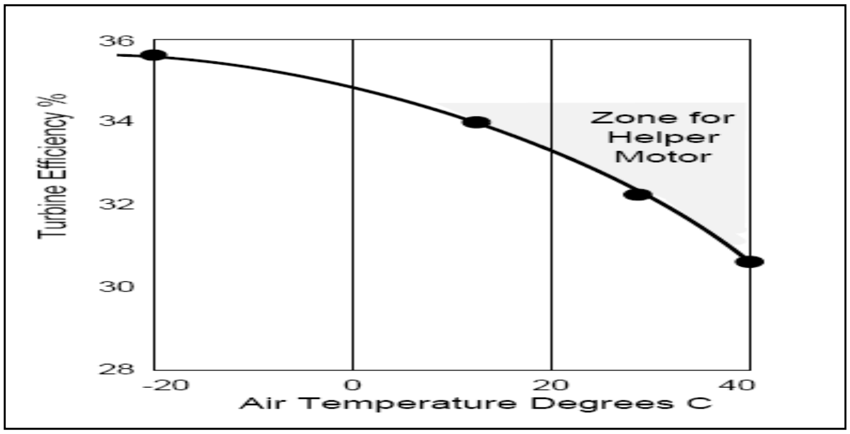


Figure 5.2: Temperature vs. thermal efficiency of gas turbine (Blaicklock et al 2013)

5.3.12 Thermal Efficiency:

Overall refrigeration-system efficiency is about 32% in a traditional gas turbine mechanical drive solutions, which can be increased to of up to 45%, with a Combined-cycle power plants fed all-electric drive system. Even if the energy conversion in the power plant is taken into consideration, the electric drive's efficiency is typically better than that of Gas Turbine direct drives due to the higher efficiency of the large Combines Cycle power plant (Kleiner et al 2005). Even including distribution losses electric drive systems achieve 96% efficiency, resulting in an including process-steam supply, overall thermal efficiency may reach 90% (Siemens, 2008).Thus, even in a not fully optimized configuration, where the efficiency of the gas turbine is about 25%, an electric drive system achieves 36% (Devold et al, 2006). A variable speed industrial gas turbine in the 25MW range driving a compressor train typically has an Efficiency of up to 30%. The average operational performance quickly falls to about 25%. A corresponding electrical drive system achieves an efficiency of around 95% over a quite wide range. In addition, the power generation efficiency is about 47%, but climbs as high as 55% for a combined cycle plant and more than 80% with triple cycle. Therefore, the savings in taxation and consumption of fuel gas at the prevailing market price could add up to as much as third of the system's CAPEX (Devold et al 2006).Electric motor variable speed drives in the upper Megawatt (MW) power range have energy efficiencies >95%, over the entire useful speed range, typically 80% to 105% of rated speed. By employing variable speed drives instead of throttling or using by-pass vanes, the energy bill can be reduced by as much as 60% (ABB, 2009).Variable speed control is the most eco-efficient way to optimize process performance. Variable speed drives reduce energy consumption and NOx and CO_2 emissions (ABB, 2009). Recent improvements in technology have resulted in a thermodynamic efficiency close to 60% for a combined cycle power generation system. In a combined cycle, the waste heat from the gas turbine exhaust is used by a steam cycle to generate power or drive another turbine. Greater reductions in fuel consumption and CO_2 emission rates may be achieved through the use of combined cycle power generation and electric motor drivers for LNG refrigeration compression. It is possible to reduce fuel consumption and CO_2 emissions by 40-50% using combined cycle power generation in conjunction with electric motor driven refrigeration compressors in place of simple cycle Frame gas turbine drivers (Chiu, 2003). The thermal efficiency of gas turbine decreases with the load as shown in Figure 5.3.

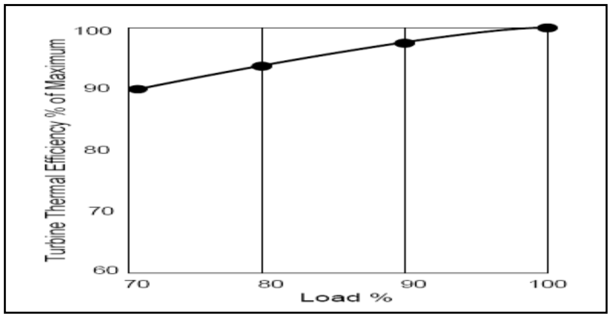


Figure 5.3: Part-load on thermal efficiency of gas turbine (Blaicklock et al 2013)

Some of the other thermal efficiency improvements are discussed in Appendix G "Efficiency improvement in LNG plants".

5.3.13 Operational cost:

The gas turbine requires several utility systems that significantly increase space, weight, operational cost and maintenance cost. The utility systems include filters, cooling, sound dampers, insulation, lube and seal oil systems and other turbine auxiliary systems.

5.3.14 Operational Economics:

More detailed assessment of opportunities demonstrates that a VFD driven electric motor of equivalent rating is significantly less expensive to buy & operate than a gas turbine. Additionally, the installation cost of a gas turbine direct drive is about double its cost as a generator drive (Kleiner et al 2005).

5.3.15 Operational flexibility and improved control of processes:

Outputs of oil and gas fields can vary greatly in their compounds, density, volume flow rates and pressure levels. This imposes varying operating conditions on process equipment, which means that compressors and pumps, which must exhibit a high degree of flexibility, cannot always be operated at their optimum design point. The employment of variable speed drives offers the possibility to control the process simply and effectively by speed control and to run equipment at its optimum operating points (ABB, 2009). Scaling up of gas turbine drives for LNG may have reached a plateau. Hence there is very little margin of flexibility. Further due to the discrete size of the gas turbines the compressor size is also restricted by gas turbine size. With E-LNG, process and compression-plant size is no longer restricted by available mechanical drives. In these systems, multiple motors with lesser outputs may serve as dedicated compressor drives, improving operational flexibility (Kalyanaraman, 2005). Outputs of oil and gas fields can vary greatly in their compounds, density, volume flow rates and pressure levels. This imposes varying operating conditions on process equipment, which means that compressors and pumps, which must exhibit a high degree of flexibility, cannot always be operated at their optimum design point. The employment of variable speed drives offers the possibility to control the process simply and effectively by speed control and to run equipment at its optimum operating points. It is easier to dial in an LNG production rate when compared to gas turbines, especially single shaft, constant speed (ABB, 2009).Apart from a smoother process and energy savings, electronic speed control also results in less maintenance because there is less mechanical stress on the machines, bearings and shafts. This prolongs operational life and keeps downtime to a minimum.

5.3.16 Operational safety:

No gas fired equipment in process area and there is no need for fired equipment and associated scheduled maintenance inside the process plant. Furthermore, the risks associated with placing gas fired equipment within the process battery limit with high pressure gas are eliminated which can result in reduced insurance costs. Enhanced safety can be achieved by removal of the gas turbines from the hydrocarbon process area. Worker risk and related insurance premiums are eliminated by removing gas turbines from the process area (Siemens, 2005).

5.3.17 Design flexibility of train sizing:

Gas turbines are generally available either in two sizes: less than 30 MW variable speed units or large 100 MW or more fixed shaft speed units. Electrical drives are available in a wide power and speed ranges, up to 100MW. Thus, the All Electric Drive system has much wider design flexibility in terms of size of trains, compressors per train shaft, and the possibility to separate smaller essential units. It has other advantages such as better overall uptime and reliability, Safe and stable operation over a wider range of process state, plant restart time is shorter, OPEX saving of 70% or more and slow roll requirement after a trip to cool down the gas turbine is not required and hence the essential auxiliary system is not required (Devold et al 2006). With electric drives, the plant can go to a production hold idle recirculation mode. In an all-Electric Drive system a low manned, remote, or unmanned operation can be considered, because electric drives have a service interval that's about 6 times longer and can operate for 100,000 hours without the need for a major overhaul as a result, fixed and variable costs are further reduced(Devold et al 2006).

5.3.18 Testing:

Lack of performance or malfunctions of subsystems after installation can have grave financial consequences and complete testing of compression systems at the manufacturer's location is thus normal. To make sure that the gas turbine drives perform to its design extensive testing has to be carried out at the factory. Later at the site extensive construction and validation testing has to be carried out. The testing duration of the all-electric drive is much shorter and less complex. It is normal practice to mount both the compressor and the motor on a common base plate or skid, and to test the entire assembly under load in the factory prior to dispatch to the job site. Full load performance tests of such compression systems can be performed up to about 80 MW, with most job equipment being part of the test, thus reducing the installation time & risk considerably(Kleiner et al 2005).

5.3.19 Optimizing size and accessibility of compressors:

Electric drive systems are always custom engineered for the application on hand, allowing the compressor to be optimized in capacity and speed for the process on hand, and not being limited by a given Gas Turbine rating. In case of twin compressor bodies, these can often be arranged on either side of the motor shaft, providing ready access to the inner bundles, bearings, and seal cartridges of vertically-split compressors, without disturbing the basic alignment of the compressor bodies. This feature is the key to larger LNG train capacities since electric motors can readily be built up to today's limit ratings of the compressors (Kleiner et al 2005).

5.3.20 Maintenance issues:

An electrically driven LNG facility requires less maintenance when compared to a gas turbine driven compressor solution as frequent turnarounds are not required for motor driven LNG plant. Further there is reduced maintenance costs and downtime for the motors and the VFDs as compared to gas turbines (Siemens. 2006). More detailed assessment of these opportunities demonstrates that an electric motor variable speed drive (VSD) of equivalent rating is significantly less expensive to buy & operate than a gas turbine. Additionally, the installation cost of a gas turbine direct drive in an LNG facility is about double its cost as a generator drive. Infrastructure improvements at the site itself can increase the price tag of the electric system, but not dramatically. In very large installations, the construction of power transmission systems or even an associated power plant may be justified if the “Total Cost of Ownership” is considered and not only the capital investment for the LNG plant (Kleiner et al 2005).In case of twin compressor bodies, these can often be arranged on either side of the motor shaft, providing ready access to the inner bundles, bearings, and seal cartridges of vertically-split compressors, without disturbing the basic alignment of the compressor bodies. This feature is the key to larger LNG train capacities since electric motors can readily be built up to today’s limit ratings of the compressors (Kleiner et al 2005). Mainly due to low thermal and mechanical stresses in the motor, and no wear parts in the drive system, service & maintenance expenses of electrical drive systems are only a fraction of those encountered for Gas Turbine drivers. Under certain assumptions, there is no scheduled maintenance for periods up to 6 years of continuous operation, and even after that no costly parts need to be replaced (Kleiner et al 2005). Gas turbine driven refrigeration compressors require periodic maintenance. Continuous production is possible up to 6 years. High thermal and mechanical stresses with resulting lifetime reductions of certain components and reoccurring service requirements requires costly spare parts, long shut down periods for maintenance. Further, complexity and sensitivity of machines due to numerous very tight clearances and tolerances between stationary and rotating parts leads to lower reliability (Kleiner et al 2005). No major refurbishment required ‘Long term services agreement’ is much cheaper and less spare part intensive.

5.3.21 Part Load efficiency:

The power required running a pump or a compressor is roughly proportional to the cube of the speed. In other words, a pump or compressor running at half speed can consume as little as one eighth of the energy compared to one running at full speed (ABB, 2009). A small reduction in speed can make a big difference in energy consumption. As many pump and compressor systems often run at partial load, the use of a variable speed drive can produce huge savings. By employing variable speed drives instead of throttling or using by-pass vanes, the energy bill can be reduced by as much as 60%(ABB, 2009).

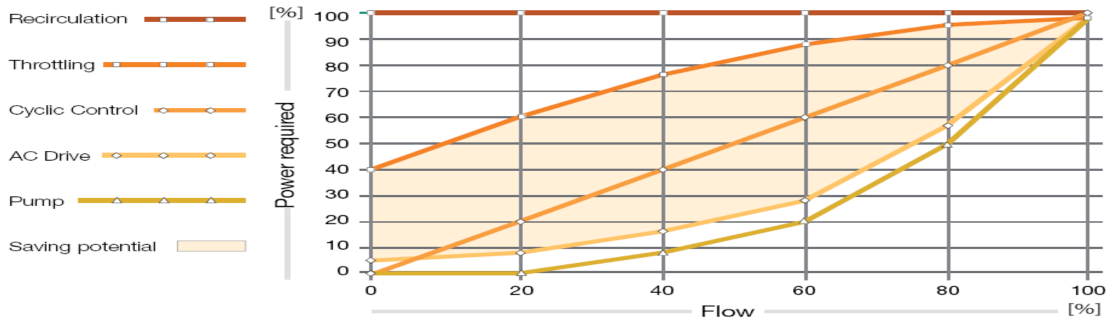


Figure 5.4: Power and consumption of control methods (ABB, 2009)

In addition to increasing efficiency electric drives can reduce NOx and CO_2 emissions on site that could delay granting of a permit and cause penalties (ABB, 2009). All trains experienced reduced efficiency in throttling mode (recycle) at low flow, driver efficiency is nearly constant at varying power levels (Man turbo AG Schweiz, 2009). The entire liquefaction process can be optimized since variable speed drive systems are more efficient at part load and require less shut down periods for maintenance. Ambient temperature swings impact both gas turbine performance and propane refrigerant condensing temperature. As the ambient temperature increases, the condensing pressure of propane and other refrigerants increase. This increase in pressure translates into power and thus places a higher demand on the gas turbine or motor driver. If this power is not available, overall LNG production will be curtailed. There is improved plant operational flexibility by using full-rated power variable frequency drives (Martinez, et al 2005).

5.3.22 Advanced surge control:

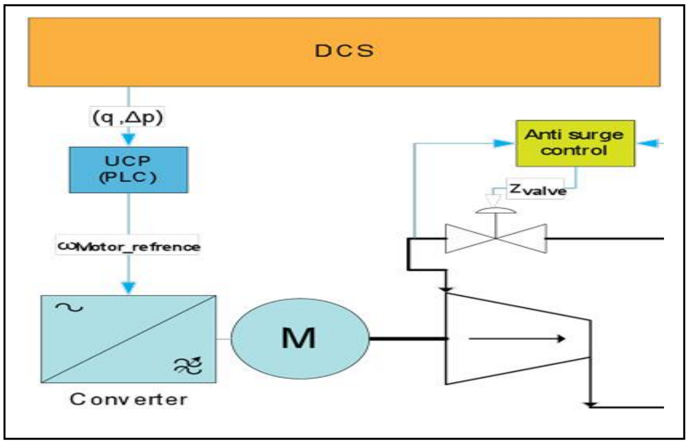


Figure 5.5: Control-system architecture applied to electric compression (ABB, 2003)

To avoid surge control methods using recirculation valves are used extensively and being opened widely well before the compressor is actually in danger of reaching surge. A VFD allows for a new strategy based on an active surge control scheme by using the motor torque as a manipulated variable. By using the fast response time of the motor, and the surge valve in a coordinated way, it is possible to improve anti-surge performance and allow the compression systems to operate with lower recirculation flows with increase energy efficiency. This facility is not available in gas turbine due to slowness of response of mechanical drives (ABB, 2005).

5.3.23 Integrated control system and process optimization:

An integrated control system can improve process performance by consolidating all available information and managing all control loops in a coordinated way. This is very important due to two process modifications that result from the adoption of VFD as compressor driver:

- A VFD system for compressor trains significantly improves the response time as compared to gas turbine driven alternatives as the electric motor has typical speed step response time of less than 200ms.
- A VFD allows for operation in a much wider operating speed range where the electrical drive and motor efficiency stay relatively constant.

In this way, motor-speed and surge-valve controls can be operated as interacting control loops, both in steady-state and during dynamic transitions. Hence a VFD solution can balance power requirements faster and better among the different sections of the LNG process. This improved control results in increased process safety and efficiency. In a parallel loop, for load sharing optimization, the possibility to operate on a wider speed range allows for the load sharing control solutions to have access to those operating points, which will minimize the total power consumed by the compressors (ABB, 2005).

5.3.24 Automation and control challenge:

The adoption of a VFD-driven compressor will also introduce a very important modification in the process-control architecture of a compressor train. The most common control architecture is still based on an old concept, where DCS (Distributed Control System) is considered is in charge only of slow-control feedback loops such as fuel valves for turbines to set rotational speed. On the other side of the classical-control concept, the fast-control feedback loops are assigned to special external dedicated hardware such as those only in charge of control of the anti-surge valve. The old control architecture approach is often still applied to VSDS (Variable Speed Drive System)/ VFD driven compressor. The classical fast-control design includes (ABB, 2005):

- A DCS (Distributed Control System) in charge to control the LNG process and, in particular, to define the working point.
- A unit control panel, which is the PLC (Programmable Logic Controller) in charge to define rotational speed of the motor and to check the relevant interlocks.
- An anti-surge control that is locally controlling the surge valve in order to avoid surging.

Modern Hardware/Software architecture-control systems are mature enough to overcome those limitations given by the usage of different Hardware platforms for different control functionalities. Actually, a modern DCS, where control cycle time can be also of 1 ms, can cover within the same platform all the functionalities required to control the entire LNG process as well as the fast loop of surge valve. Note that in the case of an existing plant, where slow DCS (cycle time higher than 200ms) is used, it is still useful to have a unique control system for VFD and surge valve (ABB, 2005).

5.3.25 Limited vendors:

Large sized gas turbines are produced by limited vendors. Most large sized gas turbine is supplied by General Electric. Whereas, electric drive system are built by many manufacturers that can provide competition in the market which will improve quality and reduce price (Kleiner et al 2005).

5.4 Other advantages of All Electric Drives:

5.4.1 Suitability of small and mid-scale LNG:

Due to the high cost and complexity of a larger and more sophisticated train and growing demand of natural gas with rising prices, there is increasing interest on limited sized, mid-tier fields, with geographical isolation or unconventional production challenges. The remote fields which constitute a major share of global natural-gas reserves were earlier thought as technically unfeasible and uneconomical for exploitation. Standardized, modularized small-scale LNG solutions offer a host of benefits for stranded natural-gas assets to be monetized requiring substantially lower initial capital investment is necessary. When the fields are depleted, the equipment associated with each modular train is still within a size range that makes it fairly easily to dismantle and relocate. All-Electric can be solution as driver as the motor can be built to ant size without restricting the capacity of the LNG trains (Chart Energy & Chemicals Group, 2013).Due to their standardized and modularized design modularized liquefaction trains and other components of a the repeatable small or mid-scale LNG facility can speed the project schedule by up to 30% percent in comparison to custom-engineered solutions (Chart Energy & Chemicals, 2013)

Figure 5.6 Modular LNG Schedule; (Chart Energy & Chemicals Group, 2013)

5.4.2 Robustness of Electric motor:

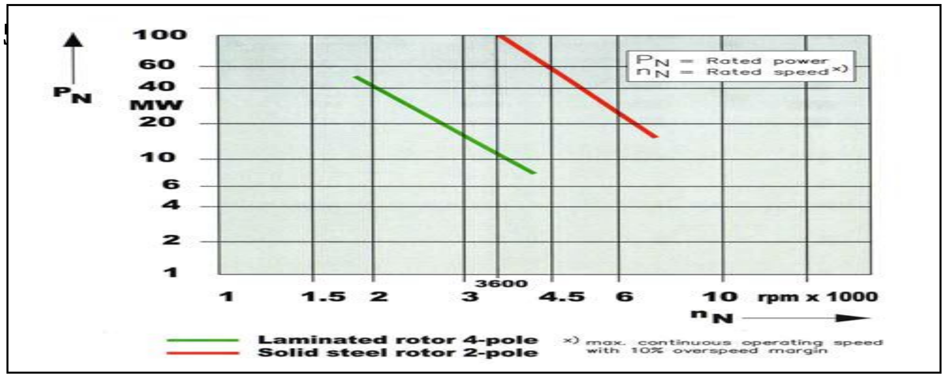


Fig 5.7; Theoretical limits for 2-pole compressor drive motors (Kleiner et al 2005)

Brushless synchronous motors with solid steel two-pole turbo rotors have been in service for decades in various industries in ratings up to 40 MW and speeds to 6600 rpm and their construction is practically identical to that of turbo generators in power stations, which have output ratings exceeding 600 MW. In 2003 Siemens built and load-tested the first “all-electric” refrigeration compressor drivers for a new LNG liquefaction plant, with rated powers of 65 MW and 32 MW at 3600 rpm, respectively, and such drives are offered in ratings exceeding 80 MW at the same speed. For lower power ratings the shaft speed can be increased somewhat with circumferential rotor speed of 200 m/s and rotor dynamic considerations up to 6600rpm (Kleiner et al 2005).

5.4.3 Modularity and prefabrication:

The frequency converter with its cooling & control systems, Low Voltage switchgears, Motor Control Centers and UPS (Uninterruptible Power Supply) systems, and the local operator interface are typically installed in prefabricated power center containers modules at the manufacturer’s location where they are also tested and pre-commissioned prior to shipment. These custom engineered modules are suited for installation outdoors in the climate zone specified, if necessary with full climate control, and meeting local building codes. With this modular building concept, the number of shipping containers and the amount of installation work on site are minimized. This module concept also facilitates the various performance and load tests typically specified for such compression systems (Kleiner et al 2005). Direct outdoor installation inside hazardous area, pluggable cables, fully climate controlled and pressurized to exclude the environment, multiple individual modules assembled on-site to form one building, safe working environment are some the advantages. Turbo-rotor-motors have been built up to 65 MW and turbo generators in ratings > 600 MW and static frequency converters of the LCI type are built in ratings to 3000 MW. Both, motors and variable frequency drives, are available today in ratings up to 90 MW (Kleiner et al 2005). Other advantages are reduced effect of harsh weather conditions during construction, reduced effect of remoteness of location and reduce the necessity of extensive steel work at site. Since there is higher productivity at construction yard in the factory the modularity offers reduce work at site in general.

5.4.4 Full drive package responsibility:

A single source offering consolidated and coordinated work from design to production, testing, and delivery and commissioning give the following advantages to customers. Minimized risk and reduced commissioning time and optimized system with all associated auxiliaries. Verification of the functionality, as well as the load performance of the drive system can be done at the manufacturer’s facility. The manufacturers can offer the entire drive system, consisting of transformer, frequency converter, filters motor, auxiliaries, re-cooling equipment, switchgear and outdoor control houses. Standard air and water-cooled designs are available for ratings up to 72 MW, engineered designs for more than 100 MW is possible (ABB. 2009).

5.4.5 No need of extensive fire suppression (Siemens 2005):

With all electric compressor train size can be tailored for a specific requirement, lower centerlines significant in seismic active and cyclone regions can be constructed, complete elimination of housings for compressor and driver with no elaborate fire suppression system is required (Siemens, 2005).

5.4.6 Better return on investment:

Electric drives offer an improved plant productivity of at least ten days of additional steam day's production per annum. Higher plant availability and operational flexibility with reduced maintenance costs and reduced peak maintenance labour are other advantages as LNG modules can run for 6 years without interruption (Siemens, 2005).

5.4.7 Other features:

The E-LNG plant concept also offers the following features:

1) Power station staging – startup can use inexpensive open cycle plant with the potential to upgrade to combined cycle.
2) Better compressor access by placement of compressor bodies on either side of the motor.
3) Shorter motor delivery times than that of a gas turbine driver.
4) LNG production is not impacted by ambient temperature swings (Siemens, 2005).
5) Issues with gas turbine such as thermal and mechanical stress resulting in lifetime reductions of certain, components and reoccurring service requirements, complexity and sensitivity due to numerous very tight clearances and tolerances between stationary and rotating parts is not there in electric drives.
6) Advantage of speed range regulation to achieve maximum compressor aerodynamic efficiency at a design point (Roberts et al, 2004).

5.4.8 Possibility of parallel operation:

A significant improvement in overall plant availability could be made by arranging the gas turbine drivers and compressors in parallel rather than in series. When one compressor or gas turbine in a refrigerant loop shuts down the parallel compressor continues to run allowing the plant to continue operation at a reduced rate. Because heat exchanger approach temperatures improve at lower production rates and duty can be balanced between refrigeration loops one of two 50% compressors can still produce 60 - 75% of total plant capacity (Jamieson, 1998). The additional capital cost for this option is small and more than offset by the improvement in availability. The parallel arrangement eliminates the possibility of a single machinery failure shutting down the whole plant and saves a lot of time when repairing a machine as the plant does not have to be completely shut down and restarted.

5.4.9 Possibility of Large Trains with higher reliability:

Large trains can be feasible and cost-effective. One major concern with “mega” LNG trains is significant reduction in LNG production when one of the refrigerant compressor trains goes out of service. This problem can be mitigated with the Phillips Optimized Cascade LNG Process “two-train-in-one” (parallel circuit) reliability concept which allows the LNG train to operate at up to 75% capacity even when one compressor string trips. LNG trains utilizing this design have demonstrated on-stream availability greater than 95%, the highest in the LNG Industry (Hunter et al, 2004). The outstanding safety, reliability, and high operating factors of the LNG industry keep building up confidence in larger trains, and the trend to design larger trains will keep accelerating. Electric motor system can come for good use for “two-train-in-one” concept. In this case the proven size of VFD driven electrical motor system of 65MW can deliver 8MTPA train or larger (Roberts et al, 2004).

5.4.10 Back-to Back testing:

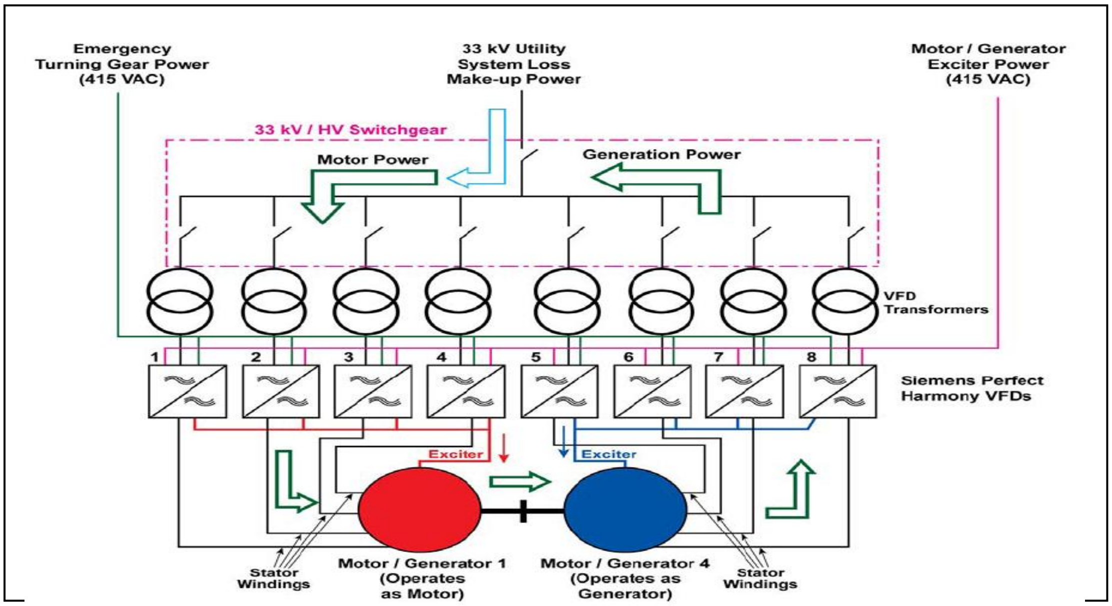


Figure 5.8: Back to back testing of 45 MW motor (Salisbury, 2008)

Back to Back testing is to validate the system design and compare its performance with predicted and guaranteed values. The configuration consists of mechanically coupling two motors with each motor fed by multiple VFDs. Operating conditions needs to be simulated while validating redundancy. Test data are recorded during both the back to back in and string testing for system performance evaluation. During this testing, one of the units was operated as a motor simulating the turbine by providing positive torque. The second unit is operated as a generator converting mechanical energy from the first unit to electric power. This configuration requires that the utility supply only enough electric power to cover system losses as indicated in the test one-line configuration below. Another advantage of the back to back testing is to check the temperature rise of the motor in actual loaded condition (Salisbury, 2008).

5.5 Tabular Comparison between gas turbine and variable speed drive:

5.5.1 Features:

Comparison of	**Gas turbine**	**Variable speed drive**	**References**
Efficiency	Low	Very high	ABB, 2009
Investment cost	High	medium	
Maintenance	High	Very low	
Reliability	Medium	High	
Availability	Medium	High	
Mean Time To Repair	A factor to be considered	Very low	
Emissions	High	None	
Speed control range	Limited	Wide	
Speed control accuracy	Medium	High	
Design flexibility	Low	High	
Starting time	Medium to high	Short	
Noise level	Very high	Medium, Low	
Influence on power supply	None	Investigation required	
Environmental permit	Required	Not required	
Weight/ space	Similar	Similar	Devold et al 2006
Minor maintenance cycle	4000 hrs.	25,000 hrs.	
Major maintenance cycle	20,000 hrs.	100,000 hrs.	
Minor maintenance	6-10 days	1-2 days	
In Operation between MTBF	4000	> 25, 000 hrs.	
Control response	Slow	Medium to quick	
Efficiency	Narrow peak range	High over a wide range	
Logistics	Delivery 3-4 years	Delivery 1-2 years	
Average operation efficiency	25%	40%	
Thermal and mechanical stresses	High	Low	Kleiner, 2005
Complexity and sensitivity	High	Low	
Products and output ratings	Standardized	Variable	
Speed range/ regulation	Limited	Wider	
Starting capability on load or no load	Unable	Capable	
Ambient temp	Reduced output	No affect	
Part load efficiency	Poor	No effect	
High Elevation	Reduction	No effect	
Vendor competition	Limited	Wide	
Efficiency Schroder, 2008	30%	52% with combined cycle 95%(Individual)	
NOx, SOx, CO_2 emission	Higher	Lower	
Process safety	Fired equipment in plant	No fired equipment	
Train sizes	Fixed by available turbine	Flexible as motor size	
Maintenance cost	High	Low	

Operating cost	High	Low	Man turbo AG Schweiz, 2009
Train full load Cycle efficiency	Low due to low driver efficiency	High due to Higher drivers efficiency	
Train part load efficiency	Low	High	
Restart capability after forced shutdown and start density	2-3 hours delay for restart due to driver thermal soak. Limited number of restart per hour	Immediate restart. No limit on number of restarts per hour	
Load assumption	Approximately one-half hour after successful start	Ability to start and come to full speed under load	
Sensitivity to site conditions	Available power reduced with increase in elevation, temperature and humidity	Full power available at all site conditions	
Controllability	Reasonably good but depends on firing temperature and heat distribution	Excellent speed controllability due to high frequency operation at about 20hz (+/-0.5hz) (30rpm)	
Ease of remote operation	Good	Excellent (all electric concept)	
Speed control range	Typically 70-105%	30-105%	
Starting reliability	Good	Excellent	
Auxiliary consumption	Lube oil, lube oil filter media, inlet air filter media, power for lube oil pumps, lube oil cooler fans, Nitrogen required for seal gas buffering, Instrument air consumption, for filter, purge pulse cleaning	Cooling gas filter media reduced instruments air, consumption due to usage of only one TCV for motor cooling. No air purge requirement, AMB power supply	
Exhaust emissions	Seal gas must be vented or flared, CO_2 and Nox emission	Zero local emissions	
Maintenance costs	Higher	lowest	
Unit availability	Lowest	highest	
Unit reliability	Lowest	highest	
Ability to trade carbon credits	Lowest	highest	
Fuel/Energy cost	Function of local cost of electricity		
Risk of stricter future emission regulations	High	low	
Insurance risk	Higher	Lower	

Table 5.1 Characteristics comparison between Gas Turbine and Electric Motor

The above table compares the characteristics of the VFD with that of the gas turbine. The comparison speaks for itself. Except the initial investment cost in all other parameters the advantage of electrical motor far outstrips that of the Gas turbine. The initial capital investment is also paid back in few month of operation due to higher availability of the electrical motor. Hence from technical as well as commercial perspective electrical motor is a logical choice to drive a compressor. A CAPEX comparison between the Gas turbine and All-Electric is shown in Appendix-A.

5.6 Conclusion:

All gas turbines, by nature of their physics and design, have inherent limitations. These limitations do not apply to electric motor variable speed drivers of equivalent rating and performance and this is the key to considering electric motor compressor drivers as a viable alternative for new installations (Kleiner et al 2005). The use of an electric motor driven compression concept is an alternative approach worth considering. This solution stands out as economically and ecologically superior, despite a higher initial investment for a larger combined cycle power plant. Contrary to the belief, the All Electric LNG concept does not employ new & unproven technology. Full load back-to-back tests and full-load compressor string tests have been successfully completed. Performance testing of compression strings and control systems in the country of manufacture reveals possible design & manufacturing flaws at an early point Back-to-back full load & speed tests of identical units possible up to 70 MW. Full load test and speed tests for complete compression strings is possible at factory to validate design and performance verification prior to shipment. All drive related electronic and auxiliary equipment can be installed in prefabricated and tested modules. Considering these advantages, the electric motor variable speed drive is in many cases a viable and economically attractive alternative to the mechanical gas turbine driver for centrifugal refrigeration compressors. With competitive & reliable electric power available at or near the jobsite, or from an associated power plant, this alternative should be evaluated. Continuous process operation is possible for six years with expected availabilities of the refrigeration compression system including the power plant can reach 360 days. Very little maintenance in the process area and few operational spares required on site, Custom-engineered drivers up to 80 MW@3600 rpm with no power reduction at elevated temperatures are available (Kleiner et al 2005). The all-electric drive option for base load LNG plants has potential benefits of increased reliability and reduced maintenance cost for refrigeration compressor drivers, and elimination of separate, smaller gas turbine driven generators for the remaining plant electric power requirements. Another advantage is that when the refrigerant compressors are driven by electric motors they can be restarted without depressurizing the casing hence reduces flaring (Chiu 2003). Main Advantages of Electric motor: are easy maintenance of motors and less maintenance for electric parts with converters having plug and play technology (Thibaut, 2007).

CHAPTER-6

Technical Challenges of all electric Concept

6.1 Introduction:

Gas is becoming a truly global commodity as volumes of production and consumption are increasingly and it is transported around the world in the form of liquefied natural gas. As a result, high reliability at the source location becomes ever more critical. Meanwhile, variable speed drives and electrical motors, hitherto used mainly as turbine starters and helpers, are being considered to be sized up as a potential compressor drive solutions for the LNG-production applications sector by replacing the gas turbine drivers. As environmental constraints, such as carbon emissions and energy efficiency, are becoming more restrictive, the classic solution with gas turbine driver is getting even less convenient. Yet, even with these considerations, obstacles existed for source companies that wish to migrate to LNG liquefaction plants with full electrical-driven compressors solution (E-LNG). The largest obstacle is that such plants will require a constant availability, reliability and adequate performance and capacity of electrical system. Continuous improvements in power electronics, advances in technology and also the availability in the market of large frequency converters up to 100 megawatt has paved the way for large variable speed drive systems (VSDS) or Variable Frequency Drive (VFD) system with electrical motor drivers to be considered as an alternative to gas turbines as main compressors driver solution. These provide flexibility by allowing variable speed operations with strong reliability and lower maintenance costs (Siemens, 2005). Whatever may be the claims, if the investors and lenders are not convinced about the reliability of the VFD driven motor system and sure that that the technical issues of the electrical system cannot be resolved they are not going to migrate from gas turbine technology to all electric technology in haste. The following chapters discuss the technical issues and their resolution for the VFD system.

6.2 Typical VFD system:

Before going into the details about the technical challenges it is useful to have a discussion about the electric drive system. As a whole, it consists of a transformer connected to the electrical grid feeding a VFD and a motor that ultimately drives a compressor. All VFDs convert Alternating Current (AC) power to Direct Current (DC) and again back to Alternating Current (AC) by means of power electronics switching devices (TM-GE Automation, 2005). The rectifier, dc link and inverter constitute a variable frequency drive system. The rectifier converts the Alternating current to Direct Current. The inverter changes the direct current to alternating current and in the process controls the frequency of the electrical voltage fed into the motor. As the speed is directly proportional to the frequency the VFD is able to control the speed of the motor. The internal components of the VFD function to convert the electrical supply three-phase AC voltage to a different voltage amplitude and frequency in order to change the synchronous speed of the electric motor (Nored et al 2009). Variable Frequency Drives can be divided into two categories based on the type of inversion scheme: voltage fed (source) and current fed (source) inverters.

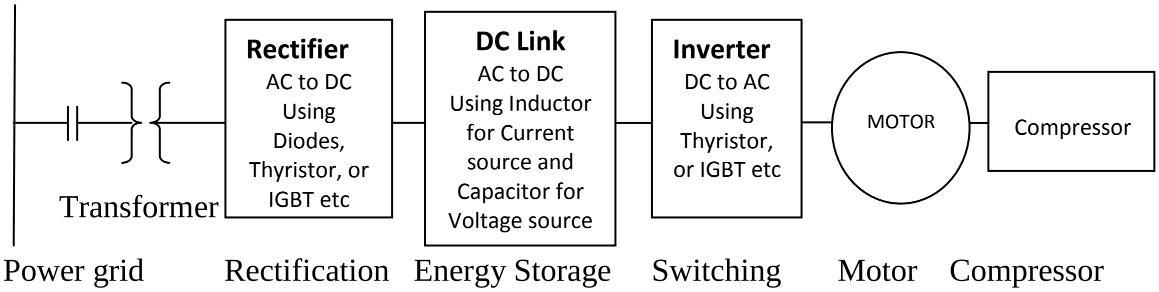


Figure 6.1: Medium Voltage Drive topology; Ref: TM-GE Automation (2005)

The input converter or rectifier determines power factor and harmonics as seen by the electrical supply side of the VFD. After the DC link, power is inverted back to AC to drive the motor. The inverter side of the VFD will determine the motor-side harmonic characteristics. Inter-harmonics can also be significant between the motor and the VFD as a system. Harmonic is the electrical noise introduced by the electronic switching devices into the electrical system by which the pure sinusoidal waves of the source get distorted. The harmonics is undesirable as it produces undue heating in equipment and also creates noises that may affect communication system. The use of 12, 24, or 30 pulse VFDs results in lower harmonics induced within the network. The VFD provides a high degree of "ride–through" capability when there is a supply voltage dip. A project specific evaluation must be made on a case-by-case basis, with respect to the use of harmonic filters. Further, the low torque ripple would help in the torsional design of the motor-compressor string. A "Full VFD" provides maximum operating flexibility during start up, trips, electrical transients, ambient swings, and turndown (Meherhomji et al 2011).The primary functions of any VFD are to communicate with an external process controller DCS (Distributed Control System) or a local control keypad to receive the user signals and commands and to transmit the status of the drive. It calculates both the voltage and frequency necessary to maintain the motor speed at either the reference torque or speed set-point and maintains the desired machine flux or Volt/Hertz. Subsequently it generates control signals required to control the power semiconductor in order to synthesize the three-phase output AC voltages or currents. Further it monitors the voltage across power semiconductor devices, motor current feedback and VFD internal temperatures to determine whether it is safe to operate the VFD. It also monitors motor and compressor parameter for safe operation (Nored et al 2009). When variable flow control is required it controls it by changing speed. By this it saves energy by replacing wasteful throttling control followed in gas turbine drives and also helps in optimization of rotating equipment performance. Since it can change speeds it eliminates gears or other power transmission devices also. It helps in efficient part load operation because of automation of process control. The part load operation in gas turbine is very inefficient. Since it starts the string slowly avoiding inrush current it reduces the rating and cost of electrical distribution by drastically reducing motor starting inrush current.

Because of reduced stress it is able to extend motor bearing and seal life. It also produces less noise and has no environmental impact; it is clean, non-polluting, quiet, efficient, and relatively easy to repair (Kaiser, 2008).

6.2.1 Current source drives:

In current-fed inverters, the inverter output to the motor is supplied in the form of current. Motor voltage is a function of the motor design and the associated load, irrespective of the inverter. The current-fed VFD uses a solid-state converter to convert the electrical supply from AC to DC. An inductor in the DC link provides constant current to the inverter which regulates the output frequency of the motor AC three-phase current. In current-fed inverters, the solid-state converter controls the amplitude of the current. In this type of VFD drives energy storage section between converter and inverter (DC Link) is an inductor (reactor), but the energy storage is very low. The inverter in the VFD of a current-fed type controls only the output frequency. Supply-side high order harmonics are typically high in current-fed VFD's. LCI drives can support high power applications, up to 100,000 hp and can be built to supply all of the motor current (Nored et al 2009). LCI current source topology is used for synchronous motor drives and, SGCT and GTO for induction motor drives. Current switched devices like SGCT and IGCT require many more parts in firing/ gate control than voltage switched devices like IGBT, IEGT(TM-GE Automation, 2005).The current source inverter can also apply pulse width modulation by varying current amplitude and frequency control through semiconductors Most current fed VFD's use the Load Commutated Inverter (LCI) or IGCT technology with large electric motors.

6.2.2 Voltage source drives:

In voltage source drives the energy storage section between converter and inverter is a capacitor. Insulated Gate Bipolar Transistor (IGBT), Integrated Gate Commutated Thyristor (IGCT), IECT (Injection Enhanced Gate Thyristor), Pulse width modulated (PWM) drive are some of the examples of voltage source drives. In voltage-fed VFD inverters, the output of the inverter to the motor is a voltage. In the voltage-fed VFD, the DC conversion is accomplished with a rectifier bridge. The DC link is heavily filtered using electrolytic capacitors. The voltage amplitude and frequency of the output to the motor are controlled by power semiconductors using a variety of different control techniques. The motor and load determine the amount of current. The use of a rectifier bridge to power the DC link helps to reduce the harmonics for these types of VFDs. The electrolytic capacitors used in the DC link have very high energy storage and are often a life-limiting component in the VFDs(TM-GE Automation, 2005). Voltage switched devices like IGBT and IEGT have much lower switching losses than current switched as they allow higher switching rates and can give better output waveforms (TM-GE Automation, 2005). Voltage Source Inverters (VSI) has been used in steel industry of 20MVA for at least a decade. Increased availability and innovative solution with better performance allows Voltage Source Inverter (VSI) to be used at even higher power levels. VSI (Voltage Source Inverter) offer better performance on harmonics, torque ripple and torsional oscillation (Meher-Homji et al 2011).A detail “Torsional Analysis Consideration of All-electric option” is discussed in Appendix: I.

6.2.3 Pulse Width Modulation technique:

Many current-fed and voltage-fed VFDs control the motor voltage/current amplitude and frequency using a control technique of pulse width modulation (PWM). In PWM the VFD turns the motor voltage on and off at a frequency much higher than that of the desired AC power. The motor inductance is used for filtering the resulting motor-side harmonics. The pattern and implementation of the pulse width modulation (PWM) is highly dependent on the particular type and manufacturer of the VFD (Nored et al 2009).The PWM voltage-source VFDs may require an input filter depending upon the different levels of current harmonics from the rectifier. Voltage harmonics are not as common with these types of VFDs. Some PWM voltage-source VFD types can function for the gas compressor/electric motor application without input filtering, depending on drive topology. (Nored et al 2009).

A comparison of advantages and disadvantages between the voltage and current source VFD is shown below in Table 6.1 which shows the advantages of Voltage source drive.

Current fed VFDs	Voltage fed VFDs
Lower cost higher horse power	Low cost and low horse power
Four quadrant	Two quadrant
P.F=P.U Speed*Load P.F	95% displacement P>f
Immune to short circuit	Require protection to short circuit
More low cost components	Few higher cost component
Large inductors (bulky and costly)	Small or no inductor
Lower motor noise	Low or medium motor noise
Non critical layout	Critical construction layout
30% harmonic current	40% harmonics current at 6 pulse
Low dv/dt at out put	High dv/dt output
High common mode voltage	Low common mode voltage
Output filter required	Output filter not needed

Table 6.1: Comparison of VFD Topology: (Kaiser, 2008)

6.3 Drive Technology Description:

There are various technologies available for the inverters. The most significant difference between various topology is the power quality of the output voltage and current fed to the motor, i.e. how close is the input current is to the sine wave and how does the output voltage resembles the sinusoidal utility voltage. The basic comparisons between various topologies are as follows (Meher-homji, 2011):

- Gate power to turn devices on and off external circuitry (firing protection). The impact is number of control devices and system reliability.

- Switching speed, switching losses on state forward drop and losses. The impact is System efficiency and cooling.
- Continuous current ratings, Forward and reverse blocking voltage. The impact is Number of power devices and system reliability.
- Physical mounting and thermal characteristics- Packaging a system sizes.

6.3.1 Load Commutated Inverter (LCI): Current source:

LCI technology is Silicon Controlled Rectifier (Thyristor) based and is high in efficiency, reliability and installed bases but draw backs are high harmonics content which caused problem in integration to the electrical grid and high torque ripple and torque pulsation which may excite torsional oscillation in the shafts of rotating equipment. Thyristors are not attractive for high torque quality drive application as power quality is poor as they can switch once per fundamental cycle and cannot be actively turned off. They need harmonic filters to be applied to the grid side, which needs careful designing and tuning (Meher-Homji et al 2011). It drives synchronous machine based on naturally commutating thyristors (natural commutation is the turn off process when the sinusoidal voltage source applies a reverse voltage to the device). Output has a substantial harmonic content which caused extra losses at the damper bars and give rise to significant torque pulsation. Now with self-commutating VFDs are available Load Commutated Inverter (LCI) is becoming less popular (Kaiser, 2008). All LCI VFD types will require input filters because of the supply-side harmonic voltage levels generated in the converter and also should consider output filtering if shaft cogging effects are present. Output filtering can, in most cases, reduce the operating temperature of the motor as the higher order harmonics in the VFD output are filtered before reaching the motor (Nored et al 2009).Among all the poorest performing VFD drive is the LCI inverter.

6.3.2 Pulse width modulated (PWM): Voltage source:

IGBT (Insulated Gate Bipolar Transistor), IGCT (Integrated Gate Commutated Thyristor) are increasingly being used in the industry. IGBT is preferable at low to medium voltage level and they facilitate fast switching. At higher voltage level their losses increase, switching frequency decreased and the decreasing current capability limit their maximum power output. This make IGCT more attractive for higher voltage power level which offers higher power capability per device which reduces the component count and leads to higher reliability with a high power quality (Meher-Homji, 2011). Multilevel topologies are chosen in case of higher voltage levels. Independent switching with effective switching frequencies results in lower level of harmonics by improvement of current and torque quality. Using multiple semiconductor in series and parallel addresses the power level and quality issues. Higher device count is a drawback in this technology as likelihood of failures, reduces the reliability. As a counter measures some means of redundancy is generally required to fulfill power level, power quality and system availability requirement (Meher-Homji, 2011). Pulse Width

Modulation (PWM) multi variable series cell circuit decreases the current distortion such that the torque ripple decreases to one percent on motor base rating. It results in low and acceptable level torsional shaft stress (Kaiser, 2008).

6.3.3 Neutral Point Clamped (NPC):

Neutral point clamp circuit has five voltage levels from line-to-line and uses Pulse Width Modulation techniques. Depending on the frequency of switching the current is less distorted and the torque ripple decreases into the vicinity of 1 to 3perent (Kaiser, 2008). The table below shows comparison between various inverter technologies:

Topology	**LCI** (Load Commutated Inverter)	**NPC** (Neutral Point Clamped)	**SGCT (**Symmetrical Gate Commutated Thyristor)	**PWM** (Pulse Width Modulated)Multi-level Series cell
Source	Current	Voltage	Current	Voltage
Switching device	Thyristor	IGBT and IGCT	SGCT	IGBT
Input harmonics	Fair (12 pulse) Poor (6 pulse)	Good (12 pulse) v. good (16 pulse)	Fair (12 pulse) Poor (6 pulse)	Excellent
Input Power factor	Fair to poor	Very good	Fair to poor	Very good
Output harmonics	Poor	Good	Fair	Excellent
Output common mode voltage	High (fair) w/o transformer	None (excellent)	High (poor) w/o transformer	None (excellent)
Output dv/dt	High (poor)	Med-high (fair)	Low (good)	Low (good)
Regeneration capability	Yes	No	Yes	No
Torque pulsation	High (poor)	Low (very good)	Low (fair)	Very low (excellent)
Special motor required	Yes synchronous	No	Yes	No
Speed range	0.15 to 2.0	0 to 2.0	0 to 1.1	0 to 3.0
Special starting mode	Yes	No	No	No

Table 6.2: Topology comparison: Source- (Kaiser, 2008)

The above table demonstrates that Pulse width modulated Multi-level series cells offer many advantages because of low input and output harmonics, input power factor, low torque pulsation and speed range. The table below shows the comparison between devices used in various topologies.

Components	**SCR**	**GTO**	**IGBT**	**IGCT**	**SGCT**	**IEGT**
Description	Silicon Controlled Rectifier	Gate Turn off Thyristor	Insulated Gate Bo-polar Transistor	Integrated Gate Commutated Thyristor	Symmetrical Gate Commutated Thyristor	Injection Enhanced Gate Thyristor
Inverter type	Current	Current	Voltage	Voltage	Current	Voltage
Efficiency (Low to rated)	High	Low (87-95)	High (93-98)	Med-High 90-97	Med-High (90-97)	High (93-98)
Gate control	Current	Current	Voltage	Current	Current	Voltage
Gate current/ Components	< 2A/ Medium	400-1000/ High	<1A/ Low	4000A/ High	4000A/ High	<1.5A/ Low

Voltage rating	High	High	To 4500V	To 6000V	To 6000V	To 4500V
Current rating	5500 A	1000 A	1200 A	4000 A	5000 A	4000 A
Switching losses	Med	High	Low	Med	Med	Low
Switching speed	Low	Low	High	Med	Med	High
Life Cycle point	Mature but current	Phasing out	Current and growing	Current	Current	Current and growing
Snubbers (Voltage suppresors)	Few	Many	None	None	None	Low
Mounting	Press pack	Press pack	Single side	Press pack	Press pack	Single side and press pack

Table 6.3: Device comparison - (Kaiser, 2008)

The above table demonstrates that Voltage source drives' demand with IGBT and IEGT components are current and growing because they offer many advantages over the current source, however the current source drives are robust and mature and hence are sometimes preferred.

6.3.4 Design constraints of VFD:

All the topologies have their advantages and disadvantages. As per Meher-Homji, (2011) the design objective of the VFDs is mainly oriented to:

- Reduce the harmonics produced and imposed on the electrical grid by the switching of power electronics, which creates disturbances in the electrical system.
- Reduces torque ripple which creates issues for rotor dynamics of the combined shaft line of motor, gear, compressor casing.
- Reliability of the power electronics that affects the availability of the system hence the production rate. The reliability depends on the number of switching components, component reliability and the redundancy option offer by the topology.
- Reduce torsional vibration level of the entire shaft center line in particular torque pulsation at start up and steady state and torsional lateral phenomena caused by excitation of the torsional modes, driving excessive train lateral vibration.

6.4 Technical challenges of VFD driven motor system:

6.4.1 Reliability of the VFD-motor drive system:

As the oil and gas industry moves towards wider adoption of application of electrical drives, there is increased expectation in improved reliability and performance of power electronics ensuring optimum integration with rotating machinery. Reliability of the electric motor system can vary greatly depending on the amount of components in the VFD, the service environment, and various operating conditions such as frequent starts/stops, transients etc. The primary causes of failure of the drive train are typically associated with defective components, inadequate maintenance, motor drive mismatch and outages from the power utility(Nored et al 2009). The reliability of the entire motor drive system can be defined as:

Mean Time Between Failures (MTBF) = Total Operating Time/Number of Failures

For large electric motor installations a formal Reliability, Availability and Maintenance (RAM) study is recommended. This analysis should consider all of the components in the drive and alternative options for the motor type, use of gearboxes; variable frequency drives (VFD) topology and component selection. The study should also include the auxiliary equipment required to support the electric motor drive system such as the cooling systems, lubrication systems for bearings, gearboxes, couplings, and bearings (Nored et al 2009).

6.4.2 Motor Design:

The major concern in the industry is that VFD of large size is not available in the market. The manufacturers believe that given the vast experiences in building large generators well over 100 MW, motors of this size are not considered new technology and can be built without employing new designs or materials. Suppliers indicate that 2-pole motors equipped with variable frequency drives (VFDs) are the most attractive and economical solution for power ranges needed for large LNG drives and operate at high efficiencies. Issues that need to be addressed in building such large motors are: (Meher-Homji, 2011).

- Ensuring adequate torque-speed capability to allow appropriate acceleration with minimal dwell time at the critical speeds while start-up of the compressor string.
- Time taken to restart of the compressor train after a motor trip.
- Range of operability (efficient turndown) - there are limitations generally imposed on the speed range of the motor and these are typically rotor dynamic constraints.
- Torsional analysis of the full compressor train under start up conditions, compressor transients such as surge and electrical transients such as power dips.
- Interaction of torsional and lateral vibration. This could be accentuated with the presence of a gearbox which may be needed to optimize compressor operation.
- Sensitivity of the motor to excitation of its critical speeds.
- Effects imposed on the power system resulting from motor trips (this is by far the most critical issue affecting the electrical system stability), switch gear and power distribution failure.
- Operation at degraded levels of the VFD may present problems.

6.4.3 Additional CAPEX due to large Power plant:

Most of the time, E-LNG plants have no grid connection and must be supplied under island conditions. The in-plant generation should be chosen in an (N+1) generation configuration where ‘N’ is the total load requirement of the facility ‘+1’ is one more generator running as spinning reserve so that, in the case of loss of a generator, the system will ride through the transient and reach a new steady-state operating condition without requiring load shedding (Siemens 2008). This large power demand leads to additional Capital Expenditure (CAPEX) to set up large power plants. The alternative to a large captive power plant is connection to the electric utility grid in which case cost of purchased power has to be factored into the analysis process.

6.4.4 ARC Flash:

Arc flash is the sudden release of electrical energy through the air when there is a breakdown of insulation between energized conductors. Arc flashes can be a spontaneous event or result from inadvertently shorting out electrical contacts or conductors with a conducting object. A phase to ground or phase to phase arcing fault can quickly escalate into a three phase arcing fault due to the expansive cloud of conductive copper vapor which can engulf all phase conductors. The chain of events during an arcing fault can be extremely rapid. Air is normally a good insulator, however when heated during a short circuit air becomes an ionized gas which is a conductor allowing the arc to continue and produce a very high temperature. These extremely high temperatures can vaporize materials resulting in fiery explosions propelling shrapnel to significant distances. VFD System design can create a significant arc-flash hazard risk considering that an extremely high short circuit current is available. There is a possibility of cooling water leak that may lead to faults when de-ionized cooling water system is used to cool IGBT cells and Transformers. Possible environmental conditions such as high humidity, salty atmosphere and extremely fine dust particles may lead to faults and result in arc flash. Possible mitigation measures should be considered during design such as described below. (Qatargas 2 VFD testing data, 2006)

- Isolation of electrical equipment before starting work.
- Arc Flash Detection System to detect and trip and isolate the VFD drive.
- Installed pressure vents, door latches, and structure supports.
- Design VFD and associated switchgears to be arc-resistant.
- Insulated bus bar and electrical conductors to reduce exposed conducting surfaces.

6.4.5 Power-line harmonics:

With the introduction of large-frequency converters, power-supply quality has become more of a concern. VFDs are non-linear electrical loads on the electrical system which have side effects in the form of power-line harmonics, inter-harmonics, Sub-synchronous torsional interaction, oscillating torques (torque ripples), in the drive motors and possible electro-magnetic interferences (EMC) throughout the electrical system. Harmonics is electrical noise which introduces distortions to the perfect electrical sine wave of the voltage and current wave forms. This is as a result of high speed switching of the power electronics. This can result in unacceptable supply-voltage distortion responsible for overheating components; insulation stresses and Electro Magnetic Compatibility (EMC) issues. Effective mitigation measures have been developed for all these unwanted effects. Passive harmonic filters are custom-engineered for each requirement. The effects of inter-harmonics are simulated, and corrections in control strategies can be implemented if necessary. Oscillating torques (torque ripples) caused by harmonics in motor-compressor strings are damped sufficiently by design measures and by rotor inertia. Effects of active and passive electro-magnetic interferences on the entire electrical distribution system are investigated and solutions can be developed (Siemens 2008). Harmonic studies should be performed to define possible actions needed to keep the harmonic distortion within the limits set by international standards. Harmonic filters can be design and installed to neutralize the effect of harmonics so as to reduce to the injection of current harmonics into the grid as much as possible. These filters are safe and reliable passive subsystems for both in indoor & outdoor installations (Kleiner et al 2005). The filters are properly tuned over chosen resonance frequencies (Siemens). The perfect harmony technology (IGBT cells with voltage source drives) from Siemens used for Qatargas VFD system produces Total Harmonic Distortion (THD) below the maximum acceptable level. The choice of the filter composition, including the number of branches and tuning, depends on harmonic analysis. Harmonic studies comprise of analyzing the harmonic sensitivity of the electrical network followed by the harmonic penetration studies, which assess the voltage and current distortion within the network. Depending on the design of the electrical system a number of harmonic mitigation options can be considered as discussed below (Siemens 2008):

- Harmonic filters can be designed to provide a low impedance path to the current injections, thus limiting the harmonic currents flowing in the network, and ultimately the total harmonic distortion. Harmonic filters can be directly connected to a switchboard or to a tertiary winding on each converter transformer.
- By choice of transformer phase shifts 24, 36, 48 pulse systems can be achieved. This limits the number of harmonic injections, however requires all drives to be operation, and full cancellation is only achieved when all drives are equally loaded.
- Large variable speed drives, and other significant harmonic sources can be supplied from a common switchboard known as a ‘dirty’ board, with the aim of containing the harmonic distortion to this switchboard alone, by supplying it via high impedance transformers. It can be dedicated to feed large variable speed drives and other significant harmonic sources.
- According to the further reduction of harmonic component of the VFD Strings in perfect harmony voltage source drives, the harmonic distortion level on the network is dramatically reduced.

6.4.6 Electrical resonance:

When performing harmonic analysis, special care should be given to the presence of cables. In full-electrical-solution LNG plants, where power is generated within the plant, the voltage is stepped up to high voltage to allow transmission to nearby facilities. Often this is done with high-voltage cables whose intrinsic stray capacitance may be responsible for parallel resonances that, when hit by the injected harmonic currents, causing unacceptably high voltage distortion, which affects power transmission quality as well as leads to failure of insulation in equipment. The resonance can lead to undesirable effects such as voltage spikes. The same may be done if the LNG plant is interconnected to the national grid, where power is already received at high voltage (ABB, 2005).This has lead to failure of several converter transformers in industry using large VFD drives. This can be mitigated by shifting the firing angle of the VFD so as to shift the harmonic frequency so as not to excite a resonance with the capacitance of the cable network (ABB, 2005).

6.4.7 Torque ripple (Kleiner et al 2005):

Torque ripple which is a pulsating torque created by the VFD drive has a potential to damage the shaft or coupling of rotating machines. The torque ripple of LCI drives (Current source drives is 3%) Neutral Point Clamped drive 1-3% and Pulse width modulated drives is less than 1%. The allowable torque ripple for system design is normally less than 2%. To match the drive's input voltage to the power line voltage on site, a transformer is required. This isolation transformer also provides for the 12-pulse line reaction of the converter towards the power system, and for fault current limitation in the power semiconductors, avoiding fuses in the power circuits altogether. This transformer is connected via power cables to the frequency converter, and screened cables also link the 'drive' to the motor. In the motor, the same 12-pulse circuits can reduce the torque ripple, which is produced by the non-linear frequency converter and is superimposed on the mean torque of the motor. A complete torsional analysis of the rotating string is nevertheless performed to identify and quantify potentially harmful harmonic torque amplifications, and to size the shafts and couplings of the machines (Kleiner et al 2005). Another main issue is related to inter-harmonic effects on the turbine-generator trains. VFD systems, depending on their technology, can continuously produce small torque oscillations for example based on the difference between the network frequency and the motor frequency on the turbine-generator shaft line. The effects of such torque pulsations should be analyzed carefully, along with other torsional excitations from the turbine-generator to prevent any mechanical resonance to reach beyond the permissible values.

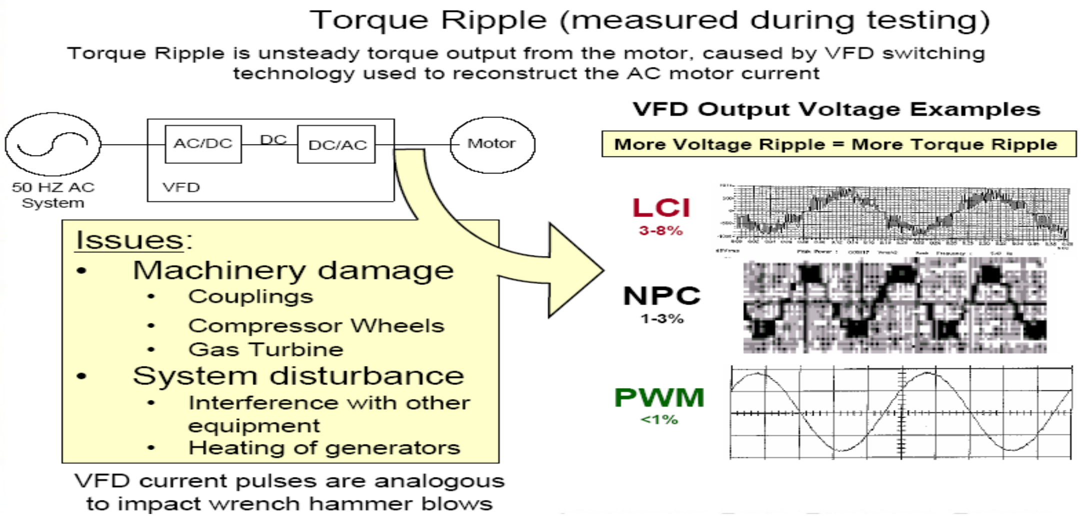


Figure 6.2: Torque Ripple; (Qatargas 2 presentation, 2004)

The above figure demonstrates that Pulse width modulated drive has a lesser output voltage waveform distortion hence a lower toque ripple than Neutral point clamped drive or Load Commutated Inverter drives.

6.4.8 Sub- Synchronous Torsional Interaction (SSTI):

Sub-Synchronous Torsional Interference (SSTI) is an electrical phenomenon that occurs when large electronic switching devices such as converter/ inverter drives produce a frequency less than system synchronous frequency (50/60Hz) on the electrical supply. This can adversely interact with the torsional mode of vibration of rotating shafts. It can be initiated during a sudden load changes or some transient response operations of the power system such as sudden load swings or an electrical fault. This sub-synchronous frequency is transferred back to power source grid in the form of an oscillating torque that acts on the rotors of generators of the connected power system which can damage the shaft. SSTI is a potential concern that could impact reliable operation of the rotating machines depending on electrical system connection and configuration. Should SSTI occurs, excitation of the rotating equipment shaft natural frequency would increase exponentially to the point that either the shaft or the coupling would break resulting in catastrophic failure of the generator. SSTI can take place due to several causes. In particular, SSTI could occur due to the presence of Variable Frequency Drives (VFD) with massive presence of cables, capacitors for the compression process in modern, partially or fully electrical LNG plants in islanded networks. This phenomenon of sub-synchronous torsional interaction (SSTI) occurs when the synchronous generator’s natural mode is excited in the sub-synchronous frequency injected from the VFD. The contemporary presence of cables and capacitances for reactive power or power factor compensation could build a resonance circuit with low resonance frequency. Furthermore, not enough accurately tuned controllers or not so well coordinated control schemes could be responsible for SSTI with power and torque oscillations, which at particular frequencies are not damped or even may be amplified (La Seta 2007). By means of an accurate time-domain simulation it is possible to detect the possibility of SSTI, determine the main cause for the torsional oscillations and evaluate the damping, and propose corrective actions or countermeasures. Torsional analysis is further discussed in Appendix-I.

6.4.8.1 SSTI Mitigation Measures:

The planned configuration of LNG applications of compressor trains may cause risk to generators in the local grid. The recommendation is to apply protection at the generators that senses shaft torsional vibration and trips either the power electronics or the generators to prevent damage. It is advisable to perform a detailed evaluation of the effect of VFD drive controls on the generator torsional modes. The right mitigation measures are always specific to a topology, machine and electrical system configuration. Some of the mitigation measures can be:

1- Constructional: Replace shaft component, transformer, series capacitors exciter at design
2- Operational: Avoid certain topology, reduced generation, generator trip

3- Passive Control: Change of reactance by different firing of the power electronics
4- Active control: AVR(Automatic Voltage Regulator) control firing control
5- SSTI Watchdog monitoring system (Torsional Oscillation Monitor):
6- Torsional Stress Relay (TSR): Provides early warning and rapid response to trip the VFDs to avoid SSTI.
7- Higher level short circuit MVA: If the electrical islanded grid is connected to external utility the SSTI concerns decreases because of higher level short circuit MVA available. This large grid is able to absorb or dampen the harmonics.
8- Number of drives on line: Probability of SSTI is higher when all drives of the VFDs per turbine compressor string are operating. SSTI could be reduced if fewer numbers of drives per strings were operated in normal production mode.
9- VFD control algorithms: SSTI can be caused by VFD control algorithms. Changing the algorithm to modify firing can change the frequency of oscillation away from the natural frequency of torsional mode of vibration of rotating machines.

6.4.9 Network studies:

Network studies, such as load flow, transient studies, harmonic analysis and short circuit calculations, should be performed to define the sizing of system components during normal and peak loadings, both for normal and contingency network configurations. These studies benefit from simulations that perform an accurate analysis and modeling of the power plant and take into account both power-control and automatic voltage regulation. Studies should include those involving the loss of generation, loss of load (in particular the loss of one large VFD) and fault recovery after system transient. Such events could cause a large mismatch in the available power generation and the system load, thus producing severe system frequency and voltage swings (Siemens 2008). Electrical power system studies routinely are necessary to ensure the correct and reliable operation of a large LNG plant. To ensure a satisfactory design for a LNG plant, the electrical power system must be designed to meet certain, minimal performance criteria of frequency and voltage variations (MottMac, 2007).

6.4.10 Power system analysis:

Models are required which represent the power plant generation including their automatic voltage regulators (AVRs) as well as the governors of the gas turbine generators. LNG systems feature a large number of induction motors drives and it is important that the momentary and decaying current contribution that induction motors will make to a system short-circuit is represented. Transformers and tap-changers (for changing secondary side voltage level) are modeled as equivalent networks. The zero sequence impedance and winding connection are used to assemble the correct zero sequence network representation when calculating earth faults. Cables and lines are modeled by a circuit length and a fixed positive- and zero-sequence resistance and reactance and shunt admittance value per unit length. The power system studies are essential to confirm the parameters of the main power system components.

6.4.11 Load flow studies:

Load flow studies confirm the rating of all system components, during normal and peak loadings for both normal and contingency network configurations. Cases which reveal insufficient circuit capacity will be highlighted. Another key parameter is the voltage profile/regulation characteristics of the system. Transformer tapping ranges and step sizes are identified and total system losses and reactive power compensation requirements can be assessed. Load flow studies confirm the rating of all system components, during normal and peak loadings for both normal and contingency network configurations (Qatargas 2 Power system studies, 2005).

6.4.12 Short circuit studies/ Fault level studies:

Fault level (or short circuit) studies are used to determine both maximum and minimum three-phase fault levels and earth fault levels at all switchboards under fault make (t=10 ms on 50 Hz system) and fault break conditions (t=60 ms), including the DC component. The above information helps in designing switchgears. Earth fault levels are dependent upon system earthling practices. The asymmetric peak fault current at 10ms determines the required circuit breaker making capacity and the dynamic withstand capability of the circuit breakers. The symmetrical RMS (Root Mean Square) fault current at 60ms establishes the required breaking capacity and the short term dynamic withstand of the bus bars. Where the predicted fault currents exceed 90% of the rating of the proposed switchgear, higher rated switchgear may be specified, or the system impedances may be increased (transformer and generator reactance). A problem with industrial systems is the high X/R (Reactance/Resistance) ratio, coupled with the large induction motor fault current contributions leading to significant asymmetric peak currents with long time constants for the AC and DC components. This makes circuit breaker fault breaking duty very onerous. For a system the symmetric fault current at break (60 ms) may be within the short circuit rating of the switchgear. However due to the high X/R (Reactance/Resistance) ratios of the HV motors and in feeding transformer the instantaneous asymmetric peak current at 10 ms may be much higher which exceeds ‘make’ rating of the switchgear necessitating consideration of a switchgear with a higher “making” rating (Qatargas 2 Power system studies, 2005).

6.4.13 Motor starting capability:

The motor starting capability of the system must be determined. Larger high voltage motors operating elsewhere in the plant may be Direct-On-Line started. The motor will have to develop sufficient torque to accelerate the driven load up to full speed. A dynamic model which represents the driven load (torque-speed curve and inertia), the variation of motor rotor resistance and reactance with slip, as well as the source generator AVR (Automatic Voltage Regulator) and prime mover responses is required. As well as ensuring that the load is successfully started, the system voltage and frequency dips and overshoots must be confirmed, particularly for the most onerous case of starting against limited system generation (Qatargas 2 Power system studies, 2005).

6.4.14 Power system Transient stability studies and Load shedding:

Events such as loss of generation, loss of load and fault recovery can cause a large mismatch in the available power generation and the system load condition, producing severe system frequency and voltage swings. Transient studies require detailed Automatic Voltage Regulator and governor models to identify the need for generator/load tripping following loss of load/generation. The power plants normally run with a (N+1) generation schedule, where 'N' is the minimum number of generators required to cater to the plant electrical load and '+1' is an additional generator running as spinning reserve to take care of the eventualities of tripping of a running generator for any reason. Following loss of a generator, the additional '+1' generator helps the system ride through the transient and reach a new, steady state operating condition without requiring load shedding. In an N+1 power plant design, all turbines in service operate permanently at part load, and the 'N' units assume full load within a very short time in the event of an unexpected shutdown of any one of the running generator (Siemens, 2008).With an 'N' generation power plant line-up it will be necessary to shed load from the system, following the loss of generator, to maintain a stable system and recover the system frequency within acceptable limits. Failing to reduce the network load, within a sufficient time, will lead to unacceptable depressions in the system frequency due to the overloaded turbines. Fault recovery studies are essential in determining the critical clearing time for three phase faults on the system. Stability in this context is essentially defined as keeping the power-system frequency within the acceptable limits. VFD employed to drive the main refrigerant compressors can function as negative spinning reserve in the power rebalancing process; they can reduce their speed and thus their power consumption instantaneously upon an unexpected loss of a turbo-generator in the power plant hence maintaining the system frequency within acceptable limits. A Stability solution is based on the principal functions: fast signal and data exchange between all control and protection systems of the power-to-compression system; intelligent use of positive and negative spinning load reserves; modified gas-turbine Inlet Guide Vanes (IGV) controls, pre-control systems; and a dedicated superimposed electrical network monitoring and control system (Siemens, 2008).In order to guarantee a high availability of the electrical and steam generation, it is necessary to overcome the planned and unplanned outage of a generation unit, considering both the steady state and the dynamic behavior (Lerch, 2013). The steam, electricity and process demands have to be coordinated to guarantee high availability in case of large disturbances in the system like generation outage, compressor outage, process chain outage or sudden loss of a production train. To find a suitable solution the LNG configuration can be modeled in a power system simulation tool including all models for generation, process equipment Variable Speed Drives (VSD), pump motors plant, house load and the control of all relevant equipment such as governors, voltage controllers and control of variable speed drives. These models allow simulating, tuning and optimizing the system reaction in case of severe system disturbances and allow defining a suitable system behaviour using adapted countermeasures in a whole system approach. Whereas in a large interconnected system the influence of one generator on the overall frequency might be negligible, under island conditions the control of the frequency is one of the main tasks of the power plant in case of a generator disturbance. In case of insufficient control and sustained imbalance, the island frequency would lead rapidly to a trip of remaining generators due to high or low frequency. Fast balancing is realized as a droop control using the measured frequency deviation with a proportional influence to the output (Lerch, 2013). In a combined cycle power plant and co-generation system the process steam pressure is an integral control parameter for the balance between steam generation and demand like grid frequency for the active power balance. Since the process steam is extracted from the steam turbines, a change in steam demand has a direct consequence on the electrical steam turbine output and hence on the frequency. A large disturbance like a gas turbine trip requires on one hand a rapid increase of electrical output in order not to reach frequency trip thresholds; on the other hand it implies a rapid loss of steam generation. In such case not only the active output has to be increased, but also the loss of steam generation and its effect on the steam turbine output needs fast compensation. Since an increase of steam generation is limited by relatively slow thermal processes with increase of supplemental firing, the use of thermal storage has to be taken into account in the control concept and hence in the model(Lerch, 2013).

In order to demonstrate the stability of the power system in case of outage of a generator or an entire VFD system, Lerch (2013) modeled a power system, including the relevant equipment with all necessary and relevant controllers to simulate and coordinate all necessary actions required in case of severe outage cases. The model comprised both the electrical and the power plant process systems. This allows to optimize the basic electrical and steam control concept and to design the load or generation shedding sequences with the corresponding load steps and process-coordinated timings, depending on the severity of the outage case. Lerch (2013) configured a large Electric LNG plant with VSD drives up to 80 MW which will be planned in 2 phases (train one and train two). The generation concept in this example is a combined cycle plant with 4 GT (Gas Turbines) and 2 ST (Steam Turbines) installed in phase 1 and additional generation of 2 GT and 2 ST in phase II. The first phase configuration is more critical in case of large outages of process components or generators as the generation is weak during the phase I (with the largest VFD drive of 80 MW, Gas turbine generator of 176 MVA, and steam turbine generator of 154 MVA). The simulation results of a Gas Turbine generator outage for the more critical phase 1, some load reduction steps and load shedding are necessary to keep the system under dynamic equilibrium.

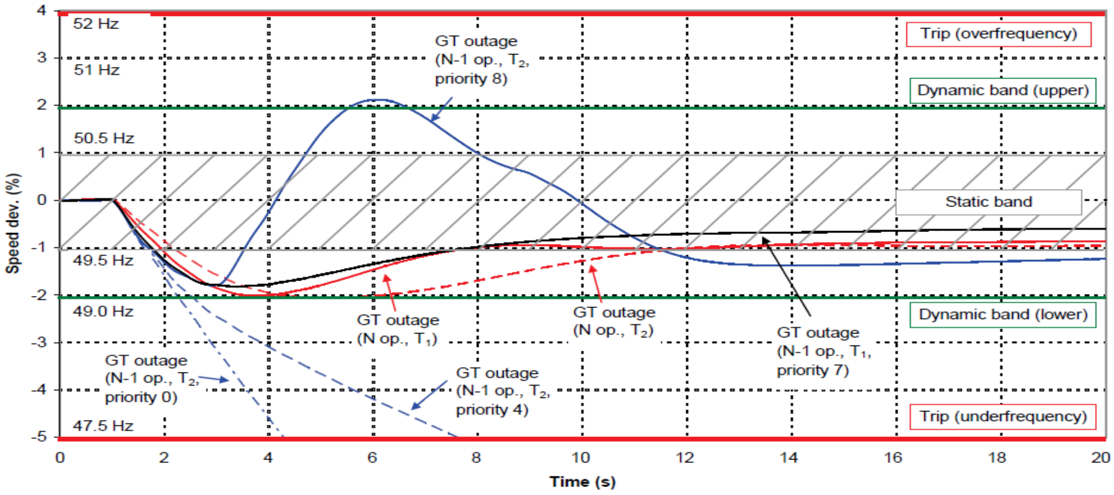


Figure 6.3: Stability in outage of a Gas turbine generator

The Fig. 6.3 shows that it is possible to ride through the disturbance and bring the system to stability. It depicts the simulation results in case of GT outage for the more critical phase I. The over frequency and under frequency limits are shown in bold red lines at the top and bottom of the curve and the dynamic frequency band is shown by bold green line The outage of a GT has been investigated in case of all generators connected (N operation philosophy, red curves), as well as in case of maintenance of one generator (N-1 operation, blue curves). In this last condition, some load reduction steps and load shedding are necessary to keep the system in stable condition. The figure shows the results in case of high ambient temperature T_2 (40°C) and no load shedding, Variable Speed Drive (VSD) speed reduction, VSD string trip and load trip. Under low ambient temperature T_1 (15°C) a load shedding with VSD speed reduction and load trip is sufficient.

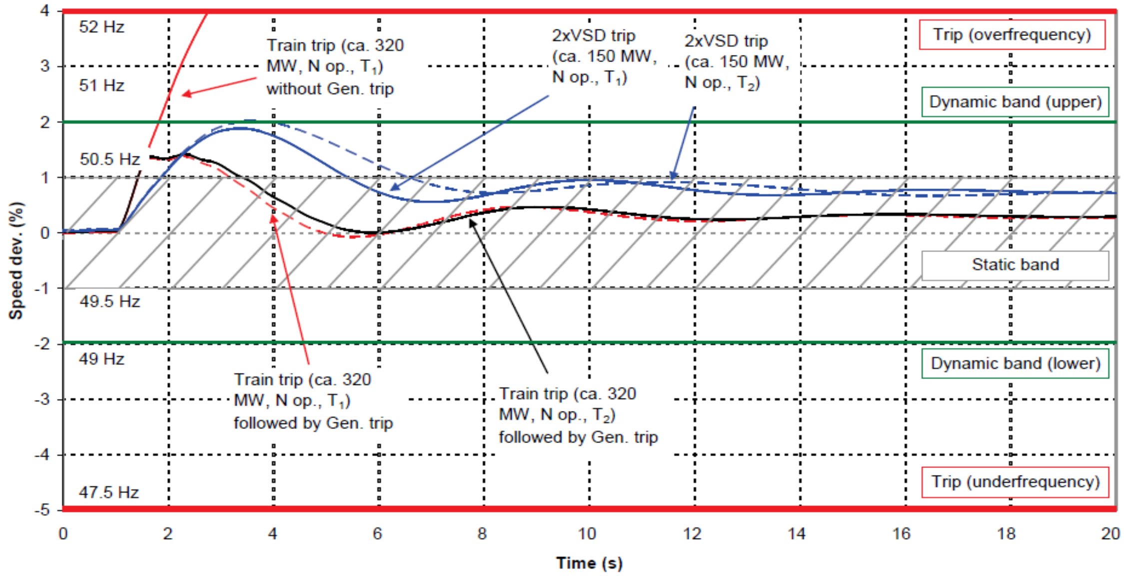


Figure 6.4: Stability in case of outage of a VFD driven Compressor

Fig. 6.4 summarizes the system response regarding the case of process outage. In the case of process outage all generators are assumed as connected (N in operation). In case of partial process outage, i.e. 150 MW (blue curves), the turbine governors can suitably react without exceeding the dynamic band in 5-6 sec with the speed deviation inside the static band of ± 1%. In case of total process outage, i.e. a 320 MW train trips (red curves by temperature T_1 and black curves by temperature T_2), the turbine governors are not fast enough to avoid over frequency generator trip. Therefore, the tripping of one or more generators is required in a suitable time after the outage. The large 80 MW VSD compressors can be used to reduce load in emergency situations up to 10 % without critical influence on the LNG-process (emergency load variation).

The above modeling demonstrates that with suitable power systems study both electrical and steam dynamic behaviours can be studied and suitable measures can be undertaken to keep the system under dynamic balance. A combined model of electrical and steam behavior allows developing a suitable design concept together with the optimization of the power plant equipment. This simulation produces additional information of the closed loop electrical and steam process to tune, stabilize and optimize components, control and power management. Critical situations can be detected in more details and counter measures can be realistically coordinated. The approach results in a higher availability and reliability of the plant with modern Variable Speed Drive and Combined Cycle Power Plant technology. With the above simulation, Lerch (2013) demonstrated the advantages of comprehensive simulation approach of a process management system which is able to handle even the most severe operational disturbances. The steam, electricity and process demands have to be co-coordinated to guarantee high availability in case of large disturbances in the system like generation outage, compressor outage, process train outage or sudden loss of a LNG production train.

6.4.15 Full Pressure restart:

Significant motor torque is required during startup (at lower speed) if the compressor starts loaded with positive pressure inside it, so as to avoid wasteful and emission-intensive de-pressurization. An electrical variable speed drive can be used to provide this feature. A VFD can be used for this duty as it satisfies the high torque starting duty with adequate reliability (Almasi, 2011). The objective of this study is to investigate the capability for the restarting of Compressor-Motor String with VFD Drive under Full Pressurized condition for a requirement of restarting the string once the process tripped. The study should be performed under considerable severest operating condition worst case scenario for the VFD Full Pressurized Restart (Qatargas 2 Power system studies, 2005).

6.4.16 Relay Coordination study:

Protective Relay Coordination Study was performed as a part of engineering work to evaluate the suitability of protective relay function and available setting range of the protective relays selected. This study evaluates adequate protective function and proper co-ordination grading for all operating voltage levels to satisfy requirement (Qatargas 2 Power system studies, 2005).

6.4.17 Transformer energizing study:

The transformer energizing study is performed with the computer simulation package to assess the transient voltage response of networks when energizing large transformers and its effect on voltage drop and transient stability. The aim of the transformer energizing studies is to determine transient over voltages and currents at various voltage levels after energizing of transformers. If the transient voltages and currents are found to be higher than acceptable limits, methods to mitigate the transient are investigated and implemented such as changing the impedance of the transformer, changing the cable size, employing soft start or changing the voltage levels (Qatargas 2 Power system studies, 2005).

6.4.18 Grounding Grid design Study:

Ground grid design is carried out for the maximum earth fault current. For this analysis of the step and touch potentials the maximum possible grid current at each substation is considered. The objective of the study is to verify the grid layout using the grid modeling methods. The grid layouts are given in the earthing layout of the respective substation. For the safety purpose, the step and touch potential must be less than the tolerable limits. Where required modifications are proposed in the grid layout to maintain the touch and step potential less than the tolerable limits (Qatargas 2 Power system studies, 2005).

6.4.19 AVR(Automatic Voltage Regulator) and Tap changer coordination:

A study which requires a different analysis approach is the coordination of Automatic Voltage Regulator (AVR) and transformer tap changing control by the Power Management System (PMS) may be required. Since tap positions are discrete, there is a risk of hunting in which the transformer taps oscillates between two positions to regulate the voltage. In this case a time domain model with appropriate control loops to represent the AVR and the PMS can be developed (ABB, 2004).

6.4.20 Pre-commissioning test:

VFD should be extensively factory tested to uncover any possible hidden weakness of components and system design before delivery. All the VFD components should be subject to routine tests during the factory acceptance test. The complete line-up should be full-load tested, back to back tested with one VFD acting as a motor and the other as a transformer, string tested with the compressor to prove system electrical performances and control functionalities. During the back-to-back test, the VFD can be tested at full power, which cannot be done during string test since compressor rating is lower that VFD one. Also, it can be tested at different operating conditions to calculate efficiency and to measure currents and voltages. Only after having satisfactorily passed these extensive tests can the VFD can be sent to a compressor manufacturer for a string test where the compressor performances are tested (ABB, 2004).

6.4.21 Advanced surge control dynamic interaction:

To avoid surge in the compressor the recirculation valves is being used extensively and being opened widely well before the compressor is actually in danger of reaching surge. A VFD allows for a new strategy based on an active surge control scheme by using the motor torque as a manipulated variable. By using the fast response time of the motor and the surge valve in a coordinated way, it is possible to improve anti-surge performance and allow the compression systems to operate with lower recirculation flows with an increase in energy efficiency. Improved VFD response time may result in dynamic interaction between VFD and surge-valve control loops, and could turn in mutual disturbance. This interaction was not present in turbine-driven compressors, since turbines have slower response times compared with surge valves so the two control loops are decoupled from the operative control-frequency point of view. This interaction needs to be closely studied for avoidance (ABB, 2004).

6.4.22 VFD System Grounding:

System grounding is critical for reliable operation of the motor drive. Proper grounding is not only required for safety reasons, but also controls common mode currents that will cause electrical noise and premature system failures, especially in the motor bearings. For these liquid cooled installations, electrical isolation should be added between the device and the cold-plate interface or by using resistive grounding techniques (Nored et al 2009).

6.4.23 Common Mode Voltage:

Common mode voltage on motor windings results from the modulation of the motor input power by the VFD to provide the correct flux or Volts/Hertz for a given motor speed. This effect is most pronounced during motor low speed operation or during motor soft-start. The motor operation at low speed or soft-start with a VFD will have the net effect of potentially doubling the voltage stress on the motor windings. Although this induces more stress on the system, most motors are designed to tolerate this starting mechanism by a VFD. Common mode voltage problems can be eliminated with an input transformer. The amount of common mode voltage seen by the motor depends on the drive topology of the VFD. This must be evaluated carefully because of the potential level of inductive and capacitive currents flowing into motor bearings. The common mode electrical current can affect bearing and seal life (Nored et al 2009).

6.5 Reliability of Qatargas VFD operated motor drive system:

To study the reliability of VFD I studied the VFD used in Qatargas for starter/helper function which is operational since last three years. I used last three years operational data to do a reliability study. In Qatargas the three process compressors N_2 (Nitrogen), C_3 (Propane) and MR (Mixed Refrigerant) are driven by Frame 9 Gas turbines. The string is also supplied with a VFD driven electric motor which functions Starter (to start the string from stand still till the turbine is fired and takes up load), Helper (to help the turbine to maintain flat production in summer when the gas turbine output decreases) and Generator (the active front end technology helps generate power back to the grid in winter when there is excess power in gas turbine because of low ambient temp). It also provides full pressure restart (FPRS) capability for pressurized restart after a trip. The electric drive system has a 45MW (continuous) 60MW (Short term) rated motor driven by a four threads of 15MW VFD threads. All the four threads are used (60MW) for short time for FPRS function. Gas turbine is the main driver in the string.

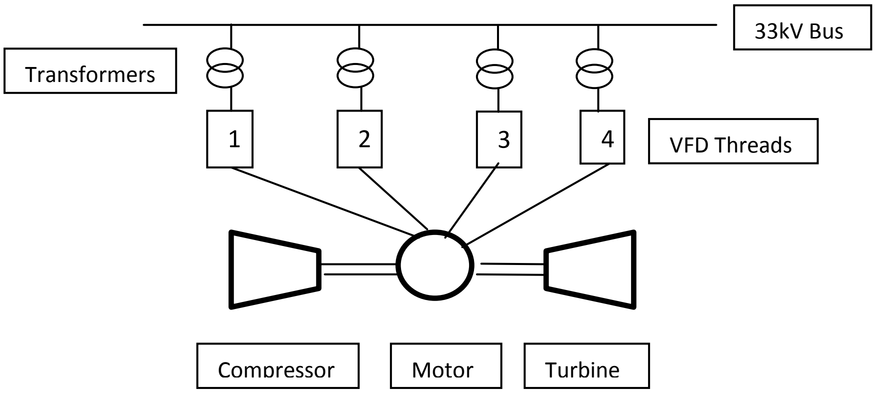


Figure 6.5: Typical four thread VFD with Starter/ helper motor configuration (Source Qatargas 2 VFD documents, 2006)

This arrangement has got all the characteristics of an “all electrical driven compressor” except that the motor is not sized to take up the entire compressor load. I chose to study it functionality to understand what the shortcomings are as regards to reliability. All Electric LNG uses a similar arrangement but the VFD and motor is increased in size to replace the gas turbine entirely and assume the function of the main driver of the compressor as described in the introduction chapter. The study of this system reliability of the Qatargas 2 VFD system can throw insight into the reliability issues facing a large electrical drive system. Further details of Reliability Analysis are in Appendix: J.

6.5.1 Qatargas VFD system Design Reliability:

The primary performance goal of the complete VFD equipment system is designed to operate as specified for a period of 7 years without the need to shut down the plant to perform any maintenance on the electrical equipment. As a minimum the equipment must be capable of running continually or as necessary in the described operating modes or combination of the described operating modes for 42 months, without requiring any service or their action that would shut down the LNG processing operation or force a string to shut down (MTech, 2008).

6.5.2 Built in Redundancy:

The system architecture is designed to achieve a high level of reliability by incorporating two levels of redundancy which makes it tolerant of the most likely component failures. The drives have redundant power cells and can continue operating after component failures within the cells hence 19 out of 21 power cells in each thread are required in each drive to operate. Three cells must fail before the drives power output is reduced by shutting down one of the threads. This redundancy is achieved by cell bypass feature incorporated, which bypasses the failed IGBT cell and keeps the system running continuously. A second level of redundancy is provided by the four winding helper motor being able to operate at 45MW (each thread and hence each winding is of 15MW capacity) with any three out of four drives connected and 3 out of four drives is required by the system/ because of this the drive failure rate is not sensitive to cell failures. The master controller is redundant. However, each thread is sensitive to single points of failure in the input transformer, controls, input reactor and cooling system (MTech, 2008). The design was based on the following:

- For a 7 years mission or a 3.5 year mission the probability of system failure is about 1% corresponding to a reliability of 99%.
- Calculated Component reliability was calculated to be 99.93% for a 3.5 year mission.
- Component reliability is expected failure of cell for 23 years of operation is 22 failures per four Trains with 48 drive fleet.
- The failure of the master controller has been found to have maximum effect on the unreliability common cause failure for the redundant master controller (MTech, 2008).

6.5.3 Reliability study of Qatargas VFD:

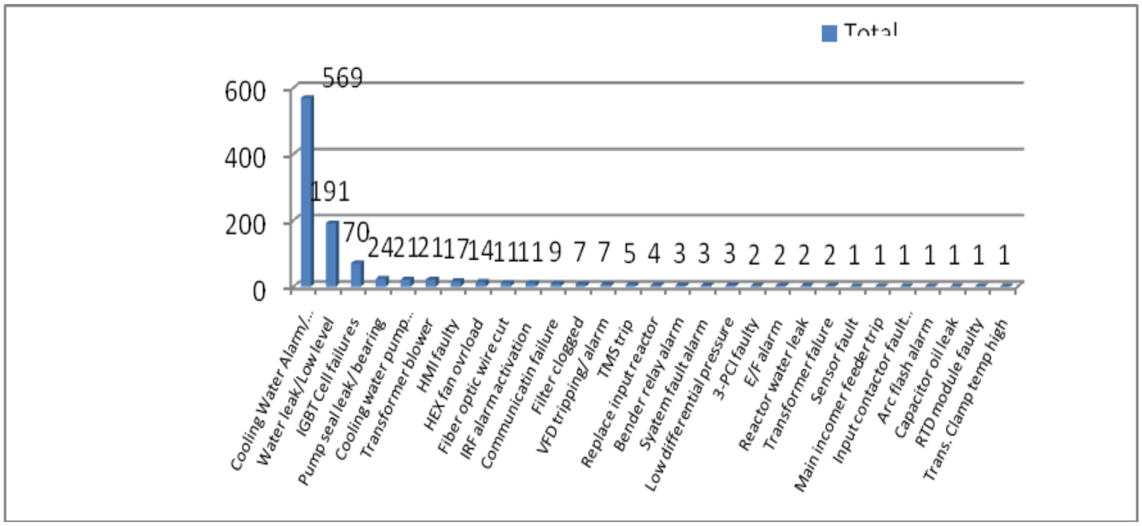


Figure 6.6: Failure chart of starter/ helper VFD

I analyzed all the failure modes of the Qatarags VFDs and the number of failures was plotted in a bar chart above (Figure 6.6). Out of the total number of failures observed the major failure mode recorded in Qatar gas is because of the cooling water alarm due to the rise in conductivity of the de-ionized water necessitating change of the de-ionizing cartridges and various leaks related to pumps seals, exchanger leaks and leaking components. The next highest failure is because of IGBT cell failure. Hence per fleet of IGBT failure per year is 1.625 per fleet and 18 per Train which is much higher that 1.8 per Train per year as envisaged in the design. The cell bypass feature which provides a built in redundancy has been disabled because of the arc flash concern, which leads to tripping of the thread in case of any IGBT cell failure. From the above it is quite evident that 80% of the failure is due to cooling water alarm resulting from fall in conductivity requiring replacement of de-ionizing cartridges. The next is reduction in water level due to pump, leaks, seal leaks and leaking exchangers and inductors. The next is the IGBT cell failures, which is investigated in further details. In reality master controller failure is not the cause of unreliability as was envisaged in the design.

6.5.4 IGBT Cell failure investigation:

The following figure demonstrates the actual reliability investigation of cell failures after collecting maintenance data from CMMS (Computerized Maintenance Management System) and analyzed through the Meridian software.

Number of cells installed in four trains with 12 helper motor drivers each having 4 VFD threads and each thread having 21 IGBT cells: 1,008
Number of Failures recorded: 70
Initial Mean Time Between Failures (MTBF): 43,258 days
Final Mean Time Between Failures (MTBF): 9,366 days

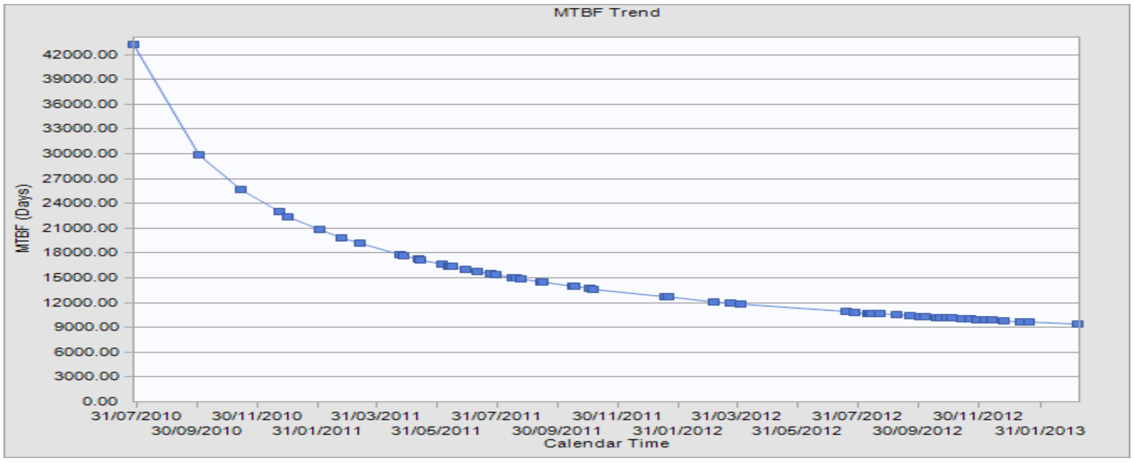


Figure 6.7: MTBF Trend of IGBT Cell failure Starter/ Helper VFD

6.5.5 Thread failure investigation:

The following figure demonstrates the actual reliability investigation of thread failures after collecting maintenance data from CMMS (Computerized Maintenance Management System) and analyzed through the Meridian software.

Number of threads installed in four trains with 12 helper motor drivers each having 4 VFD threads = 48,
Number of Failures recorded: 69
Initial Mean Time Between Failures (MTBF): 2092 days
Final Mean Time Between Failures (MTBF): 452 days

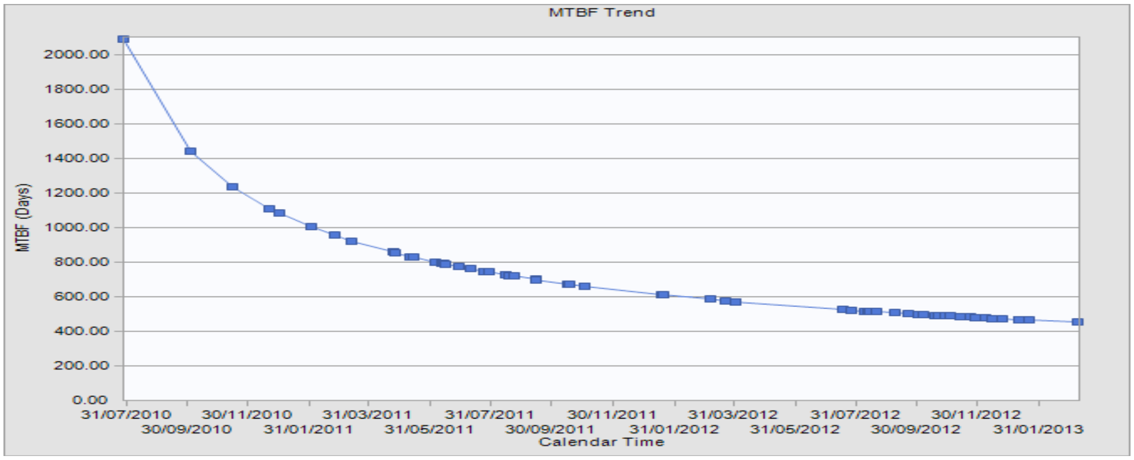


Figure 6.8: MTBF Trend of Thread failure Starter/ Helper VFD

Description	Cell	Thread
MTBF days	9000	452
λ= 1/MTBF	0.000111	0.002212
t= No. of Days in a year	365	365
λt	0.040556	0.807522
Reliability %= $e^{-\lambda t}$	**96.02558**	**44.59617**

Table 6.4 Reliability calculation Starter/ Helper VFD (individual cell and thread)

After above analysis it is found that the IGBT cell component reliability is 96% against the designed 99.8%. The rate of IGBT cell failure should be further investigated and should be brought close to the design In case of thread reliability the achieved reliability is 44.5% against the designed 98%. This is because the cell bypass feature, which allows two IGBT cells to fail before the thread trips, is disabled because of an incident of arc flash that happened during initial testing. This happened because of a malfunctioning bypass contactor. If the bypass function is re-installed the reliability will greatly improve. Hence the main reliability issue with the VFD system is related to the cooling water issue. Further study should be done in this direction to improve the reliability.

6.5.6 Motor failure:

In Qatargas one of the motors fed by the VFD functioning as a starter/helper motor failed resulting in a number of days of down time. As the root cause failure analysis is progressed it was clear that due to the partial discharge inception in the air gap left between the insulation layers caused by commutating diode in the field protection circuit led to the failure of insulation and resulting in the failure of the rotor. The insulation between the pole and the turns was reinforced by a layer of partial discharge tolerant mica insulation to reinforce the fault location. Hence during design stage partial discharge phenomenon needs to be studied in details and mitigation measures taken.

6.5.7 Transformer failure:

In another LNG company many VFD transformers failed. The root cause failure analysis discovered that the capacitance of large length of cables used to feed the VFD, interacted with the harmonic frequency and created high voltage resonance leading to the failure of the transformers. This was mitigated by shifting the firing angle of the VFD.

6.6 Conclusion:

VFDs are non-linear electrical loads on the electrical system which have side effects in the form of power-line harmonics, inter-harmonics, oscillating torques (torque ripples) in the drive motors. Effective mitigation measures have been developed for all these unwanted effects. Passive harmonic filters are custom-engineered for each project as necessary. The effects of inter-harmonics are simulated, and corrections in control strategies can be implemented, if necessary. Oscillating torques (torque ripples) in motor-compressor strings are damped sufficiently by design measures and rotor inertia. Effects of possible active and passive electro-magnetic interferences (EMC) throughout the electrical distribution system can be investigated and solutions developed ensuring quality from component to system level. Full lateral and torsional analyses according to international standards can be performed on each rotating string prior to detail design. Electrical stability of the power system, load-flow and short-circuit calculations, protection coordination, and load-shedding scenarios based on specified emergency shut-down (ESD)actions are routinely carried out for all electrical installations (Siemens 2008).High dynamic performance of full-electric driven compressor brings new challenges. Some plants have experienced a torsional vibration in mechanical chain compressors. This is a typical situation that occurs when high-performance VFD drives are introduced. In these cases, a good control system becomes the best weapon to monitor and solve vibration problem. This is done with a mix of offline tools to analyze the overall processes, such as fluid-dynamic, mechanical, electrical, and control systems, and online-control functions to measure and solve the problem (ABB, 2005).Anti-vibration control systems are a mix of function to avoid exciting resonance frequencies and to modify the physical characteristics of the process. Maintaining an early exchange of information between operator, contractors and vendors of various parts of "all electric" LNG plant, including vendor of motor driven compressor, contractor of the power plant, vendor of electric transmission and distribution systems, etc can reduce cost and risk by critically reviewing various available designs and options (Almasi, 2011). There is enough relevant experience within other industries so that the application of electrical motors on base load LNG technology would be but a small extension of existing experience (Shu, Harrison 2002). The use of electrical motors is not without risk, however, which of course is the case with anything being done for the first time. Shu, Harrison (2002) of Foster Wheeler believes that the risks are well understood and can be managed as part of a project's development and execution. Evaluating electric drive LNG processes has moved on from conceptual technical aspects, in particular, focusing on technical risk as well as economic comparisons. Studies by ChevronTexaco and Shell Global Solutions corroborate the view that such risks are well known and manageable through detailed design. Subsequent further development of the motor drive system by a number of manufacturers, specifically for LNG application, validates this view. Most conclusively however, the successful manufacturing, testing and full compressor/drive string testing now completed for the Norwegian Snøhvit project has shifted owner/operators interest in the electric drive from risk assessment to opportunity framing, especially if the total refrigeration system, including the power plant, forms the basis for performance guarantees (Kleiner et al 2005).

CHAPTER 7

Case Studies

There are several studies carried out by different individuals and also by various oil and gas companies and related Engineering Procurement and Commissioning (EPC) contractors to study the pros and cons of all electric LNG. Some of the case studies are discussed below. Some more case studies have been included in the Appendix B.

7.1 Case Study-1:

Kleiner and Kauffman (2005) of Shell Development (Australia) Pty. Ltd conducted a case study to evaluate the benefits of using an all-electric LNG system for Liquefied Natural Gas (LNG) and Gas to Liquid (GTL) plants over gas turbine drive system. Their case study used liquefaction process designed specifically in single train and multi-train configuration. The direct drive with conventional gas turbines (D-drive) concept used the well-known application of two Frame 7 industrial gas turbines each equipped with a 20MW starter/helper motor for starting the turbine compressor string. Waste-heat was modeled to be recovered from the pre-cooling gas turbine exhaust. The electric drive concept (E-drive) used the LNG 'Game changer' configuration of Shell Global Solutions. Waste-heat is similarly recovered via the power-generation turbine exhausts. Additional harnessing of waste heat to support combined cycle facilities was also explored. Both concepts had the same number of rotating equipment per train of four drivers and four compressors and also required the same individual components to transmit electricity from generation to mechanical power. The key differences between the concepts were the increase in the sizes of motors for E-drive. D-drive case uses starter/helper motor drive of 20 MW to start and help the main drive for the compressor which is a gas turbine, whereas the main drive in the E-drive case65 MW motor were used by elimination of the gas turbine as the main driver.

7.1.1 Economic drivers for electric drive:

The cost/benefit equation was compared as the "incremental" EPC cost difference between E-drive and D-drive for a train delivering the same daily LNG production of 5 MTPA (Million Tons Per Annum). Comparing the result, Kleiner and Kauffman (2005) opined that the higher electrical load needed for the 5 MTPA, 'E-drive' concept, only enhances the advantages to be realized from a full 'E-drive' arrangement during the entire life cycle. Further as the electric drive configuration at 5 MTPA is far from any equipment size constraint, with a potential to be larger in capacity without any change to configuration, technical step-out or equipment type. To study this potential economy of scale, three designs were made and compared by the team; a 5 MTPA direct drive as a base case and two electric drive options, one at 6 MTPA and the other at 7.5 MTPA. The latter, utilized 65 MW motor/compressor strings. Power generation in the electric drive cases included co-generation of electricity and process heat with a combined cycle generation option. The summary of the Cost-benefit calculation was tabulated as follows:

Cost-Additional cost of E-Train drives because of a larger power plant	US$20M
Main Equipment difference	
Electric Train drive	**Direct drive Train**
360MW Centralized power plant with a N+1 sparing philosophy	110MW centralized power plant with a N+1 sparing philosophy
Centralized waste heat recovery	Local waste heat recovery from pre-cooling gas turbine
Variable speed motor drive system	Gas turbine plus helper motor drive systems
Larger Electrical distribution and auxiliary system	Similar Electrical Distribution and auxiliary system
Minimum 10 (ten) additional on stream days per LNG, which is around 150,000 tonnes p.a US$ 3.5/MMBTU F.O.B (Free on Board)	US$29.6M
Reduced maintenance and shutdown costs average over 6 years maintenance cycle as typically used for direct drive plants	US$1.8M
Reduce fuel by 5% priced at US$1.0/MMBTU	US$2.1M
Reduced emission and losses by around 100,000 tons per annum CO2 e	US$0.6M
Annual Benefit (total of items below)	**US$34.1M**

Table 7.1: Cost/benefit tabulation of Direct drive (D-Drive) vs. Electric Drive (E-drive) in large LNG plants (Kleiner and Kauffman, 2005)

Figure 7.1 below shows the specific cost ($/ton of LNG) for a Direct drive vs. an Electric drive (Kleiner and Kauffman, 2005). With a Frame 7 gas turbine drive the maximum size that can be achieved is just above 5MTPA. The typical economy of scale is shown as a straight line and the improvement of specific cost of an Electric train shows a clear benefit with an increase in Train size in Figure 7.1.

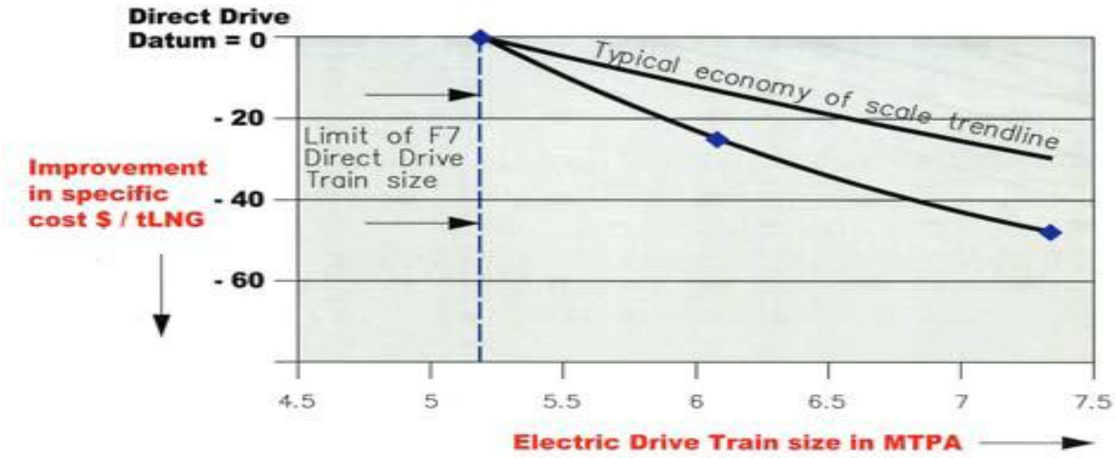


Figure 7.1: Specific cost $/t LNG of D-drive vs. E-drive in large LNG plants (Kleiner and Kauffman, 2005)

7.1.2 Conclusion:

Total Installed Cost build-up was carried out by Shell Global Solutions with cost differences between options being validated by a separate engineering service. A key observation was that the 2 x Frame 7 gas turbine direct drive design could, at a stretch, reach just over 5 MTPA while the electric drive could approach 7.5 MTPA. The results shows that the specific cost (cost/ton of LNG produced) of a single Electric drive train can be expected to continue to decline with increasing train size, reaching about 20% lower than the direct drive case as the Train size reaches 7.5MTPA. More importantly, this allows the capacity of a single Electric drive train to be tailored specifically to the requirement of the developers. Additional Capital Expenditure (CAPEX) of US $20 m has been incurred to install an Electric Drive over a Direct Drive system because of a large size power plant. However annual benefit of US$ 34m can be reaped if an Electric Drive is selected which more than offsets the initial CAPEX incurred in the first year of operation itself and proves as a considerable profitable option from the subsequent years onwards. Further, with fewer components and more robust drivers the Electric drive has the potential for significantly improved operating reliability and availability.

7.2 Case Study-2:

Håvard Devold, Tom Nestli and John Hurter of ABB Process Automation Oil and Gas conducted a study in 2006 for a comparison between a conventional Gas turbine driven LNG plant and an all electrical driver concept from availability, reliability, and cost performance, longevity and safety stand points. Devold et al (2006) concurred that a straightforward replacement of gas turbines with electric drives is a viable alternative. They further inferred that gas turbines are generally available either in less than 30 MW variable speed units or large 100 MW or more fixed shaft speed units, whereas electric drives are available in wide power and speed ranges up to 100 MW. They concluded that, the “All Electric Drive system” has much wider design flexibility in terms of size of trains and compressors per train shaft. The other opportunities presented by the All Electric Drive system as per Devold et al (2006) are increase overall uptime and reliability of trains, safer and more stable operation over a wider range because of wider range of speed control and reduced plant restart time. With electric drives, the plant can go to a production hold idle recirculation mode presenting an Operating Expenditure (OPEX) saving of 70% or more. The restarting after a trip is almost immediate.

7.2.1 Design Case (6.25MTPA LNG Train):

For a LNG plant there is a requirement of 150MW for the trains and 50MW Electrical power including smaller electrical drives with a production of 6,250,000 Tons/ year. The conventional production Train with gas turbine system has six 30 MW gas turbine driven trains in a 5+1 configuration plus two 30 MW electrical power generation units. The “All Electric Drive” alternative configuration has four 40 MW trains, fed by a 200 MW power plant that is designed to capitalize on the efficiencies of electric drives. In addition, three 10 MW smaller drives for both systems have been considered. The plant is with an energy need of 32 MW/MTPA. The effect of tighter control and better balance results in lower recirculation losses with an estimated benefit of U.S. $5 million per year. Maintenance, unavailability, and reduced downtime benefits typically gives 10 additional production days' equal to U.S. $36 million per year for an all-electric LNG plant vs. a conventional gas turbine run system. An annual saving from operation of an electric vs. a gas turbine driven plant was calculated as shown in Table7.2.

Characteristics	**Electrical drive**	**Gas turbines**	**Difference**
Capital expenditure (main drives, auxiliary and power generation	US$30M main drive US$35M Power plant US$7M auxiliary drive	US$25Mmain Gas Turbine US$14M power plantUS$7M auxiliary drive	US$ (26M)
LNG production	6,250,000 tons/ year	6,250,000 tons/ year	
Maintenance costs	US$5 M/ year	US$10M/year	US$5M
Shaft power efficiency	36%	25%	
Fuel gas consumption	450mm SCM	648mm SCM	200mm SCM
CO2 emission	800,000 TONS	1,160,000 tons	360,000 tons
CO2 tax (EU where applicable)	US$24 M	US$35M	US$11M
Value of fuel gas	US$100M	US$145M	US$45M
Ten additional production days	US$36M	0	US$36M
Recirculation losses	0	US$5M	US$5M
Annual saving			=91-102 M

Table 7.2 Annual Savings Using an All Electric Drive (MUSD (Devold et al, 2006)

7.2.2 Conclusion:

Devold et al (2006)'s calculation clearly demonstrates the value of an "All Electric Drive" system. The study demonstrates that an "All Electric Drive system" is the way to reach the industry's goal to reach a 7.2% ratio of field gas consumption to LNG production. The further concurred that with the added safety and operational benefits, as well as shorter delivery times and flexible design parameters, an "All Electric Drive system" is easily the logical choice, with a payback time of only four to five months for additional cost incurred as the initial additional CAPEX is $26M with an annual marginal benefit of $90-102M. Reduced environmental impact becomes an important added benefit, although not critical to the economic analysis. The reduced fuel consumption and greenhouse gas emissions lead to large savings in operational expenditure in addition to being environmentally sound hence making "All Electric system" a highly attractive option.

7.3 Case Study 3:

Bobby Martinez, P.E ConocoPhillips.; Cyrus B. Meher-Homji, P.E.; Bechtel Corporation John Paschal, P.E.; Bechtel Corporation Company Anthony Eaton, P.E., PhD; Formerly ConocoPhillips Company, LNG PDC Director conducted a study for an All Electric Motor Drives for LNG Plants in 2005 and presented to GASTEC 2005, Bilbao, Spain. They studied the incorporation of electric motor drives in ConocoPhillips LNG Process (Phillips Optimized Cascade LNG Process) with an article entitled "Incorporation of Electric Motor Drives in the Phillips Optimized cascade LNG process:. The ConocoPhillips-Bechtel Global LNG Product Development Center (PDC) studied several LNG driver configurations that utilized industrial gas turbines, aero derivatives, electrical motors, steam turbines and combinations thereof. The standard designs for the ConocoPhillips LNG Process incorporates a "two trains in one" concept with a view to maximizing plant availability, reliability and overall production efficiency. That is, the refrigerant cycle (Propane, Ethylene and Methane) has a minimum of two compressors operating in parallel, while the liquefaction plant is a single train. It is the parallel configuration of the refrigerant compressors that allows the plant to operate at production rates in excess of 50% while a single gas turbine compressor unit is off line. Furthermore, it is this operating flexibility, equipment reliability, and overall inherent design of the ConocoPhillips LNG Process technology that allows the LNG plants employing this technology to demonstrate production efficiencies greater than 95%. In an All Electric concept the Frame 7EA gas turbine drivers and respective starter-helper motors were replaced by an electric motor. This configuration was designed to ensure maximum flexibility and overall plant availability.

7.3.1 Study Objectives:

The fundamental objectives were to examine various electric motor drive solutions, determine the benefits claimed, and evaluate the technical risks and derive estimates of the installed costs. Specific goals of this study included a preliminary Life Cycle Analysis to determine the sensitivities of using electric motor drivers to key parameters, e.g. cost of electricity, cost of fuel and plant availability. Further, the objective was to examine power generation solutions to support the all-electric LNG concept, unless low cost, reliable external grid power is available from outside. On study a determination was made that self-generation would be a must, unless economical hydroelectric power was available.

7.3.2 Electric Motor design and motor/VFD suppliers:

It was determined that a single electric motor required to replace the gas turbine starter-helper configuration can range from 95 to 100 MW. The manufacturers' views that generators construction and operation is synonymous to synchronous motors, and given their vast experiences in building generators in excess of 250 MW, motors of this size are not considered new technology. These motors could be built without employing new designs or materials. Suppliers also have indicated that 2-pole motors equipped with variable frequency drives (VFDs) are the most attractive and economical solution for the power ranges under consideration. Electric motor suppliers stated that the 2-pole motors can be built and operated at high efficiencies. Electric motor and VFD suppliers considered for this study included: Mitsubishi-Melco-Toshiba, Alstom, Ansaldo Robicon, ABB, Brush Motors, and Siemens.

7.3.3 Economic Analysis:

LNG plants are typically based on the lowest possible Total Installation Cost (TIC). The lowest TIC option for an electrically driven LNG plant is a third party external grid. The electric motor costs less than a gas turbine, but the power system of the All Electric LNG plant which has now grown from 30MW to greater than 260 MW for a 5MTPA plant, needs a higher initial cost outlay. The LNG plant has to accommodate a large power generation and distribution system with built in redundancy. Both the simple cycle and combined cycle power generation were considered. The combined cycle power solution is more complex but more thermally efficient. Simple cycle power plant solution is the least complicated to operate, involves the shortest installation time and lowest overall total installed cost when compared to a combined cycle plant. The combined cycle power plant solution is more complicated to operate, requires greater attention to maintenance, requires a larger plot plan and is greater in TIC than the simple cycle solution. However, the combined cycle solution does benefit from a much greater thermal efficiency of 48% -vs. - 33% (Martinez et al 2005). Power plant reliability and availability are very important to the success of an electrically driven LNG Plant. The power plant solution must consider capital cost, operating cost and the stability of the system to mitigate against power instabilities due to generator trip, mechanical failures, electrical faults, and transient events of with multiple power generation packages. The economic analysis for this study is between gas turbine driven LNG plant and that of electric motors, it was concluded that self-generation power plant solution is necessary to ensure LNG plant availability greater than 96. Clear understanding of the economic parameters is crucial when evaluating a grid power solution along with the geographical locations at which LNG plants are being installed. The alternative to grid power is self-power generation. Self-power generation can either consist of a simple or combined cycle solutions. Each solution has its advantages and disadvantages. The LNG plant overall production efficiency must be in excess of 95% to be economic when compared to the gas turbine driven solution.

7.3.4 Conclusion of Study-3:

The inference drawn from this study was an electric motor driven LNG plant is theoretically a viable solution with today’s technology. Motor manufacturers are confident that large motors around 90-100 MW are feasible. Furthermore, large motors and VFDs can be built without employing new technology and materials of construction thus minimizing technical risk. The success of any LNG plant is fostered by low capital investment (CAPEX), low operating cost (OPEX), and high production efficiency. A third party, external grid power solution can satisfy the low capital investment and low operating cost drivers, but it could fall short in the area of plant production efficiency thus negatively impacting project economics. The self-generation plant requires a much greater up front capital investment than a gas turbine driven LNG plant. This initial capital investment is further complicated by the need to achieve production efficiency greater of 96% necessary to boost the project NPV (Martinez et al 2005). In conclusion, while an electric motor driven LNG plant is technically feasible, careful attention is required when evaluating the project economics. For example, the value of the fuel gas, credit for reducing CO_2 emissions, sufficient real estate for the LNG plant and power plant solution, schedule advantage when the LNG tanks are critical path, Total Installed Cost (TIC), simplicity of design, location of the plant. The answers to these questions and many others will be site dependent and client driven (Martinez et al 2005).

7.4 Case Study 4:

An Environmental life cycle assessment (LCA) is an accepted method to systematically quantify and assess environmental impacts during the life cycle of product, process or activity. It can be described as a ‘cradle to the grave’ assessment of greenhouse gas emissions of Liquefied Natural Gas (Barnett, 2010). Emissions of interest are carbon dioxide, methane and nitrous oxide, which are classed as greenhouse gases related to global warming. Okamura et al (2007) demonstrated emissions had reduced since 1997 and projected the feasibility of further reductions. Liquefaction remains the highest component of energy use within the product lifecycle resulting in 75% of emissions (Okamura et al 2007). 95% of liquefaction emissions occur due to fuel used by process refrigeration generators, acid gas processing and power generators (Barnett, 2010).The main types of greenhouse gas emissions in LNG liquefaction identified by Arteconi et al (2010) were:

- Fuel consumption for driving turbines and motors to operate equipment.
- Combustion of waste gases in flares.
- Gas losses from venting associated with pre-treatments, maintenance processes and losses from equipment and pipes.

As international energy companies are increasing their participation in more and even all segments of the LNG chain, a systematic approach to the reduction of greenhouse emissions across the LNG chain can yield reduced emissions. A case study was conducted by Coulson et al (2010) with one Train Greenfield Liquefaction with $C_{3/}$MR (Propane/ Mixed refrigerant) Technology cases and assumptions and the results are briefly discussed below (Coulson et al, 2010).

7.4.1 Case Study Scenarios:

- Base case – Gas-turbine drives; no carbon capture
- Option 1 – Gas-turbine drives with heat recovery; no carbon capture
- Option 2 – Gas-turbine drives with heat recovery without supplementary firing; with carbon capture
- Option 3 – Gas-turbine drives with heat recovery including supplementary firing; with carbon capture

- Option 4 – Electric-motor drives with CCGT power block; with carbon capture

Parameter	**Base Case**	**Option 1**	**Option 2**	**Option 3**	**Option 4**
Refrigeration Compressor Drivers motors	2 x Frame 7 GTs each with 8 MW helpers	2 x Frame 7 GTs each with 8 MW helpers	2 x Frame 7GTs each with 8 MW helpers	2 x Frame 7 GTs each with 8 MW helpers	3 x 65 MW Electric motors
LNG Production (TPD)	13,560	13,560	13,560	13,560	13,560
Overall Thermal Efficiency (%)	91.9%	94.2%	92.6%	92.9%	93.1%
Total Fuel Gas Rate(TPD)	2,030	1,660	1,930	1,865	1,840
CO_2 emitted (TPD)	3,319	2,377	840	270	264
Total CO_2 (TPD)	3,319	2,377	3,062	2,904	2,835
CO_2 captured (TPD)	0	0	2,222	2,633	2,572
CO_2 captured (%)	0%	0%	73%	91%	91%
CO_2 emissions relative to Base Case (TPD)	0	-942	-2,480	-3,049	-3,056
CO_2 reduction relative to Base Case (%)	0%	28%	75%	92%	92%
CO_2 emissions relative to Option 1 (TPD)	n/a	0	-1,537	-2,106	-2,113
CO_2 reduction relative to Option 1 (%)	n/a	0%	65%	89%	89%
Tonne CO_2 / tonne LNG	0.24	0.18	0.06	0.02	0.02

Table 7.3: Environmental Performance summary: (Coulson et al, 2010)

It is evident from the above study that option 3 and option 4 are the best in terms of thermal efficiency and over all CO_2capture and emission. However a deeper look will reveal that Option 4 (electric motor) is better than Option 3 (gas turbine) in terms of overall thermal efficiency, fuel gas rate and Total CO_2emitted and captured.

7.4.2 Capital cost comparison:

Of the above options the electric motor driver case is supported by a lower CO_2emission than the gas-turbine direct driver options as shown in Figure7.2. This is attributed to the higher availability assumed for the all-electric motor driver plant. Carbon capture has the potential to reduce the total CO_2emissions from the liquefaction facility to around 0.02 tonne CO_2 / tonne LNG. However, heat recovery and integration optimization has the potential to significantly reduce CO_2 emissions at a relatively low specific CO_2 avoided cost when compared to other options (Coulson et al, 2010).

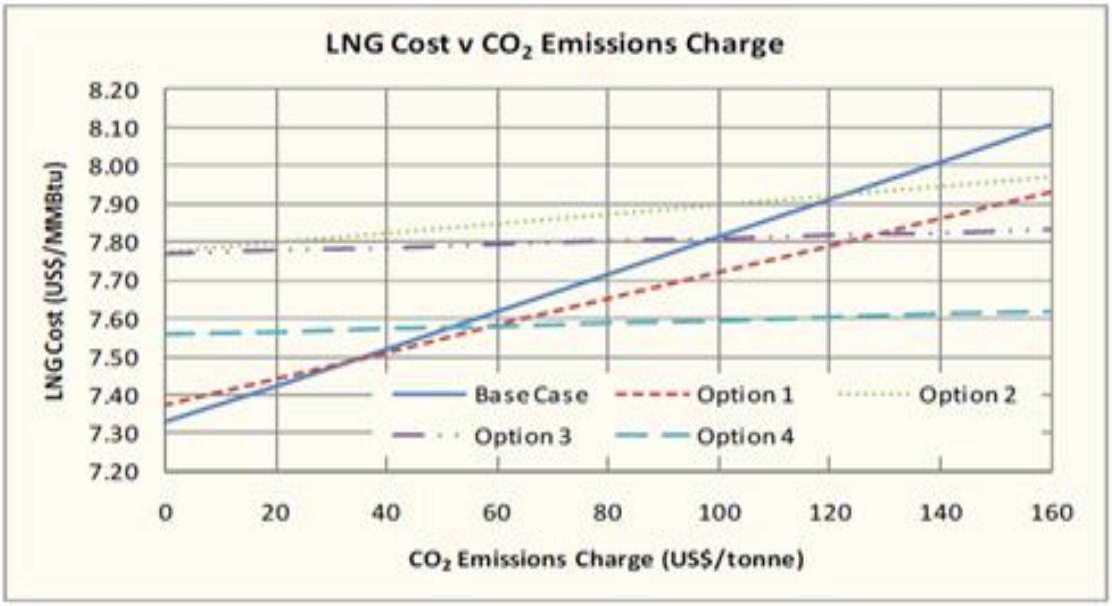


Figure 7.2: LNG cost v Co2 emission charges (Coulson et al, 2010)

The case study indicates that the cost of post-combustion capture equipment to remove CO_2 from gas-turbine flue gas sources requires significantly higher investment and consequently higherCO_2 emissions charges to provide an economic incentive. With 90% of the carbon in the feed gas to the liquefaction facility leaving in the products, almost all of which will be combusted producing CO_2, a greater reduction will be achieved by improving combustion system efficiency and capturing CO_2 at end users. It was Yost and Di Napoli (2003), by assessment of various LNG projects in Oman, Nigeria, Qatar, Ras Laffan, Trinidad and Tobago, determined that an average Gas Index (CO_2-e emitted to the atmosphere for every ton of LNG shipped) of 0.35 could be achieved based upon inflow gas quality of1006 Btu/standard cubic feet (s.c.f) which extrapolates to emissions of 3.83 g CO_2-e/MJ (Coulson et al, 2010).

7.4.3 Conclusion of the study:

It is clearly demonstrated from the above discussion that out of all the options Option 4 Electric-motor drives with CCGT power block; with carbon capture looks to be best option in terms thermal efficiency with CO2 capture option. The world's most efficient LNG facility is Statoil's Snohvit LNG in Norway, which is an all-electric LNG facility, recording a Gas Index of 0.22, extrapolating to 2.41 g CO2-e/MJ in contract to of Gas Index of 0.35with emissions of 3.83 g CO2-e/MJ for a conventional LNG plant. The reason for the low GI (high efficiency) is due to its geographic location at very low ambient temperature, waste heat recovery and reliable access to an electricity grid for standby power supply (Barnett 2010). It is to be also noted that Snohvit also uses an all-electric system for LNG compressor application.

7.5 Critical analysis of case studies:

A number of case studies have been discussed in this chapter and a few have been included into the Appendix B. It can be observed that the cost estimation of various parameters for life-cycle cost calculation is different. However in the final analysis there is considerable economic benefit, which cannot be denied. The reasons for this could be the following:

- The case studies are conducted at different year and hence the costs are different
- The cost parameters are site dependent and country dependent hence the final estimates are different.
- The price of LNG considered for each case is different
- The plant sizes are different hence there may be different estimates.
- Cost of fuel is treated differently as in one case it is treated as LNG price and it is treated as cost of purchase of gas
- Air Emissions cost differs for different sites
- Saving due to faster project schedule is different for project located at different sites/

The case studies demonstrate that electric drives are practical over a much wider range of sizes and speeds and are now available to meet the full range of mechanical system requirements for direct drive main gas compressor applications. Electric motors hold an economic advantage over mechanical drivers in several important aspects in terms of improved full load and part load efficiency, no ambient temperature impact, speed control accuracy, range of control, remote control and automation, reduced annual maintenance costs, air Emissions, reduced noise, and system reliability perspectives. The motor driven system has immediate restart facility with no limit on number of start whereas a gas turbine system has to wait for two to three hours for restart due to driver thermal consideration and the limited re-starts per hour. The gas turbine has reduced power availability with increase in elevation, temperature and humidity whereas an electric motor driven has no such impact. The electric compression has variable speed range and ability to start and come to full load upon starting, whereas gas turbine assumes load one-half hour after start. The gas turbine seal gas needs be vented or flared increasing CO2 and NOx emission, which is much reduced in case of a motor driven system fed from a combined cycle power station. If the electric motor is properly sized it can restart a pressurized system whereas the gas turbine system has to flare the inventory to be able to restart. Electric compression has the ability to trade carbon credit, which has the lowest risk of future emission restriction and has a lower insurance risk. The auxiliary consumptions of gas turbines are higher in comparison to an electric motor. Flexibility and unknown upcoming future emission regulations are the keywords in today’s changing gas storage and gas transport business. Although the capital expense (CAPEX) may be higher with the motor solution, a higher LNG production can create a more favorable return on investment over the life time.

The case studies discussed in chapter 7 validates that ‘All Electric LNG’ is a viable option because of all the above points discussed briefly. The information collected from these case studies have been further utilized for calculation and validation of the life cycle cost benefit model in Chapter 8.

7.6 Overall Conclusion of Case Studies:

The case studies discussed in the previous chapters have demonstrated the technical and commercial advantages of all electric LNG over the conventional gas turbine driven LNG. Kleiner et al (2005) study concluded that the specific cost (cost/ton of LNG produced) of a single Electric-drive train can be expected to continue to decline with increasing train size, reaching about 20% lower than the Direct-drive (gas turbine) case. Further, the capacity of a single E-drive train can be tailored specifically to the requirement of the developers. Devold et al (2006) study demonstrates that an “All Electric Drive system” is the way to reach the industry’s goal to reach a 7.2% ratio of field gas consumption to LNG production. It has added safety, operational and environmental benefits as well as shorter delivery times and flexible design parameters, with a payback time of additional CAPEX of only four to five months. The inference drawn from study conducted by Martinez et al (2005) is that an electric motor driven LNG plant is theoretically a viable solution with today’s technology and materials of construction thus minimizing technical risk. Further, with all electric potential for consequential damage if process trip happens is minimized by dynamic breaking using VFD. Shu et al (2002) believe that there was enough relevant experience of application of electrical motors within other industries and use in a base load LNG technology would be but a small extension of existing experience. The risks of using electrical motors were well understood, and can be managed as part of a project’s development and execution. Coulson et al (2010)’s study demonstrated that Electric-motor drives with combined cycle power block; with carbon capture is the best option for improved thermal efficiency and least environmental impact. few more case studies have been discussed in Appendix E. Rama and Giesecke (2006) opine that electric drives are practical over a much wider range of sizes and speeds and hold an economic advantage over mechanical drivers in several important respects. As per Blaiklock (2010) both turbines and motors have advantages and disadvantages for LNG plant use. When deciding on the best choice the main considerations are the amount and value of LNG produced over the life of the plant and the initial capital expense. Although the capital expense may be higher with the motor solution, increased LNG production can create a more favorable return on investment. Grapow (2009)’s research demonstrate that general statement cannot be made on advantages of all-electric, as too many project dependent variables will influence the result. A detailed Life Cycle Cost analysis has to be made for each project individually. He further opined that future emission regulations are the keywords in the decision. Sawchuk et al (2003) opine that there is a high level of confidence that “Next Generation” LNG plant designs is achievable with raised standards on design, capacity, and life-cycle cost and greenhouse gas emissions. As per Thomas et al, (2009) based on thermal efficiency improvement for LNG plants and a long term quest for reduced CO_2 emission an Electric LNG based on combined cycle generation and associated with heat driven absorption chillers for cooling the inlet air of the gas turbine in tropical area should be pursued.

CHAPTER 8

Life Cycle Cost Benefit Analysis

8.1 Introduction:

Life Cycle Analysis (LCA) is a holistic method used to evaluate economic consequences resulting from a process, product, or a particular activity over its entire life cycle (LC). The LCA, also known as a cradle-to-grave analysis, is studied within a boundary extending from the acquisition of raw materials, through productive use and finally to either recycling or disposal. An LCA study can yield a true-cost-of-ownership, which can be compared with results for other alternatives, enabling a better informed analysis. With the competitiveness of current technologies, LCA is a perfect tool to provide an analysis of performance and cost to help discern differences in the types of plants (Life Cycle Analysis, 2010). The study needs to address the commercial impact of using large electrical motors instead of gas turbine. The expectation is that the capital cost in an all-electric option would be higher as a result of the need to provide gas-turbine generators, steam turbine generators and electric motors in the combined cycle power plant to feed the large electrical motor drives. The commercial evaluation of a life-cycle analysis should demonstrate the benefits of the alternative options. Any commercial benefits to the use of all electric option must be evaluated for their impact on project net present value (NPV) or life-cycle benefit. Not surprisingly, when electrical motors are used, the capital cost is likely to escalate because of the need for a larger power plant. The commercial benefits therefore rely upon increased revenue streams to balance the higher capital expenditures **(**Shu, Harrison 2002). Some further discussions on Life Cycle cost Analysis can be seen in Appendix F entitled “Life Cycle Cost Analysis”.

Detailed studies have been conducted on Chapter 4 (Life cycle challenges) on various factors which have implication in the life cycle cost calculation. Securing the finance for an All- Electric LNG is to convince the lenders that it can provide an edge over the conventional gas turbine driven LNG in terms of better return on investment and an improved environmental performance. Economy of scale brings down specific cost of production and improves the project competitive position. The Capital Expenditure (CAPEX) and Operating Expenditures (OPEX) account for a substantial amount of the total investment cost. Hence there is major life cycle cost saving that can be realized both in CAPEX and OPEX, if these can be reduced in a liquefaction project. Considerations such as rapid commercialization, reduced technology development cost, market penetration, lower cost, shorter contract period and a reliable operation with reduced environmental concern are some of the other important factors. In Life cycle cost analysis important factors such as operational benefits, operational cost, maintenance cost, major maintenance interval, operational safety, thermal efficiency, emissions, performance deterioration, flexibility of operation, ambient temperature considerations, design flexibility, optimizing size and, Long Term Services Agreement

(LTSA) for Gas Turbine Maintenance; additional stream days, project schedule, which have been discussed in details in Chapter 4 (Life cycle challenges) have been utilized for the overall Life cycle cost calculation in this chapter.

Further, Chapter 7 and Appendix F discuss various case studies conducted by eminent and experienced personnel in LNG field. The information from these case studied conducted by Kleiner and Kauffman (2005), Devold et al (2006), Coulson et al (2010), Rama and Giesecke (2006), Martinez et al (2005)and (Shu, Harrison 2002)from chapters have been extensively used in the life cycle cost calculations in this chapter.

8.2 Common Definition:

A financial evaluation based on a full Life Cycle Cost analysis has to be performed for all alternative technologies available. Some of the terms need to be defined for a clear understanding of project evaluation (Grapow 2009).

a) **Life Cycle Costing** (LCC) = Capital Expenditure (CAPEX) + Operating Expenses (OPEX) + Maintenance Expenditures (MAEX)
b) **CAPEX** = Costs of construction of the facility + Costs of building + Cost of connection to electrical grid + Costs of erection& commissioning+ Costs for getting permissions etc
c) **OPEX**= Energy costs + Costs of operating personnel + Costs of buildings operations + Costs of emissions+ Money interests+ Costs of downtime costs
d) **MAEX** = Spare parts costs of maintenance personnel + Costs of downtime

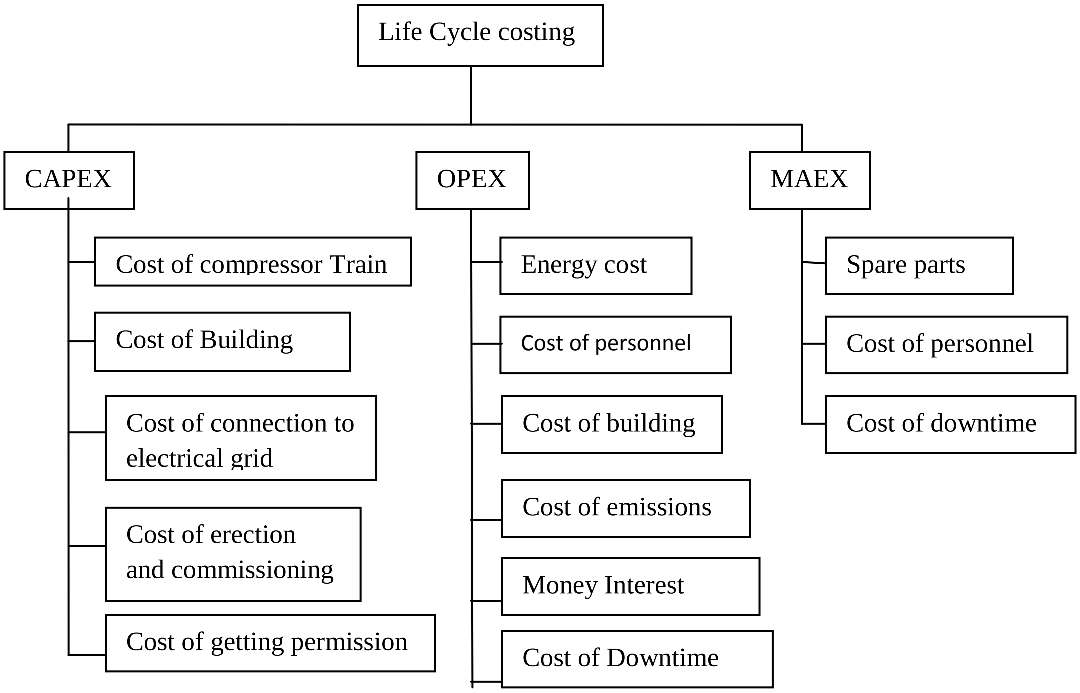


Figure 8.1: Life cycle costing: (MAN Turbo AG Schweiz, 2009)

8.3 Life cycle Analysis of a 7.8 MTPA plant:

Out of the total CAPEX (Electric or Gas) cost the division between various costs are Field development 26%, Liquefaction 32%, tankers 32% and Re-gasification 10%. The division between various OPEX costs are Field development 24%, Liquefaction 35%, Tankers 29% and Re-gasification is 12% (Deloitte Resource News, 2005). The CAPEX and OPEX costs of Liquefaction part are roughly the same and also the largest in the LNG value chain. About 60% of the investment and value creation are located in the producing country, 30% in transportation and the remaining in the consuming country (Deloitte Resource News, 2005). I have made a life cycle calculation for a 7.8 MTPA plant. I have selected this size because this is the largest Train that has been built till date with gas turbine drive and would like to make a comparison and evaluation to demonstrate the life cycle comparison of the all-electric LNG against the gas turbine alternative. Smaller trains will also be economical which will be demonstrated later in the chapter in Table 8.10.

8.3.1 Improved Efficiency:

The production impact of moving to electrical motors is achieved through higher thermal efficiency of the plant. Centralized power generation involves larger and more efficient gas turbines, which along with a heat recovery system in a combined-cycle power generation environment make the combination more energy efficient hence economical. The sizes of the generators in the combined cycle plant can be optimized to get the optimum thermal efficiency. Balanced against this increased efficiency are the electrical transmission and drive losses. The first of these increases thermal efficiency is about 12%; and then loses of about 4% because of the drive and transmission losses. The result is an overall increase in efficiency of 8% that translates to an additional 0.5% increase in LNG production (Shu, Harrison 2002).There is a potential 4-5% improvement in system thermal efficiency compared to single cycle gas turbines for a compressor station(Rama and Giesecke 2006).

Kleiner, Kauffman (2005) estimate a reduced fuel gas consumption of 5% due to the improved thermal efficiency. Priced at US$ 1.0/ MBTU for the fuel gas cost a net saving is US$ 2.1M has been achieved for a 5.0 MTPA plant.

Devold et al (2006) estimated fuel gas consumption for a LNG production train of 6.2MTPA capacity or both the alternatives. For an All Electric Drive LNG plant the fuel gas consumption is about 450 MMSCM (Million Metric Standard Cubic Meter) per year with a cost of $100M and for a conventional Gas Turbines LNG plant the consumption is about 648 MMSCM with a fuel gas cost of $145M. The difference in consumption is 200 MMSCM with a total net saving is $45m for a 6.2MTPA plant.

1- Boil off Gas used for fuel consumption by a 7.8 million tons train is about 850 tons per day (Qatargas daily report, July 2011). If Electric LNG uses 5% less because of improved thermal efficiency the additional saving is about 42.5 tons per day which could be sold as LNG. Annual saving is 15,045 tons (354 days at 97% availability). At a rate USD $800/t (@ $16/MMBTU, LNG price in 2013) of LNG the additional income as of 2013 is **$ 12m** per year.

2- With Shu, Harrison's (2002) estimate of 8% improved efficiency converted to 0.5% additional LNG production the additional income is:

    a. From Shu, Harrison's (2002) estimates an 8% efficiency improvement will result in **$19.2m** additional income per year at a rate of $16/MMBTU (Million Metric British Thermal Units, which is the LNG price in 2013) for a 7.8, million tons train. This is calculated with boil off gas for fuel consumption of 850 tons per day consumption for a 7.8 MTPA is about (Qatargas daily report, July 2011). The above cost is 8% of 850tons multiplied by 354 days (at 97% availability) at a rate USD $800/t (at $16/MMBTU).

    b. 0.5% additional LNG for selling will realize in to $31.2mper year for 7.8, million tons train for the entire year.

3- With Kleiner, Kauffman (2005) figures of fuel gas cost of US$ 1.0/ MMBTU, a net saving of $3.3m can be realized for a 7.8MTPA plant with US$16/MMBTU ($800/t) the additional income is $52.8m per year.

4- As per Devold et al (2006) figures of $45m savings for a 6.2MTPA plant, the net saving on fuel gas for a 7.8MTPA plant is $56M per year with the same gas price as in 2006.

8.3.2 Annual Maintenance Costs:

As per (Devold et al 2006), the maintenance cost per year for a 6.2 MTPA train is given below:

Characteristics	Electric Drive	Gas Turbines	Difference
Minor maintenance cycle	25,000 hrs.	4000 hrs.	
Major maintenance cycle	100,000 hrs.	20,000 hrs.	
Minor maintenance duration	1-2 days	6-10 days	
In operation system MTBF	>25000 hrs.	4,000 hrs.	
Maintenance costs	$ 5M/ year	$ 10M /year	$ 5M/year, in favour of all-electric

Table 8.1: Maintenance Cost of a 6.2 MTPA plant (Devold et al 2006)

As per Kleiner, Kauffman (2005) reduced maintenance and shutdown costs averaged to US$ 1.8M for a 5.0MTPA plant for an All-electric plant vs. a gas turbine driven plant. It is quite obvious that there is substantial savings in maintenance cost of an All Electric LNG plant over a conventional Gas turbine driven LNG plant.

With an extrapolation of Kleiner, Kauffman (2005) figures of US$ 1.8M (for a 5.0 MMTPA) plant and with an estimated 10% annual compounded increase over every year, the maintenance cost saving will be about US$ 5.4m per year for a 7.8MTPA all-electric LNG plant. As per Devold et al (2006) figures $ 5M/year (for a 6.2 MTPA) with an estimated 10% annual compound increase for a 7.8MTPA LNG plant saving from reduced maintenance cost of 2013 will be about **$9.7m** per year in 2013.

8.3.3 Initial Capital Cost and Installed Cost:

Additional cost is about US$ 20M (Kleiner, Kauffman 2005) for installing a 360MW combined cycle power plant unit for an all-electric LNG instead of a 120MW power plant required for a gas turbine driven LNG plant of 5 MTPA size. With an estimated 10% compound increase in cost per year the extrapolated additional cost for putting a power plant of 500MW power plant is about US$ 54Mfor a 7.8 MTPA plant. It is considered that a 500MW plant is required for a 7.8MTPA all electric LNG by optimizing power consumption. Shu, Harrison (2002) calculated the impact of capital cost of the change to an all-electric plant of 4 MTPA capacity, which is given in the following table:

Effect of change on CAPEX:	$ million
Adders	153
340MW Centralized power generation	25
Centralized waste heat recover	18
Electrical Motor drivers	39
Electrical Infrastructure	
Total Adders	235
Deductions	
Four Frame 5 gas turbines	45
Three frame 7 gas turbines	81
Localized waste heat recover units	28
Steam turbines	7
Electrical Infrastructures	14
Total deductions	175
Net increment	60

Table 8.2: Total Installation cost for a 4 MTPA LNG Shu, Harrison (2002)

As expected, the capital cost for the electric-motor option increases because of the installation of a large combined cycle power plant, if the power is generated in-house. The major "adder" is the cost of the power station, whose capacity has risen because of the all-electric option **(**Shu, Harrison 2002). As per his calculations, the additional outlay with an estimated 10% compounded increase in cost every year (from 2002 to 2013) for a 7.8 MTPA plant will be about $333M as of 2013.

Devold et al (2006) calculates the additional CAPEX for an all-electric LNG system for LNG Production of 6.2MTPA.

6.2 MTPA LNG plant	
Electric drive:	$ 30M
Main drives, $35M	Power plant, $7M
Auxiliary drives Gas Turbines	$25M
Main G	$14
Power plant auxiliary drives	$7M
Difference:	$29M

Table 8.3: Installation cost calculation for a 6.2 MTPA plant Devold et al (2006)

Devold et al (2006) considers that for a 6.2MTPA plant an All-Electric plant will have additional Capital outlay of $29M. By considering an estimated 10% compounded increase (from 2006-2013) an extrapolated additional cost is about **$71M**for a 7.8MTPA LNG Train as of 2013.

8.3.4 Production due to additional stream days:

Higher plant availability increases annual revenue for the entire project life, due the time value of money, as it brings forward a revenue stream. This evaluation will obviously vary with the particular configuration of prime movers selected. Increased production availability results from two sources: (Shu, Harrison 2002)

1. Power sparing or spinning reserve is more cheaply available on centralized gas turbines for a combined cycle power plant rather than on localized gas turbine used as compressor drivers. Therefore, a highly reliable power-supply service can be provided economically.
2. The scheduled maintenance needs for electrical motors are much lower than for gas turbines.

As can be seen from the previous discussion, the reliability and hence the risk of an unscheduled shutdown are much the same for all components. The scheduled maintenance downtime for gas turbines is five times greater than the next most demanding component. When all of these factors are considered, production availability increases by 2.9% (Shu, Harrison 2002).Typical component availability is given in Table 8.4 below: (Shu, Harrison 2002)

Equipment	Average reliability	Scheduled maintenance avg. hrs./yr.	Scheduled maintenance number of days/yr.
Centrifugal compressors	0.998	50	2.08
Electric motors	0.997	25	1.04
Gas turbines	0.994	270	11.25

Steam turbines	.994	45	1.875

Table 8.4: Schedule maintenance comparison: (Shu and Harrison 2002)

Hence for installing an all-electric plant the additional number of work days available is the difference of 11.25 days (for gas turbine) and 2.08 days (down time of compressors), which is 9.17 days. For a 5 million tones plant Kleiner and Kauffman (2005) estimates a minimum additional on-stream days per year of ten (10) days for an all-electric plant, which is around 150,000 tones p.aof LNG at a constant daily capacity. Priced at US$ 3.5/MBTU f.o.b. (Kleiner, Kauffman 2005) additional income is US$ 26.2M. (Cost per ton is about $175).

Devold et al (2006) also estimate a minimum of 10 additional production days per year of LNG Production. For a 6.2MTPA plant driven by an all-electric Drive an additional income of US $36M can be realized with a price at US$ 3.5/MMBTU.

For a 7.8MTPA plant daily production with 97% availability (354 working days per year) is 22,030 tones. For 10 additional stream days of production, at the same price of $3.5/MMBTU additional income per year is US$ 38.55m.

For a 7.8 MTPA plant with an average price of $16/MMBTU in 2013 the additional income for 10 additional stream days of production with a rate of 22,030 tons per day is about **US$ 176m**. (1metric Ton is about 49.2MMBtu)

8.3.5 Air Emissions:

Rama and Giesecke (2006) believe that as such, the benefit of emission reductions of the electric-motor driven system is reason to consider this technology. Kleiner and Kauffman (2005) calculated reduced CO_2 emissions for 5 million tones plant of about 100,000 tons per annum (T.P.A) of CO_2, with an estimated saving of US$ 0.6M. For a 7.8MTPA plant with an estimated 10% compound increase in cost the saving is US$1.82M in 2013

Devold et al (2006) estimate thatCO_2 emissions for a LNG Production of 6.2MTPA for an All Electric Drive is 800,000 tons per annum whereas for a Gas Turbine driven plant is about 1.160,000 tons with an overall difference of 360,000 tons. With Kleiner, Kauffman (2005) cost estimate of carbon emission (reduction of 100,000 t.p.a CO_2e with a saving of US$ 0.6M for 5 million tones plant) the saving is $ 2.16M for a reduction of 360,000 tons for a 6.2MTPA plant. This cost can be extrapolated at an estimated 10% compound increase every year from 2006 to 2013 for a 7.8MTPA plant the saving is**US$5.3M**.

8.3.6 Recirculation loss:

The main operating parameters for a compressor are the flow and pressure differential. At lower flow, there is a minimum pressure differential before the compressor surges. Recirculation is used if variations in flow are expected or if there is a difference between

common shaft compressors. The surge response is determined by the volume of the recirculation system, the surge loop response, and the overall system response time. A faster speed control response time improves surge performance and allows the system to operate with less recirculation. Recirculation causes energy loss and increased fuel consumption. The All Electric Drive system can operate with significantly less recirculation than a gas turbine driven example due to tighter and faster control (ABB, 2005). In a “no surge” principle whereby compressors can be safely be controlled in surge even without recirculation facilities enhancing control over surge, helping to avoid recirculation during normal operation, and opening up opportunities for reduced anti-surge equipment costs. An electric drive system significantly increases the response time and offers a much wider efficient operating speed range than a gas turbine. As a result, the electric drive system balances power requirements faster and better between different sections of the process. Tighter control means higher overall process efficiency and safer operation, with increased overall efficiency and less wear on equipment due to excessive stress (ABB, 2005).

For a 6.2MTPA all-electric plant net saving on recirculation loss is $5M (Devold et al 2006).Reduction in Recirculation loss, extrapolated from 6.2 MTPA plant resulting in additional production for a 7.8MTPA Electric driven plant is **US$ 6.3**.

8.3.7 Project Schedule:

The FOB delivery of large electrical motors is about 24 months, in comparison to GE Frame 7 GTs which is about 36 months (Shu, Harrison 2002). It is usual for a LNG projects to place the order for the gas turbines much before the final investment decision on the project is taken. Thus, the use of motors would not have much advantage in this case. Delivery of either gas turbines or a motor is assumed to be to the compressor vendor's works for assembly and testing of the drivers and compressors. It is also expected that up to 2 months would be saved in the assembly of motors and compressors vs. turbines and compressors (Shu, Harrison 2002). In all electric case the gas turbines is off the project's critical path and transfers the critical path onto the LNG storage tanks or the construction of the now larger power plant. As important, it helps to reduce schedule risk by elimination of a schedule-driving event (Shu, Harrison 2002). As per Martinez et al (2005) LNG tanks are critical path and therefore no schedule advantage is assumed. A typical schedule advantage is shown in Table 8.5.

	Base case in months	Electrical drivers
Frame 7 Gas Turbine FOB	36	
Electrical drivers FOB		10-12
Frame 5 Gas turbine FOB	14-15	

Frame 6 gas turbine		14-15
Electric infrastructures	12	14
Large refrigeration compressors fabrication	16	16
String test for hook up	2.5	0.5
String tests	2	2
Total with Frame 7	68.5	59.5
Difference	9 months	

Table 8.5: Delivery times for key components: (Shu, Harrison 2002)

Shu, Harrison (2002) of Foster Wheeler states that it is possible to reduce the engineering, procurement, and construction (EPC) phase of the project by 2 months, resulting in a life-cycle cost benefit of approximately $125 million for a 5 MTPA plant. As gas turbine is not in the critical path because storage tanks and piping being in critical path, I have not considered this for my life cycle calculation.

8.3.8 Strategic Fuel Source Options:

If electric energy rates remain competitive with gas energy rates, the economics of electric drives become as superior to those of gas-powered options as to become indisputable. The inclusion of an electric option can become part of a system strategy to improve cost performance and to reduce the cost on environmental impact (Rama and Giesecke 2006).

8.3.9 Reduced Noise:

Another form of emissions coming under more scrutiny is noise. The typical high-speed electric drive system is 7-10 dB (A) quieter than any of the mechanical driver alternatives (Rama and Giesecke 2006). This is a safety advantage and has not been considered for life cycle calculations.

8.3.10 Shorter Permitting Time:

Limitations on emissions can make new installation licensing a burdensome exercise. Salable emissions credits may be available by adopting a strategy of integrating electric motor system options. Therefore, it is much easier to secure permitting because of a much better environmental performance (Rama and Giesecke 2006).

8.3.11 Social Policy Benefits:

That the impact of converting the 325,000 HP of gas-fired reciprocating engine to electric motor systems would be equivalent to removing 5 million cars from roads each year. The net potential benefit, when considered on a national basis, would appear to be substantial (Rama and Giesecke 2006).

8.3.12 Tailor made train size: (Kleiner and Kauffman, 2005)

All electric allows the capacity of a single E-drive train to be tailored specifically to the aspirations of owners. Capital efficiency is improved with larger train sizes using E-drive concepts and allows owners to select any train size as best fits the opportunity (Kleiner, Kauffman 2005).

8.3.13 Control response:

The control response of electric motor is Medium to quick, whereas that of Gas Turbines is slow (Devold et al 2006).

8.3.14 Weight and space:

Electric Drive itself is a light unit but has space and weight consuming auxiliaries. Same applies to gas Turbines which is also a light unit with space and weight consuming auxiliaries (Devold et al 2006).

8.3.15 Power Factor:

The VFD operated synchronous motor can be operated at unity power factor so that it does not have a negative impact on the MVAR (Mega Volt Ampere Reactive) demand and hence on the power factor of the power system. If the power factor is lower, more current have to be supplied for a given amount of power use resulting in more line loss and need much larger size equipment in place than otherwise may be necessary.

8.3.16 Soft Start Equipment:

Because of the soft start capability the start can be smooth and does not impact in voltage dip of the power system during starting. When starting an electric induction motor, it takes a lot of energy to get all the components of the motor and the compressor rotating. The initial current is therefore much larger than the normal operating current. Application of VFD, which is soft-start equipment, the surge can be considerably reduced and the string can be started in a controlled manner without any voltage dip.

8.3.17 Comparison of equipment and plant size:

Kleiner and Kauffman (2005) worked out the cost/benefit equation to express as the “incremental” EPC cost difference between All-Electric drive and direct gas turbine drive for a train delivering the same daily LNG production. To study this potential economy of scale, three designs were made and compared; a 5 MTPA direct drive (as a datum) and two electric drive options, one at 6 MTPA and the other at 7.5 MTPA. The latter, corresponds to a 65 MW motor/compressor string. Total Installed Cost build-up was carried out by ‘Shell Global Solutions’ with cost differences between options being validated by separate engineering services. These results demonstrated that the specific cost (cost/ton of LNG produced) of a single Electric-drive train can be expected to continue to decline with increasing train size, reaching some 20% lower than the direct drive (Kleiner and Kauffman 2005).

8.4 Annual savings:

An additional CAPEX of US $20 m has been incurred to install an Electric drive against a direct gas turbine drive system for a 5 MTPA LNG train. However annual benefit of US$ 34m can be reaped if an E-Drive is selected which more than offsets the initial CAPEX incurred in the first year of operation itself and proves as a considerable profitable option from the subsequent years of operation (Kleiner and Kauffman, 2005). For further details of the above calculations please refer to Chapter 6 section 6.1 (Case studies). For LNG plants, for example, industry goals are currently to reach a 7.2% ratio of field gas consumption to LNG production. An All Electric Drive system is the only way to reach that ratio (Devold et al, 2006). With the added operational safety and operational benefits, as well as shorter delivery times and flexible design parameters, an All-Electric Drive system is easily the logical choice, with a payback time of additional CAPEX only in 4 to 5 months for a 6.25MMTPA LNG plant (Devold et al, 2006).In this context the environmental impact becomes an important added benefit, but is not critical to the economic analysis (Devold et al 2006).

8.4.1 Life cycle benefit for a 7.8MTPA plant with All Electric system:

From the preceding discussion the annual cost saving and additional income of an all-electric system over a gas turbine driven LNG can be calculated with a LNG price of US$16/MMBTU for a 7.8MTPA unit: (scheduled advantage not considered)

1- Saving due to improved efficiency= $56m per year.
2- Maintenance cost saving: $ 9.7m per year.
3- Production due to additional stream days with $16/MMBTU: US$ 176m.
4- Air Emissions 7.8MTPA plant in 2012 is US$5.3M.
5- Reduction in Recirculation loss resulting in additional production for a 7.8 MTPA Electric driven plant is US$ 6.3m.
6- Additional Capital Cost and Installed Cost: (-) $71m.
7- Total additional income per year (at $16/MMBTU): $56m + $9.7m +$176m +$4.8m +$6.3m= $253.3.
8- Monthly income = 253.3/12 =21.10.
9- Additional initial capital investment is $ 71m for larger power plant installation.
10- Extra income in the first year after taking care of the additional capital investment =253.3 - 71=182.3.

11- The additional CAPEX can be paid back in which can be paid back in months = (Additional CAPEX for all-electric/ monthly income) = 71/21.10 = 3.36 months of the first year of operation.

12- For a 25 year operation total additional flat rate income with discounting = 182.3 + (24 x 253.3) = US$6261.5M.

8.5 Sensitivity analysis of LNG price and plant size variation:

Sensitivity analysis is carried out with various different price of LNG and corresponding yearly additional income and annual cost saving of an all-electric system over a gas turbine driven LNG and calculated for a 7.8MTPA plant.

LNG Price in $/MM BTU	Saving by improved efficiency US$ M	Maintenance cost saving US$ m	Production due to additional stream days US$ m	Reduction in Air emission US$ m	Reduction of recircul-ation loss US$ m	Total income per year	Additional CAPEX due to a combined cycle plant US$ m (-)	Extra income in the 1st year in US$ m
6	21	9.7	66	5.3	6.3	108.3	71	37.3
8	28	9.7	88	5.3	6.3	137.3	71	66.3
10	35	9.7	110	5.3	6.3	166.3	71	95.3
12	42	9.7	132	5.3	6.3	195.3	71	124.3
14	49	9.7	154	5.3	6.3	224.3	71	153.3
16	56	9.7	176	5.3	6.3	253.3	71	182.3
18	63	9.7	198	5.3	6.3	282.3	71	211.3
20	70	9.7	220	5.3	6.3	311.3	71	240.3

Table 8.6: Sensitivity analysis of annual income a 7.8MTPA plant for various LNG prices:

The following sensitivity analysis is carried out for Annual total income in US$M per different sizes of the plants and with different LNG prices in $/MMBTU. Here the income is extrapolated from a plant of 7.8MTPA capacity with extrapolation of saving due to improved efficiency, maintenance cost saving, reduction in Air emission and reduction in recirculation without deduction of the initial additional CAPEX.

	Annual total income in US$M per different sizes of the plants						
LNG Price in $/MMBTU	3 MMTPA	4 MMTPA	5 MMTPA	6 MMTPA	7 MMTPA	8 MMTPA	9 MMTPA
6	41.65	55.53	69.42	83.3	97.19	111.0	124.96
8	52.80	70.41	88.01	105.61	123.21	140.82	158.42
10	63.96	85.28	106.6	127.92	149.24	170.56	191.88

12	75.11	100.15	125.19	150.23	175.26	200.30	225.34
14	86.26	115.02	143.78	172.53	201.29	230.05	258.80
16	94.42	129.89	162.37	194.84	227.32	259.79	292.26
18	108.57	144.76	180.96	217.15	253.34	289.53	325.73
20	119.73	159.64	199.55	239.46	279.37	319.28	359.19

Table 8.7: Sensitivity analysis of annual income of various sizes of plant with LNG prices

8.6 Net Present Value (NPV) calculation:

The figure below demonstrate the movement of LNG price over the last 10 years, which shows that there is a increase in trend except a dip observed in 2008-2009 due to the global slowdown. A sample NPV calculation is shown in Appendix K.

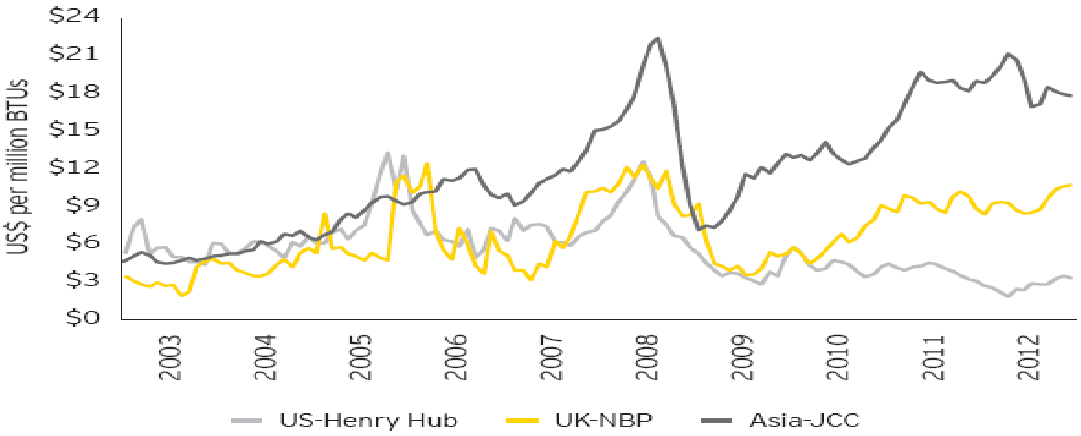


Figure 8.2: Global Natural gas price monthly average (Ernst and Young, 2013)

The table below demonstrates the Net Present Value (NPV) of expected cash flow with a flat rate of annual income for 25 years of operation, and a discount rate of 7% for a 7.8MMTPA plant, which clearly shows the economic advantage of an all-electric system.

LNG price ($/MMBTU)	Income per year (US$M)	Net Present value of expected cash flow with discount rate of 7% (in US$M) (A)	Additional CAPEX due to a combined cycle plant (B)	Net Present Value (NPV) after discounting for CAPEX(C=A-B)
6	108.3	1,262	71	1,191
8	137.3	1,600	71	1,529
10	166.3	1,938	71	1,867

12	195.3	2,276	71	2,205
14	224.3	2,614	71	2,543
16	253.3	2,952	71	2,881
18	282.3	3,290	71	3,219
20	311.3	3,628	71	3,557

Table 8.8: Net Present Value (NPV) calculation for a 7.8MTPA plant with 7% discount rate for various LNG unit price:

The table below demonstrates the net present value of future cash flow at a flat rate of annual income for different sizes of LNG plant with respect to various LNG price and varied discount rates for a 25 years of operation. No matter what is the discount rate the NPV value looks very attractive.

	NPV of total income in US$M per various sizes of the plants and various discount rate with flat rate of annual income for 25 years of operation															
LNG Price $/MMBTU	3 MMTPA (Various Discount rates)				5 MMTPA (Various Discount rates)				7 MMTPA (Various Discount rates)				9 MMTPA (Various Discount rates)			
	7%	8%	9%	10%	7%	8%	9%	10%	7%	8%	9%	10%	7%	8%	9%	10%
6	485	445	409	378	809	741	682	630	1133	1037	955	882	1456	1334	1227	1134
8	615	564	519	479	1026	939	864	799	1436	1315	1210	1118	1846	1691	1556	1438
10	745	683	628	581	1242	1138	1047	968	1739	1593	1466	1355	2266	2048	1885	1742
12	875	802	738	682	1459	1336	1230	1136	2042	1871	1722	1591	2626	2405	2213	2045
14	1005	921	847	783	1676	1535	1412	1305	2346	2149	1977	1827	3016	2763	2542	2349
16	1100	1008	927	857	1892	1733	1595	1474	2649	2427	2233	2063	3406	3120	2871	2653
18	1265	1159	1066	985	2109	1932	1777	1643	2952	2704	2488	2300	3796	3477	3200	2957
20	1395	1278	1176	1087	2325	2130	1960	1811	3256	2952	2744	2536	4186	3834	3528	3260

Table 8.9: Sensitivity Analysis with various discount rates for different plant sizes and varied LNG prices for 25 years of operation.

The Figure 8.2 above shows that the price of LNG has increased from US$ 4.5/MMBTU in 2003 to US$ 16/MMBTU (Asia-JCC price) which is an annual rate of increase of 14%. The table below demonstrates the net present value of future cash flow at 14% increase in the gas price every year, for different sizes of LNG plant and varied discount rates for 25 years of operation.

	NPV of total income in US$M per various sizes of the plants and various discount rate with annual rate of LNG price increase of 14% for a period of 25 years operation															
LNG Price $/MMBTU	3 MMTPA (Various Discount rates)				5 MMTPA (Various Discount rates)				7 MMTPA (Various Discount rates)				9 MMTPA (Various Discount rates)			
	7%	8%	9%	10%	7%	8%	9%	10%	7%	8%	9%	10%	7%	8%	9%	10%
6	2306	1988	1723	1502	3843	3314	2872	2503	5381	4639	4021	3504	6918	5965	5170	4506
8	2923	2520	2185	1904	4873	4201	3641	3713	6822	5881	5098	4443	8771	7562	6555	5712
10	3541	3053	2646	2306	5902	5088	4411	3844	8263	7124	6175	5381	10624	9159	7939	6919

12	4159	3585	3108	2708	6931	5976	5180	4514	9703	8365	7251	6320	12476	10756	9323	8125
14	4776	4117	3569	3110	7960	6863	5949	5184	11145	9608	8328	7258	14329	12353	10708	9332
16	5228	4507	3907	3405	8990	7750	6718	5855	12586	10850	9405	8197	16181	13950	12092	10538
18	6011	5182	4492	3915	10019	8638	7487	6525	14026	12092	10482	9135	18034	15548	13477	11745
20	6629	5715	4954	4317	11048	9525	8256	7195	15467	13335	11559	10074	19887	17145	14861	12952

Table 8.10: Sensitivity Analysis of annual income of various plant sizes with different discount rates and annual compounding increase of LNG price of 14% over the base.

The above figure demonstrates that for various sizes of the plant and various discount rates with an annual 14% compound increase in LNG price the net additional income and overall cost saving of all-electric case over gas turbine case looks much more attractive over a flat LNG price.

8.7 Conclusion:

From the above discussion it is quite evident that there is good economic sense to consider all-electric as an option. If all the technical issues are studied in advance and mitigated, the electric option can be made a reliable and a viable alternative to the Gas Turbine driven LNG. For an electric LNG at a discount rate of 7% and a span of 25 years, the projected cash flows for LNG price of $16/MMBTU for a 7.8MTPA LNG plant which is the largest plant that has been built till date is worth $ 2,952M, which is much greater than the initial additional CAPEX outlay of $71.00M. The resulting positive NPV of the above project after catering for the initial additional capital outlay is US$2881M, which indicates that pursuing the above project may be optimal. Initially in Table 8.9, I have considered that the LNG price is going to remain constant over the entire period of 25 years, but historically LNG prices increase over a period as shown in Figure 8.2. If we take the historical trends of increase in price and extrapolate it the project annual cash flow the Net Present value will still improve and make the project look much more attractive, which is demonstrated in Table 8.10.

CHAPTER 9

Questionnaire Survey Discussion

9.1 Introduction:

I conducted a questionnaire survey with twenty questions with an intention to get feedback from experienced personnel who have worked in the LNG field. I received some very interesting answers which have thrown further insight into research. Some of the critical reviews made by the respondent were worth further detailed investigation before considering all electric as viable alternative. At this point it is worth mentioning Shu et al (2002) view 'however large the commercial benefits, if the technical risks are too high, then the electric-motor option would not be selected'. The feedback response from the survey is discussed below. A sample of questionnaire is included in Appendix L

9.1.1 Summary table of participants:

Number of participants	42 Response both questionnaire (37) and interviews (5)
Employment level	Managers, Engineers, Planners, Operators, Technicians
Relevant expertise	Expertise in their own field and craft
Company relevance	LNG Industry
Average Years of experience	16

9.1.2 Questionnaire discussion:

1. **All Electric equipment has an overall advantage over Gas turbine (GT) alternative in engineering, manufacturing, transportation and installation.**

Most of respondent agreed with the above statements with those strongly agree and agree at 83%, neutral at 8% and disagree at 8%. Some pointed out that the simplicity of electric equipment with respect to gas turbine counterpart. Electrical equipment is a simple rotating machine requiring less auxiliary equipment and consists of fewer parts and hence requires lesser capital intensive spare. The primary drivers for the capital cost of an LNG liquefaction facility are site specific in nature. A large part of LNG plant cost is capacity related. As a result, most of the cost of an LNG liquefaction project is a function of site-related conditions, project development and project execution efforts. Even with all these elements, each LNG plant is unique to a specific location and market destination. Cost of site preparation will vary significantly with soil conditions and location. This cost is also dependent on plant size. Although the agreement generally in favour however the availability of electricity and/or how it is generated could make one or the other option more attractive.

2. **All Electric LNG requires smaller foot print (floor area) for installation, lesser capital intensive spare parts than Gas turbine driven LNG.**

Most of the respondent agreed on the above statement with strongly agree and agree at 87.5% and neutral at 12.5%. One of them made an interesting observation that if foot print is a concern depending on horse power requirement an aero-derivative Gas Turbine has smaller foot print in comparison to frame gas turbine. However, the aero-derivative turbines, which have a higher thermal efficiency than that of frame gas turbine, are available in smaller sizes. Further they can be considered as drivers in combined cycle power generation option improving overall thermal efficiency. Whether one is considering on-site power generation or purchased power from a utility has bearing on the decision. If site power generation is considered the footprint of an “all-electric” LNG facility would be larger than and more capital intensive than gas turbine driven LNG facility. Electric motors would have a smaller footprint than the gas turbine in the process plant, but a larger understanding of the equipment failure rate need to be considered to determine need for spares and their respective costs.

3. **All Electric LNG Factory acceptance tests is less complex, less time consuming and has a shorter and cheaper validation testing schedule with fewer bottlenecks than the GT counterpart.**

Most agreed that an all-electric LNG requires less complicated tests with strongly agree and agree at 87.4% and neutral at 6, 4%. Now a day’s major LNG construction is done by joint venture EPC contractors to spread their risk. The contractor selection and relationship and capability of the joint venture contractors and their subcontractors are seen by some as significant factors affecting cost. Large electric drives depending on topology can also create unique challenges that may not be recognized during the system design such as harmonics, resonance or torsional oscillation. One very interesting observation was it is not unusual for design engineers to miss the converter effect when a single diode fails in the Dead Front End of a medium voltage variable frequency drive. This failure mode causes the drive capacitor bank to increase the short circuit asymmetry during a fault which may exceed equipment ratings, which should be recognized and addressed during design. Further string test for electrical motor with compressor cannot be carried out in the factory due to requirement of a large amount of power which the grids are not able to supply and hence the test have to be shifted to site and wait to be conducted till the power is available. This may delay finding of issues delaying the risk mitigation to the site, hence may delay the site testing and completion schedule. Some doubted whether there will be any major advantage considering large motors to be used in LNG plants testing would be rather non-standard thus may increase the risk. Other agreed that mechanical Factory Acceptance Tests do tend to be fairly complex and lengthy. Gas Turbines have to undergo different tests, under various scenarios to meet the acceptance criteria. System validation testing can pay huge dividends if properly done and not just a “dog and pony” show for the customer and hence any undetected VFD system problems can significantly delay startup and impact production.

4. **It is more likely that All Electric LNG can be completed within schedule and budget considering simplicity in construction, testing and commissioning.**

Out of all the responses strongly agree and agree stood at 80% neutral at 16% and disagree at 4%. The answer to the above somewhat depends on electrical power generation requirements. If all power were purchased from a utility then agreement is unanimously and strongly in favour of the statement, whereas if all power is site produced some doubted whether the electric drives will have any scheduled advantages. Competition among contractors and liquefaction process technologies are often seen as significant factors affecting cost. As per some technology selection does not have a significant impact on project being completed in schedule; however, it does impact plant operation, availability, and efficiency. With equal conditions among participating contractors, the cost impact of contractor competition is limited. Most of the project cost is beyond the influence of designers and contractors and is mainly a function of site related conditions, project development and project execution objectives.

5. **All Electric LNG will need a shorter overall schedule than a conventional LNG plant with GT driven compressors.**

The responses are strongly in favour of the statement with those who strongly agree and agree at 82% and neutral at 18%. Some are in favour, if the power is purchased and schedule completion is very much dependent on whether one considers purchase of utility power rather than site generation. Another important insight was that if GT modular design is considers than that would reduce the overall schedule of installation. VFD driven electric motor also has a modular construction and testing facility at the manufacturer and can provide compressed schedule. Some of the respondent mentioned that to build a large LNG train such as 7.8MTPA and above a dual circuit for compressor is needed for mixed refrigerant compression with the present maximum reference of VFD motor system being 65MW motor in a LNG environment. To this effect, Shu, et al (2002) believes that LNG plants have traditionally used the largest technically proven gas turbines as drivers and built their compression strategies around them. This has meant that, often, two compressors in separate casings are driven on a single shaft by a single gas turbine. For the motor option, the refrigerant compressors can be split and driven by individual motors. This would reduce the motor size to one with an operating reference. The capital cost will increase but may be compensated by each compressor being driven at a speed optimized to improve life-cycle benefits. Some believe that if a large combined cycle power plant is built that may get into the critical path. Other pointed out that in large LNG plants, turbine is not in critical path for an LNG installation, as vessels and piping and storage tanks are on critical path and require considerable work effort to achieve, hence all electric may not provide an overall advantage to the schedule.

6. **The overall technical issues related to 'Variable Frequency Drives (VFD) in All Electric LNG" such as Harmonics, Torque ripple, Sub-Synchronous Torsional Interaction (SSTI), Electrical Resonance due interaction of harmonics with circuit parameters can be studied and mitigated to an acceptable level.**

Mostly respondent remained neutral to the above statement with those strongly agree and agree stood at 40% and neutral at 60%. Only 40% of them agreed that the technical issues can be resolved. There is a concern that most known issues can be studied and mitigated but not all concerns can be identified until the facility is placed in operation under site conditions. This will place some risk on the all-electric consideration. From experience "the 8Hz low frequency instability issue which was indicated during string test of Qatargas 2 introducing some instability to the turbine-compressor string driven by VFD fed Electrical motor and sub-synchronous torsional interaction concerns. This issue was not predicted and realized till quite late in QG2 project since the fact that magnitude and frequency of this instability is dependent on system short circuit availability". Once identified, it was studied and necessary actions were taken. Electrical resonance can be one of the factors that need to be focused. An electrical resonance can be created when a voltage excitation source frequency matches with the natural frequency of the electrical circuit causing high voltage to be generated. A number of transformers of a major facility feeding the VFD drive failed recently due to resonance high voltage created by interaction between the circuit parameters and the presence of harmonics. A large motor has also failed due to high voltage created by commutation of the sacrificial diode connected to the protection of the field excitation, which gave rise to inception of partial discharge causing failure of the field insulation. Some pointed out the Stator earth fault and rotor earth fault of the motor is a major concern. An earth fault detection system if incorporated will increase the ability for fault detection and reduce damage. One point worth mentioning is that in theory much can be designed for but operational reality has shown that we cannot account for everything.

7. **All Electric LNG has a Life cycle cost advantage over a conventional GT LNG because better efficiency and better availability because of more available production days than the GT counterpart.**

The response rate to the above statement was in favour of strongly agreed and agreed at 87% and neutral at 13%. A cost benefit analysis has to be carried out with relevant and credible data to agree with the above statement. Kotzot et al (2009) believe that for a project the capital cost is given more significance than the life cycle cost. Project stakeholders prefer a lower CAPEX (Capital Expenditure) as the most desirable project goal and most crucial driving factor in their decision making process. This is the largest single cost component of life-cycle. The difficult part is defining what is "right" so as to achieve the lowest cost and shortest schedule. Although life-cycle cost is often cited as a criterion in plant design, it seldom becomes more influential than lowest capital cost. Based on the number of Turbine overhaul days required for large turbines some believe this would prove to be an accurate statement. It is important to understand that in order to have a greater availability/reliability all the parts must be able to work at the same level. When ancillary components such as cooling requirements are considered it is found that an electric LNG still depends heavily on mechanical components with a lower reliability may bring down the overall reliability. It is also true that electrical components become obsolete in a rather short period of time and hence may involve high cost in upgrade, repair or replacement. Some pointed that as the electrical system is not proven in this large scale hence cannot be relied unconditionally.

8. **All Electric LNG have a safety benefit over the conventional Gas Turbine LNG as all fired equipment can be located out of the process area and the process areas can be made less noisy.**

Overall response rate was strongly agreed and agreed at 87% and neutral at 13%. Capital cost reduction must be balanced with other important objectives, such as safety, reliability, operation and maintenance practices. In that respect as regards to safety all-electric LNG marches ahead of conventional LNG plant. LNG industries put a lot of emphasis on safety of the plant and hence adequately design and maintain them for the above purpose. All Electric facility will be definitely quieter with marginal risk improvement by removing fired equipment. Other mentioned that we are shifting the gas turbine to a combined power plant which is located inside the facility hence the fire equipment is moved from one location to another inside the plant, hence does not bring in a whole lot of benefit. However, one must consider that the process plant that handles bulk of the natural gas at high pressure can be made considerably safer by moving the fired equipment out.

9. **All Electric LNG has an Operational benefit over conventional Gas Turbine LNG such as; faster start up, accurate and wider speed variation, better control, full pressure restart capability and faster cool down due to absence of slow roll, no effect of ambient temperature, more number of production days and better capacity utilization.**

The agreement rate for the above statement is 100% with strongly agree at 50% and agree at 50%. There are not many references or case of precedence of All-Electric LNG other than the Snohvit LNG, which also has been involved with some constructional and electrical failures bringing down the confidence level. There is not much experience of real life operational issue with the All-Electric LNG with VFD so as to make a critical decision for major capital investment. Considering environmental impact, ambient temperature limitation and ease of operation an all-electric LNG easily scores over GT LNG.

10. **All Electric LNG cost less to maintain than GT LNG considering the fewer and lesser number of planned outages, less spare parts and a cheaper Long -Term Services contracts etc.**

Most generally agree with this statement with those who strongly agree and agree stood at 87% and neutral at 13%. Some would like to slightly differ from the above pointing the reason that past failures of transformers and motors due to circuit resonance has brought considerable downtime to the plants. Hence sufficient spares in terms of transformers, motors and power electronics have to be stored to meet eventuality of failure and to reduce downtime. Outages may not be solely limited to mechanical turbine as inspection requirements also dictate Shutdown requirements. Hence any additional efficiency improvement in this area is limited to available technology. One also must consider the ancillary components for a VFD when answering which may also need periodic inspection.

11. **All Electric LNG has better availability due to a longer Mean Time Between Failure (MTBF) and Mean Time Between Maintenance (MTBM) and a shorter Mean Time to Repair (MTTR) longer than a GT LNG.**

The response to the questionnaire survey was strongly agreed and agreed at 70% and neutral at 30%.Many doubted the reliability of the VFDs from their own experience. As per Shu et al (2002) the stability studies have indicated that the design of certain combined-cycle configurations may be problematic. The larger the gas turbines and the lower the sparing selected, the less able is the system to survive the trip of one of the gas turbines without a drop in frequency. Selecting a proper combination of gas turbine and cycle configuration could improve system operational stability. Shu, et al (2002) believe power system stability to be the most important impediment to the use of electrical motors. However, through stability studies a number of stable solutions can be configured and that there are tools that exist to manage the technical risks. This problem can be overcome in a number of ways:

- The use of more, smaller gas turbines makes the impact of a trip of any one turbine proportionately less important. This may favour use of aero-derivative gas turbine generators, which run at higher efficiencies, for lower capacity plants and in cooler climates.
- The use of auxiliary firing on the waste-heat recovery units helps to reduce the impact of a trip of the gas turbine on the steam turbine.
- Fast-acting inlet guide vanes on the gas turbine can considerably improve its ability to ramp up in the event of a trip.

12. **All Electric LNG are more reliable than Gas Turbine driven LNG considering that GTs run with tighter parameters and clearances and lesser flexibility of operation.**

The response rate to the above statement was strongly agreed and agreed at 78% and neutral at 22%. Depending on overall system design all-electric machinery can have this advantage. The reliability of the VFDs has been brought to the notice due to number of power electronics failure and leakages in the de-ionized cooling water system. This is further accentuated by transformer and motor failures. Hence all the failure modes have to be closely studied and mitigated before building confidence in VFD driven electric motor system.

13. **All Electric LNG in a combined cycle generation configuration has a higher overall thermal efficiency over the GT driven LNG counterpart.**
14.

The response rate was strongly agreed and agreed at 88% and neutral at 8% and disagrees at 4%. It is highly dependent upon the configuration one is choosing. The size of the Gas turbine generators and waste heat recovery steam generators system can be optimized to get higher combined cycle efficiency. Hence an All-Electric system can provide a higher overall plant thermal efficiency than the GT driven compressor. This hybrid solution can generate enough steam which can be used for process heating, in addition to power generation. Shu et al (2002) believes that the combined cycle–the most efficient and most integrated of the power generation solutions.

15. All Electric LNG in a combined cycle generation configuration is more environmental friendly because of lesser plant emissions than the GT driven LNG plants.

This statement is generally agreed by most respondent with strongly agree and agree at 78.4%, neutral 17.3% and disagree at 4.3%. Some mention that installation of Heat Recovery Steam Generation (HRSG) System in conjunction with gas turbine exhaust system, in a conventional plant, can improve the overall system thermal efficiency to bring it close to the motor driven compression system in a combined cycle power plant environment. Other said that the electricity has to be produced somewhere inside or outside to supply the electric motors, which in turn creates emissions. The amount of emission would highly dependent on the source of electricity and method of generation. Combined cycle generation efficiency has to be closely studied before making any decision. All Electric would be preferred in countries where cost of production of electricity is cheap and more renewable energy production is available especially large amount of hydro-electric power is available.

16. All Electric LNG has a lesser Payback period as it has a higher number of available production days than the Gas Turbine option.

The response rate was strongly agree and agree at 70% and neutral at 30% respectively. All electric LNG can have a much shorter payback period depending on utility generation availability and LNG prices but increasing availability (i.e. more number of production days) requires redundancy in system design that increase initial costs of investment. The motor size reference available in the LNG market is 65MW and hence for large size LNG production there may be a requirement of dual or parallel circuits if one motor cannot cater to the entire compression load. Due to economy of scale, a relative increase in capacity will usually lower specific costs (US Dollars per ton) as long as equipment sizes increase proportionally as opposed to adding one or more parallel modules of equal capacity. Since a 7.8 MTPA LNG (largest Train built so far) train may need a driver of the capacity of 120MW and present largest reference is 65MW in a single cycle configuration, hence a dual circuit configuration may be required. Electrical motor drive needs high initial investment since the motor will be tailored to the plant size needs. Gas turbine in the other hand is common product which has big fleet in the world. Limited experience on large motor maintenance might lead to unpredicted high maintenance costs, while gas turbine maintenance can be predicted more easily.

17. All Electric LNG has a faster restarting capability which has a life cycle cost advantage than Gas Turbine alternative.

The response rate to the above statement was strongly agreed and agreed at 87% and neutral at 17%. A lot of this depends on overall plant design and the need for pressure reduction for a restart. If the VFD and motor/utility source electric power (generation or utility) can support a full pressure restart of the pressurized compressor following a trip this would allow a faster restart. The alternative is to flare the inventory with loss of revenue and with additional emission. External cooling sources also have an impact on

LNG production. VFD eliminates turbine warm up and cool down requirement following a trip.

18. **All Electric LNG has an ability to de-couple plant production from ambient temperature which will help maintain flat LNG production throughout the year.**

96% of the response was in favour ‘strongly agree’ and ‘agree’ and neutral response was 4%. As long as generation supports electrical power requirements under worst case ambient conditions it is possible to decouple plant production from ambient temperature in an electric drive scenario. This is a major advantage; however, the combined cycle power plant which may employ gas turbine may have to face this issue. Hence, the power plant has to be sized to handle this challenge. External cooling sources also have an impact on LNG production. One point of view is that cooling water is the key point, as a sizeable amount of cooling would also be required for VFD’s.

19. **All Electric plant can be built to any capacity as motors have flexibility on sizing whereas Gas Turbines are available in fixed sizes hence the plants can be built to standard sizes only.**

Response to the above statement was strongly agreed and agreed at 74%, neutral at 22% and disagree at 4%. Some raised doubt as regards to how big the motor can go as the present maximum reference in LNG environment is 65MW. For large size LNG plant built to date will need very large electrical motor. A 7.8MTPA LNG train utilized gas turbine with an ISO capacity of about 130MW hence will need a motor of an equivalent size. As the modern production trains are gradually increasing in size to take advantage of economy of scale and specific cost of production, which will need larger size drivers as years to come. Shu, Harrison (2002) opines that there are a number of useful reference points in industries unrelated to LNG. The largest two-pole motors (3,000–3,600 rpm) in the world are slightly larger than 50 Mw. Larger but slower speed motors have been fabricated at more than 100 Mw. The availability of a large motor supply would seem to be the least of the technical risks, i.e. the ability of the market to supply a reliable large electrical motor. These are within a range that would be suitable to drive an LNG plant, although there are advantages to going higher still. Most major suppliers of large motors for LNG projects and all are confident of their abilities to design and fabricate motors at higher ratings (Shu, Harrison 2002). VFD driven Electric motor sizes give an additional flexibility of as they are no longer limited by starting current as the VFD can start them with low inrush.

20. **Based on technical and economic reasons ‘All Electric LNG’ can be preferred over a gas turbine LNG.**

The response was strongly agreed and agrees at 69.6% and neutral at 30.4%. Most agreed that it is technically preferred; however a detail cost benefit analysis is required to prove the case in point. Some of them have mentioned that there is insufficient data and lack of experience and reference and lack of confidence on the reliability of the VFD has prompted deep study before making a crucial decision changing the preferred option. All electric generally gives higher reliability and ease of operation however for it to be the selected technology one must consider the availability and cost of electrical of power to validate this statement. Present projects prefer GT because it has a large installed base and has been there for a long time. The advantages of size, easy start & stop, simpler control system, simpler shut down logics/safety system are a definite plus for the electric equipment's over the Gas turbines.

21. **General comments, if any, for or against "ALL Electric" as a preferred alternative to conventional LNG.**

In the experience of some respondents all electric facilities are more reliable and easier to operate, however the cost of energy related to an all-electric facility tends to be higher than an all gas powered facility so how you generate or obtain the electricity is very important to the economics. Additionally the larger the motors utilized the more complex and unreliable they become. One wonders, if an electric LNG plant is actually more viable for all the reasons asked above then why are there not more of them– especially considering that oil and gas companies are always looking to become more efficient at installing and operating facilities. It needs to be proven that all-electric LNG can be a better alternative as Sonhvit has not proven itself fully. Less emission, less parameter monitor, lesser space occupation, less inventory, less maintenance cost, greater control over demand / production. There are definite indications that "All electric" can be a viable and preferred alternative to a GT driven plant from a theoretical standpoint. However, in terms of actual performance, one would recommend to study and analyze the performance of the only "all-electric" LNG plant in Norway. Some believe that it should help to establish the points marked in this survey as a real case example and give an opportunity to implement the same in high capacity LNG plants. The requirement is high availability of LNG production with low unit cost of production. Reliable power availability is required for evaluating the selected case. High initial investment, less operating & maintenance experiences will be some of the requirements from investor side. More electric drives means, it will have an impact on power quality and power system will have more harmonics. Hence Power system will have to be designed such that it will have limited impact.VFD systems are often included as part of the rotating equipment. The vendor's focus is then on the compressor package and drive details such as short circuit ratings may be a lower priority during the initial design. Some of the VFD drive manufacturer claim high reliability of their drives which should be backed by proof of claim with validation witness testing.

9.2 Some other technical risks mentioned by the respondents:

1) **Startup-**Some of the respondents who do not have thorough knowledge about VFD raised the issue of large motors starting. Their experience with the electrical motor taking large amount of electrical current at starting bringing the system voltage down to a low level leading to tripping of the electrical system, The VFD can adjust the voltage and frequency directly thus the current to build up slowly during all situations especially starting unlike direct on line starting when the starting current

can be up to 7 times the full load current of the motor (Kaiser, 2008). This control starting has a very mild effect on the inrush current hence on the system voltage.

2) **Short circuit**-Some of the respondents have raised doubt about the short circuit in the stator of the motor which may reduce availability. It is important to understand that the VFD limits short circuit at its output and input to the motor. The short circuit protection is included in the VFD to prevent of the damage of the VFD when short circuit occurs at the cable or the motor (Kaiser, 2008).
3) **Bus-Transfer-**Some electrical engineers raised doubt on the bus transfer. During bus transfer from one bus to another during the open interval the motor flux does not decay much but the rotor position begins to fall behind where the stator flux will be when reconnected. If reconnection occurs at the wrong time the inrush current reacts with already present flux to create very large torque transient. This will trip the VFD when the utility voltage goes to zero and smoothly restart when the voltage is restored. Hence bus transfer need to be avoided (Kaiser, 2008).
4) **The options for risk reduction in compressor configuration-** In the area of compressor configuration, there are really two issues to be addressed: the speed at which the compressor is driven and how it is started.
5) **Limitation of motor speed-** The large gas turbine market has grown around the need to drive large power-generation plants. Thus, the running speed of gas turbine and compressor is 3,600 rpm, equivalent to a two-pole electrical motor with 60 Hz supply. Electrical motors installed in a 50-hz supply scheme where two pole motors will run at 3,000 rpm may be disadvantaged. This can mean either that the compressor needs to be redesigned for the lower speed or that a gearbox is needed. A third option is to use a variable speed drive (VSD) capable of driving the motor and compressor at 3,600 rpm without a gearbox. The option for power generation to provide a design, sufficiently robust enough to survive transient conditions, has to be designed.
6) **Use of VFD:** VFDs have the ability to ride out voltage drops that result from upstream electrical faults. This can be a major advantage on a grid-connected facility but less important on an island power plant. Shu, Harrison (2002) believes that the disadvantage is that the VFD is in circuit all the time, overall efficiency is lower, and unless significant redundancy can be included availability may be affected. One of the key issues to be addressed in the design and installation of a large island-configuration power plant is the stability of the system and its ability to survive trip and upset conditions.

9.3 Conclusion:

The general response from the experts is that the cost of site preparation and the construction of the All Electric plant will be considerably higher. But it needs to be considered that the operational benefit will outweigh the initial CAPEX. The availability and reliability of the electricity is one of the important points to be considered during the conceptual stage. Another important factor is a larger understanding of the equipment failure rate to determine need for spares and their respective costs. Further string test for electrical motor with compressor needs a large amount of power. Hence this test has to be shifted to the site and has to wait till the power generation plant at site is commissioned. This may delay finding of issues delaying the risk mitigation. In addition, testing has to be fairly complex and lengthy which may increase the risk. Hence any undetected VFD system problems can significantly delay startup and impact production. As far as schedule of completion is concerned, a large combined cycle power plant may get into the critical path. Some believe that vessels and piping and storage tanks are on critical path, hence all electric may not provide an overall advantage to the schedule. Some believe that some of the technical challenges are so complex that in reality in spite of all the testing and mitigations that can be incorporated one cannot account for everything. It is also true that electrical components become obsolete in a rather short period of time and hence may involve high cost to upgrade, repair or replace. Some respondents pointed that as the electrical system is not proven in this large scale hence may bring down the overall reliability and cannot be relied unconditionally. Hence all the failure modes have to be closely studied and mitigated before building confidence in VFD driven electric motor system. Limited experience on large motor maintenance might lead to unpredicted high maintenance costs, while gas turbine maintenance can be predicted more easily. Present projects prefer GT because it has a large installed base and has been there for a long time. The advantages of size, easy start & stop, simpler control system, simpler shut down logics/safety system are a definite plus for the electric equipment’s over the Gas turbines. The use of electrical motors is not without risk, however, which of course is the case with anything being done for the first time. Studies corroborate the view that such risks are well known and manageable through detailed design. Subsequent further development of the motor drive system by a number of European manufacturers, specifically for LNG application, validates this view. Successful manufacturing, testing and full compressor/drive string testing of the all-electric Snøhvit project has shifted interest in the electric drive from risk assessment to opportunity framing. Specifically, there are strong reasons to consider use of electrical motors on LNG projects and probably other base load facilities, as well. There are potentially large commercial benefits to be reaped in terms of plant availability and project schedule. Shu and Harrison (2002) believe that there is enough relevant experience within other industries so that the application of electrical motors on base load LNG technology would be but a small extension of existing experience. They further state that the risks are well understood and can be managed as part of a project's development and execution. Kleiner et al (2005) opine that evaluating electric drive LNG processes has moved on to evaluating an effort which is directed at technical aspects and in particular focusing on technical risk as well as economic comparisons.

CHAPTER -10

Conclusion and Further Research

10.1 Introduction:

Gas turbines have long years of service experience in the LNG industries as reliable drivers and have their fair share of advantages. They are simple, robust, and sturdy machines. These drivers have a lower risk of technology, design, construction, testing and operation. They do not need large complex electric power generation and distribution system. Although they have a lower availability because of routine time consuming and costly maintenance regime the reliability of the machine is quite high. Integrated approach to design, engineering, manufacturing and testing ensures that the machines are of high quality and performance (General Electric, 2006). Rigorous testing regime has established an improved performance and reliability. Full load String test up to 130MW in the manufacturer's facility is possible, which can identify issues so that they can be fixed before the machines are transported to the site (GE, 2006).Because of the long years of dependable service all the stakeholders are quite confident in its performance. Dependable global service network is available for gas turbine in terms of personnel and spare parts (GE, 2006).

On the other hand the All-Electric Drive system delivers numerous benefits for any high energy consuming process within the gas value chain, including processing facilities, compressor stations, LNG liquefaction plants, and CO_2 injection. With the added safety and operational benefits, as well as shorter delivery times and flexible design parameters, an All-Electric Drive system is easily the logical choice, with a payback time of only a few months as demonstrated in the life cycle analysis section 8.4.1 bullet 11. The reduced fuel consumption and greenhouse gas emissions lead to large savings in operational expenditure in addition to being environmentally sound. In this context, the environmental impact becomes an important added benefit, but even without considering this aspect, the economy of the All-Electric Drive system makes it highly attractive (Devold et al 2006).In addition to the above the Net Present Value (NPV) for the future cash flow is very attractive. In an extremely safety-minded and highly competitive LNG industry, an evolution of all-electric is emerging that dramatically improves the reliability and productivity of base-load LNG plants not to mention the added safety benefit as all the fired equipment being located away from the high pressure gas processing plant. The noise level of the process plant is also much lesser than the gas turbine driven plans. Considering these advantages, the electric motor variable speed drive is in many cases a viable and economically attractive alternative to the mechanical gas turbine driver for centrifugal refrigeration compressors. With competitive & reliable electric power available at or near the jobsite, or from an associated power plant, this alternative should be evaluated at a very early stage of any new project. Major vendors offer a complete electric-driven compression solution for LNG liquefaction plants from the power plant through to the VFD electric motor driven compressor trains including the control system. Several reputable manufacturers are experienced and qualified to engineer and supply integrated refrigeration systems, alternatively with gas turbines or electric motor compressor drivers, including the compressors themselves and the power plant or just parts thereof (Kleiner 2005). Compressor train size can be tailored for a specific requirement for customer benefits. Simpler LNG process design possibilities, lower shaft centerlines significant in seismic active and cyclone regions, elimination of housings for compressor and driver, packaging and pre-testing at factory are some of the added benefits (Siemens, 2005).

- The availability of all electric plant is higher than that of conventional gas turbine driven plant. (ABB, 2009).
- Electric drive systems are custom engineered for the application on hand, allowing the compressor to be optimized in capacity and speed for the process on hand, and not limited by size and rating as in case of gas turbine rating (Kleiner et al 2005).
- The gas turbine is not inherently self-starting and need a starter. All electric plant do not need starter as the VFD driven motor can start on its own.
- Full power is instantly available over the entire temperature & speed range, and the number of successive and cumulative start-stop and load cycles is possible unlike gas turbine plant. Once shut down, planned or unscheduled, re-starting is less time consuming leading to operation flexibility (Kleiner et al 2005).
- In a gas turbine LNG the gas turbine needs to cool down slowly before it is restarted which is not required in all Electric LNG (Devold et al 2006).
- VFD is always sufficient to start even a fully loaded compressor– a valuable asset in case of process trips because the compressor circuit does not have to be depressurized (no flaring or loss of refrigerant) and the cryogenic process elements do not warm up (ABB, 2009).
- A critical factor in any LNG operation is the life cycle cost that is impacted in part by the maintenance cycle and engine availability. Electric drives have lower maintenance cost and higher availability than gas turbines (Meher-Homji et al 2007).
- Electric drive systems do not require de-rating. Gas Turbine on the other hand suffer from Dirty engine losses, Fuel composition and heating value losses and silencer, filter and ducting losses (Sheldrake, 2003).
- There is no speed control range restriction in electric drive. The speed of each compressor can be optimized to achieve maximum compressor aerodynamic efficiency at a design point and at the warm and cold ambient temperature extremes and as per process requirement (ABB, 2009).
- Higher efficiency and reduced fuel consumption and reduced CO_2 emissions by 40-50% can be achieved by using combined cycle power generation in conjunction with electric motor driven refrigeration compressors in place of simple cycle Frame gas turbine drivers (Chiu, 2003).
- A faster string test programs, modular motor-drive systems, and shorter installation times offer a potential for months of schedule reduction and a substantial decrease in related costs (Siemens, 2008).
- Decoupling of plant production and ambient temperature is possible with electric drives as typical gas turbines lose approximately 0.33% of their output for every one ^{0}F increase in ambient temperature (Martinez, et al 2005).
- There is overall increase in thermal efficiency by 8% which translates to an additional 0.5% increase in LNG production (Shu et al 2002).

- The employment of variable speed drives offers the possibility to improve control the process simply and effectively by speed control and to run equipment at its optimum operating points and operational flexibility (ABB, 2009).
- Enhanced safety is achieved by removal of the gas turbines from the hydrocarbon process area. Worker risk and related insurance premiums are eliminated by removing gas turbines from the process area (Siemens, 2005).
- There is design flexibility of train sizing as electrical drives are available in a wide power and speed ranges, up to 100MW. Thus, the All Electric Drive system has much wider design flexibility in terms of size of trains, compressors per train shaft, and the possibility to separate smaller essential units (Devold et al 2006).
- In case of twin compressor bodies, these can often be arranged on either side of the motor shaft, providing ready access to the inner bundles, bearings, and seal cartridges of vertically-split compressors, without disturbing the basic alignment of the compressor bodies. (Kleiner et al 2005).
- There is a reduced maintenance cost and downtime for the motors and the VFDs as compared to gas turbines (Siemens. 2006).
- Part load efficiency of gas turbine is much lower unlike electric drive. A small reduction in speed can make a big difference in the energy consumption. As many pump and compressor systems often run at partial load, the use of a variable speed drive can produce huge savings.
- By employing variable speed drives instead of throttling or using by-pass vanes, the energy bill can be reduced by as much as 60%. All trains experience reduced efficiency in throttling mode (recycle) at low flow, whereas electrical driver efficiency is nearly constant at varying power levels (Man turbo AG Schweiz, 2009).
- Surge control: By using the fast response time of the motor, and the surge valve in a coordinated way, it is possible to improve anti-surge performance and allow the compression systems to operate with lower recirculation flows with increase energy efficiency. This facility is not available in gas turbine due to slowness of response of mechanical drives (ABB, 2005).
- Electric drives have suitability of small and mid-scale LNG due to their standardized and modularized design, modularized liquefaction trains and other components of a the repeatable small or mid-scale LNG facility can speed the project schedule by up to 30% percent in comparison to custom-engineered solutions (. Chart Energy &Chemicals Group, 2013). This module and prefabrication concept also facilitates the various performance and load tests typically specified for such compression systems.
- Direct outdoor installation inside hazardous area, pluggable cables, fully climate controlled and pressurized to exclude the environment, multiple individual modules assembled on-site to form one building, safe working environment are some the other advantages (Kleiner et al 2005).
- With all electric compressor train size can be tailored for a specific requirement, lower centerlines significant in seismic active and cyclone regions can be constructed, complete elimination of housings for compressor and driver with no elaborate fire suppression system is required. Packaging and pre-testing reduces on-site construction (Siemens, 2005).
- Higher plant availability and operational flexibility with reduced maintenance costs and reduced peak maintenance labour are other advantages as LNG modules can run

for 6 years without interruption and offer a better return on investment (ROI) (Siemens, 2005).

However, before making a general statement, various project-dependent variables will have to be analyzed. A detailed Life Cycle Cost analysis has to be made for each project individually. Final decision for electric compression or for gas engine driven compression can only be made after considering all project related costs over the life time of the project. Stringent future emission regulations are the keywords in today’s changing gas storage and gas transport business. Electric compression is preferred to cope with these uncertainties. Power plant configuration and sizing is perhaps the most critical aspect of implementing an all-electric solution and a detailed study need to be done on the transient characteristics of the overall electrical system. It is important that in evaluating the overall availability, the electric supply system availability needs to be taken into account and built into the overall project economic evaluation (Meher-Homji, 2011). If the power is obtained from an external source the cost of electricity has to be factored in to the overall analysis. If the power is generated inside the facility a combined cycle power plant needs to be built which is more complicated, with a higher total installation cost and with greater attention to maintenance than a simple cycle power plant solution. However, it offers a much greater thermal efficiency which more than offsets all the negative features discussed above. With island type power generation sub synchronous torsional Interactions (SSTI) must be carefully analyzed. To summarize, power plant reliability and availability are very important to the success of an electrically driven LNG Plant. A thorough investigation of the power plant solution must be performed on a case-by-case basis, taking into account, capital cost, operating cost and the stability of the system to transient upsets (Meher-Homji, 2011). The constraints are that the largest motor reference in the LNG environment is 65MW and Siemens offer 90MW motor system at 3600 rpm (Siemens, 2005). With this size of motor a LNG Train of 8MTPA can be easily built. Even with the largest proven motor size of 65MW in the LNG environment a process train of 8MTPA can be built by dual circuit compression. It should be remembered that certain conditions need to be fulfilled before considering electric option.

Lower Initial Capital Expenditure (CAPEX): The industry is quite sensitive to CAPEX during the project stage (Devold et al, 2006). In this context the electric drives cost more initially than conventional gas turbine drives. If factored in at an early stage in a plant’s design, an All-Electric Drive system produces major savings every operating year. Hence Life cycle cost and not the Capital Expenditure should only be the metric of comparison.

Reliable power source: The reliability of the power system is a paramount factor in the design of the all-electric LNG. With competitive & reliable electric power available there is no doubt that an all-electric can provide a better return on investment in the entire life cycle. Proper stability study should also be carried out and mitigation incorporated.

Competitive power cost (OPEX): A thorough analysis of the electric price/gas price ratio has to be accounted for in the lifecycle evaluation. If electric power is to be generated at site, the decision of going with gas turbine or electric driven trains is generally driven by OPEX (fuel/electric costs). For a decision from CAPEX perspective, a decision on gas turbine or electric driven equipment is generally based on the availability of electric power on site, or the cost to bring the power to the site.

Large LNG production Train a possibility: Contrary to the belief that proven 65MW motor size date in the LNG process is not sufficient to produce a large train. Robert et al (2004) of Air Products chemical Inc. (APCI) have demonstrated that it is possible to produce 8-10MTPA production train with available capacity proven drives using AP-X™ LNG (Air products proprietary) Process. With the specific arrangement shown in Figure below depending on the desired capacity and the maximum motor size of 65MW considered proven by the LNG owner an 8MTPA train can be built.

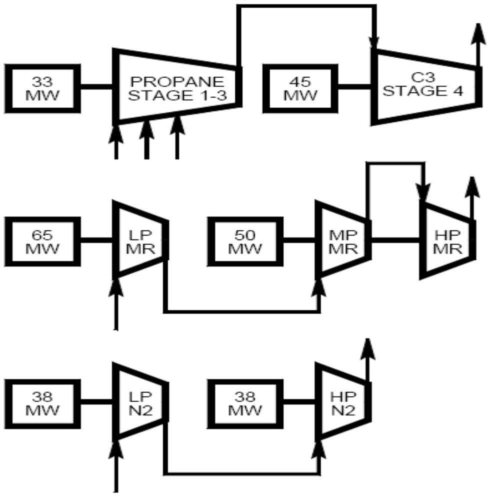


Figure 10.1: An 8MTPA train with 65MWmaximum motor size (Roberts et al, 2004)

All Electric economics promises to provide better Return on investment (ROI)through improved plant productivity (at least ten days of additional production per annum), higher plant availability and operational flexibility, reduced maintenance costs and should be the preferred solution for the major LNG project in future.

10.2 Other potential uses of All Electric concepts:

Wherever there is use of Gas turbine as a main driver for rotating equipment such as compressors and pumps VFD driven electrical motor can be a viable alternative driver. Some of the potential uses are in the following. The details are provided in Appendix H.

a) Offshore LNG plants/ Floating LNG
b) Mini LNG Plants
c) Stranded LNG:

d) Compressor stations LNG ships:
e) Gas-To-Liquid plants

10.3 **Further research:** Further research topics have been listed in order of priorities

a) Use of de-ionized water as coolant for the VFD and Transformer:

For large VFD drive air cooling is not sufficient hence de-ionized cooling is used. As ordinary water is a good conductor of electricity, de-ionized water, which is an insulator, is used in electrical circuit to cool the power electronics cells, the transformers and reactors used in the drive. To keep the electrical conductivity below a threshold the water is allowed to flow through de-ionized cartridges. These cartridges have to be replaced from time to time for which the VFD thread may need to be shut down. This regular changing of de-ionized cartridges leads to down time and spares. Further studies have to be done whether a centralized cooling can be carried out through a common cooling system so that frequent changing of cartridges can be avoided and threads do not have to be shut down for changing cartridges (Qatargas Maintenance documents, 2013).

b) Water leakages in de-ionized cooling circuit:

In addition, in VFD many instances of water leakage issues are faced by users of the VFD. This not only asks for increased maintenance but it also increases arc flash concerns with water dripping on the electrical equipment. Further research is required to use such material and construction to make sure that such leakages are avoided as much as possible.

c) Cell bypass to improve redundancy:

Cell bypass feature is provided in the VFD threads to improve redundancy so that in case of failure of a single cell it can be bypassed and the thread can continue to run. This feature improves the availability of the VFD. Due to unreliable bypass contactor leading to arc flash concerns this feature has been disabled in some VFD users leading to reduced availability. Further study needs to be carried out so as to make a robust cell bypass contactor design with improved quality and reliability so as to realize the redundancy fully thereby improving availability (Qatargas VFD commissioning documents, 2007).

d) Improvement in reliability of IGBT (Insulated Gate Bi-polar Transistor) cells:

Although IGBT cells used in the VFD design are designed for higher reliability they keep failing because of various reasons such as poor workmanship, poor material selection, design deficiencies etc. Further research is required to improve the reliability of the cells to win confidence of the investors.

e) Failure rates and mitigation in motors, transformers switchgear:

There are some cases of failures in transformers and motors used in VFDs, used for starter/helper applications, leading to extended outage. The factor such as electrical resonance, which is created by capacitance of long cable interacting with harmonic voltage, excites to create resonance over voltage phenomenon damaging insulation. Proper study has to be undertaken during the design stage to mitigate against this. Further the transformer and motor need to be made robust in design to withstand this phenomenon.

f) String testing:

String test, where the entire VFD-motor-compressor string is capacity tested to determine any deficiency, has limitations to be carried out in the factory due to requirement of large amount of electrical power, which the electrical grids in the manufacturer’s facility may not able to supply and hence the test have to be shifted to site. Further this test has to wait till the power generation and distribution system is substantially built and commissioned. This may delay finding of issues, which may further delay the risk mitigations and hence may delay the final completion schedule. Further studies have to be carried out as to how to validate the capability of the motor and compressor at the manufacturing facility. A back to back set up in which one of the machines acts as a generator and the other as a motor can be worked out so that power consumed by the motor can be generated back to the grid hence requiring a small amount of power from the grid to cater for the losses of both the machines. By this the VFD motor system can be load tested, however for a full string test to be carried out an extensive arrangement with adequate electrical power supply is required.

g) Further study on avoiding single point failure:

Single point failures can lead to outage of the VFDs. This can be because of lack of redundancy of electronic control circuits or electrical hardware. Proper study should be carried out to improve reliability and availability of circuit components so that a single failure does not lead to decrease in availability. Unless significant redundancy can be included availability may be affected.

h) Arc flash concerns:

Arc flash is a major concern in VFDs. Hence a proper study has to be conducted and proper counter measures have to be taken in terms of designing the system to withstand arc flash with increased safety provided to personnel and equipment. The exposed electrical conductors should be properly insulated and the switchgears have to be built to be arc flash resistant.

i) Further study on overall related technical issues:

One of the key issues to be addressed in the design and installation of a large island-configuration power plant is the stability of the power system and its ability to survive trip and upset conditions. Detail study has to be carried out during design to guard against such instability due to system disturbances.

j) Installation of major equipment:

Sometimes installation of the equipment is such that in case of failure of major electrical equipment like transformer and motor it is difficult and time consuming to replace the failed equipment. Study has to be carried out on how major equipment should be installed so that they can be easily removed and fixed back with least amount of downtime.

k) Outages due to inspection:

Shutdowns may not be solely limited to mechanical turbine as periodic inspection requirement for static equipment such as vessels; exchangers and piping etc. also dictate shutdown requirements. Any additional efficiency in this area is limited to available technology. Further studies have to be carried out to do more non-intrusive inspection so as to delay intervention of the process train for inspection purpose for which a shutdown is required.

l) Fuel gas and steam balance:

Gas turbine based LNG plant provides a way to balance fuel gas and Boil Off Gas used as fuel, to avoid flaring; on the contrary Electric LNG does not provide this facility and hence options need to be explored further as to how to balance the fuel gas and steam for the entire plant.

m) Further study on site specific factors:

Before taking a decision all site-specific factors should be closely studies and the overall effect on the life cycle of the plant should be thoroughly analyzed.

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Appendix: A

CAPEX (Capital Expenditure) Comparison between Gas Turbine and Electric

As far as the Capital expenditure goes, if there is direct comparison between a gas turbine and an electrical motor an electrical motor fares much better if the power is sources from across the fence. However the price of the purchased power has to be factored in to the life cycle cost equation. Only if a combined cycle power plant is installed inside the facility an electrical motor combined has a higher CAPEX than the gas turbine drive. There is another option of power from across the fence purchased from a utility company.

Comparison of	**Gas turbine**	**VFD**	**References**
CAPEX for compressor train			
Driver	Least	More	
Centrifugal compressor	0	0	Man turbo AG Schweiz, 2009
Gear/ Gear not needed	-1	2	
Bearing system	0	-2	
Lube/ Control/ Working oil system	-1	2	
Dry gas seal system	-1	2	
Capital spare parts	-1	1	
CAPEX for plant			
Building area height/ Hazardous area	-2	2	Man turbo AG Schweiz, 2009
VFD building area	2	-1	
Power supply installation (fuel gas piping)/ Electrical cable	1	-1	
Oil system air cooling	-1	2	
Equipment installation and commissioning	-2	2	
CAPEX for Building			
Foundation site civil work	-1	2	Man turbo AG Schweiz, 2009
Interconnect piping of Lube/ Control/ Working oil to air cooler	-1	2	
Noise mitigation	-2	1	
Interconnecting piping DGS	-1	2	
Crane capacity	-1	2	
CAPEX for Auxiliaries			
Intake filter system	-2	2	Man turbo AG Schweiz, 2009
Fire and gas detection system	-1	1	
Emission control	-1	2	
Harmonic filer (LCI only)	2	2	
Environment Related Cost			
VFD cooling system noise emission	2	-1	Man turbo AG Schweiz, 2009
Oil cooling system noise emission	-1	2	
Fulfillment of emission regulation	-2	2	
Emission credits	-2	1	
Permitting cost	-1	2	

Weighing of Train characteristic with each other in respect of capital investment cost (+2 Most beneficial, -2 Least beneficial)

Table A.1; CAPEX comparison between Gas Turbine and Electric Motor(Man turbo AG Schweiz, 2009).

Appendix: B

Additional Case Studies:

B.1: Case Study-A: (Rama, Giesecke, 2006)

Rama and Giesecke opine that the comparative simplicity of an induction rotor allowed lower cost solutions, solutions that made electric drives practical over a much wider range of sizes and speeds. With the evolution of induction motor drive technology, electric motor drive solutions were now available to meet the full range of mechanical system requirements for direct drive main gas compressor applications. Electric motors hold an economic advantage over mechanical drivers in several important respects.

a. Improved Efficiency:

The efficiency of a typical natural gas driver might be 30% or less. Total efficiency of the high speed electric drive system remains 4-5% greater than that of the typical mechanical drive alternative. The high-speed machine eliminates the approximately 2% losses from a gearbox that would be required with a conventional speed machine.

b. Ambient Temperature Impact:

Gas turbine and engine drive capacities vary inversely with air temperature. Electric motors are not impacted by ambient temperature variations and can operate at the same capacity in all ambient conditions.

c. Speed Control Accuracy and Range of Control:

The accuracy of electrical adjustable speed controllers far exceeds that of any of the mechanical alternatives.

d. Remote Control and Automation:

The reliability and accuracy of current-design medium voltage speed controllers can be an aid to optimize throughput and energy/cost conservation.

e. Annual Maintenance Costs:

Annual maintenance costs for electric motor-driven pipeline compressor stations have been proven to be substantially less than those at stations with turbine or engine drivers.

f. Initial Capital Cost and Installed Cost:

Initial cost of an electric motor driver and adjustable speed controller, is well below the cost of a turbine driver (approximately half of the system capital cost for power imported from outside.

g. **Strategic Fuel Source Options:**
If electric energy rates remain competitive with gas energy rates, the economics of electric drives become as superior to those of gas-powered options.

h. **Air Emissions:**

As such, the benefit of emission reductions of the electric-motor driven system is reason to consider this technology.

i. **Reduced Noise:**

Another form of emissions coming under more scrutiny is noise. The typical high-speed electric drive system is 7-10dB (A) quieter than any of the mechanical alternatives.

j. **Shorter Permitting Time:**

Limitations on emissions can make new installation licensing a burdensome exercise. Salable emissions credits may be available by adopting an electric motor system. Therefore, securing permitting for allowances is simply no longer an issue.

k. **System Reliability:**

Any combination of operating and maintenance costs, age, and environmental benefits can make the benefits of electrical motor become more attractive. Because of their many advantages, electric drives must be seriously evaluated for compressor applications. Electric drivers offer an opportunity for efficient use of natural resources, clean and quieter power conversion, improve process control, and very attractive life-cycle cost.

B.2: Case Study B - (Blaiklock, 2010)

Blaiklock (2010) of TMEIC GE opines that both turbines and motors have advantages and disadvantages for LNG plant use. When deciding on the best choice the main considerations are the amount (value) of LNG produced over the life of the plant and the initial capital expense. Although the capital expense may be higher with the motor solution, increased LNG production can create a more favorable return on investment. Medium-voltage electric motors have been used to drive pipeline compressors and pumps for years and their lifecycle costs are well known. With four banks of 25 MW Variable Frequency Drive (VFD) with a soft motor starting and variable speed operation option a capacity of 100MW can be achieved.

Driver type	**Major Overhaul period**	**Typical major outage**	**Minor Maintenance period**	**Typical minor Outage**	**Unscheduled downtime**	**MTTR Mean Time to Repair**
Gas Turbine Industrial	3-6 years	14-40 days	6 months	5 days	Several	Days

Gas Turbine Aero derivative	3 years	4-40 days	6 months	5 days	Several	Days
Electric Motor VFD and Transformer	10 years	1 day	5 years to replace fans	10 hours	Very few	2 hours

Table B. 1- Comparison of operation and maintenance features of drive solutions

Blaiklock (2010) lists the advantages of VFD run electric motor over a gas turbine:

- Higher reliability and shorter repair time, higher uptime (availability) and hence higher LNG production; higher overall efficiency, so operating costs are less. Also less NOx is generated and noise is minimized; The LNG production is not affected by rise in ambient temperature.
- Electric drives and motors can be delivered in a shorter time, reducing the overall construction schedule. VFD expected Mean Time Between Failures (MTBF) in excess of 20 years and a Mean Time To Repair (MTTR) of two hours if spare modules and equipment are available. Higher availability means increased LNG production and higher return on investment.

Driver type	**Power MW**	**Efficiency %**	**Relative CO2 emission**	**Speed RPM**	**Wight Kg**	**Availability**
Gas Turbine Frame 5	32.5	29.4% gas to shaft	1.0	4670	110,000	Average
Gas Turbine Frame 5	87.3	33.1 gas to shaft	0.93	3600	121,000	Average
Gas Turbine Frame 5	43.9	41.9 gas to shaft	0.71	3600	31,000	Better
Electric motor VFD with Transformer	25	95.3 electrical to shaft	Depends on source	3600	159,000	Best
Electric –Two motor VFD with Transformer	50	95.3 electrical to shaft	Depends on source	Up to 4200	286,000	Best

Table B.2- Comparison of compressor drivers (TMEIC-GE, 2005)

B.2.1: Conclusion:

Blaiklock (2010) states that as the LNG trade increases and becomes more than a small niche-market. Owners continue to look for ways to lower costs by benefiting from economies of scale. The effort has concentrated, as plant capacity grows, on building larger single LNG train plants. Large trains are feasible and cost-effective. To achieve the desired results, it requires innovation, "out of the box" thinking, technological rigor, and a "can-do" attitude. The electrical motors have the potential to provide a viable cost effective solution to LNG compression.

B.3: Case study-C: (Grapow, 2009)

Matthias Grapow (2009) in his presentation entitled “Why Electric Compression or otherwise why still Gas Engine driven Compression” in Gas/Electric Partnership Special Workshop Electric Compression Economics, August 27 2009, Houston discussed the pros and cons of the Electric gas compression in comparison to the conventional gas turbine driven compression.

B.3.1: Overall efficiency comparison: As per his calculation the overall thermal efficiency of All Electric system is at 44%, which significantly more than Gas turbine run compressor system which is 36%.

B.3.2: The study concluded that:

- The motor run system has considerably higher full load or part load cycle efficiency than a conventional gas turbine driven system.
- The motor driven system has immediate restart facility with no limit on number of start whereas a gas turbine system has to wait for two to three hours for restart due to driver thermal consideration and the limited re-starts per hour.
- The gas turbine has reduced power availability with increase in elevation, temperature and humidity whereas an electric motor driven has no such impact.
- The Train full load and part load cycle efficiency is considerable higher in Electric than gas turbine compression.
- The electric compression has variable speed range and ability to start and come to full load upon starting, whereas gas turbine assumes load one-half hour after start.
- The gas turbine seal gas need be vented or flared increasing CO_2 and NO_x emission which is much reduced in case of a motor driven system fed from a combined cycle power station.
- The maintenance cost is much lower and the unit availability and reliability is much higher as compared to a gas turbine driven system.
- If the electric motor is properly sized it can restart a pressurized system whereas the gas turbine system has to flare the inventory to be able to restart.
- Electric compression has the ability to trade carbon credit which and has the lowest risk of future emission restriction and has the lowest insurance risk.
- Over all life cycle cost the motor concept was by far the lower than the GT concept.
- Electric motor has excellent speed controllability due to high frequency operation.
- Electric motor has ease of remote operation, speed control range, starting reliability.
- The auxiliary consumptions of gas turbines are higher whereas the auxiliary consumption of electric motor is much lower.

B.3.3: Electric compression is of advantage when:

- A secure and economic source of electric power is available
- Capital investment should be as low as possible
- High humidity and ambient temperatures requires de-rating of the gas turbine
- The electric price/gas price ratio is reasonable
- Low-cost night-time energy available

- Environmental restrictions, gaseous and noise emission limits and architectural restrictions apply.
- Varying fuel gas qualities or limited transmission capacity in the pipeline exists
- High operating flexibility is required (starting frequency, frequent load cycles, and wide speed range)
- High starting and operating reliability/availability is required
- Low operation costs / unmanned operation is required
- LCC are mainly defined through OPEX

His research revealed that general statement cannot be made, because too many project dependent variables will influence the result. A detailed Life Cycle Cost analysis has to be made for each project individually. A decision from CAPEX perspective for fuel or electric driven equipment is generally based on the availability of electric power on site or the cost to bring the power to site. If electric power is available at site, the decision going with fuel/electric driven trains is generally OPEX driven (fuel/electric costs). Final decision for electric compression or for gas engine driven compression can only made after considering all project related costs over the life time of the project. He further opined that flexibility and unknown upcoming future emission regulations are the keywords in today’s changing gas storage and gas transportation business.

B.4: Case Study D: (Sawchuk et al 2003):

Sawchuk (2003)of British Petroleum and Charles (2003) of Kellogg Brown and Root undertook a program by close collaboration between the owners, contractors and process licensors for a fair and unbiased comparison of the technologies that evaluated key aspects of design and engineering of a Base load LNG Liquefaction plant through the Big Green Train Project. The study results provided a high level of confidence that “Next Generation” LNG plant designs is achievable with raised standards on design, capacity, and life-cycle cost and greenhouse gas emissions.

B.4.1: Study Objective:

The objective was to develop next generation LNG plant options that are Big, Green and Low Cost to produce 5+ MTPA of LNG and with an intention to reduce the EPC cost by 25% and reduce CO_2 emissions by 50% in comparison to a conventional LNG Train target (Atlantic LNG Train-1) per ton of LNG produced. In 2002, BP and KBR completed the Select Stage engineering of the Big Green Train (BGT) project. As part of the Select Stage work scope, an LNG process technology benchmarking effort was undertaken to compare available LNG processes. The approach to the Big Green Train benchmarking effort began with developing a process basis of design, which was based on the All-Electric LNG plant design. This basis of design ensured that the plant designs by the various process licensors were comparable without design restrictions. The All-Electric plant design was based on a power island that consisted of three Frame 7FA Dry Low NOx (DLN) gas turbine generators. Each was equipped with a two pressure level heat recovery steam generator (HRSG) to utilize the hot exhaust gas. One Frame 7FA and its HRSG were considered a spare to provide an N+1 sparing philosophy. This allowed for higher plant availability than gas turbine driven LNG plants. One of the objectives was to evaluate a large range of refrigeration driver-compressor options in various LNG plant designs and then ranked them based on parameters including life cycle costs, capital cost per ton of LNG, energy efficiency, plant availability and CO_2 emissions. Three key project objectives were established for the Select Stage of the BGT Project. The priorities used to evaluate the LNG process technologies included life-cycle economics, specific power, capital cost (CAPEX) per annual ton of LNG production, CO_2 ton per ton of LNG production, modular plant design for ease of expansions, overall plant availability, and plant efficiency (defined as energy content of the total products divided by the energy content of the plant feed stream).

B.4.2: Conclusion:

The benchmarking study showed that all of the Licensors can provide Big (large capacity) LNG plants with All-Electric LNG plant design. The results of the CO_2 emissions metrics for the Big Green Train (BGT) benchmarking designs showed that all of the LNG process technologies evaluated generated world-class emission levels. With some optimization, the emission levels of all the LNG process technologies are expected to equalize at or above the 50 percent CO_2 reduction. The All-Electric LNG plant designs developed during the benchmarking effort yielded energy efficiencies that are far superior to the existing LNG plant designs. The benchmarking results for capital cost reduction generated for the different LNG process technologies show that all of the designs would set new cost benchmarks in the industry. Nearly all meet the cost reduction metric of twenty-five percent in EPC Cost per annual tonne of LNG with possible further reduction in cost through additional optimization. Consequently, all of the plant designs are expected to meet or exceed the twenty-five percent cost reduction versus the target Atlantic LNG Train-1. The conclusion was that

- Big, Green LNG plants can provide low cost LNG
- Plant capacities above 8 MTPA are economically feasible
- Big Green Train (BGT) plant designs are LNG process independent

B.5: Case Study-E: (Thomas et al, 2009)

Thomas and Chrétien et al of TOTAL conducted a study in 2009 to the various LNG options. Plant owners have historically preferred robust and dependable facilities rather than a very efficient process with more stringent operating constraints. In today’s environment, improving energy efficiency of LNG Plants is a major focus for Operators. Main factors contributing to this shift toward enhancing efficiency are:

- Higher price of feed gas/sales gas.
- Reduction of feed gas supply in some LNG Plants.
- Worldwide pressure to reduce the GHG footprint of industrial facilities.
- Actual or potential CO2 taxes.

The study reviewed various options to increase the energy efficiency for a brand new plant for a given liquefaction process. The various options scrutinized are listed below:

- Heat recovery options (combined cycle and others).
- Large Frame or aero-derivative driver for refrigerant compressors or power generator.
- Electric drivers for refrigerant compressors or E -LNG.
- Heat absorption systems / chilled water loop duty
- Cooling of Gas turbine Air inlet
- Combination of the above.

Expected efficiency enhancement was evaluated and a 30 % improvement compared to robust and simple LNG facilities could be achieved. For existing facilities some practical energy efficiency improvement could be implemented as well. There are a great number of possible options to improve the energy efficiency.

B.5.1: Study Cases for a new plant:

The comparative study is based on a well-knownC3MR APCI process with upstream NGL recovery. To simplify the comparison, the study is only based on the liquefaction process downstream the NGL recovery. Three cases with different production levels and different main refrigeration drivers have been defined as follows:

- Two FRAME 7 with 20 MW helper/booster each for one train; required power is supplied by FRAME 6's
- Two FRAME 9 with 23 MW starter each for one train ; required power is supplied by FRAME 6's
- E-LNG : Electric motors on main refrigeration drivers associated to a power plant base

The duty of the chilled water closed loop produced by the absorption chiller units encompasses:

- Gas turbine air inlet cooling
- Sub-cooling Propane refrigerant
- Pre-cooling the feed gas and the MR refrigerant instead of propane cooling service
- All utilities requirement (power, heat and cooling media) have been estimated for all cases. As a result, for a base case without heat recovery the specific energy consumption of the various cases with heat recovery schemes is given in the following. For E-LNG case, the combined cycle option is not considered as the heat is recovered to meet process duty only. Additionally, absorption chillers can boost the production potential of LNG trains when compared with combined cycle. This production improvement partly comes from the improvement of specific energy, partly from enhanced available power (cooler air feeding the gas turbine).

Taking into account the simplistic hypothesis of the study, the following conclusions was drawn:

- The absorption chillers compared well with Combined cycle in terms of energy efficiency and can be used in conjunction with Combined Cycle
- There is a good match in terms of heat level between heat recovered at the exhaust of aero derivative gas turbine and the heat requirement of absorption chillers.
- The efficiency of the liquefaction part of the process can be improved by some 30% when combining E LNG with aero-derivative gas turbine and absorption chillers when compared to a base case without heat integration. However given the limited size of current available aero derivative gas turbine, the required number of generators can be high for large LNG Plants
- In all cases, use of absorption chillers increases the potential capacity of the liquefaction process for a given refrigeration power duty.

B.5.2: Conclusion:

Thermal efficiency improvement for LNG plants is an ongoing trend with more new grass-root projects featuring various degrees of heat integration towards a long term quest up to the zero CO_2 LNG facility. Future projects could make use of absorption chillers as part of heat integration systems. Energy efficiency improvement with combined cycle or heat driven absorption chillers can be considered. Most favorable case being E-LNG based on aero-derivatives gas turbines associated to heat driven absorption chillers in tropical area. Absorption chillers require only low pressure steam and are less complex than combined cycle powered by high pressure steam. Enhancing the energy efficiency of existing LNG facilities is also a robust business case when associated with additional potential production to pay for the modification project. However practical improvement of the thermal efficiency is depending on original design features of the facility such as lay-out or choice of refrigeration drivers. Absorption cooling can be implemented in Gas turbine air inlet cooling, Sub-cooling Propane refrigerant and Pre-cooling the feed gas and the MR refrigerant instead of propane cooling service to improve overall thermal efficiency.

B.6 Case study- F:

Sonangol/Texaco engaged Foster Wheeler as part of the CFAST consortium (comprising Chiyoda, Foster Wheeler, ABB and Stolt consortium) investigated the use of large electrical motors to replace the gas turbines and to use a central power station to supply the power to the complete facility for the Angola LNG Project and investigated the use of large electrical motors to drive the refrigeration (liquefaction) compressors for the onshore LNG plant. The onshore LNG plant was a single train of about 4 MTPA with the potential for future expansion to as many as four trains. The objectives of the study were to assess the technical risks associated with the use of large electrical motors in a base load LNG facility and to quantify the life cycle benefits on the basis of such an application (Shu et al, 2002).

B.6.1 Life Cycle Cost Analysis:

Any commercial benefits were evaluated on their impact on project net present value or life cycle benefit. Because of the need for a larger power plant, the capital cost for an Electrical solution was likely to escalate, so the commercial benefits relied upon increased revenue streams to balance the higher CAPEX. The Life Cycle Benefits were dominated by these four factors:

a) Capital cost b) Plant availability c) Project schedule d) Plant production

The marginal value was the value achieved net of all costs (other than the variable production costs) generated by marginal production. Thus, it was assumed that any additional LNG produced can be delivered to market and sold, to generate a marginal profit of $149/tonne (equivalent to $3/MMBTU).

B.6.2 Impact on Production Efficiency

The production impact of moving to electrical motors is achieved through higher thermal efficiency of the plant. Centralized power generation involves larger and more efficient gas turbines; which make heat recovery and combined cycle power generation economic. Balanced against this increased efficiency are the electrical transmission and drive losses. The first of these increases thermal efficiency by the combined cycle power plant option of about 12%: the second is the transmission and drive loses about 4% of the benefits gained. The result is an overall increase in efficiency of 8% which translates to an additional 0.5% increase in LNG production.

B.6.3 Impact on Plant Availability:

Increased production availability results from two sources:

a) Better sparing or spinning reserve is possible on a centralized basis than on a localized basis. The meaning of the above statement is rather than using localized gas turbines in the conventional case a better sparing and spinning reserve is possible when gas turbine are centralized at the combined cycle power generation station with heat recovery option where the sizes of each unit can be optimized, so a highly reliable power supply service can be provided economically.
b) The scheduled maintenance needs for electrical motors are much lower than for gas turbines. The increased sparing allows the scheduled maintenance to be carried out without production impact.

The table below summarizes Typical Component Availabilities:

Equipment	Average Reliability	Schedule maintenance (hrs./yr.)
Centrifugal compressors	0.998	50
Gas Turbine	0.994	270
Steam Turbine	0.994	45
Electrical motors	0.997	25

Table B.3: Equipment reliability and maintenance

The scheduled maintenance downtime for gas turbines is five times greater than the next most demanding component which is the centrifugal compressor. When all of these factors are considered, production availability is increased by 2.9 %, which equates to a life cycle benefit of nearly $210m.

B.6.4 Impact on Project schedule and other key factors:

It is also expected that up to two months would be saved in the assembly of motors and compressors versus turbines and compressors. Switching to motors impact on overall project schedule is to take the gas turbines off the project critical path and transfer the critical path elsewhere, probably onto the LNG storage tanks or the construction of the a larger power plant. As important, it helps to reduce schedule risk by elimination of a schedule-driving event. On the base project used for this study, the EPC phase of the project is reduced by 2 months resulting in a life cycle cost benefit of approximately $125m.

B.6.5 Capital Cost Impact:

The table below shows the impact on the capital cost of the change. The capital cost for the electric motor option increases, in this case by about 5%. The major ‘adder’ is the cost of the power station, whose capacity has risen from 55 MW to 380 MW. The table below shows the additional Capital cost of $60M for opting for an electrical motor solution.

Adders	$M
340MW centralized power generation	153
Centralized waste heat recovery	25
Electrical motor + drivers	18
Electrical infrastructure	39
Total adder	235
Deducts	
Four Frame 5 GTs	45
Three Framed 7 GTs	81
Localized Waste heat recovery Units	28
Steam turbine	7
Electrical infrastructure	14
Total deducts	175
Net increment	60
Revised option total installed cost	

Table B.4 Capital cost calculation

B.6.6 Life Cycle Cost Benefits:

The life cycle benefit of approximately $300 m was achieved as shown in the figure below. It is readily apparent that the benefits are dominated by the higher availability and by the shorter EPC schedule. If either of these can be achieved, then the benefits are still positive as either of them outweighs the higher capital cost. Economic benefits could be improved further: The range of gas turbines available for power generation is large. The capital cost estimate could be improved through optimization and competitive bidding.

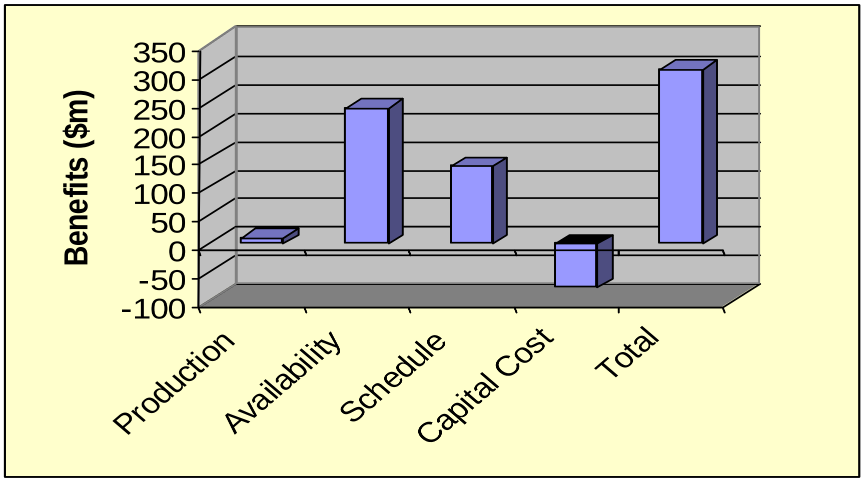

Figure B.1: Life cycle benefit (Shu et al 2002)

B.6.7 Conclusion of Study-4:

The study was conclusive in its findings that the technical risks associated with the use of large electrical motors are well known and would be manageable as part of the detailed design of the project and the life cycle benefits are potentially significant, making this a very real option to be considered for the Angola LNG Project. The study believes that there was much relevant experience within other industries such that the application of electrical motors on base load LNG technology would be but a small extension of existing experience. However large the commercial benefits are, if the technical risks are too high then the electric motor option would not be selected. The use of electrical motors was not without risk, which of course was the case with anything being done for the first time. The risks were well understood, and can be managed as part of a project’s development and execution. There were strong reasons to consider the use of electrical motors on base load facilities too. There are potentially large commercial benefits to be reaped in the areas of plant availability and project schedule. Whether these can be realized on a given project depend upon four key factors (Shu et al, 2002):

- The marginal value of production.
- Realization of the availability benefits in the refrigeration circuit across the whole project value chain.
- Realization of the schedule benefits by ‘managing’ the other items competing for the project critical path.
- Management of this technical development in the context of a large base load LNG project.

Appendix: C
Characteristics of various LNG Contracts

C.1 EPC Contract characteristics:

DLA Piper (2011) suggests the following features for an EPC contract:

a) **A single point of responsibility:** The contractor is responsible for design, engineering, procurement, construction, testing activities and problem fixing.

b) **Advantageous for owner** as he can have a "hands off" approach with a minimal staffing requirement as the bulk of the responsibility lies with the contractors.

c) **A fixed contract price:** Since the price is determined upfront the risk of cost overruns and the benefit of any cost savings are to the contractor's account.

d) **A fixed completion date:** EPC contracts include a guaranteed completion date with a liability for Delay Liquidated Damages ("DLDs") for late completion.

e) **Performance guarantees:** It contains Performance Liquidated Damages ("PLDs") if the contractor fails to meet the performance criteria.

f) **Caps on liability:** Contractor's liability may be limited such as DLDs and PLDs might each be capped at 20% with an overall cap of 30% of the contract price.

g) **Consequential damage:** No claiming of consequential damages with exceptions to fraud, willful misconduct, minimum performance guarantees and breach of the intellectual property.

h) **Security:** The contractor provides performance security to protect the project company if the contractor does not comply with its obligations under the contract.

i) **A parent company guarantee:** This is a guarantee from the ultimate parent of the contractor which provides that it will perform the contractor's obligations if, for some reason, the contractor does not perform.

j) **Variations:** The project company can order variations and agree to variations suggested by the contractor with pricing provided in the contract, referred as change orders (Greer, 2006).

k) **Defects liability/Warranty:** The contractor is usually obliged to repair defects that occur in the 12 to 24 months following completion of the performance testing.

l) **Intellectual property:** The contractor has rights to all the intellectual property used in the execution of the works and indemnifies the owner if any third parties' intellectual property rights are infringed.

m) **Force majeure:** The parties are excused from performing their obligations if a force majeure event occurs.

n) **Suspension:** The project company usually has the right to suspend the works.

o) **Termination:** The contractor's termination rights are the right to terminate for non-payment, prolonged suspension or force majeure. Owner's right includes the ability to terminate for certain major breaches or if the contractor becomes insolvent.

C.1.1 The disadvantages of EPC contract:

a) Contractor should have sufficient knowledge and expertise to execute the works.

b) Given the significant monetary value and the adverse consequences of failure, the lowest price should not be the only factor used when selecting contractors.

c) EPC contract can result in a higher contract price for allocating all construction risk to the contractor for building contingencies for events that are unforeseeable.

d) In an area with unknown geology or lack of time to undertake a proper geotechnical survey, the contract may ask for the contingency in return for passing on the risk to the contractor.
e) The scarcity of contractors willing to enter into EPC contracts can also result in relatively high contract prices. This limited number of experienced suppliers, along with the understandable reluctance of the LNG industry to try new things, has probably contributed to the price increases (Jamieson, 1998).
f) In return for receiving a guaranteed price and a guaranteed completion date, the project company gives away most control over to the contractor and has limited ability to intervene. Interference by the owner helps contractors claim additional time and costs and defeats claims for liquidated damages and defective works.

C.2 EPCM Contract features: (Prodigy 2006):

This form of contract requires a combination of management skills on both the part of the Owner and Contractor together with a well-structured contract that is designed to meet the changing needs of a major Project.

a) Under right circumstances the EPCM is the 'best' contract, from the Owner's perspective, in terms of quality, achievement of schedule objectives, lower cost, owner Staff's Sense of Ownership and control over process. It is for this reason that the 'majors' have moved towards this form of contracting and rarely use the EPC (Lump Sum Turn Key) form of contracting in the western world (Agnitsh et al, 2001).
b) Incentives to Contractor for the achievement of Project objectives may include milestone payments for the achievement of key schedule objectives, and cost incentives with contractor sharing in cost under run/overrun's.
c) It has a well-defined basic engineering package.
d) It is services reimbursable. It ensures that the project is well funded and vendors, Sub-Contractors and the EPCM are paid promptly and owner has financing flexibility.
e) Eliminates commercial restraints for utilizing additional resources (man-hours and expenses) in the interests of the Project. It is preferred for less defined projects with anticipated changes to scope of supply.
f) Recovery plans can be deployed without any much negotiation on price and schedule impact.
g) Owner can get involved in equipment selection, commercial negotiation with major vendors and sub-contractors and alliance arrangements can be easily implemented.
h) The basic misunderstanding of EPCM is the perception that the risk remains with the contractor as in EPC. There **is** less possibility of legal litigations.
i) All review and approval processes for scope, engineering, design, procurement and contractual issues are primarily the obligation of the Owner; hence the overall risk of meeting or not meeting the project objectives of time, cost, quality and safety lies substantially with the Owner.
j) Failure to recognize and properly manage the shift in risk can impede the progress of the project, and can in fact negate the advantages of the EPCM strategy.

Appendix: D

Testing requirement of Gas turbine

D.1 FACTORY TESTING OF GAS TURBINE:

Testing and validation process of gas turbine is quite extensive. It involves testing at the manufacturing plant as well as through construction, commissioning and start up process. Factory testing of gas turbine has been described below:

a) **Speed studies:**

Components are assessed to verify life expectancy over the entire speed range from 95% 105% speed) was extensively tested. Operating ambient temperature from 4^0C to 49^0C with 5 to 30 starts per year are incorporated into the speed studies and the effect of speed assessed (Salisbury et al, 2007).The gas turbine components are subject to a number of failure mechanisms such as low cycle fatigue (LCF), crack initiation, cycling crack propagation, disc burst and creep etc. During the design, construction and testing stages all of the above failure modes need to be evaluated at baseline conditions and between the speed ranges it is required to operate. In Qatargas 2, a finite element analysis (FEA) model was developed based on parameters that defined the thermodynamic behavior of the unit such as power output, pressure ratio, mass flow, speed ramps, etc. The FEA model was then used to calculate transient temperature distribution, aero mechanical loads, inertia loads, etc. After completing the structural analysis, low cycle fatigue (LCF), and creep life was evaluated against the design requirements (Salisbury et al, 2007). Further study evaluated the Frame 9E compressor airfoil rotor and stator blades ability to operate in the 95% to 105% speed range. An FEA analysis was also performed on all rotor and stator blades with the appropriate constraints and loads. The rotor and stator blades were also analyzed at zero speed with no pressure and temperature load and then validated that the stresses were within allowable limits (Salisbury 2007). If Variable Frequency Drives (VFDs) are used for starter/helper/ generator applications the torque ripple effect contributions from the VFDs to the compressor blades need to be assessed. Hot gas path components need to be analyzed for aeromechanical (modal) creep and low cycle fatigue (LCF) capability. Creep resistance of the rotor is evaluated against the operating hours of the gas turbines. Other than the above the turbine rotor margin to operate at maximum design temperature at continuous speed and also the effect of variable speed at highest operating speed and maximum ambient temperatures are analyzed to identify and quantify Low cycle fatigue (LCF) rotor components life(Salisbury et al, 2007).

b) **Fuel and emission studies/ Dry Low NOx (DLN) Testing:**

The gas turbines need to be installed with Dry Low NOx (DLN) combustion system for emission abatement. The DLN technology adopted for gas turbines needs to accommodate the inherently large range of fuel gas compositions created within the

LNG process, as well as the rate of change in conditions associated with plant equipment upsets. In a normal application this system is capable of 25 ppm (parts per million) of NOx and requires a variation of no more than +/- 5% from a given Wobbe Index (WI), which is a measure of the energy density of the fuel, target value for the fuel gas. WI is the ratio between the fuel lower heating value (LHV) and the square root of specific gravity multiplied by fuel temperature. The fuel gas may have a WI variation as high as +/- 26%. The WI range and rate of change is limited to ensure adequate pressure ratios across the fuel nozzles. If the pressure ratio is too low, then the combustion dynamics amplitudes can increase to unacceptable levels leading to shortened operating life and poor reliability. Combustion testing is performed to verify the combustion hardware is capable of handling fuel gases ranging from 4% up to 48% N2 (Salisbury 2007). Higher flame temperatures yield higher NOx emissions, but yield lower CO emissions. This increases the margin from the blow-out region, achieving a more robust design with a wider operating envelope. Different dilution holes needs to be tested for best trade-off between emissions and combustion stability over the operating range. Critical testing needs to be performed with test parameters such as air inlet temperature, inlet pressure, fuel composition and air-flow and/or exit temperature to change combustion boundary conditions and set points (Salisbury 2007).NOx emissions reduce as the N2/CH4 ratio in the fuel gas increases. While this effect is beneficial for reducing emissions, it can have a negative impact on the reliability of the combustion system. Extremely low NOx emission values for this combustion system can indicate a very weak flame, which in turn could lead to a combustion blow-out or high combustion dynamics. To compensate for the high N2 fuel content, the dilution area of the liners has to be increased to achieve a robust flame overall operating conditions (Salisbury, 2007). The majority of the normal operating fuel gas is derived from nitrogen rich (~ 35 – 42%) End Flash Gas (EFG), a by-product of LNG production, which is not available until the plant is online. The only fuel gas available prior to LNG production is the start-up and back-up fuel gas derived from the plant feed gas, Fuel From Feed (FFF), which has very low nitrogen content (~ 2 - 4%). The variation in nitrogen content of these fuels results in a large variation in the fuel gas Wobbe Index, which is the primary parameter that defines the similarity of different fuels (Judd et al 2007).The unplanned downtime risks associated with implementing the new emissions reduction technology on these challenging applications mitigated through a number of activities during the execution of the project (Salisbury et al, 2007).

a) **Laboratory Combustion Tests.** Combustion tests sized and then validated the recommended nozzle and dilution holes using actual site hardware and expected gas compositions, validated the design and highlighted potential operating modes where final control system tuning might be required to avoid operability/reliability risks (Salisbury et al, 2007).
b) **Combustion Control Logic Re-design.** A gas turbine control logic, which was earlier designed for a power plant, has to be changed to suit compressor application. The redesigned logic incorporates a) modified light-off sequence for reliable start-up with variable fuel gas b) String acceleration sequence with coordinated control of turbine c) New control logic for the DLN combustion modes during steady state and transient conditions: process upsets; start-up; shutdown d) Improved exhaust temperature control logic increasing control accuracy of combustion parameters

while improving overall gas turbine performance e) Software to calculate remaining gas turbine power available to base load considering turbine degradation and a wide range of fuel gas compositions(Judd et al 2007).

c) **String Testing.** The prototype string testing program provided initial validation of the new control logic while also validating the new combustion hardware performance in an operating gas turbine (Judd et al 2007).

c) **Turning gear Function test:** Either a VFD or other standard accessories such as a DC or AC the strings turning gear functions such as the breakaway torque, slow roll turning, purge, starting, and water wash and cool down. A dedicated emergency power circuit has to be incorporated into the VFD design to permit turning gear operation in the event of a plant blackout. The functionalities of the above needs to be extensively tested during the testing phases to validate their functionalities (Salisbury et al, 2007).

d) **Common lube oil testing:** The standard generator drive gas turbine utilizes an accessory base arrangement, incorporating the string lube system, the drive for the main oil pump and other functions such as turning gear, starting and cool down. A common oil system needs to be tested for its proper functionalities (Salisbury et al, 2007).

D) **String test:** The string tests are conducted to replicate as much as possible the plant site configuration so as to test the complete string to detect any defects and rectify before being shipped to site. A large portion of the string testing is also dedicated to the final validation of the VFDs system and its integration with the main equipment as well as with the power supply grid. Shaft torque ripple, a well-known weak point of variable frequencies systems, and the amount of harmonic disturbances injected by the system into the surrounding electrical grid also are closely monitored during the string tests. Results need to validate acceptable torque ripple within the design basis, so as to avoid external torque ripple suppression. The gas turbine, compressors, motor/generator and associated VFDs also including the subcomponents such as inlet air filtration system, inlet Bleed Heating, oil system and the DGS system need to be used. (Salisbury et al 2007).

D.2 SITE COMMISSIONING AND VALIDATION OF GAS TURBINE:

For safely starting the machinery on schedule and minimizing future unplanned shutdowns a detailed commissioning program scope and execution plans have to be developed and executed. It may need a Failure Mode Effect Analysis (FMEA) review for commissioning test protocols to validate applied technologies and reveal any new issues so that could be addressed prior to start of production. A rigorous validation and prerequisite steps has to be incorporated to confirm closure of FMEA prior to starting each test run activity. A static commissioning, is normally executed which involves energizing equipment and validating correct functionality of the many individual subsystems involved. It includes the instrument loop checks, switch gear function tests, motor solo-runs and cause and effect testing to ensure safe operation. The second phase of commissioning starts when process fluids are introduced, activities become more complex and involved in working to rigorous step by step procedures. Figure below depicts the relative schedule of key activities in both the Static and Dynamic Commissioning phases (Judd 2008).

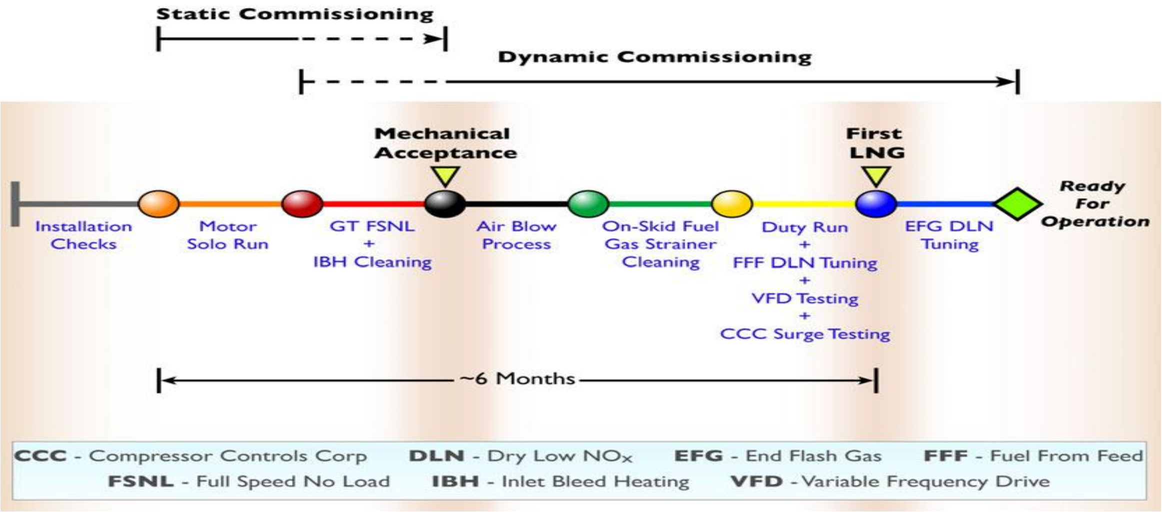

Figure D.1: Commissioning Program Schedule for Gas turbine driven compressor string (Judd, 2008)

Inlet Bleed Heating Cleaning:

One prerequisite step involved confirmation of the cleanliness of the Inlet Bleed Heating (IBH) system prior to commencing the gas turbine full speed no-load (FSNL) test to prevent IBH control valve damage because of construction debris. The potential risk of construction debris leading to potential damage of compressor anti-surge valve seats and other sensitive equipment is present. To address this risk dynamic air blows to validate line cleanliness is adopted as a commissioning strategy (Judd, 2008).

Frame 9E Dry Low NOx (DLN) Combustion Validation Tests:

The gas turbine DLN system needed to be fully validated to be operated using the final plant fuel gas system and the starter/motor/generator/VFD needed to be proved reliable when integrated into the total power system of each of the plants (Judd, 2008).

Fuel Gas System Design Optimization:

The established test results for maximum allowable Wobbe Index rate of change from manufacturing tests has to be utilized. The size of the fuel gas mixing drum and the final fuel gas system control strategy are critical in preventing flame-out as the fuel changed from End Flash Gas (EFG) to Fuel From Feed (FFF) and vice versa. The Dynamic simulations of the fuel systems need to be run to ensure that all operating scenarios were covered. The highest risk scenario is to check whether the gas turbine behaviour following a trip of the fuel gas compressor which would result in a sudden stop of the EFG fuel gas supply as can be seen in Figure below (Judd, 2008).

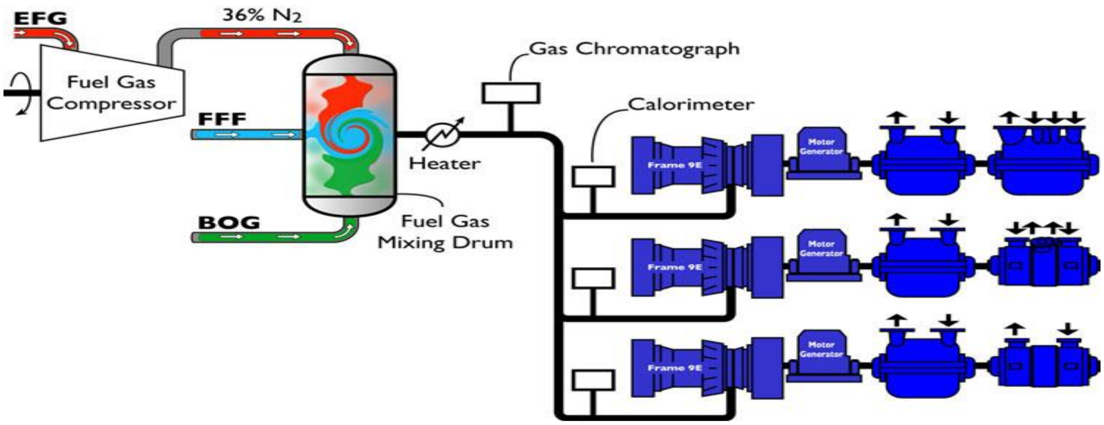

Figure D.2: Fuel supply to Gas turbines

Adequate cleaning of the fuel gas supply lines is a prerequisite for reliable operation of the gas turbine since the fuel nozzles have relatively small holes that may clog or prematurely wear if debris is carried into the combustor. During commissioning, temporary strainers have to be fitted immediately before the fuel gas manifolds on the gas turbine to be only removed once the supply lines had been proven to meet the cleanliness criteria of the manufacturer. Since EFG is not available until after start-up the temporary strainer cleaning usually takes place after first LNG production resulting in start-up and shutdown cycles to complete the cleanliness inspections (Judd, 2008).

DLN testing:

The first of these final tests are the DLN tuning runs in premix mode on Fuel From Feed gas with nitrogen in the nitrogen loop and methane in the C3 / MR loops. DLN testing program is required to achieve (Judd, 2008):

- Emissions performance targets is met under operating conditions
- To prove combustion dynamics within expected range
- LNG production is not significantly impacted during DLN test program
- No significant production losses associated with verifying system cleanliness

Gas turbine Start up and operation:

The comprehensive operational and technology validation tests completed within the dynamic commissioning program prior to start-up, ensures that all major reliability risks were addressed prior to the introduction of feed gas into the LNG trains (Steve Judd 2009). The remaining validation steps happen once the refrigeration compressor strings were put into operation and LNG production commences. One key operability feature validated after reaching normal operating conditions was the ability to complete a rapid pressurized restart following a trip of any of the machinery strings. The final settle-out-pressure of each refrigeration loop and the compressor anti-surge control supplied by Compressor control vendor settings utilized at start-up were two critical factors (Judd, 2008).

Appendix: E

Life Cycle Management Challenges

E.1 Procurement and Logistics Challenges:

The procurement activities include information and tracking of requisitions and purchase orders and materials delivered relative to plan, with particular emphasis on the long lead or technically complex items requiring special attention. This further includes status of expediting, inspection, testing, and material transportation. Terms and conditions for procurement of materials and services such as purchase orders, bid inquiries, evaluation summaries, should be reviewed; and monitored and in compliance with Safety Health, Environmental, Security, quality, technical, and schedule objectives should be ensured (Qatargas 2 project documents, 2005).

E.1.1 Purchasing plan:

A Purchasing Plan, procedures, and vendor qualification process for the acquisition of materials for the work need to be prepared. Spare parts and aftermarket services technical assistance during commissioning and start up, long-term maintenance or service agreements, parts pricing and availability agreements with vendors and sub-vendors aligned with project milestones is also a part of the overall effort.(Qatargas 2 project documents, 2005).

E.1.2 Critical items procurement list:

This list should include items that are considers to be of prime importance to the successful and timely execution of the project.

E.1.3 Qualification of Vendors, sub Vendors and Subcontractors:

Qualification of vendors, sub-vendors and subcontractors by undergoing a stringent approval process has to be undertaken based on their ability to supply the material or service required in conformance with specifications and schedule. Their ability to consistently meet the delivery schedule, demonstrated technical competence and quality assurance of products and services is important (Qatargas 2 project documents, 2005).

E.1.4 Inspection:

The purchase order terms should make vendors responsible for providing materials that comply with specification and are capable of performing the function for which they were intended. The inspection requirements for materials being ordered should contain the Inspection and Test Plan and criticality assessment required for Quality Assurance (Qatargas 2 project documents, 2005).

E.1.5 Spare Parts / Operating Supplies/Supplier startup services:

Capital spares and special tools are part of purchase order of major individual items or sub-assemblies of equipment such as compressor rotor, special valves, etc. to be designed and fabricated by equipment vendors required for installation, on-site repair, or dismantling/maintenance purposes and should be part of the equipment package delivery. Construction Spare Parts and Commissioning Spares should be procured in time so as to support these activities. Commissioning and start-up supplier services need to be requested in advance (Qatargas 2 project documents, 2005).

E.1.6 Receiving:

It is the process of checking incoming shipments to ensure that the materials comply with the purchase order requirements and ensure the ‘Bill of Materials’ are available when incoming materials are received. Implementation of Positive Material Identification (PMI) is implemented to ensure that the materials received are of the correct (Qatargas 2 project documents, 2005).

E.1.7 Expediting:

The expediting strategy include preparing, maintaining, and implementing procedures covering all aspects of expediting from placement of the purchase order through receipt of materials, including receipt of spare parts, operating and maintenance manuals, and “as-built drawings”(Qatargas 2 project documents, 2005).

E.1.8 Logistics:

It involves freight movements, material received in ports, congested schedule, against limited capacity of the airport and sea ports, shortage of container storage capacity.

E.1.9 Warehousing:

Warehousing should ensure that the materials are kept in a secure area, that there is no mix up and that access to inventory is properly controlled and identified, protection of equipment from rain, heat, humidity, ultraviolet rays, sand, etc. maintenance procedures that comply with manufacturer’s warranty requirements; preservation measures according to extent of storage period, temperature, storage conditions, manufacturer’s recommendations (Qatargas 2 project documents, 2005).

E.1.10 Procurement challenges for All Electric LNG:

The procurement activities include information and tracking of requisitions and purchase orders and materials delivered relative to plan, with particular emphasis on the long lead or technically complex items requiring special attention. This further include status of expediting, inspection, testing, and material transportation; significant accomplishments during the periods of review and the major activities planned for the future highlighting any problem areas and corrective actions and a separate equipment and material commitments to-date versus plan. The procurement and logistic activities of an All LNG project will be more or less the same as the conventional LNG project.

E.2 Quality Challenges:

Basic quality requirements for projects are defined by the International Standard such as ISO 9001 in accordance with international best practices; need to have a documented Quality Management System in place to assure the quality of the work. It is essential to establish implements and maintain a quality program, which ensures that its requirements are communicated to all employees, vendors and contractors. In order to implement quality policy, one should ensure that quality is built into the work through the use of documented control processes. Quality organization is established to effectively administer and implement the quality policy. All necessary procedures, guidelines and work instructions need to be prepared to provide the framework for a Quality Management System. There should be a functioning audit program in place to provide verification of compliance for checking, verification, surveillance and auditing functions, and take all necessary corrective actions to comply with quality requirements (Qatargas 2 Project Document, 2006).

E.2.1 Vendors and Contractor’s Quality Management System:

Owner’s personnel should have access for assessment and oversight of Contractor’s or Vendor's Quality Management System for the purpose of: conducting pre-award quality assessments. The Company personnel should conduct quality audits during execution of the scope of work and monitor execution, inspections and testing. Vendor needs to identify all the managing and manufacturing processes. Records need to be generated in connection with the Inspection Test Plan (ITP) and Control Procedures. The quality organization identifies quality problems, recommends corrective actions, verify implementation, and control further processing, delivery or installation of nonconforming conditions until an approved disposition has been obtained. Inspection & testing activities should be conducted during manufacturing, fabrication, construction, installation and start-up, as applicable to the scope of work which are in accordance with approved control procedures. These should be hold and witness points requiring participation and supported by documentation generated to provide objective evidence of acceptable quality and compliance with specified requirements(Qatargas 2 Project Document, 2006).

E.2.2 Quality Document Requirements:

Project Specific Quality Plans, Inspection and Test Plans (ITP) and Control Procedures are required from manufacturing till hook-up activities. There should be identification of the stages requiring approval, inspection and testing. Control procedures should be established to reflect the requirements of specifications so as to safeguard the quality of the work with appropriate level of details (Qatargas 2 Project Document, 2006).

E.2.3 Quality Audits:

Inspection surveillance is required to utilize a quality audit program to provide verification of compliance with the approved quality plans, Inspection & Test Plans and associated control procedures. Quality Audits may be conducted to assess compliance with quality plans and control procedures. Quality activities are driven by a formal criticality rating process, with safety, operability and financial consequences, and probability factors (Qatargas 2 Project Document, 2006).

E.2.4 Control of Deviation from Specifications:

All deviations, alternations, exception or clarification should be resolved to the specifications requirements prior to the acceptance. Conditions of deviation, alternatives or exception from the specifications need to be documented. Any deviation, alternative or exception can be proposed with technical justification during the design and engineering stages in the case of improvement of performance or functions of product and other major design constraints (Qatargas 2 Project Document, 2006).

E.2.5 Control of Nonconforming Products:

The use or supply of any products that do not conform to specified requirements should be controlled until the nonconforming condition has been rectified or replaced with new, so that it conforms to specified requirements (Qatargas 2 Project Document, 2006).

E.2.6 Positive Material Identification (PMI):

The vendors need to perform positive material identification in accordance with Requisition, data sheet or applicable specifications. The PMI plan and results shall be included in inspection and test plan and manufacturer’s data report (Qatargas 2 Project Document, 2006).

E.2.7 Manufacturer’s Data Repot (MDR):

The vendors need to compile and submit the manufacturer’s data report in accordance with requirements stipulated.

E.3 Safety Challenges:

Loss Prevention systems as a combination of measures selected to prevent, control, and mitigate the life cycle hazards associated with the facility(Qatargas 2 project documents, 2005). These systems should take account of those associated with construction, simultaneous operations, start-up, shut-down, and maintenance. It is philosophy to design for the protection of health and safety of plant personnel and the public, as well as for the integrity of operations and equipment along with economic considerations. Engineering designs should protect operating and maintenance personnel during normal operations and against contingency situations involved in start-up, shutdown and emergency control of the operating plant and/or unit. Analysis should be made with regard to equipment layout and spacing, exposure to or from other process units or adjacent off-site operations, safe mechanical design, and types and capacities of fire prevention and fire protection equipment required. The design also tries to eliminate / mitigate the resultant risk by minimizing the potential release by appropriate provisions of isolation, emergency shutdown and de-pressuring equipment; eliminating or minimizing the spread of spills and leaks by containment and drainage and eliminating or minimizing the potential for fire spread, and providing for extinguishing and/or containment of fires through a combination of fixed and portable fire fighting equipment. As per Meyers et al (2007) it is imperative for the LNG industry to use all reasonable resources to maintain, and enhance, its enviable record on safety. Effective LNG risk management weighs all data points, historical as well as recent, to provide business with the qualitative and quantitative tools necessary to proceed, reassess, or halt based on concrete scientific analysis instead of perceptions, hopes, or fears. Safety level on a site directly depends on the skill level of the manpower and their safety awareness. So maintaining a high level of safety performance is a real challenge hence an intensive training program should be considered (Qatargas 2 project documents, 2005).

E.3.1 Hazard evaluation techniques:

There are several methods currently being used for risk evaluation in the Oil & Gas Industry. Safety Reviews, The complexity of the Modification/Change influences the selection of a risk evaluation technique.

E.3.1.1 Qualitative analysis: (Qatargas 2 project documents, 2005)

a) **Safety Review (SR):** Studies which usually involves less complex work are handled through Safety Reviews. The study is closed after implementing corrective Actions.

b) **Joint Safety Review (JSR):** It usually involves relatively complex projects requiring a need for multi-discipline review. Study is closed after the corrective actions are implemented, documents updated and training provided as required.

c) **WHAT-IF:** The What-If method is used to evaluate potential risks induced by complex modifications/Changes/Critical with involvement of several departments. It may be used either as an initial hazard evaluation method or as a supplemental method to systematic techniques.

d) **HAZOP (Hazard and Operability Study):** The HAZOP method is a structured method used to identify potential risks associated with complex modifications, extensive changes, critical tasks such as emergency and shut-down procedures and capital Projects. The HAZOP method is based on the principles of hazards identification, consequences determination and evaluation of adequacy of safeguards to mitigate associated risks (Qatargas 2 project documents, 2005).

e) **Project Technical Review (PTRs):** The Project Technical Review (PTR) procedure is applied as an independent audit at specific stage of all major projects to ensure that all reasonable measures are provided to ensure the operation, health and safety and minimize impact on the environment (Qatargas 2 project documents, 2005).

E.3.1.2 Quantitative and Semi quantitative Risk Analyses (QRA):

These techniques are formal and systematic approaches to identifying potentially hazardous events and estimating likelihood and consequences to people, environment and resources, of accidents developing from these events. QRA techniques are used to quantify the level of risk so that it can be effectively evaluated and determination made to tolerate it, transfer it or mitigate it (Qatargas 2 project documents, 2005).

a) **Failure Modes, Effects and Criticality Analysis (FMECA):** Failure Modes, Effects and Criticality Analysis (FMECA) evaluate the ways equipment can fail or be improperly operated and the impacts these failures can have on a process. FMECA identifies failure modes that either directly result in or contribute significantly to an accident (Qatargas 2 project documents, 2005).
b) **Fault Tree Analysis (FTA):** Fault Tree Analysis (FTA) is a deductive technique that focuses on one particular accident or main system failure, and provides a method for determining and understanding of causes of that event. Data used should be directly related to the equipment and service under consideration (Qatargas 2 project documents, 2005).
c) **Event Tree Analysis (ETA):** An Event Tree Analysis is developed by inductively reasoning chronologically forward from an initiating event, through intermediate safeguards and conditions, to the ultimate consequences. Data used is from an industry-accepted source, and directly related to the subject equipment and service.
d) **Human Reliability Analysis (HRA):** HRA techniques will be applied to the identification and improvement of Performance Shaping Factors (PSF), thereby reducing the likelihood of human errors. This technique should be considered whenever human error is known or expected to be potentially significant contributor to process risk (Qatargas 2 project documents, 2005).
e) **Consequence Analysis:** Consequence Analyses are used to find the maximum hazard zones, the extent of the flammable/toxic dispersion, the extent of the radiation hazard from fires and the extent of explosion overpressure (Qatargas 2 project documents, 2005).

E.3.2 Noise Control:

Noise control is considered as an essential feature in the design of new plant and equipment. The sound pressure level normally should not exceed 90 dBA (decibel Absolute) as a general rule in the plant work areas and 75 dBA at the inner edge of perimeter. Employees should not be subjected to sound levels in excess of 110 dBA for personnel safety (Qatargas 2 project documents). It should be ensured that all individual equipment items comply with noise mitigation and abatement methodology consistent with the sound level limits of the project specifications (Qatargas 2 project documents).

E.3.3 Security Considerations:

Project is responsible for assisting in designing, deploying, and delivering security and safeguards as needed to protect the project personnel, assets, operations, facilities, and business information during development, project design, fabrication, construction, and installation, commissioning, and continuing throughout the life of the operation. A dynamic, visible security program, which addresses the threats, related to Protection of assets, Office and residential security, Personnel transportation/travel and Communication/Information security need to be addressed (Qatargas 2 project documents, 2005).

E.4 Human Resources Challenges:

Implementing new project is never just about installing a system of machinery; it has tremendous impacts on its users, which must be assessed and addressed throughout the entire life cycle. Implementing a project is never a simple matter most of which are not related to the technology. Rather, they are related to the people who will be designing, implementing, and using the system. Progress in business, can be greatly impeded by not taking human resources needs into account and by not allowing people enough time to learn and become accustomed to new technology (Kostur, 2009). It is important to communicate the project goals to all involved.

E.4.1 Building a Project Management Organization: (Luan and Wray, 2009). To build large facilities it is important to build a Project Management Organization with clear roles, responsibilities, goals and objectives. Some of the steps are as follows.

a) **Call for Action and Share the Vision**: It establishes a sense of urgency which is critical for instituting the new project delivery system. It moves staff from comfort zone and emphasizes that not achieving the objectives is a clear recipe for failure. The top management should share their vision for the future course of action so that employees buy into the vision (Luan and Wray, 2009).

b) **Organize a Project management Team:** A strong team is needed to overcome resistance to change within the organization. A powerful coalition made up of leaders with positional as well as expertise within the organization is necessary with initiative driven from the top (Luan and Wray, 2009).

c) **Remove Organizational and work process Barriers:** There is bound to be organizational internal resistance to change Project team members, as well as functional managers, goals and performance evaluations must align with project business objectives. The existing work processes barriers should be removed (Luan and Wray, 2009).

d) **Train Staff:** Training based on individual needs is the most effective. How the new project delivery system will facilitate the project team’s work, how it can reduce confusion and stress around roles and responsibilities, how it creates more opportunities for the firm and the staff, etc should be the focus (Luan and Wray, 2009).

e) **Get a Quick Win:** Quick wins confirm that the initiative is worthwhile and also provides validation to management that the new project delivery system is working (Luan and Wray, 2009).

f) **Celebrate:** Achievements should be celebrated. This is also an opportunity to thank the team and their family for the extra work put in by the personnel and the support they receive by the family. This is also a good opportunity to team building (Luan and Wray, 2009).

g) **Use a Scorecard:** If it doesn't get measured, the task will probably not get done. Development of a set of metrics to measure progress as well as effectiveness is required (Luan and Wray, 2009).

h) **Build a cross-functional, collaborative leadership team. It** requires players from many different areas throughout the organization. A broad stakeholder group that participates in the selection, design, and implementation will be less likely to resist it and more likely to adopt any new or redefined processes (Kostur, 2009).

i) **Prepare a change plan and a communication plan.** Creating a project site on the intranet should be considered that allows people throughout the organization to see status reports, project plans, and provide input (Kostur, 2009).

j) **Setting realistic deadlines:** The deadlines should be challenging yet realistic. All the collaborative work required to identify needs, analyze contents, communicates project goals and provides training should be considered.

E.4.2 Building The Producing Organization: (Qatargas BTPO Road map, 2006)

It is the responsibility of the company to build the producing organization that takes over and operate and maintain the plant once the commissioning and start up is over. The entire organization should be prepared to assume operatorship of the facilities and achieve desired production, safety, and availability goals when completed. A coordination Team should be created:

(i) To develop the road map or execution plan for a changed organization.
(ii) To identify, plan, schedule, and be responsibilities required to ensure readiness for operations consistent with the project schedule.
(iii) To steward overall execution progress.
(iv) To identify and work key interfaces necessary to achieve operational readiness.

A roadmap is a systematic way to consider all aspects of operational readiness well in advance through effective use of a multidiscipline team, and broad exposure to the organization, assist in identifying and resolving early potential issues that may possibly impact successful startup and/or continued long term operations. This process describes the objectives, strategies and execution plans required to support flawless startup and to assure continued long-term safe, reliable, and environmentally sound operations consistent with project objectives. This process designed to ensure optimum operational readiness and assurance should receive full management attention and support.

E.4.3 Human Resources challenges for large projects:

a) Design manufacturing and procurement work locations are worldwide with engineering offices at many locations around the world with work site at a different location.

b) Many nationalities and people of many cultures and religions background work on large site with different perception and behavioral approach. It is necessary to understand (Lagrange, 2009) It is important in assessing the expectations of the different cultural or religious group and identifying the common elements between the different groups and the elements that can potentially cause issues

c) Diversity comes from personal characteristics such as background, culture, personality and work-style in addition to the characteristics such as race, disability, gender, religion and belief, sexual orientation and age. Harnessing these differences can create a productive environment in which everybody feels valued, their talents are fully utilized and organizational goals are met.

d) The camp having a large diverse populace has its own issues. There need to be adequate water supply, power for camp utilities and sewage disposal facilities and entertainment facilities for the camp inmates.

E.5 Construction:

Items of prime importance during construction are Safety, Health, Environmental and Security requirements.. A monitoring system that can quantify, plan, measure, and control the physical progress and system completion status of construction, and mechanical completion activities needs to be implemented. Based on such system. actual and planned physical quanity progress and equivalent manpower curves and tables for each major section/area can be monitored closely. (Various Qatargas 2 construction plan documents)

E.5.1 Construction Execution Plan:

The overall Construction Execution Plan should fully comprehend all construction activities. The Construction Execution Plan should include Safety, Health, Environmental and Security Plan, Subcontractor Management Plan, Manpower and construction equipment requirements, Temporary Facilities Plan, Traffic Flow Plan, Logistics plan, manpower housing, transportation and security processing; material delivery, storage and transport; Port utilization; telecom. A detailed "Path of Construction" for each subcontract activity, including the sequence, key milestones, and target dates for each subcontract activity amd various interface procedures should also be included (Qatargas 2 construction plan documents).

E.5.2 Constructability:

The objective of a Constructability Program is to produce a concerted inter-disciplinary effort to incorporate all phases of the Project into a single Project program, resulting in improved Project safety and quality, reduced construction costs, improved Project schedule, and a smooth commissioning and start-up phase (Qatargas 2 construction plan documents, 2005).Constructability is the systematic use of construction knowledge and experience in planning, engineering, design, procurement, and field operations to facilitate the construction activity. With influx of new employees during construction poses a real challenge. There is a need to implement good safety orientation programs, robust HSE (Health Safety Environment) management systems that require adequate safety training. Jacobsen (2009) experienced that in such a situation it may be a challenge to a hazard identification and embedment of a “stop work” culture. Other construction challenges one can face are poor labor productivity, weather delays and the need to supplement critical subcontractor operations. It is generally observed that piping subcontractor is a “bottleneck in the progress. Materials and labor costs escalation may result in the need for additional spending. Labor shortages, technical problems during construction and delays in commissioning shortages of all kinds of skilled workers are few things which should be closely followed.The extent of the local content of material and labor,which could affect not only the optimum construction method as well as the sourcing of materials but also the investment cost of the plant, should be discussed between owners, suppliers and contractors in order to find ways of improving development of the region without unduly penalizing the project (Durr et al 2001).

E.5.3Other construction challenges (Qatargas 2 construction plan doc. 2005):

a) **Traffic:** Traffic jams due to high volume may become a logistical nightmare. The absence of space adds to logistical difficulties slowing down construction.
b) **Safety-** To make an incident and injury free work place an overall safety performance with Quality/Cost/Schedule/Operability standards has to be implemented
c) **Regulatory & Environmental:** To carry out construction that meets regulatory requirements and standards with no environmental incidents, no delays due to permitting and no business ethics violations
d) **Quality:** Achieve facilities delivery to project specifications; flawless execution, no rework that meet specified requirements
e) **Cost:** Control costs so as to complete the project below the approved capital budget
f) **Schedule:** Objective to meet or beat project schedule milestones
g) **Operability:** Completed facilities are capable of long term safe, reliable, environmentally sound, cost effective, life-cycle operations.

E.6 Commissioning:

A monitoring system that can quantify, plan, measure, and control the physical progress and system completion status of commissioning activities has to be prepared in advance. Based on such a system, actual and planned progress and equivalent manpower curves and tables, for each major section/area of the work can be determined (Qatargas 2 Project Documents, 2005) Weighting factors based on estimated commissioning man-hours shall be applied to each commissioning activity and the corresponding progress will be earned when that activity has been completed, independent of the actual man-hours expended to accomplish that task.A significant testing and qualification effort is required to adapt the large gas turbine for system reliability. The gas turbine output changes considerably with ambient temperature variations. A LNG plant with gas turbine as a main driver has to undergo extensive testing and validation not only during the design and construction at manufacturing site but also during pre-commissioning and commissioning. Appendix D describes the details of the extensive testing requirement of gas turbine. In case of VFD with motor in the all electric alternative the extensive testing and validation can be drastically reduced by carrying out factory testing, which will help in earlier commissioning and start up activities (Siemens, 2005).

E.6.1 Completion/ Turnover/ Startup and acceptance:

A Mechanichal Acceptance Cerificate (MAP) is issued at a point in the project when all construction, testing, and pre-mechanical completion activities has been completed.

E.6.1.1 Mechanical Acceptance Packages:

The entire facility is generally divided into variousMechanical Acceptance Packages (MAP) which require MAP's to include component systems and subsystems that will allow to logically accept, commission, start-up, and operate the facilities as a fully operational system, including ancillary support systems. Mechanical Acceptance Certificate are ussed on completion of a package. In addition, the work shall be completed in a sequence that allows owner to logically accept, commission, and startup the facilties (Qatargas 2 commissioning documents, 2005).

E.6.1.2 Pre-mechanical Completion Activities:

As part of Mechanical Completion appropriate documentation is provided to allow owner to verify successfully completion of the activity. To facilitate pre-mechanical completion activities, plant utilities systems and components to achieve completion requirements is utilised (Qatargas 2 commissioning documents, 2005).

E.6.1.3 Punch-listing:

Prior to requesting a Mechanical Acceptance certificate for a package, a punchlist, which is bascially a snag list of all items, is developed that are not completed in accordance with project specifications and that cannot be completed by that time due to reasons that are acceptable Each item on the Master Punchlist, containing items of each disciplines, is categorized according to its criticality. As punchlist items are resolved in the field, it is inspected and approved to be cleared from the master punchlist (Qatargas 2 commissioning documents, 2005).

E.6.1.4 Start up of LNG plant:

In large sites early commissioning of the Utilities systems is taken up so that all utilities demand can be met during further construction start up and commissioning phases. For a phased commissioning and start up the execution plan should go through internal and independent reviews. The startup sequences should also go through an integrated team review. For all new technologies that are incorporated all the critical actions as a result of risk mitigation should have been completed. Technical and vender support plans developed and in place for new technologies and key operating systems. A start up contingency (what-if) workshops needed to be held and all identified actions identified on schedule for completion before systems start ups. Internal Readiness Self-Assessment

Reviews should be completed for key areas that needed to be started up in sequence and progressed (Qatargas 2 commissioning documents, 2005).

E.6.1.5 Simultaneous Operations (SIMOPS):

All critical actions to be identified for Simultaneous Operations and close out on schedule for startup critical actions identified.

Appendix: F

Life Cycle Cost Analysis

F.1: Introduction:

A lifecycle cost analysis is recommended to assess the large cost items in the motor installation project. Tradeoffs associated with initial cost, service factor, power rating, size and overall life should be evaluated through this analysis. Process variations will determine how much torque variations are likely to impact the motor/drive train design. For some applications with constant process conditions and a narrow operating window, a lower cost, less sophisticated drive train may be possible. The lifecycle cost analysis should include: (Nored et al 2009)

- Production downtime (estimated based on system availability).
- Fuel cost and electric utility cost.
- Equipment (purchase price, transportation to site, lead time/project delay time, permitting)Air permits will be less for electric motors compared to gas turbines without back-up generators on site, design cost.
- Installation/commissioning (estimated based on size and weight).
- Operation and maintenance expenses (estimated based on previous performance and should include parts and tools, labor, training, and possible emissions reduction credits. Also should include vendor and sub-supplier service capability, recycling/disposal of waste streams.).
- Procurement (present value of payment schedule, re-inspection costs).
- Engineering and project management.
- Insurance.
- Decommissioning or product retirement and phase-out (based on equipment removal and replacement, if needed, and equipment salvage value or disposal cost).

Issues to be considered for an All Electric Solution:

While an electric motor driven LNG plant is technically feasible, careful attention is required when evaluating the project economics. Key issues that have to be considered are: (Meher-Homji, 2011).

- Sensitivity of the project to CAPEX
- Value being placed on the fuel gas
- CO2 emission considerations and possible credits
- Real estate availability for the LNG plant and power plant solution
- Export power considerations
- Load shedding philosophy in the event that power is also exported.

F.1.1 Designs for Maintenance Prevention:

a) Total Cost of Ownership over the Equipment Lifetime:

This is the Span of time over which the equipment is expected to fulfill its intended purpose of the core aspects of ‘cradle to grave’. Lifecycle Asset Management Process, Systems, subsystems, and equipment within a facility are interrelated. Expected lifetimes vary by circumstances and equipment type. In a typical facility, the buildings, structure, large heat exchange and pressure vessels, piping, major mechanical equipment and electrical distribution system components have an expected lifetime more than the design life of 25 to 30 years. Over 60 percent of equipment lifetime maintenance costs were caused by preventable errors during design, procurement, installation, operation, and maintenance (Scheller, 2004).

b) The Design, Installation & Start-Up phase: Design for Maintenance Prevention:

Operating Equipment Asset Management requires “eliminating defects introduced directly during the design process (Maintenance Avoidance Design) as well as defects introduced through fabrication, construction, installation, operation, and maintenance due to design weaknesses. Fundamental reliability-enhancing strategies must be incorporated in the design process. Preventable design errors were responsible for approximately 17 percent of equipment lifetime maintenance costs (Scheller, 2004). Optimizing equipment lifetime reliability at design depends on several issues. System Reliability, Availability, and Maintainability including component life and ease of repair, are inherent characteristics that originate at design and strongly influence the lifetime cost of ownership. Lifetime costs must be assessed more fundamentally during the design process. Good design eliminates or minimizes problems, including opportunity for operating mistakes. Compromises to reduce cost often result in facilities and equipment that are difficult and costly to operate and maintain. Once a system has been fielded, no improvement of performance can be achieved without significant expense. A reliability risk analysis is useful to ensure that in-service performance will meet lifetime expectations and requirements. Return on capital necessitates that new manufacturing facilities are designed with reduced operating margin and redundancy. This philosophy requires a different design approach and investment to ensure the resulting reliability meets mission requirements.

F.1.2 Procurement of Equipment:

Measures to reduce cost of parts and labor often result in reduced production availability and output and increased long-term costs. Relaxing material specifications, purchasing equipment sized to barely meet specifications, and challenged designs are examples of how savings at procurement can cause enormous losses during operation. A decision to purchase lower cost components that turn out to have a significantly shorter service life compared to the components they are replacing. Assuming the failure pattern is recognized, there must be some record of the change, why it was made, conditions prior to the change, and expected return. Otherwise, the failure pattern may continue without anyone recognizing the deterioration from prior performance (Scheller, 2004).

F.1.3 Installation and Commissioning of Equipment:

Equipment installation is equally important to optimized lifetime cost. Only a few industry leaders rigorously apply equipment installation specifications that include foundation preparation, base-plate leveling and grouting, pipe flange and shaft alignment, oil system flushing, and pipe and separator cleaning. Inadequate installation and commissioning can cause a lot of expenditure which can be solved by following installation and commissioning "best-practice". The cost to correct the problem during operation is multiple times the cost of proper installation (Scheller, 2004).

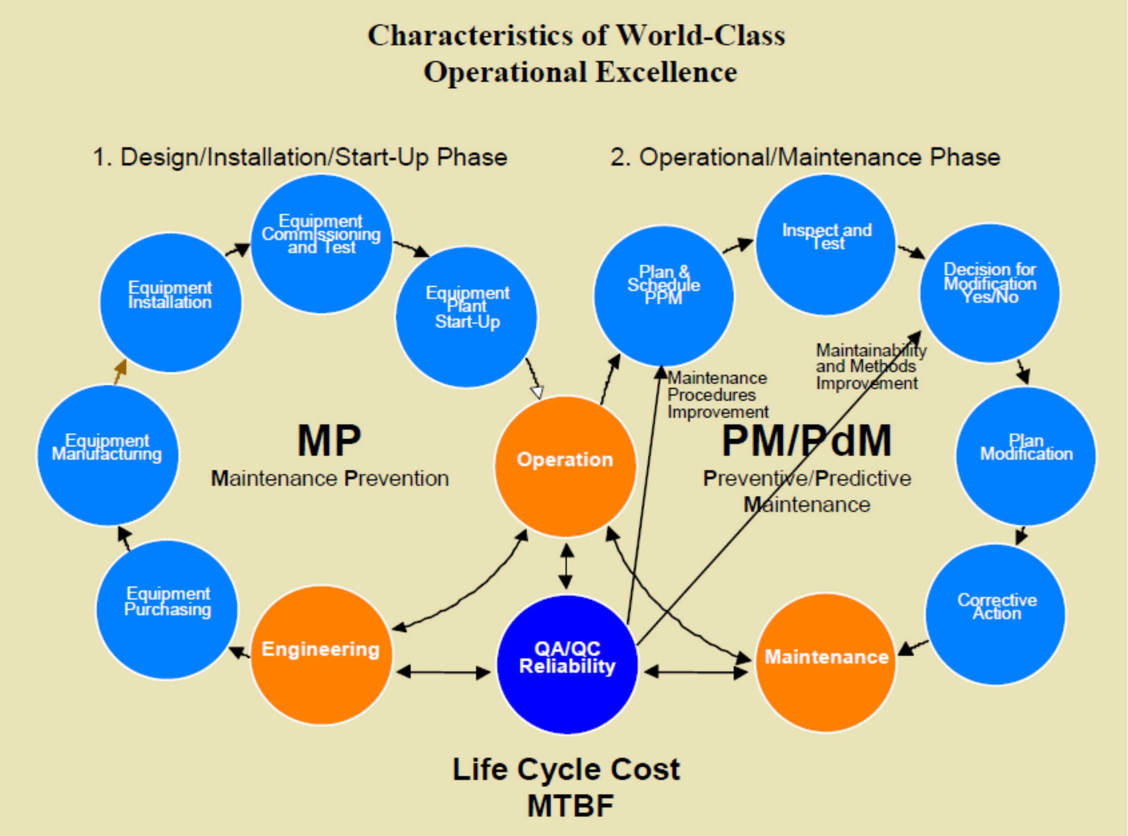

Figure F.1: Equipment asset management process (Scheller, 2004)

Appendix: G

Efficiency Improvements of LNG Plant

G.1: EFFICIENCY IMPROVEMENTS OF LNG PLANT:

G.1.1: With Aero-Derivative Gas Turbines:

LNG plants have used industrial type simple cycle gas turbines, commonly called a “Frame” machine, to drive refrigeration compressors. Lighter duty, higher efficiency aero-derivative gas turbines have not been used in LNG refrigeration service, although they have been used extensively in electric power generation and in pipeline compression facilities. Due to their low heat rates and hence significantly higher efficiency, use of aero-derivatives in place of the conventional Frame machines could reduce fuel consumption and associated CO_2 emissions by up to 20-30% with a small increment in the total capital cost (Chiu 2003). However, dry low NOx (DLN) removal technology may be required to reduce NOx emissions for the aero-derivatives due to higher flame temperatures in their combustors. Turbines equipped with an air intake cooling system or water injection system to cool the inlet air to generate additional power for the refrigerant compressors will increase the thermal efficiency (Chiu 2003).

G.1.2: Application of Combined Cycle Systems:

In a combined cycle, the waste heat from the gas turbine exhaust is used by a steam cycle to generate power or drive another turbine. Greater reductions in fuel consumption and CO_2 emission rates may be achieved through the use of combined cycle power generation and electric motor drivers for LNG refrigeration compression. Chiu (2003) states that recent improvements in technology have resulted in a thermodynamic efficiency close to 60% for a combined cycle power generation system. However the additional capital costs need to be evaluated against increased potential for improved efficiencies. It is possible to reduce fuel consumption and CO2 emissions by 40-50% using combined cycle power generation in conjunction with electric motor driven refrigeration compressors in place of simple cycle Frame gas turbine drivers (Chiu 2003).

Model	Gas turbine Drivers	ISO Rating in kW	LHV Heat rate kJ/kWh	LHV efficiency	Relative CO2 emission
Frame mechanical drives					
1F	M5382C	28.337	12,309	29.3	1.03
2F	M5432D	32,587	11,899	30.3	1.00
3F	M6511B	37,800	11,120	32.4	0.93
4F	M7111EA	81,557	11,022	32.7	0.93
Aero Mechanical Drives					
1A	LM2500+	31,319	8,757	41.1	0.74
2A	Coberra 6761	33,482	8,994	40.1	0.76

3A	LM6000PC	44,619	8,452	42.6	0.71
4A	Trent 800 DLE	52,549	8,479	42.5	0.71
Combined Cycle power generation					
S-206FA	2xMS6001FA	218,700	6,652	54.1	0.56
S-207FA	2xMS7001FA	529,900	6,373	56.5	0.54
2X1 701F	2Xm701f	799,600	6,283	57.3	0.53

Table G.1: Typical Gas turbine Performance and relative CO2 emission (Chiu 2003)

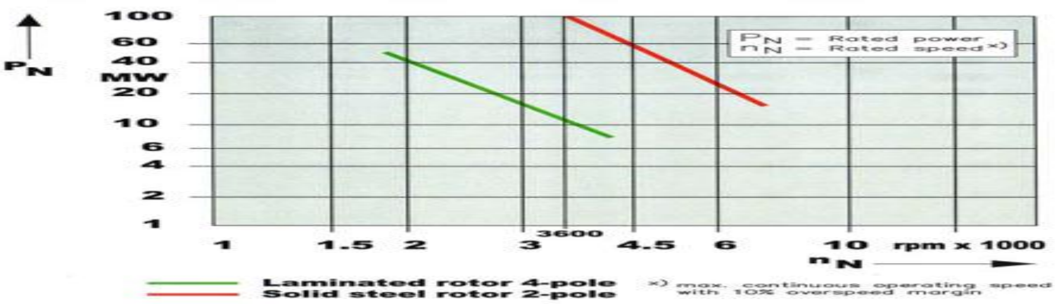

Figure G.1: Theoretical limit rating curves for 2-pole compressor drive motors (Kleiner et al 2005)

G.1.3: Application of Liquid of Liquid Expanders in LNG Plant:

Cryogenic turbines expand liquefied gases from high pressure to low pressure converting the hydraulic energy into electrical energy to reduce the enthalpy of the liquefied gas and to recover energy. For LNG expanders installed between the main heat exchanger and the atmospheric pressure LNG storage tank, a variable speed liquid expander can be used also as a control valve to increase the process efficiency. Many LNG plants use cryogenic turbine to expand the condensed natural gas from high pressure to low pressure, and substantially improved the thermodynamic efficiency of the existing refrigeration process, contributing to an increase of LNG output by about 6% and also a reduction of the greenhouse gas emissions (Chiu 2003).

G.1.4: Inlet Air chilling: (Thomas et al, 2009)

Air evaporation or air chilling at the Gas turbine air inlet: reducing air inlet temperature marginally improves the efficiency while increasing available power in tropical locations. For an LM 6000 the efficiency between air temperature of 35 deg. C and 15 deg. C increases by 7% in relative terms. A Heat Driven Absorption Chiller is a cooling machine using thermal energy (steam, hot water) instead of mechanical compressors consuming electricity or valuable fuel gas. The most common working fluid pair is composed of water and Lithium Bromide, a non-toxic and stable salt instead of troublesome fluids (CFC or ammonia). A general scheme is provided in figure 1

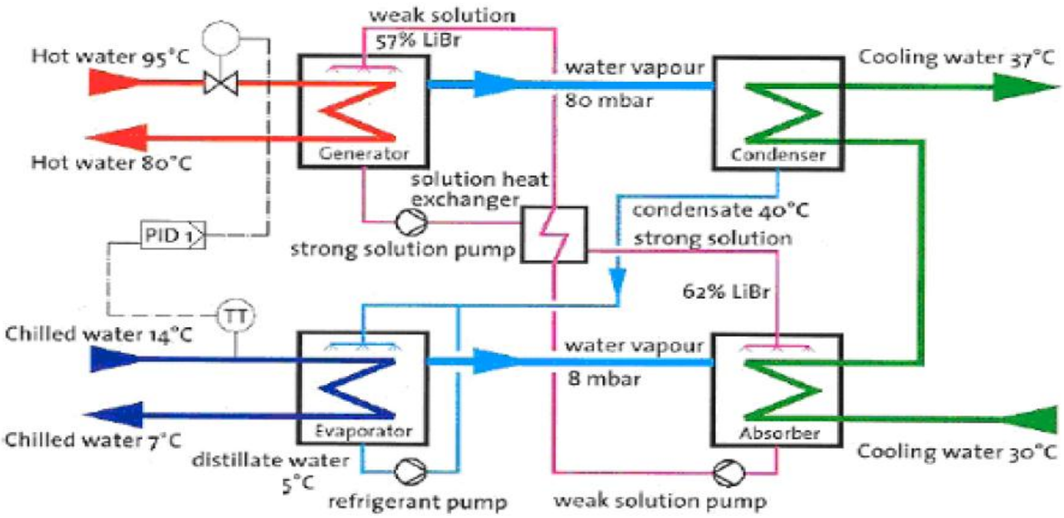

Figure G.2: Heat Driven Absorption chiller (Thomas et al, 2009)

Absorption systems are widely used for air conditioning mainly in South East Asia and US. Industrial applications are fewer but still some hundred units are installed in Oil & Gas, Refineries or Petrochemical facilities. The main benefits of Heat Driven Absorption machine are to make use of low level thermal energy otherwise cooled by external cooling media or release to atmosphere. Using Li-Br based absorption system in a new plant or for a revamping doesn’t increase the level risk as opposed to Ammonia. In hot climate conditions a chilled water loop (7deg.C) can be used to cool down process fluid lower than available ambient temperature cooling media. Conversely, cold climate limits the benefits of typical Absorption Chillers. Several suppliers can provide large packages than can be adapted to local conditions. The operation of absorption chillers is easy with a limited number of small pumps and trouble-free static equipment. However corrosion if not considered with care can be detrimental to the availability of the chillers. All the above characteristics are winning advantages for a successful integration in a LNG Plant. Many patents have been applied to use absorption chillers to lower the air inlet temperature to gas turbine. However few patents focus on the use of the absorption refrigeration cycle for gas liquefaction.

Appendix: H

Other potential uses of All Electric concepts

H.1 Introduction:

An LNG project represents an integrated chain of investments and commercial agreements linking exploration, production, transportation and marketing activities. Natural gas has inherent market risk. Once the final investment decision is made it entails a high fixed investment in stationary facilities that cannot be easily changed without incurring substantial expense. The design concept of an electrical LNG plant aims to ensure up to 365 days per year of uninterrupted refrigeration-gas circulation or for periods not limited by either the power plant or the compressor strings. Initial additional investment costs for the power plant are expected to be amortized within a period of less than five years, depending on the value of LNG at the time. Even including distribution losses, electrical drive systems achieve 96% efficiency, resulting in an overall refrigeration system efficiency of up to 45%, compared with approx. 32% for traditional mechanical drive solutions. Combined-cycle power plants also reduce greenhouse gas emissions by around 30% compared with traditional mechanical compressor drives. Including process steam supply, overall thermal efficiency may reach 90% (Devold et al, 2006).The rapid and controlled starting and restarting of pressurized compressors minimizes downtimes and eliminates flaring of expensive refrigerant gas, while compressor speeds can be optimized and target production can be reached with smaller train capacity and unaffected by ambient temperature. All Electric LNG can be designed to provide this useful additional feature. All Electric offers the following functions: (Siemens, 2009):

- Electronic variable speed drives for current source (LCI)
- Electronic variable speed drives for voltage source (PWM)
- Optimized compressor selection
- Customized and optimized compressor string design
- Power ratings of up to 90 MW
- Speeds in excess of 3600 rpm
- Proven modular designs
- Rapid on-site installation
- Pre-installed and pre-commissioned for compressor-string performance tests
- Capability to start up with no flaring
- Efficient energy conversion
- Always full power independent from ambient conditions
- Increased availability
- Lower production costs
- Lower CO2 emissions

Other than Onshore all-electric LNG, VFD driven Electrical motor have several other applications that are discussed below:

a) Offshore LNG plants/ Floating LNG:

Offshore LNG plants may make sense in cases where large ‘stranded’ gas reserves exist at great distance from any shore line. In these cases, use of a floating plant may be more economical than a traditional shore-based approach. Offshore liquefaction is not a new or novel idea. It was considered in the Kangan natural gas field in the Persian Gulf during 1970s. Several studies have been conducted for building a barge mounted LNG plant offshore. A floating facility that can be moved and re-used will substantially reduce the risk associated with a stationary investment facility. A floating liquefaction plant can reduce the cost of the production as well as provide maximum flexibility in developing a gas resource. It has been estimated that a floating LNG project might be 20-30% cheaper than a comparable size project and the construction time 25% faster. The floating plant’s mobility will reduce the construction cost of new pipelines and compression facilities that might otherwise be required to bring the gas to a land-based plant. It’s also possible to build an LNG plant on a floating platform—a barge—that can be towed to the next gas field as soon as the first goes dry. This reusability would make it commercially viable to tap smaller natural gas fields, since an LNG plant is a very expensive piece of technology (Schröder, 2008). All Electric concepts can be used for Floating LNG application. "Whatever the solution here, an E-LNG-based concept would seem to be ideal for mobile LNG plants. This is because the entire process has to be accommodated in a very small area. On a single floating platform, electric motors are much easier and, in all likelihood, safer to integrate than gas turbines, with their fiery hearts. Yet irrespective of just how LNG plants will look in the future, electric motors, electro-technology know-how, most of all, compressors, is ideally positioned to exploit this developing market (Schröder, 2008).

b) Mini LNG Plants:

Small and flexible LNG plants are an enticing prospect. They need to be designed in such a way that they can be easily adapted to the requirements of a new location with, for example, different gas compositions or production volumes. Applying Electric Motor Drive System to Mini LNG plant (Schröder, 2008)

- Mini LNG plant with high energy efficiency by applying electric motor drive system with GTG, inverter, motor and centrifugal compressor
- Availability of conventional LNG plant using direct mechanical driver is not so high due to long (20-40 days/year) periodical maintenance of the GT (gas turbine).
- Design flexibility for small scale LNG is not so high due to limited available models of GTs. This flexibility is available with electric motors.
- Electric motor drive system enables high efficiency of plant operation.

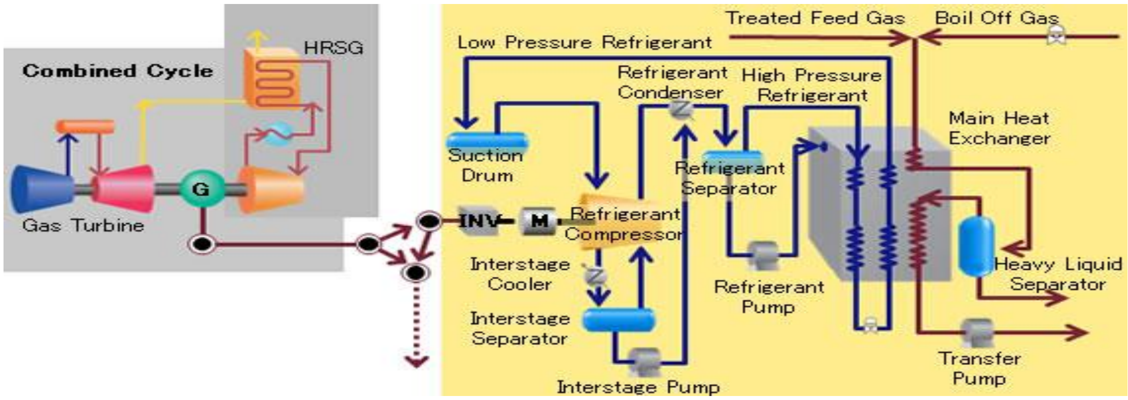

Figure H.1: Mini LNG Plant (Schröder, 2008)

b) Stranded LNG:

Liquefied Natural Gas (LNG) is becoming a desirable source of energy. Pipelines are unprofitable at lengths upward of 3,000 km. For gas fields in remote regions, where a pipeline would be too costly, liquefaction and transport via tankers offer a viable alternative. Thanks to extremely rapid growth in demand for energy over the last few years, LNG has become an energy carrier worth taking seriously. The solution to this is to provide a standalone island featuring a dedicated power plant to provide the requisite electricity to run electric motor driven LNG plants, the additional costs of such a power plant can be recouped within just a few years (Tim Schröder, 2008). In fact, the benefits of the stand-alone solution are substantial, not least because such a power plant operates in a combined cycle process, which is substantially more efficient than a solitary gas turbine in an LNG plant which has broken new ground (Tim Schröder, 2008).

c) Compressor stations:

Grapow (2009) has evaluated the pros and cons of the All Electric compression station to the conventional gas turbine driven station. As per this study the overall thermal efficiency of Electric compression is at 44% which significantly more than a Gas turbine run compressor system. The CAPEX comparison reveals that electric motor is the costlier than a Gas turbine option. However the motor run system has considerably higher full load or part load cycle efficiency than a conventional gas turbine driven system. The motor driven system has immediate restart facility with no limit on number of start whereas a gas turbine system has to wait for two to three hours for restart due to driver thermal consideration and the limited re-starts per hour. The gas turbine has reduced power availability with increase in elevation, temperature and humidity whereas an electric motor driven has no such impact and has full power available at all conditions. The gas turbine has CO_2 and NOx emission which is much reduced in case of a motor driven system fed from a combined cycle power station. The maintenance cost is much lower and the availability and reliability is much higher for a motor driven compression station as compared to a gas turbine driven system. In terms of Maintenance expenditure GT concept has a much higher cost than the motor run counterpart. In terms of controllability, ease of remote operation, speed control range, starting reliability and auxiliary consumptions High Speed Electric motor provides a better advantage over a Gas Turbine counterpart. Overall life cycle cost of a motor driven station is much better than Gas Turbine compressor station.

d) LNG ships:

LNG ships use large mechanical drivers for propulsion and compression. The VFD driven electrical system can be of good use in which it offers a number of life cycle advantages along with added safety benefits.

e) Gas To Liquid Plants:

Electric Drive system delivers numerous benefits for high energy consuming process such as Gas to Liquid plants where large conventional mechanical compressor drivers can be replaced with VFD driven motor system which can deliver a number of life cycle benefits same as those which are already discussed in the LNG plant.

Summary:

According to the International Energy Agency (IEA) in Paris, global demand for natural gas is set to increase by about 3.5 % a year until 2020. By then, natural gas will cover one-quarter of the world’s energy needs, compared to around 20 % at present. Although the non-liquefied variety still accounts for the lion’s share of gas sales, LNG is making steady inroads and, according to the IEA, is destined to increase its share of the world’s natural gas market from the current figure of 7 % to 10 % by 2010(Schröder, 2008).

Traditional gas turbines can only operate at fixed rotational speeds, are heavily dependent on the ambient temperature, and can’t really be regulated. The performance of the compressor, is determined by the gas turbines the output control of which is quite limited. That makes it difficult to respond flexibly to changes in production volumes. Electric motors, on the other hand, are simple to regulate and can also be water-cooled, which makes them largely independent of ambient temperatures (Schröder, 2008).

Electric motors have one major advantage: they are virtually maintenance free. Gas turbines have to be shut down several days a year for routine maintenance, which has a significant impact on output at an LNG plant. By contrast, electric motors can operate for as long as five years nonstop. In addition, whereas the efficiency of a gas turbine is generally around 35 %, an electric motor can manage up to 95 %. And once the efficiency of the power plant that is used to generate the electricity is also taken into account, the facility’s overall efficiency turns out to be around 52 %. This means reduced raw materials consumption and CO_2 emissions (Schröder, 2008).

All-Electric Solution "The oil and gas industry is watching the Snøvhit project with great interest it’s a highly conservative sector as far as new technology is concerned. Mechanical solutions have been used for decades, but the fully electric system represents a sea change. The new technology will need to prove its reliability over a full year before other oil and gas companies climb on the bandwagon. In spite of such industry hesitation, Siemens was recently awarded a contract for an E-LNG plant for Energy World Corporation on the Indonesian island of Sulawesi. The powerful electric motors will drive the compressors (Schröder, 2008).

Appendix: I

Torsional Analysis Consideration of All-electric option

I.1 Introduction:

Full lateral and torsional analyses according to international standards need to be performed each rotating string prior to detail design (Siemens 2008).In LNG services critical aspects must be carefully considered are shaft torsional behavior and electromechanical interactions between the Variable Speed drives (VSD) and shaft-line. If torsional issues are not addressed then they can cause coupling failures, broken shafts, worn gears, fractured gear teeth. The issues can be mitigated by careful designing the entire shaft-line by precise modeling of the forcing torsional phenomena, and by considering the selection of couplings, gearboxes and rotors from a torsional standpoint. Excitation of torsional natural frequencies may come from many sources such as running speed, aerodynamic excitations, and misalignment effects and also the pulsating torque ripple on the shaft line which is created by the switching nature of the VFD (Meher-Homji, 2011). The VFD harmonic content which depends on VFD topology must be included in the transient torsional analysis. The variations in the type of VFDs and the topologies will affect the torsional excitation orders produced by the drive train. Output filters may be used to reduce high frequency harmonics entering the motor for both current and voltage source types of VFDs. In a pulse width modulation VFD, if the application does not require high switching frequencies, the harmonics may be reduced by changing the angles of the modulated pulses during the design stage (Nored et al 2009). VFD harmonic excitation tends to occur in many discrete frequencies. The harmonic content must be included in the transient torsional analysis, particularly for the startup event. The variations in the type of VFDs and the topologies will affect the torsional excitation orders produced by the drive train. The use of voltage source or current source topology may determine the amplitude of harmonic fluctuations although other factors can influence the harmonic amplitudes as well.

I.2: Critical Speed Options for the Motor Drive System (Nored et al 2009):

The selection of the drive train speed range is a critical part of the design process. Although some compressors may have a large operating window, the torsional or lateral rotor-dynamic analyses may limit the speed range. The torque and power limitations of the motor can restrict the operational window as well. Successful system design frequently involves a compromise between offering as wide a speed range as possible to allow for increased operational flexibility and efficiency, while simultaneously avoiding rotor-dynamic problems. Other constraints on the speed range can result from machinery speed limitations and/or a requirement to avoid certain process conditions (overload, low pressure, high pressure, etc). Different gas compositions and pressures/ temperatures will affect the torque requirements of the motor. The linearity assumption for speed and power is not always valid. The motor must be capable of accelerating the load and functioning within the stated operational boundaries. The torque speed curve for the motor should include margins for operational variability. When the motor must operate over a range of speeds, additional analyses should be performed to characterize how the compressor torque requirements vary with the speed. If any torsional or lateral critical speeds overlap the desired operational speed range, additional analyses should be performed to characterize the prevalent excitation energy at the overlapping speeds. If the rotor-dynamics are not analyzed, the resulting vibration levels at or near the critical speeds have the potential to cause significant cumulative fatigue damage and possibly lead to failure of drive train components. Three approaches (or any combination thereof) may be considered for dealing with lateral or torsional critical speeds that fall within the speed range of the motor and compressor system (Nored et al 2009).

The approach to modify the design of the system to place the critical speeds outside the planned operating speed range is preferred and is generally possible if the rotor-dynamics are characterized early in the design process (Nored et al 2009).By avoiding any coincidence between the critical speeds and significant excitation energy, the possibility of extremely high vibrations or life-reducing events is reduced. Typical modifications, if required, include changes to the coupling stiffness and hub characteristics, flywheel inertia, shaft diameters, shaft strength (material changes, additional heat treatments, or both), bearings, loading conditions, etc.

The option of critical speed avoidance by changing the operating speed range may allow the drive train to be designed with more flexibility without reducing the operating range of the compressor significantly (Nored et al 2009). The anticipated separation margins between the calculated critical speeds and operating speeds should account for any uncertainty in the rotor-dynamic analysis. This option requires active control in the VFD system to avoid the critical speed windows and is especially useful in cases where a sufficient operating window is available above or below the calculated critical speed of concern. However, it should be noted that if the critical speed is below the planned operating speed range, a quick transition through the critical speed will be necessary during start-up events.

A less desirable and not recommended option is to allow short-term operation near critical speeds with sufficient damping (Nored et al 2009). This is to let the critical speeds to exist within the operational range so long as the response is well-damped, and prolonged operation at the subject speed is avoided such that fatigue damage is limited. Damping mechanisms may be time-dependent if implemented (examples include viscous dampers, elastomeric couplings, bearings, etc.) and should be weighed against increased long-term costs associated with maintenance and the implications of high vibrations and fatigue failure, if operation near the critical speed is allowed to occur for longer than planned, or with insufficient damping present in the system.

I.3: ROTORDYNAMIC CONSIDERATIONS (Nored et al 2009):

Rotor-dynamic analyses are critical to trains involving electric motor drives and must be considered an integral part of the design and selection process. The rotor-dynamic studies should be performed early enough in the design process to make changes if the predicted stress or torque levels exceed relevant criteria, or if the anticipated separation margins between calculated critical speeds and prevalent excitation are inadequate. The first steps in conducting these types of analyses usually involve the determination of lateral critical speeds (primarily for the motor and any attached gearbox or compressor shafts) and torsional critical speeds (for the entire train). The predicted critical speeds are used in conjunction with the mode shapes and a critical speed map (lateral analyses) and/or interference diagram (torsional analyses) to determine the likelihood of exciting the critical speeds during the planned operating conditions. Similarly, for some systems (especially those involving synchronous motor drives or VFD systems which produce significant alternating torque) transients, such as start-up or short circuit events, should be evaluated with torsional cumulative fatigue calculations. Additionally, lateral analyses should be conducted for electric motors, centrifugal compressors, and gearbox shafting.

I.4: Types of Torsional Analyses:

Three types of torsional analyses are generally required for electric motor drive systems:

- *Critical speed analysis:* should be conducted for all compressor/motor systems. In terms of critical speeds, the primary torsional design method used for electric motor driven compressors is avoidance of critical speed which should be tuned, if necessary, to provide an acceptable separation margin from significant excitation orders (Nored et al 2009).
- *Forced response analysis:* should be conducted for each relevant speed and operating condition – In cases where operation near a critical speed is absolutely necessary, a forced response analysis should be used to determine the stress levels. The resultant stresses should be analyzed for each planned operating condition over the anticipated speed range and compared to clearly defined allowable stress values to determine acceptability.
- *Transient torsional analysis:* should be conducted for start-up and short circuit conditions involving large driven inertia loads, critical speeds below the operating speed range, long acceleration times, significant compressor loading during start-up, or large VFD induced alternating torques, to characterize the cumulative fatigue damage which occurs during start-up and any potential 2-phase short circuit, and 3-phase short circuit conditions short circuit conditions. The results of the cumulative fatigue analysis should be compared to the anticipated service life of the train to determine acceptability.

I.5: Torsional Damping:

For most torsional systems, damping is provided via the coupling or an attached viscous damper. Most modern fixed ratio gearbox designs provide only minimal torsional damping. Damping may be added to the train, typically with elastomeric couplings or viscous dampers, in order to provide additional damage tolerance, if necessary. As a last resort, the operating envelope of speeds and/or loading conditions may need to be changed to avoid situations which cause excessive stress levels in the shafting(Nored et al 2009).

I.6: Allowable Stress and Torque Criteria:

An allowable stress value should be calculated for each section of shafting, for any forced response or transient torsional analysis. This allowable stress value should be based on the effective endurance limit for the shaft material, which is generally developed by applying strength modification factors to the material ultimate tensile strength. These factors should include the tensile to shear energy factor, endurance ratio, size factor, surface finish factor, reliability factor, safety (design) factors, etc. The calculated allowable stress for each section of shafting should be compared to the calculated intensified stress from the forced response or transient torsional analysis to determine acceptability for each anticipated operating condition. The calculated steady-state and dynamic torque values should also be compared to the maximum limits given by the coupling manufacturer and the gearbox manufacturer (Nored et al 2009).

I.7: Synchronous Motor Slip Frequency Excitation:

Synchronous motors produce a very large excitation torque during the start-up event. The frequency of this excitation typically varies from two times the line frequency at zero speed, to zero at full speed (motor synchronized), and is commonly referred to as the “2x slip frequency.” This excitation should be included in the transient torsional start-up analysis (Nored et al 2009).

Appendix: J

Reliability Analysis

J.1 Introduction:

A reliability analysis was carried out on Qatargas starter/helper/ generator VFDs to determine the reliability of the IGBT cells and threads by obtaining data from the SAP (CMMS software) and the analyzing y Meridium software. The details are given below:

J.2: VFD Cell Failure: Analysis Summary

Number of Assets: 1,008
Number of Failures: 70
Initial MTBF: 43,258.35 Days
Final MTBF: 9,366.75 Days
Observation Time: 1,040,256.00 Days
Time to Next Failure: 9,342.17 Days
Time Terminated: No
Confidence: 90.00 %

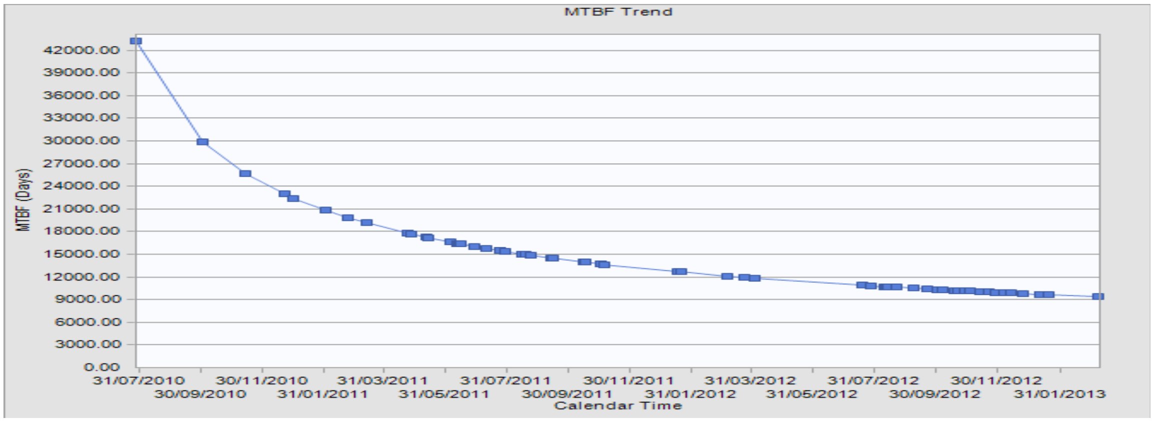

Figure J.1: MTBF Plot of VFD cell failure

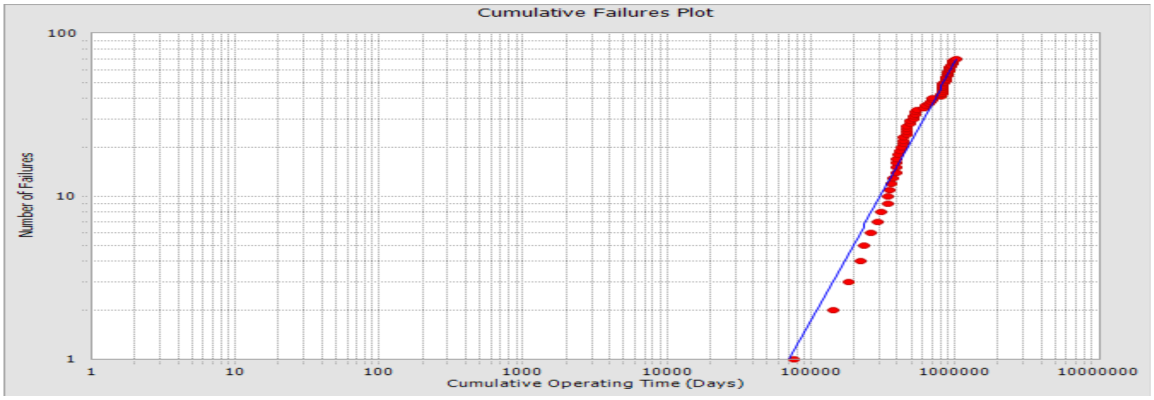

Figure J.2: Cumulative failure Plot of VFD cell failure

J.3 Thread failure: Analysis Summary

Number of Assets: 48
Number of Failures: 69
Initial MTBF: 2,091.90 Days
Final MTBF: 452.35 Days
Time to Next Failure: 451.15 Days
Observation Time: 49,536.00 Days
Confidence: 90.00 %

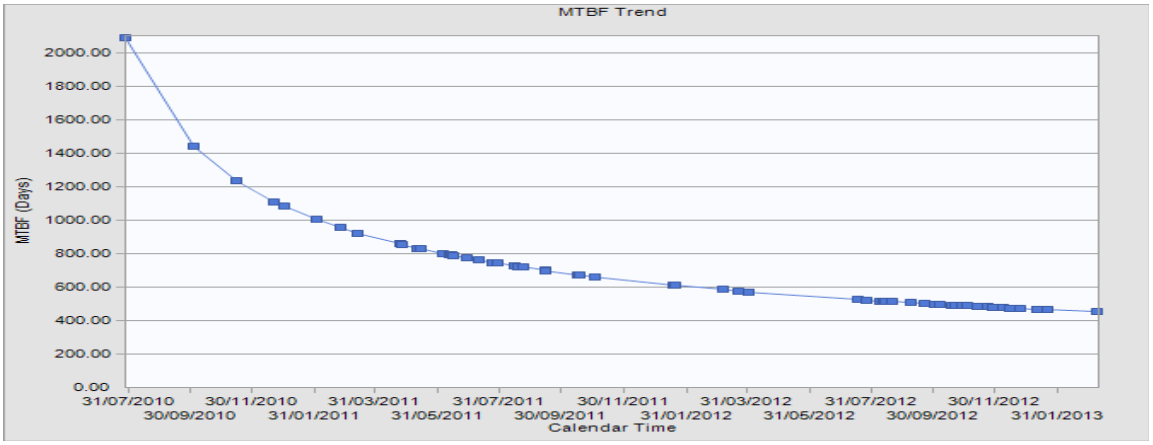

Figure J.3: MTBF Plot of VFD Thread failure

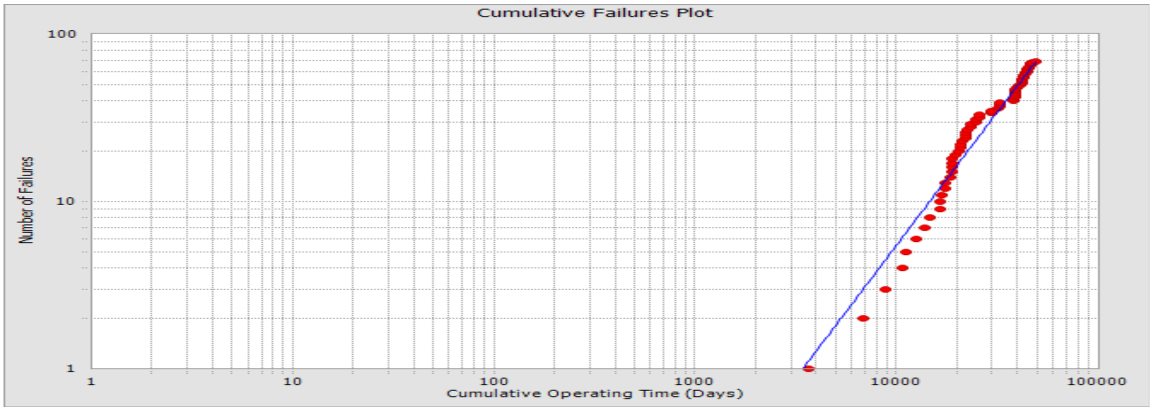

Figure J.4: Cumulative failure Plot of VFD Thread failure

J.3 Summary:

The analysis demonstrate the falling Mean Time Between Failure of both IGBT cells and VFD threads. Further action should be taken to improve the reliability of the threads and cells to improve the confidence on Power electronics components.

APPENDIX-K

Net Present Value (NPV) sample calculation

NPV calculation for LNG plant - NPV over 25 years

Evaluation Period	25	years
Interest rate	7.0%	
LNG Price	**$20/MMBTU**	for a 9 MMTPA plant
Rate of rise of LNG price	14%	

Revenue in the first year is US$ 359.19m is extrapolated from cot of 7.8 MTPA LNG plant and revenue is increased at a rate of 14% every year and discounted at a rate of 7% for the life of the project of 25 years

Year (end)	Revenue	Discounted Revenue
1	359.19	$336
2	409.4766	$358
3	466.803324	$381
4	532.1557894	$406
5	606.6575999	$433
6	691.5896639	$461
7	788.4122168	$491
8	898.7899271	$523
9	1024.620517	$557
10	1168.067389	$594
11	1331.596824	$633
12	1518.020379	$674
13	1730.543232	$718
14	1972.819285	$765
15	2249.013985	$815
16	2563.875942	$868
17	2922.818574	$925
18	3332.013175	$986
19	3798.495019	$1,050
20	4330.284322	$1,119
21	4936.524127	$1,192
22	5627.637505	$1,270
23	6415.506756	$1,353
24	7313.677701	$1,442
25	8337.59258	$1,536
PV of expected cash flow		$19,887

APPENDIX- L

Sample Questionnaire

1. **All Electric equipment has an overall advantage over Gas turbine (GT) alternative in engineering, manufacturing, transportation and installation:**

Strongly disagree	Disagree	Neutral	Agree	Strongly agree	N/A

Comment (optional) ---

2. **All Electric LNG requires smaller foot print for installation, lesser capital intensive spare parts than Gas turbine driven LNG:**

Strongly disagree	Disagree	Neutral	Agree	Strongly agree	N/A

Comment (optional) ---

3. **All Electric LNG Factory acceptance tests is less complex, less time consuming and has a shorter and cheaper validation testing schedule with fewer bottlenecks than the GT counterpart:**

Strongly disagree	Disagree	Neutral	Agree	Strongly agree	N/A

Comment (optional) ---

4. **It is more likely that All Electric LNG can be completed within schedule and budget considering simplicity in construction, testing and commissioning:**

Strongly disagree	Disagree	Neutral	Agree	Strongly agree	N/A

Comment (optional) ---

5. **All Electric LNG have will need a shorter overall schedule than a conventional LNG plant with GT driven compressors:**

Strongly disagree	Disagree	Neutral	Agree	Strongly agree	N/A

Comment (optional) ---

6. **The overall technical issues related to 'Variable Frequency Drives (VFD) in All Electric LNG" such as Harmonics, Torque ripple, Sub-Synchronous Torsional Interaction (SSTI),Electrical Resonance due interaction of harmonics with circuit parameters can be studied and mitigated to an acceptable level:**

Strongly disagree	Disagree	Neutral	Agree	Strongly agree	N/A

Comment (optional) ---

7. **All Electric LNG has a Life cycle cost advantage over a conventional GT LNG because better efficiency and better availability because of more available production days than the GT counterpart:**

Strongly disagree	Disagree	Neutral	Agree	Strongly agree	N/A

Comment (optional) ---

8. **All Electric LNG have a safety benefit over the conventional Gas Turbine LNG as all fired equipment can be located out of the process area and the process areas can be made less noisy:**

Strongly disagree	Disagree	Neutral	Agree	Strongly agree	N/A

Comment (optional) ---

9. **All Electric LNG has an Operational benefit over conventional Gas Turbine LNG such as; faster start up, accurate and wider speed variation, better control, full pressure restart capability and faster cool down due to absence of slow roll, no effect of ambient temperature, more number of production days, better capacity utilization and better transient characteristics etc:**

Strongly disagree	Disagree	Neutral	Agree	Strongly agree	N/A

Comment (optional) ---

10. **All Electric LNG cost lesser to maintain than GT LNG considering the fewer and lesser number of planned outages, less spare parts and a cheaper Long -Term Services contracts etc:**

Strongly disagree	Disagree	Neutral	Agree	Strongly agree	N/A

Comment (optional) --

11. All Electric LNG has better availability due to a longer Mean Time Between Failure (MTBF) and Mean Time Between Maintenance (MTBM) and a shorter Mean Time to Repair (MTTR) longer than a GT LNG:

Strongly disagree	Disagree	Neutral	Agree	Strongly agree	N/A

Comment (optional) --

12. All Electric LNG are more reliable than Gas Turbine driven LNG considering that GTs run with tighter parameters and clearances and lesser flexibility of operation:

Strongly disagree	Disagree	Neutral	Agree	Strongly agree	N/A

Comment (optional) --

13. All Electric LNG in a combined cycle generation configuration has got higher overall thermal efficiency over the GT driven LNG counterpart:

Strongly disagree	Disagree	Neutral	Agree	Strongly agree	N/A

Comment (optional) --

14. All Electric LNG in a combined cycle generation configuration is more environmental friendly because of lesser plant emissions than the GT driven LNG plants:

Strongly disagree	Disagree	Neutral	Agree	Strongly agree	N/A

Comment (optional) --

15. All Electric LNG has a lesser Payback period as it has a higher number of available production days than the Gas Turbine option:

Strongly disagree	Disagree	Neutral	Agree	Strongly agree	N/A

Comment (optional) --

16. All Electric LNG has a faster restarting capability which has a life cycle cost advantage than Gas Turbine counterpart:

Strongly disagree	Disagree	Neutral	Agree	Strongly agree	N/A

Comment (optional) --

17. **All Electric LNG has an ability to de-couple plant production from ambient temperature which will help maintain flat LNG production throughout the year:**

Strongly disagree	Disagree	Neutral	Agree	Strongly agree	N/A

Comment (optional) --

18. All Electric plant can be built to any capacity as motors have flexibility on sizing whereas Gas Turbines are available in fixed sizes hence the plants can be built to standard sizes only:

Strongly disagree	Disagree	Neutral	Agree	Strongly agree	N/A

Comment (optional) --

19. Based on technical and economic reasons 'All Electric LNG' can be preferred over a gas turbine LNG:

Strongly disagree	Disagree	Neutral	Agree	Strongly agree	N/A

Comment (optional) ---

20. Please give your comments, if any, for or against "ALL Electric" as a preferred alternative to a conventional Gas turbine driven LNG plant:

Comment: ---