DISTRIBUTED STATIC COMPENSATOR (DSTATCOM) FOR VOLTAGE SUPPORT IN SINGLE WIRE EARTH RETURN (SWER) NETWORKS

A Thesis submitted by

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Abstract

This investigation is concerned with the effectiveness of Distributed STATic COMpensators (DSTATCOMs) at providing voltage support in Single Wire Earth Return (SWER) networks. The reason for the focus on SWER lines is the high cost of upgrading them in the traditional way to solve voltage regulation problems that result from load growth in some of the feeders. A number of aspects of DSTATCOM installation and operation have been explored. These include their location, reactive power circulation, reactive power prioritising, four quadrant operation and the timing of installation and operation.

It has been possible to derive analytical expressions only for the case of a single Thevenin source equivalent and a single load in parallel with a DSTATCOM. From one of those expressions it was deduced that, on a voltage increment per kVAr basis, DSTATCOMs are most effective as voltage regulators when they are installed at the customer terminals rather than further upstream into the network. This result has been found to apply generally to all practical SWER lines. Another derived expression predicted a peak value of customer terminal voltage when active power (P) and reactive power (Q) are injected by the DSTATCOM at constant kVA (S). This maximum voltage represents a stability limit for the case where DSTATCOMs are controlled to operate at constant kVA. Load flow studies revealed that in general this stability limit exists for all practical SWER lines.

To avoid VAr circulation it is proposed that droop control with hysteretic band is used for DSTATCOM operation. The standard Newton-Raphson load flow formulation has been extended to accommodate DSTATCOMs operating under droop control and with operating point on a defined trajectory on the P-Q plane. Four defined trajectories have been investigated under given hourly load demand profile. These are the Q-only scheme, the constant kVA scheme with Q-priority, the load power factor follow scheme and the power factor correction scheme. For each one of those defined trajectories a modified Jacobian had to be derived. Load flow studies were based on each of the modified formulations. The load flow programs were designed to automatically provide a solution for each hour of a 24-hour demand profile representing the worst case peak demand for a particular year in the life of any practical SWER line. The customer DSTATCOM is either left on line, brought on line, left off line or taken off line, depending on the calculated customer voltage. Those special features of the load flow programs allowed them to be used to determine when and at what customer location DSTATCOMs should be installed and what their ratings should be. While the focus of the thesis has been on undervoltage problems; the proposed solutions and algorithms are applicable to overvoltage problems caused by the Ferranti Effect.

Certification of Thesis

This thesis is entirely the work of *Seyed Javad Mirazimiabarghouei* except where otherwise acknowledged. The work is original and has not previously been submitted for any other award, except where acknowledged.

Principal Supervisor: Assoc Prof Tony Ahfock

Associate Supervisor: Dr Les Bowtell

Student and supervisors signatures of endorsement are held at USQ.

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Abbreviations

LV	Low Voltage
MV	Medium Voltage
HV	High Voltage
SWER	Single Wire Earth Return
DG	Distributed Generation
STATCOM	STATic COMpensator
DSTATCOM	Distributed STATCOM
EPR	Earth Potential Rise
SC/GZ	Steel Cored / Galvanized Zinc
SC/AC	Steel Cored / Aluminium Clad
ADMD	After Diversity Maximum Demand
PV	Photovoltaic
POE	Probability Of Exceedance
RE	Renewable Energy
LTC	Load Tap Changer
OLTC	On Load Tap Changer
FACTS	Flexible Alternating Current Transmission System
AVC	Automatic Voltage Control
PFC	Power Factor Correction
LVR	Low Voltage Regulator
SSSC	Static Synchronous Series Compensator
UPFC	Unified Power Flow Controller
TCSC	Thyristor Controlled Series Compensator

SVC	Static Var Compensator
VSI	Voltage Source Inverter
VSC	Voltage Source Converter
SMES	Superconducting Magnetic Energy Storage
BES	Battery Energy Storage
ESSs	Energy Storage Systems
RGA	Real Genetic Algorithm
PSO-TVAC	Particle Swarm Optimization-Time Varying Acceleration Coefficients
IA	Immune Algorithm
PSO	Particle Swarm Optimisation
CPF	Continuation Power Flow
GUSS	Grid Utility Support System
RUSS	Residential Utility Support System
VS	Voltage Support
SVS	Static VAr System
PF	Power Factor
CB	Circuit Breaker
DERs	Distributed Energy Resources
DICs	Distributed energy resources Interface Converters
IPV	Interline Photo Voltaic
PCC	Point of Common Coupling
BDC	Bounded Droop Controller
RDC	Robust Droop Controller
VDB	Voltage Dead Band

AC	Alternative Current
MNR	Modified Newton Raphson
pu	Per Unit
RMS	Root Mean Square
DS.NS	DSTATCOM Network Side
DS.CS	DSTATCOM Customer Side
R/X	Resistance over Reactance
DSSL	DSTATCOM Steady state Stability Limit
HR	Hours
CUS	Customer Number
EHV	Extra High Voltage
UHV	Ultra High Voltage

Nomenclature

R_L	Load resistance
I_L	Load current
T_{12}	Isolating transformer located between bus 1 and 2
T_{34}	Transformer connected to the load and is located between bus 3 and 4
R+jX	Transmission line impedance
X_{T12}	The reactance of transformer T_{12}
X_{T34}	The reactance of transformer T_{34}
V_i	The voltage at bus *i*
$I_{DS.NS}$	Network side DSTATCOM current
$I_{DS.CS}$	Customer side DSTATCOM current
$P_{Li}+jQ_{Li}$	Load active and reactive power connected to bus *i*
$P_{DSi}+jQ_{DSi}$	DSTATCOM active and reactive power connected to bus *i*
$S_{DS.NS}$	Switch to connect network side DSTATCOM to the network
$S_{DS.CS}$	Switch to connect customer side DSTATCOM to the network
$Q_{DS.NS}$	The reactive power of network side DSTATCOM
$Q_{DS.CS}$	The reactive power of customer side DSTATCOM
$I_{DS.NS}$	Network side DSTATCOM current
$I_{DS.CS}$	Customer side DSTATCOM current
$\Delta\|V_{NS}\|$	Voltage boost due to network side injection
$\Delta\|V_{CS}\|$	Voltage boost due to customer side injection
$(R/X)_{N.S}$	R/X ratio of network side installed DSTATCOM
$(R/X)_{C.S}$	R/X ratio of customer side installed DSTATCOM

ΔV_x	The real component of voltage drop ΔV
ΔV_y	The imaginary component of voltage drop ΔV
S_{DS}	DSTATCOM size in kVA
P_{DS}	DSTATCOM active power in kW
Q_{DS}	DSTATCOM reactive power in kVAr
ϕ_{DS}	DSTATCOM operating point angle
ϕ_{DSSL}	DSTATCOM Steady state Stability limit operating angle
dP_{DS}/dQ_{DS}	The derivative of DSTATCOM active power with respect to its reactive power
$\partial V/\partial P_{DS}$	Partial derivative of voltage with respect to DSTATCOM active power
$\partial V/\partial Q_{DS}$	Partial derivative of voltage with respect to DSTATCOM reactive power
P_{DSSL}	DSTATCOM active power when it is operating at DSSL point
Q_{DSSL}	DSTATCOM reactive power when it is operating at DSSL point

Publications

The following publications are the direct outcomes of this research project:

S.J.Mirazimiabarghouei,T.Ahfock and A.Helwig, "Placement of Distribution STATic COMpensator (DSTATCOM) as Voltage Support Equipment in Single Wire Earth Return (SWER) System" *IEEE 6th International Conference on Power and Energy,* 'PECON 2016', Malaysia, Melaka, 28-29 November 2016.

S.J.Mirazimiabarghouei,T.Ahfock and A.Helwig, "Single Wire Earth Return (SWER) System Voltage Support Using Four Quadrant DSTATCOM" *IEEE 6th International Conference on Power and Energy,* 'PECON 2016', Malaysia, Melaka, 28-29 November 2016.

CHAPTER 1

INTRODUCTION

1.1 Background

A Single Wire Earth Return (SWER) system is a single wire distribution line for supplying single phase electric power. It has a distinguishing feature in that it uses the earth as the return path for the current thus avoiding the need for a second or neutral wire to act as a return path [1]. Power is supplied from the main backbone to the SWER line by an isolating transformer. This transformer isolates the grid from ground or earth, and changes the grid voltage to the SWER voltage [2]. SWER distribution systems have been recognized as able to provide cost effective electricity over long distances to sparsely populated rural areas in a number of countries such as Australia, New Zealand, Canada and United States for over 50 years [3]. Currently more than 150000 km of SWER lines are in use all over Australia [4].

Whilst SWER systems are still currently being utilised in Queensland, there are problems and issues that limit their full potential to deliver power of acceptable quality. As a result of relatively long distance, the most serious power quality problem with SWER distribution system is voltage regulation. The long distance lines will result in low voltage at the end of the lines during peak demand [5, 6]. When the SWER line was first installed, while low voltage was not a problem, steady load growth will cause the problem to surface at some point in the life of the SWER line.

The above concerns may be addressed by changing taps of distribution transformers [7], the use of voltage regulators [8], capacitors [9], reactors [10], Distributed Generators (DG) [11], Static Var Compensators (SVC) and STATic COMpensators (STATCOM) [12, 13]. Considering load growth in SWER lines, these solutions may not be able to address the voltage problem. On the other hand upgrading of the network by using heavier conductors is a relatively expensive option [3].

Significant research has been conducted in the STATCOM area considering it as voltage support to enhance the voltage profile of the system either in typical three phase systems or in SWER networks [14-16]. The performance and effectiveness of STATCOMs, either reactive power only or four quadrant, will be affected by their location in the power network, number and size. Placement is one of the key factors and plays an important role in this matter. When considering placement of STATCOM, there is the possibility of mounting it at the customer side or network side of the customer transformer. In this study the Distribution STATCOM (DSTATCOM) is being used to improve under-voltage problems due to load growth in dispersed rural SWERs. In fact, four quadrant DSTATCOM is able to supply or absorb active power as well as reactive power using generator or storage such as a battery [4]. However installing DSTATCOMs in the system as voltage support equipment increases the possibility of VAr circulation. DSTATCOM operating modes, load sharing control methods, droop characteristic design and practical implementation are the challenges to be considered in this study.

1.2 Research Objectives

This thesis addresses the following questions in the context of SWER lines:

(a) How effective are DSTATCOMs at providing customer voltage support?

(b) Where and when should DSTATCOMs be installed?

In line with the above research questions the project objectives are:

(a) To compare the effectiveness of reactive power only (Q-only) DSTATCOMs with four quadrant DSTATCOMs at providing SWER line customer voltage support;

(b) To compare the effectiveness of connecting DSTATCOMs on the primary side of the SWER line customer transformer to connecting them on the secondary side;

(c) To propose and verify by simulation a control method for Q only DSTATCOMs connected to a realistic SWER line to automatically inject or absorb appropriate amount of reactive power while ensuring absence of VAr circulation;

(d) To extend the method proposed in (c) above to four quadrant DSTATCOMs connected to a SWER line.

1.3 Thesis Outline

This thesis is organised as follows:

Chapter 2 provides background knowledge about DSTATCOMs and SWER lines. The chapter also includes an overall literature review on current approaches for DSTATCOM integration in SWER systems as voltage support equipment. The placement of DSTATCOM, which can be at the customer or network side, is highlighted. Furthermore, the droop control method is reviewed in detail.

Chapter 3 compares the placement of the DSTATCOM on the network side of the customer transformer with its placement on the secondary side. It also analyses the level of voltage support provided by the DSTATCOM as a function of its operating point on the P-Q plane at rated kVA.

Chapter 4 introduces the Q_only DSTATCOM operating mode as a VAr compensator. The classical droop control strategy is modified to avoid VAr circulation in the network. The effectiveness of the proposed modification is demonstrated by load flow studies on a real SWER line. A new Jacobian had to be derived to enable those studies to be carried out.

Chapter 5 develops the Q_priority DSTATCOM operating mode. In this mode the DSTATCOM acts as a source of active and reactive power. However, the DSTATCOM operates in reactive power only mode until it reaches its kVA rating. Active power is injected at rated kVA, only if additional voltage support is needed. Hence reactive power injection is given priority as its nominal cost is zero. A new droop control characteristic is proposed to maximize the voltage support capability of the DSTATCOM operating in this mode. To ensure stable operation hysteretic control is combined with the proposed droop characteristic. Load flow studies, based on a modified Jacobian, are carried out to demonstrate effectiveness of the Q_priority DSTATCOMs.

Chapter 6 proposes the load power factor follow DSTATCOM operating mode and power factor correction mode for voltage support. In these modes, the DSTATCOM is guaranteed not to contribute to the possibility of islanding.

Chapter 7 concludes with a summary of findings of this research. Proposals for further research are presented.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter begins with providing an outline of SWER lines and DSTATCOM technologies. It systematically reports a comprehensive literature review on different issues of DSTATCOM integration in distribution systems from the perspective of system voltage profile and voltage support. The issues of DSTATCOM usage in bulk size as a single device or in a number of small sizes are thoroughly reviewed in this chapter. The placement of DSTATCOM either at the customer side or network side, from the literature is highlighted. The second part of this chapter is related to different ways of controlling DSTATCOMs. A droop control method is reviewed in detail as one of the popular control techniques, as well as load sharing strategies. Finally, the gaps and limitations relating to DSTATCOM placement and conventional and modified droop control methods, in terms of voltage control of systems, are discussed.

2.2 SWER Line Characteristics

2.2.1 SWER History

Nowadays, billions of people have no access to basic energy services. This is an important and significant concern. A recent report in [17], World Energy Outlook 2015, highlighted that 1.2 billion people from all over the world are living without electricity. It was also discovered that 2.7 billion people are using traditional ways of cooking, such as charcoal and wood fires that present a significant indoor air pollution threat. More than 80% of the above mentioned populations are living in rural and remote areas. It has been predicted that more than half a billion people will still be living without electricity in 2040.

The dominant obstacle to rural electrification is high cost [18]. In order to avoid the expensive cost of power line upgrading and extensions, the World Bank is supporting the expansion of simple distribution networks for rural electrification [19]. Single Wire Earth Return (SWER) technology is one of the most reliable and cost effective methods of rural electrification with a suitably low load density [20]. It is a single wire electrical system used to provide electrical power to remote and sparsely populated regions at a reasonable and cost effective price. Using SWER line technology, a single conductor is used to transmit the electricity to the distribution transformers at consumers' homes, adapting all equipment grounded to the earth in order to provide a return path for the current [2].

Lloyd Mandeno invented the idea of SWER networks in New Zealand in 1920. His published paper in 1947 proposed SWER lines as an economic alternative to the typical distribution network for remote electrification [21]. Nowadays this SWER technique has become popular all over the world and many countries, such as Australia, USA, New Zealand, South Africa, Brazil and Canada are using it to supply rural electrification [22].

In order to electrify agricultural and rural regions, Australia recognised a need for power system expansion in the1950s. Australian electricity authorities turned to the SWER system due to its application years earlier as an economical solution for low load density areas [23]. In 1959, an area in Central Queensland named Bajool began to use the SWER system. Consequently, years later, thousands of kilometres in remote regions of Queensland have installed SWER for rural land electrification [24].

Currently more than 150000km of SWER lines are in use all over Australia [4]. Ergon Energy, a local Queensland based distribution company, covers the operation and maintenance of 97% of the State of Queensland, where they manage around 150000km of power lines. Of these power lines, 65000km are SWER lines supplying approximately 26000 customers. The SWER system voltage level operates at 11kV, 12.7kV or 19.1kV and supplies electricity to farms and small country towns in rural Queensland [25]. Depending on the life of the hardwood pole, the maximum lifetime of these Australian SWER networks is considered to be around 70 years, with a replacement cost of around $30000 to $50000 per kilometre [26].

For residential low voltage customers, Energy Queensland, formerly known as Ergon Energy, are required to operate within the National Electricity Rules which legislates a 240V connection point must remain within 240V with maximum variation of 6%. Considering the standard variation, the provided voltage level has to be between 225V and 255V which are 0.94pu and 1.06pu respectively [27].

2.2.2 Isolating Transformer

Commonly, a three phase supply feeder is used to feed a SWER line. SWER networks are presented in two basic types: firstly through an isolating transformer from the main supply as is illustrated in Figure 2.1 and secondly, directly from the main supply named direct SWER as shown in Figure 2.2. To isolate the earth current that circulates in SWER line as a return current, from three phase system, an isolating transformer is installed at the beginning of the feeder. As a result, not only it remains earth fault protection sensitivity but also avoids possible interfaces with underground telecommunication cables [23]. In addition, it provides earth fault protection on Medium Volt (MV) networks in terms of grid extension [28-30].

Earth Potential Rise (EPR) is an issue of concern in SWER networks, and it is important to assure of designing, constructing and maintaining of earthing system [20]. Isolating transformers in SWER lines have to be capable of transferring all the currents, such as load current, and line capacitive charging current. Due to high charging current of SWER long feeder, low isolation transformer impedance is necessary. Also, to avoid presenting potential step and touch hazards, earth return currents are kept as low as possible [23]. The typical size of SWER isolating transformers range between 100-300kVA, depending on the system design and specifications [2].

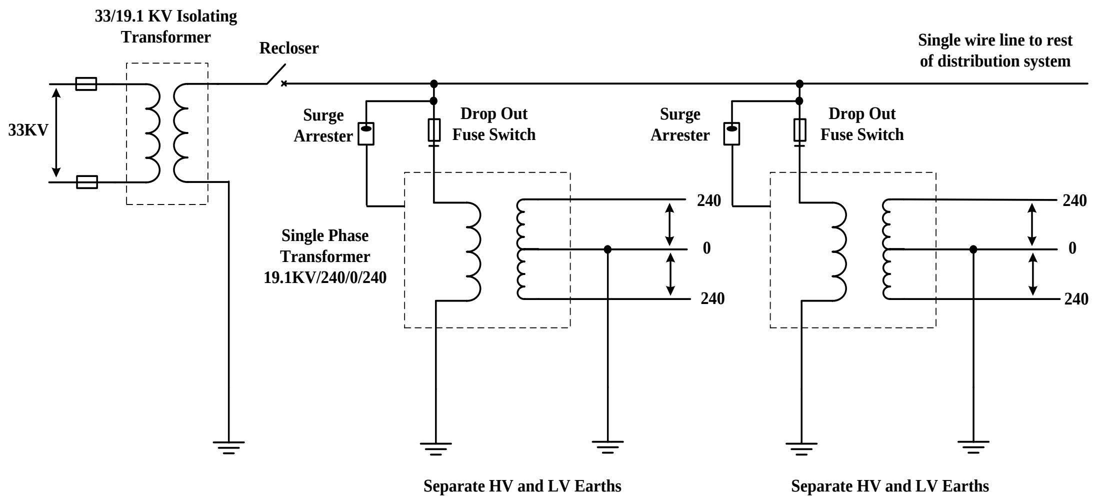


Figure 2.1: SWER network with isolating transformer [20].

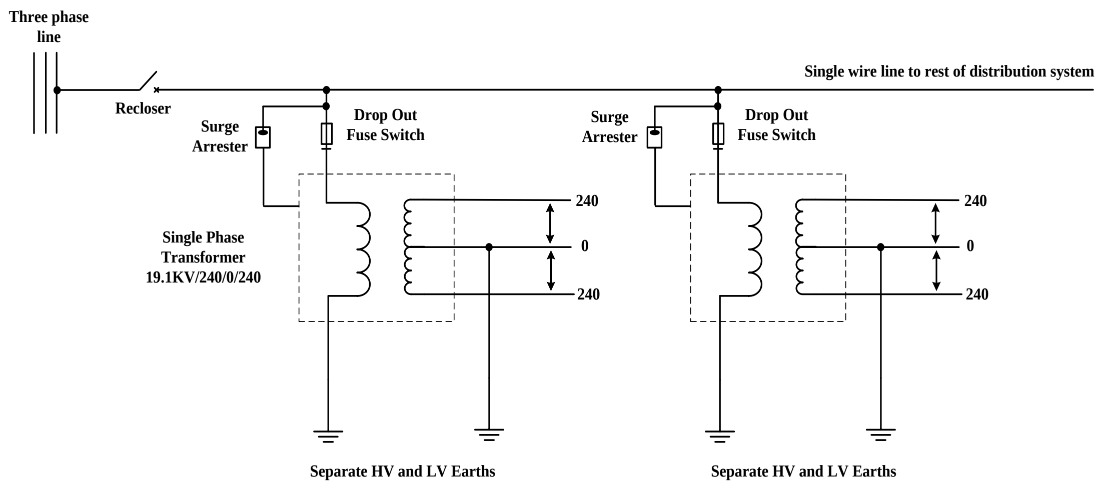


Figure 2.2: Direct SWER network [20].

As can be seen in Figure 2.1, the isolating transformer input is 33kV. Alternatively, in other cases this can be 22kV or 11kV. Only one phase of the three-phase system is connected and the output is single phase 19.1kV (alternatively 12.7kV or 6.35kV for 22kV or 11kV input, respectively). A single phase step down customer transformer (distribution transformer) is used to reduce the voltage level to 240V [1].

While substation at the source has an entirely grounded neutral, using an isolating transformer is not essential [20]. Excluding it and connecting one of the phases directly to the SEWR line is currently used in some countries, for example Brazil [30].

Direct SWER means lower cost and no constraint of load but it also may cause interference to telecommunication cables or high voltage concerns to electrical apparatus due to the flowing back of current [28]. On the other hand, using an isolating transformer controls SWER earth fault currents, maintains the sensitivity of earth fault protection and limits the load [31].

According to Ergon energy reports, more than 80% of SWER lines are isolated in SWER voltage break down percentage of 55% in 12.7kv, 36% in 19.1kv and only 9% in 11kv [2]. Figure 2.3 shows a SWER line isolating transformer in Ergon Energy operation.

Figure 2.3: SWER line isolating transformer [2].

2.2.3 Conductors

Based on load and customer density, line length changes with an average of 60km for SWER feeders, even though there is a 400km SWER system available in Australia [23]. However, the length of lines between customers varies from 1km up to 20km, with some rural properties up to 25km [3].

Typically, SWER lines use low quality conductors, relatively resistive, cheap in price, with low load transmission capacity, due to small load current compared to normal three phase system. The most common types of power line conductors in SWER networks at spurs (toward customers) are Steel Cored Galvanized Zinc (SC/GZ) and Steel Cored Aluminium Clad (SC/AC). It has to be noted that steel conductors are harder and stronger than others with the ability to stand much longer distances. Conductors Banana and Sultana, with less resistivity and smaller R/X ratio, are more suitable to be used in main backbone feeder areas. They are closer to substations and have to carry more currents than other feeders. Other types of conductors are also used in limited applications [2]. Table 2.1 shows the properties of common SWER conductors in Ergon Energy [32].

Table 2.1: Properties of common SWER conductors in Ergon Energy

Conductor code	**Conductor type**	**Area of Section (mm2)**	**Overall diameter (mm)**	**Calculated breaking load (kN)**	**Unit mass (kg/km)**	**Final modulus of elasticity (GPa)**	**Coefficient of linear expansion (xE-6/°C)**	**AC Resistance (at 75°C) (ohms/km)**
3/2.75	3/2.75 SC/GZ	17.82	5.93	22.2	139	192	11.5	12.05
3/2.75	3/2.75 SC/AC	17.82	5.93	22.7	118	162	12.9	5.75
Apple	6/1/3.0 ACSR/Z	49.48	9	14.9	171	79	19.3	0.893
Raisin	3/4/2.5 ACSR/Z	34.36	7.5	24.4	193	134	13.9	2.047

2.2.4 Loads and Customers

Small density of load is a distinguishing characteristic of rural electrification including SWER networks. Typically, a normal SWER line has a load density of around 0.5kVA per kilometre, reported to be in a range of between 0.3 to 0.5kVA, with 3.5kVA as After Diversity Maximum Demand (ADMD) in Queensland, Australia [2, 32, 33]. The maximum customer load size starts from less than 2kW up to around 15kW [3].

SWER distribution level transformers, to be used at the customers, are sized in 10kVA, 25 kVA and 50kVA [3]. The distance between the customers varies from one to 20km due to SWER low load densities. They are fed by distribution transformer secondary windings with voltage levels of either 240V or 480V. A typical SWER customer transformer mounted on a termination pole at the end of the branch is shown in Figure 2.4.

Figure 2.4: SWER customer transformer [34].

2.2.5 SWER Advantages

The SWER network key advantages are outlined below [2, 20, 35]:

- Simplicity: Can be constructed quickly due to simple design and simple wire.
- Maintenance: Simple and cost effective to maintain as a result of having one wire and less pole top hardware.
- Cost: Fewer protection and switching devices decrease the capital cost
- Metering: Less complicated metering method as Low Voltage (LV) instruments are able to connect directly to the earth lead.
- Hazards: Hot metal and arcing are the result of two wires clashing. Using only one wire significantly decreases the possibility of hazards.
- Spans: A single light conductor makes the spans longer and the pole quantity fewer.
- Reliability: Increased network reliability due to a decrease in equipment failure.

2.3 SWER Issues

SWER networks do suffer from some issues relating to their design and operation. Some of these issues will be investigated in this part of study. There are three main concerns:

- Load growth
- Ferranti effect
- Voltage regulation

2.3.1 Load Growth

Over the last decades Australia has seen a substantial rise in its energy usage, including electricity. SWER electricity consumption is increasing at an average of 3% per annum [32, 36]. However, this does depend on the geographical location, and the load type to be used. Demand growth can be increased to 7% as an average [37]. It also has to be noted that residential load growth is greater than the consumption growth in significant areas of Australia [38].

Ergon Energy estimates a load growth for a period of 10 years (2015-2025) as 10% Probability of Exceedance (POE). This is illustrated in Figure 2.5. Due to demand, continued growth and limited capacity of peak load supply, Australian energy companies encounter with the experiment of affordability. As a matter of concern, some SWER networks may over loading, or close to entirely cycle capacity or even operating near voltage margin [2].

2.3.2 Ferranti Effect

Voltage increase happening at the receiving end of a long energized power lines compare to the sending end voltage is known as the Ferranti effect. Usually, it appears on a live long line with a length of more than 80 kilometres and very light load. In fact, the greater the voltage and the longer the length of line, the greater the Ferranti effect will be. Such lines include EHV, UHV or SWER [39].

Ferranti effect will be influenced by two associated parameters, line capacitance and charging current. Line capacitance and charging current increase subsequently as the length increases and load current drops respectively. Figure 2.6 illustrates that with increasing distance, the Ferranti effect causes a voltage rise along the line. This effect is not notably remarkable in many distribution networks, but due to long line lengths and off peak light load, it is conspicuous in SWER lines and possibly able to harm electrical apparatus and equipment [34].

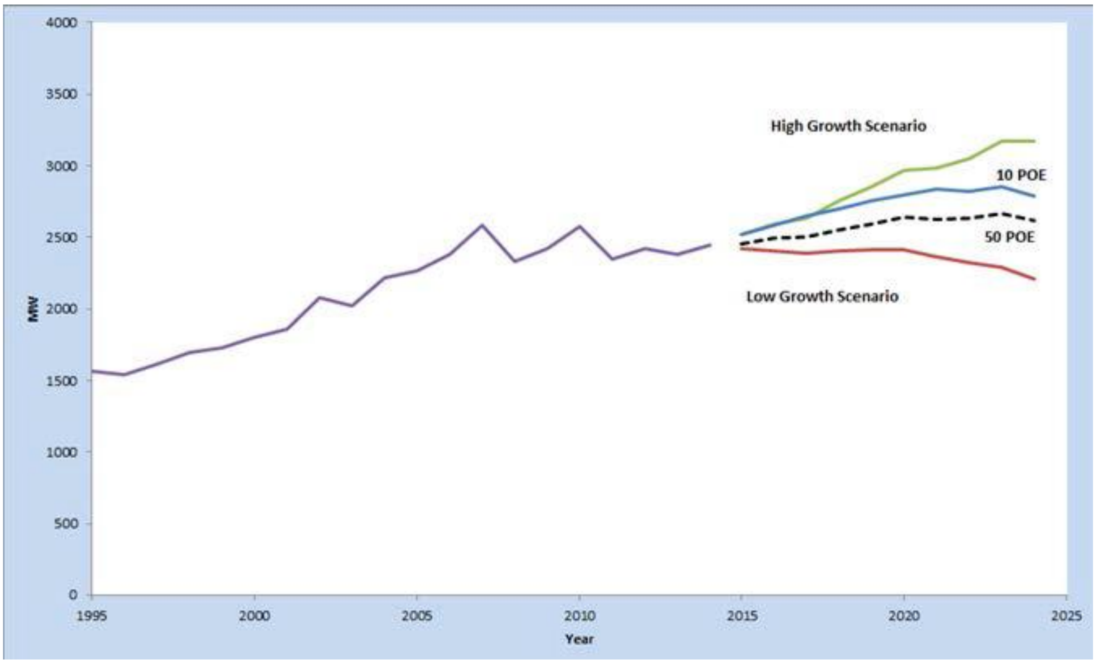


Figure 2.5: System demand forecast(2015-2025, Ergon Energy) [40].

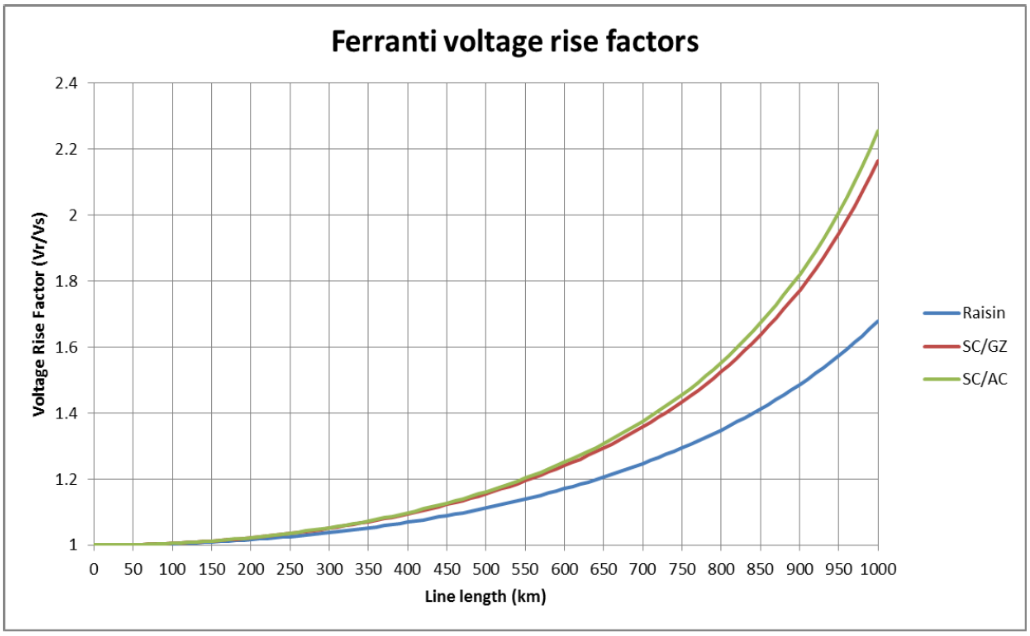


Figure 2.6: Ferranti voltage boost due three SWER conductors [2].

2.3.3 Voltage Regulation

Voltage regulator has been one of the popular forms of power conditioning over the past years. The concept involves monitoring load voltage level (generally RMS value) and adjusting it within acceptable limits. This is defined as a ratio of voltage change magnitude among the sending and receiving end of transmission or distribution line over the receiving end voltage. It presents the power system capacity to deliver almost the steady voltage to customers in different load situations.

Voltage regulation issues can last a few cycles or longer, perhaps many hours. The short term problems can be recognised as voltage sags or surges, and the longer lasting ones are known as a LV and High Voltage (HV) challenges [41].

Voltage regulation in SWER networks is a typical challenge for Australian electrical energy distributers due to a mixture of causes, such as locating at the end of network, where system regulation is already largely high [24]. Field tests performed on SWER networks in 2015 reported both overvoltage and undervoltage problems [40]. In addition, capacity constraints are happening due to voltage regulation issues in SWER lines [5].

2.4 Voltage Regulation Options

Regulating the supplied voltage to customers within acceptable limits is one of the distribution network operator’s responsibilities [42]. Voltage regulation is the main concern for SWER lines within the Ergon Energy distribution portfolio [6].

As a result of performing with the voltage lower than standard, electrical equipment may overheat, break down or operation may be unstable. On the other hand, high voltage can result in component failure or overheating due to voltage stress. In either case, a voltage regulator would be applied to supply voltage within the normal operating parameters of the loads [41]. The desired voltages can be obtained by one of, or combinations of the techniques described in the following subsections [4].

2.4.1 Load Tap Changer (LTC)

Load Tap Changer (LTC) adds turns to or subtracts turns from the winding of transformer which results in a change in voltage level of both sides due to transformer ratio difference. This can be done whether the power transformer is carrying a load or de energised. It would call On Load Tap Changer (OLTC) if transformer number of turn ratio changes while it is supplying the load [7]. Typically, OLTC transformer coupled with a relay named Automatic Voltage Control (AVC) to adjust tap position in order to regulate the voltage [43]. Generally, it determines whether to modify the tap position or not, and will be limited by the number of taps and steps. The OLTC is commonly used in the distribution systems to transform from 33kV to 11kV or 6.6kV [42].

While the secondary voltage noticed to be operating apart from the permitted value, the tap changer mechanism corrects its tap position to recover the required voltage level in order to AVC relay command. The main drawback of this structure is that the limitation of tap changer operation to its tapping constraints and capacity [44].

2.4.2 Series/Shunt Capacitors

One of the major roles of capacitors in power systems is regulating the voltage, whether connected as a single unit or bank, either in series or shunt, or even fixed or switched. In order to minimize the voltage drop caused by inductive reactance, series capacitors act as a negative reactance (capacitive) used to compensate the positive reactance of system.

Using capacitors in series decreases the dropped voltage due to lagged load current for all customers downstream from the capacitor. It performs like a voltage regulator that improves the voltage which is proportional to the current amplitude and power factor angle. Unlike shunt capacitors, the series one minimises the fluctuation of voltage sourced by quick inductive load variation [9]. Upstream customers do not realise any flicker difference [8]. The effectiveness of the series capacitors are less for the more resistive loads. Series capacitors are also more practical and efficient on the system with higher X/R ratios [9]. They have been used to address voltage issues on electrical power networks for more than 65 years, but in limited options. Ferroresonance possibility through downstream transformers, difficulties on short circuit protection and their cost has made them less popular in practice [8].

Power Factor Correction (PFC) is the method shunt capacitors apply to improve the voltage in the power network. Due to shunt capacitor reactive power injection to the system, the source current magnitude is cut down and consequently, the dropped voltage between the source and customer reduced [45]. Moreover, the feeder power and system resistive losses are reduced, due to transmission line current reduction [46].

Switching on the switchable shunt capacitors at the peak demand and switching off these capacitors at the light load would result in boosting their effectiveness. It is important to control the switched capacitor correctly due to load variation during the day [7]. Some of the gains and benefits of shunt capacitor usage include, power bill reduction, system capacity rise, voltage improvement and losses reduction [47]. Distributed LV switched shunt capacitor banks at Weir SWER networks with 400km length and 96 customers are used to provide voltage support [6].

2.4.3 Fixed/Switched Shunt Reactors

Voltage rise occurs due to the charging capacitance of long transmission lines with a light load at the end of the feeder [4]. It might be not noticeable in a typical three phase distribution system, but due to low load density and very long power lines, it is a remarkable challenge for SWER networks. It makes it difficult to keep the SWER customers voltage within an acceptable range [10].

Fixed shunt reactors have been introduced to address such an issue, by installing them in a SWER system to reduce the capacitive loading of the line and regulate voltages during off peak period. Such a solution regulated the voltage issue at light load. These reactors sat on top of the existing load during heavy consumption. It reduced the SWER line load ability and increased the low voltage problem that already existed [4]. The ideal way of combatting this challenge is to replace fixed shunt reactors with a switchable reactor through a circuit breaker or a contactor, including multiple smaller reactors (preferably LV as it is economic and simpler [48]). Voltage problems during peak times can be avoided by switching them off [34, 49]. A low voltage controllable reactor that is connected to the LV side of a SWER distribution transformer, has been proposed to regulate the voltage in two SWER systems, Jericho North and Stanage Bay, located in Queensland, Australia [4, 10].

Switched inductors are used to limit the line voltage rise at light load in a typical transmission system. Likewise, switched shunt capacitors are applied to raise the line voltage at peak load. Unfortunately, a SWER line has a high R/X ratio and these techniques of reactive compensation will be rather limited in the case of SWER networks. The resistive line loss will remain high in any case [50].

2.4.4 Distributed Generation (DG)

Implementing Distributed Generation (DG) in a typical three phase power system has been a popular choice due to several advantages such as power loss reduction, decreased cost, voltage enhancement, system upgrade deferral and improvements in reliability [51]. It operates in a very effective form of voltage support by injecting real power in to the system. It can be generated from renewable or non-renewable sources, throughout various types of technologies [7, 50].

There is great potential for the use of DGs in SWER lines in terms of improving voltage regulation. This is due to SWER lines often being considered as a weaker network with a notable resistive element to the impedance of lines [11]. DG gains cause a line power flow reduction leading to improvement of voltage profile [52]. The voltage rise, due to injected DG power, can be higher at the connection point than substation point; as a result it can pass to the transmission system from distribution level [7].

DGs are considered allocating in two cases, centralised or distributed. Results show a single DG can lead to more benefits for a typical three phase power system. On the other hand, SWER networks with a long power line, distributed customers, and motor starts, can have more benefits allocating distributed DG than a single DG [11]. DG development in diverse technologies and its usage in distribution levels of systems raise a stability concern, and there is a necessity for further study on the avoidance of adverse effects [7, 53].

2.4.5 Voltage Regulator

Voltage regulators were developed to provide a more stable source of voltage than the electric utility can provide [41]. New technologies to improve SWER distribution systems operation, which includes LV voltage regulators, have been introduced recently, although HV voltage regulators are still considered one of the traditional solutions [4]. In comparison with HV regulators allocated at SWER backbone transmission lines, the LV regulators benefit from being cost effective and easy to install [2]. Traditionally, the LV side of a SWER distribution transformer is connected to a single load and supplies just one customer. This means, aside from upstream voltage issues, customer's individual voltage can be adjusted exclusively [2].

A generous regulation range of ±16% and a very short response time of 33 milliseconds make LVRs advantageous and beneficial in terms of SWER system voltage support. Energy companies, like Ergon Energy in Australia installed LVRs in SWER systems in order to enhance the voltage level for their consumers [2]. More than 1000 LVRs are being installed throughout the SWER networks. Figure 2.7 shows LVR mounted on a SWER transformer pole for a 240V single phase supply by Ergon Energy [54].

It should be noted that, in the case of power outage or circuit breaker reclosing, LVRs are not able to maintain supply due to lack of battery backup. Furthers, sags and swells are the concerns that may lead the LVRs in to a temporary pass through due to their voltage operating range [54].

2.4.6 FACTS Devices

Flexible Alternating Current Transmission System (FACTS) devices are a power electronic built structure that arranges part of AC transmission system factors control in order to raise capacity of power transferring and controllability of the network [55]. Parameters such as the voltage needs of a particular customer, power line impedance of a specific pattern, phase shift angle and real and reactive power flow,

Figure 2.7: Low Voltage Regulator (LVR) mounted on a SWER transformer pole for 240V single phase supply [54].

are directly or indirectly related to FACTS devices. In addition, they are also applicable in terms of voltage stability and voltage profile section of electric power systems. Some typical and popular examples of FACTS devices are Static Synchronous Series Compensator (SSSC), Unified Power Flow Controller (UPFC), Thyristor Controlled Series Compensator (TCSC), Static VAr Compensator (SVC) and STATic COMpensator (STATCOM) [12, 13].

It is usual to classify FACTS devices based on their connections type in three different groups; series connected, shunt connected and combined series-shunt. FACTS devices connect to the system in series such as TCSC, control power flow. Shunt connected FACTS devices, such as SVC or STATCOM, however, manage the voltage. Devices like UPFC, which have both series-connected and shunt-connected components, are known as combined series-shunt devices and can control voltage and power flow simultaneously [12].

The three FACTS Controllers, TCSC, SVC and STATCOM, are able to regulate the system dynamic control efficiently [56]. The shunt FACTS devices, SVC and STATCOM are considered as a reactive power source with the capability of avoiding voltage collapse in the system and are able to control its operation at a stable level

[57]. FACTS devices connected in shunt have potential to bring some benefits for power systems due to their usage in appropriate locations and size. Some of these advantages are listed as below [58]:

- Improving voltage profile of power systems
- Reducing or clearing away power line overload
- Boosting power system dynamic and transient stability
- Cutting down the value of energy losses remarkably
- Deferring the necessity of system upgrading
- Adding further capacity to the existing structure

Both STATCOM and SVC are suitable for use in voltage control, compensating regular voltage variation and over voltage reduction [56]. Basically, their operation principals are the same while STATCOM is capable of producing more reactive power during below voltage regulation range and also responding faster due to no delay in thyristor firing of Voltage Source Converter (VSC) [2]. Providing more voltage stability margin than SVC at the weakest bus [59] and having superior performance with newer technology makes STATCOMs completely reliable and a popular choice [56].

2.4.7 STATic COMpensator (STATCOM)

Power electronic parts of STATCOMs are able to control the flow of power in the system and enhance the transient stability of a network. Power electronic control systems adjust the voltage level at the terminals of a STATCOM by regulating the injected or absorbed reactive power from the system. A STATCOM acts in a capacitive mode and injects generated reactive power into the system while the voltage level is less than a certain value. Conversely, it absorbs reactive power from the network and operates like an inductor to bring down the voltage when it is above a certain level [2]. In fact, STATCOMSs are also able to supply or absorb active as well as reactive power by having sources such as a generator or a battery [56].

STATCOM key advantages are listed below [60]:

- Fast dynamic response to system load changes
- Moderation of harmonics
- High efficiency low voltage regulation
- Real power source injection

Much research has been conducted in regard to the usage of STATCOM systems, considering them as a voltage support device to enhance the voltage profile of the system either for typical three phase systems or for SWER networks [14-16, 59-63].

A distributed approach of supporting voltage and modifying reactive power can apply to STATCOM systems in various sites with voltage and reactive power issues for both transmission applications and at distribution levels. This dispersed approach of STATCOM application in the distribution system is referred to as Distribution Static Compensation (DSTATCOM). In the event of a lone bulk reactive support component failure, the risk of reactive power support loss will be lower due to the usage of DSTATCOM in the network [61].

In addition, DSTATCOM has been developed to boost power system efficiency and reliability of a distribution network due to its shunt connected voltage source converter. DSTATCOMs play a vital role in distribution systems in terms of voltage support improvement and power loss reduction, under two different circumstances, steady state and dynamic [64]. Gains such as reactive support, voltage control and quick voltage recovery support, improving system voltage stability, enhancing system transient stability, increasing system reliability, boosting line capacity and decreasing system losses are considered some of the benefits of employing a DSTATCOM system due to flexible voltage and reactive control approaches [61].

Due to the benefits of both FACTS devices and Energy Storage Systems (ESSs), combining DSTATCOM with ESS like Battery Energy Storage (BES) or superconductor devices, can be a means of increasing the flexibility and capacity of such equipment in case of system voltage support. Superconducting Magnetic Energy

Storage (SMES) applied with DSTATCOM can be a solution to raise the capacity of transmission including power flow controls. DSTATCOM has the ability to supply and absorb active and reactive power, known as four quadrant DSTATCOM operation. Not only does this have the ability to raise and lower the voltage, but can also control the series impedance or phase angle of the system. It makes it possible to have a system with lower line losses and transmission lines close to the thermal limits operation [65].

The FACTs are normally reserved for power electronic equipment (SVCs, STATCOMs) used in HV, EHV and UHV transmission. On the other hand, DSTATCOMs are used at distribution level. However design and operation of FACTs and DSTATCOMs are based on the same fundamental principles.

2.5 DSTATCOM Placement

The performance and effectiveness of FACTSs devices like DSTATCOM, either alone or combined with an active power source, will be affected by their number, size and location in the power network. Placement is one of the key criteria and plays an important role. Many researchers have investigated the location of FACTSs devices including DSTATCOMs in order to enhance power network operation using placement algorithms. Some of these algorithms are Particle Swarm Optimization (PSO), Tabu Search (TA), Simulated Annealing (SA), Genetic Algorithm (GA), Evolutionary Algorithm (EA), Bees Algorithm (BA), Harmony Search Algorithm (HSA), Group Search Optimizer with Multiple Producer (GSOMP) and Bacterial Swarming Algorithm (BSA) [65].

One of the other ways of considering placement of DSTATCOM is the possibility of mounting it on the customer side at distribution level or on the network side at transmission level. Either way it could be applied in multiple locations or in a centralised single point placement.

2.5.1 Network Side Injection

The research by [66] presented steady-state performance figures of Voltage Source Inverters (VSI) including DSTATCOM and DG for voltage regulation in a radial distribution system. Devices were connected to the system in parallel through a coupling transformer allowing them to be considered at transmission level. The optimal voltage profile during light load conditions and under full load conditions were accomplished by applying an optimisation algorithm. This was developed by calculating terms of the required active and reactive power for placing voltage support equipment in a single location, or distributed in two locations. It has been concluded that multiple injection, in this case from two locations, will be more effective in enhancing voltage regulation. Furthermore, results show that it would be more efficient for the power to be injected from the end of the line rather than closer to the primary source.

In a similar study [61], a distributed approach of DSTATCOM in multiple locations in order to provide voltage support and reactive power control has been suggested for transmission application and smaller utilities. Results show multiple installation of DSTATCOM is more effective than a single large lumped solution where voltage and reactive power is a concern. Another achievement of the distributed approach is higher system reliability e.g., a single point failure with a single centralised unit removes reactive power support.

Studies by [67] examined DSTATCOM for distribution voltage regulation predominantly on long feeders with voltage issues. It has been considered that a single DSTATCOM mounted somewhere between the source and the customer with a specific distance from the substation. DSTATCOM is given to be a cost effective solution to solve voltage regulation problems in long feeders. DSTATCOM usage for supporting the voltage in a lumped load system raised the system capacity of the line in order to improve its transient response and bulk capacity for voltage control. In addition, DSTATCOM may supply loads with low loss factors as a backup when placed in the middle of a distribution power line.

The study in [60] proposed Real Genetic Algorithm (RGA) technique to find the optimum location for one DSTATCOM in order to improve system voltage security margin under peak load condition. The best location has been carried out to be somewhere in between 2 lines of the test system with significant cost saving and an active power losses reduction on top of voltage security enhancement.

Another study in [63] developed an algorithm named Particle Swarm Optimization-Time Varying Acceleration Coefficients (PSO-TVAC) to support the voltage by supplying or consuming reactive power due to DSTATCOM installation in suitable site and size. The optimal location and size of DSTATCOM found to be beneficial and increased the power system voltage profile on standard IEEE system.

In addition, a recent study in [64] proposed a practical technique with the objective of minimizing losses and improving voltage profile using DSTATCOM. This technique finds the best potential busbar in a radial distribution system, based on different defined indexes, with the aim of raising the candidate bus voltage to 1pu. The results indicate a reduction in active power losses and an improvement in system voltage profile. It was concluded that the DSTATCOM made a significant change in distribution network voltage profile and presents itself as a cost effective and reliable solution in terms of loss saving.

Further research [68] studied the optimal location and sizing of DSTATCOM using Immune Algorithm (IA) in order to improve the current and voltage profile of the system. Biologically inspired algorithm was applied to find the optimum location and size of DSTATCOM in three different load conditions, light, medium and peak. Results show that using this technique to find the optimal size and location for voltage support equipment can decrease power losses, cost of DSTATCOM and current profile and also boost the buses voltage.

The research in [65] proposed a genetic algorithm to find the best location of injecting or absorbing power using DSTATCOM in two different methods, combining with storage or without storage. It has been concluded that using DSTATCOM alone will improve the load ability of a system but not as much as using it combined with storage system. One single DSTATCOM with storage is the best solution to address the voltage problem in the system.

Another study [69] used PSO algorithm to find out the best place and size of DSTATCOM and DG to be used with the objective of improving voltage profile and reducing power losses in radial distribution networks. Based on defined scenarios these devices can be used either alone or together, either in the same place or in a different location. This study examined three different power systems, and all concluded a single result. The optimal placement and size of DG and DSTATCOM boosts the voltage profile and decreases system losses. Moreover, it has to be noted that placement of DG and DSTATCOM in the same bus has been more effective than placement in different buses, with respect to voltage improvement.

In a similar study [70] an analytical method to find the optimal place for DSTATCOM in power networks was proposed. This method is based on a simple load flow to calculate the system power losses and voltage. It has been considered that the DSTATCOM is able to inject and absorb active power as well as reactive power due to its storage device. DSTATCOM has been modelled to maintain the voltage of the connected bus at 1pu. The proposed method was found to be implemented effectively and easily, resulting in system voltage improvement of IEEE 33bus systems. One method, presented in [15] used Particle Swarm Optimisation (PSO) and Continuation Power Flow (CPF) to find the optimum location of DSTATCOM. It aimed, with respect to the DSTATCOM size, to enhance system voltage profile, reduce power losses and improve the load capability of the system. The results showed that following this proposed method of allocating multiple DSTATCOM, in different sizes, distributed in multiple locations which were suffering from voltage problems, can help to reach the mentioned goals. In addition, the voltage stability of power systems remarkably increased using 5 different sized DSTATCOMs, spread over an IEEE 57 bus test power system.

Similarly another study [71] uses the PSO optimisation algorithm to solve efficient size and location problems for multiple DSTATCOM devices in different load conditions from low to peak. The results indicated that, as the size of the load changed, the optimum location of DSTATCOM may vary, but certainly the size was increased. In addition, an important conclusion to consider is as the load increases, the impact of having two DSTATCOM units in the network becomes more effective than having only one, in terms of network voltage improvement.

Recently, a report from Ergon Energy [72] showed that the Grid Utility Support System (GUSS) units are an advanced, cost effective technology solution that will improve the quality and reliability of electricity supply to rural customers on constrained single wire high voltage distribution lines, known as SWER. GUSS works on rural and remote sections of the electricity network by charging batteries overnight, when demand for electricity is low, and discharging during peak demand periods. The main functions of GUSS are peak load reduction and voltage support of the SWER line. Additionally, customers on constrained networks who have had to limit their demand due to the available capacity may be able to access additional supply.

2.5.2 Customer Side Injection

The study in [73] compared two voltage compensation schemes of DSTATCOM. One to be placed alone where it is connected at a single feeder node, or multiple installations, where two of them are connected to two different places along a feeder. It is assumed that DSTATCOMs are connected at the customer at distribution level and are considered to be a customer side injection solution. The steady state results indicate that distributed point reactive power injection can greatly enhance the system voltage profile compared to single point injection.

SVC in [74] and DSTATCOM in [75, 76] were proposed as load Voltage Support (VS) equipment in a radial distribution network to be installed, in order to boost the voltage profile of the system. Both are considered as VAr compensator only with no storage elements and the line resistance has been ignored, as it assumed to be small compared to the line reactance. Results indicated that spreading out the VS devices between all loads and placing them at the customer side was advantageous over lumped VS on the network side. Benefits mentioned were lower VAr requirements, enhanced voltage regulation, cost effectiveness and higher reliability.

Similar studies in [75, 77] introduced Static VAr Systems (SVS) to regulate the voltage when the load centres required support. These studies examined whether voltage support devices, with the availability of DSTATCOM or SVC, should be connected to a single or a few large SVS, connected on the network side through a transformer, or distributed amongst a number of smaller ones in between customers without the need for transformers. It was concluded that distributed individual SVS, placed at the distribution level among the loads was more beneficial than centralised support equipment mounted at the transmission line level.

2.6 Load Sharing Control Methods

The DSTATCOM, as a source of active and reactive power, has to be considered from a control and load sharing point of view. To accomplish proper flows of real and reactive power in the system, several control techniques are proposed. The most popular ones are the master-slave control method [78], the power deviation control method [79], and frequency and voltage droop methods [80]. The droop technique is one of the most effective methods of control that is able to organise automatic load sharing between generators and develops the inverter operating power with the given ratings [81].

2.6.1 Droop Based Control Method

Researchers have recently been more interested in the employment of droop control methods, with the following advantages: [82-86]:

- Easy implementation
- No communications required
- Flexibility, redundancy and expandability
- High reliability
- Different power ratings

As reported in [87], the concept of the voltage droop control method can be applied to different types of networks such as radial, meshed and SWER distribution systems. The Q-V droop method is considered as a popular technique to control the PCC voltage magnitude as studied in [88]. Two different types of droop method, frequency and voltage, are developed by the researchers in [89-91]. As these are decentralized control methods, the real power-frequency droop (P–f) control and the reactive power–voltage droop (Q–V) are used in distributed energy resources (DERs), Interface converters (DICs) [78, 86, 88, 92-97], micro grid environment [92, 94] and UPS systems [78, 86, 93]. This control strategy can be adopted with no external communication in between the units (inverters) [90, 98], to avoid circulating currents [96, 99, 100]. It can be a suitable method to control injected active and reactive powers to the grid [101].

2.6.2 Modified Droop Control Method

Modifying the conventional droop control method will improve the load sharing of the power network as reported in [102]. The power sharing between the inverters via several control designs are investigated in [85, 103-106]. Furthermore, the droop method with some modification was developed to make the system operation stable and secure [94, 96, 107-116]. In these papers, real and reactive power controls the frequency and voltage respectively.

A new droop control technique for interline photovoltaic (IPV) systems has been proposed in [117]. The Point of Common Coupling (PCC) voltage on the system will be regulated via IPV, which is operating as a FACTS device. To achieve voltage regulation in the system, the coupling effect between active and reactive powers, due to complex network impedance has to be considered. The modified P-Q-V droop control strategy is able to regulate the PCC voltage in low X/R ratio systems. The performance of typical and proposed droop control is compared and analysed.

As shown in [118], to improve the stability of parallel inverters in regards to boundedness and load sharing, the new droop named Bounded Droop Controller (BDC) is proposed. The BDC also introduces a bounded characteristic for the control output by considering the theory of Robust Droop Control (RDC). The closed loop stability of the system for the proposed bounded control method, regardless of the load type, (linear or nonlinear), is analysed via the small gain theorem. To increase the robustness of the controller against numerical errors and external disturbances, its structure is modified by forming an attractive oscillator scheme.

The combination of conventional and modified droop methods to control the system voltage is proposed in [119]. It has been considered as a reliable and effective technique in low voltage distribution networks in cases of severe voltage issues. It works by changing the mode of droop control from typical to modified droop control and vice versa. The conventional droop method controls the voltage while it is within the Voltage Dead Band (VDB). On the other hand, when the voltage is operating below or above the VDB, the modified droop control method will be applied to regulate the voltage within the requested range. It is concluded that the proposed droop control method can extend the state of voltage emergency and keep it in the normal level.

To improve the reactive power sharing of DG units in AC micro grids, a new reactive power control technique is developed in [120]. The proposed control method is based on the operation of sharing error reduction and voltage recovery. The voltage bias of the droop characteristic curve is activated by the low-bandwidth synchronization signals and changed via sharing error reduction operation. The voltage recovery operation is performed to restore the output voltage to its rated value. Simple communications between the DGs has been considered to improve their power sharing and it does not affect the plug-and-play feature of each DG unit. As only a low bandwidth communication network is needed, it is recognised to be a cost effective and practical control method.

Another new load sharing method for parallel connected three phase VSCs is adopted in [121]. In this study the focus is on improving the frequency droop for real power sharing and developing a new droop control method for reactive power sharing. The improved frequency droop method operates on the phase angle of the VSC instead of frequency. To achieve the desired system response, the operator tunes the real power sharing controller without adding an integral gain term into the real power control algorithm to regulate the frequency. On the other hand, the new reactive power sharing applies integral the load bus voltage control, combined with a reference that is drooped versus reactive power output. The desired speed of response will be achieved by varying the gain of integrator without affecting voltage regulation

In [122] the operation of droop control is improved as the decentralized control strategies in DICs for autonomous power sharing. In this study the voltage restoration mechanism is applied in the Q-V droop control method to improve the reactive power sharing among DICs in the network. In the new reactive power-voltage droop control method, the voltage shows the rate of change of the voltage magnitude with time. The mentioned mechanism is proposed to maintain the magnitude of voltage at steady state.

Searching for optimal values of the droop coefficients is also addressed in [123], where the share of reactive power supply is determined by using particle swarm optimisation.

There are several methods reported in [124] to simulate distribution systems over the last few decades. These network simulations are known as power flow and the most common calculation procedure is based on the solution of the non-linear equations of the studied network by means of a Newton-Raphson solver. Modified Newton Raphson (MNR) method is applied for implementation of the DG droop control method into a load flow through a novel approach for an islanded micro grid in [125].

In [62] it is reported that the recent increase of DGs in distribution networks has made necessary the development of new control strategies for the mitigation of power quality issues. One of these functions, considered as one of the most promising solutions for the management of voltage congestion, is represented by the droop control method of DG units. The traditional power flow formulation often does not allow for easy integration of these functionalities in the simulation environment and alternative strategies are normally adopted in order to investigate the effects of local controllers on the network electrical quantities. This study applied a simple modification for power flow that allows the integration of local controllers for distributed generation.

2.7 Summary

This chapter provided a brief overview of SWER line characteristics and related issues including voltage regulation. It also provided a literature review on the voltage regulation options to be applied in SWER systems. The concept and application of a STATCOM as voltage support equipment were also reviewed in this chapter. In addition, a comprehensive literature review discussed the placement of DSTATCOM in terms of system voltage improvement, either by centralised or decentralised application. It also analysed the possibility of network side injection or customer side injection placement. However, a clear study on DSTATCOM placement as voltage support equipment to be installed at distribution level or SWER line level has not been reported in literature. Moreover, the DSTATCOM operation point in networks with different specifications and load situations and its effect on system voltage has not been discussed.

This chapter also provided a review of parallel invertor operation and load sharing control methods. It also discusses the different modifications applied to improve the load sharing of active and reactive power components in the network. It has also been reported that the reactive power will not be shared accurately and in some stages, it can result in reactive power circulation and stability problems. The modification to be applied in the DSTATCOM droop control method to avoid VAr circulation has not been reported. Moreover, the control mode of DSTATCOM from a voltage support point of view and a practical solution to avoid islanding in the network has not been discussed in literature. In addition, the implementation of a droop based DSTATCOM control mode in a load flow study has not been reported.

CHAPTER 3

DSTATCOM PLACEMENT AND OPERATING POINT IN SWER SYSTEM

3.1 Introduction

In this study DSTATCOM is being used as voltage support equipment in a SWER system. When considering placement of DSTATCOMs, there is the possibility of mounting it on the customer side or the network side. Firstly, the DSTATCOM will be considered as a reactive power source, able to support the voltage via VAr compensation. Secondly, the four quadrant DSTATCOM, as a source of active and reactive power, will be applied. After that, the effect of voltage support equipment location, load size and SWER line R/X ratio on the DSTATCOM operating point will be investigated. After that, voltage sensitivity analysis is performed to assist with discussion of the DSTATCOM operating point. Finally, the SWER system configuration is developed, using MATLAB, to study the DSTATCOM location and operating point as voltage support equipment.

3.2 Long SWER Line Voltage Support

In order to provide dynamic voltage support by VAr compensation, DSTATCOM will be used. The compensator is treated as a reactive current source. To cancel voltage drop and to keep load voltage within nominal values, additional capacitive current has to be injected into the system.

Two SWER line voltage support schemes are presented in this section:

- Voltage support provided by DSTATCOM at the Network Side (DS.NS).
- Voltage support provided by DSTATCOM at the Customer Side (DS.CS).

If the voltage support is provided on the customer side; the injected capacitive current leads the voltage by 90°. If the voltage support is provided on the network side, then the injected capacitive current leads the customer transformer primary voltage by 90°. In both cases the line current is the vector summation of the load current and compensation current.

3.2.1 Single Line Diagram of a Four Bus SWER System

A single line diagram of a simple SWER line including four nodes is shown in Figure 3.1 The SWER line is connected to an infinite bus with voltage V_1=1pu. Transformer T_{12} is an isolating transformer which is located between bus 1 and 2 and transformer T_{34} connects the line to the load and is located between buses 3 and 4. The SWER line is a long SWER line with a high R/X ratio. The SWER line impedance is represented by R+jX . The load R_L is connected to bus 4 as a customer and draws I_L from the network.

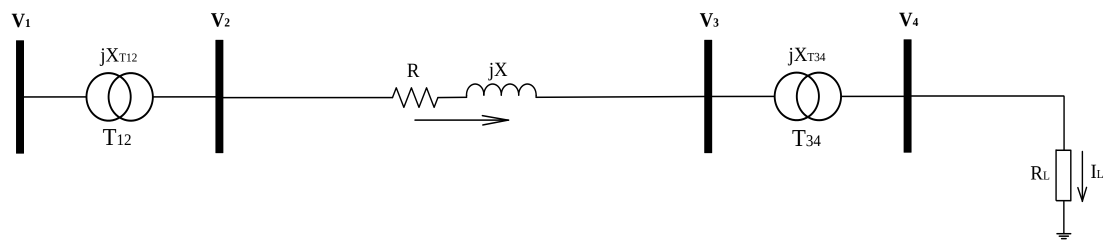


Figure 3.1: Single line diagram of a four bus SWER system.

3.2.2 Phasor Diagram

In this part of study, the power factor of the load is assumed to be corrected. The current drawn by the load depends on the load impedance and the voltage V_4. Current causes the voltage drop in the transformer and line reactance which results in a drop in transmission voltage V_3 and the load voltage V_4. The load voltage V_4 is in phase with the load current I_L. This is represented by the phasor diagram as shown in Figure 3.2.

Load current and voltage are in phase as the power factor is corrected to be unity. Voltage drop is caused by the load current I_L, through the SWER line impedance R+jX and isolating and distribution transformer reactance $j(X_{T12}+X_{T34})$. It means the voltage drop at bus 4 will be the amount of $R+j(X+X_{T12}+X_{T34})$ multiplied by I_L.

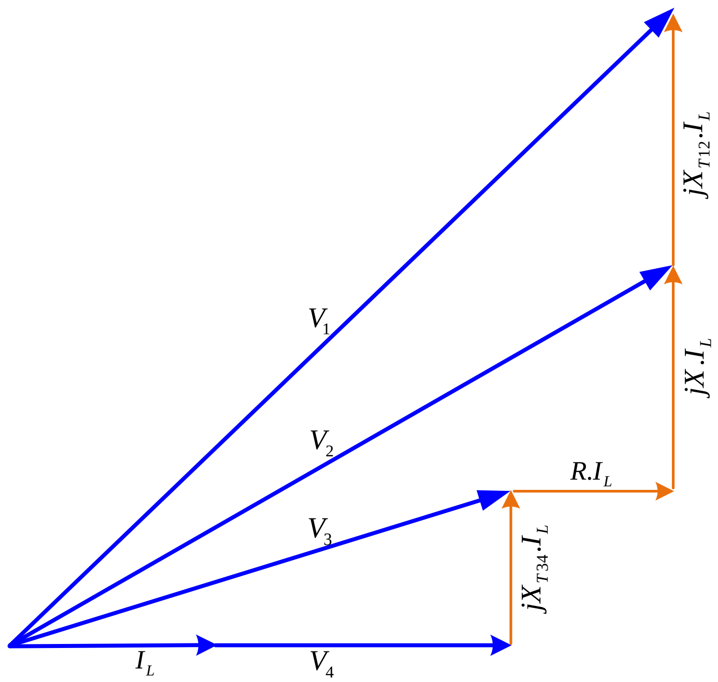


Figure 3.2: Phasor diagram of a four bus SWER system.

3.3 Placement of Voltage Support Equipment

In this part of the study, the same size DSTATCOM will be located in two different locations, .i.e. the network side and the customer side.

3.3.1 Network Side Voltage Support

The DSTATCOM in this instance is voltage support equipment provided on the network side. Figure 3.3 shows single line diagram of a four bus SWER system, including a network side DSTATCOM. As can be seen, the DSTATCOM is connected to bus 3, which is the supply side of the customer transformer. The network side DSTATCOM current is $I_{DS.NS}$. All the voltages, except V_1, will be changed due to the installation of DSTATCOM at bus 3.
It is possible to calculate the value of voltage support due to the DSTATCOM reactive current ($I_{DS.NS}$) injection into the network side of the customer transformer.

Voltage boost due to the network side DSTATCOM injection at bus 4 is $\Delta|V_{4.NS}|$ and will be calculated as below:

$$|V_{4newNS}| - |V_4| = \Delta|V_{4.NS}| \tag{3.1}$$

$$\Delta|V_{4.NS}| = |R_L(I_L - I_{LnewNS})| \tag{3.2}$$

$$|I_L - I_{Lnew}| = \left|\frac{jI_{DS.NS}(R + j(X_{T12} + X))}{(R + R_L) + j(X_{T12} + X + X_{T34})}\right| \tag{3.3}$$

Substituting equation (3.3) in (3.2) will show the voltage change at bus 4 as follows:

$$\Delta|V_{4.NS}| = \left|R_L \cdot \frac{jI_{DS.NS}(R + j(X_{T12} + X))}{(R + R_L) + j(X_{T12} + X + X_{T34})}\right| \tag{3.4}$$

As shown in equation (3.4), $\Delta|V_{4.NS}|$ is the voltage boost at bus 4 due to DSTATCOM current injected $I_{DS.NS}$ at bus 3.

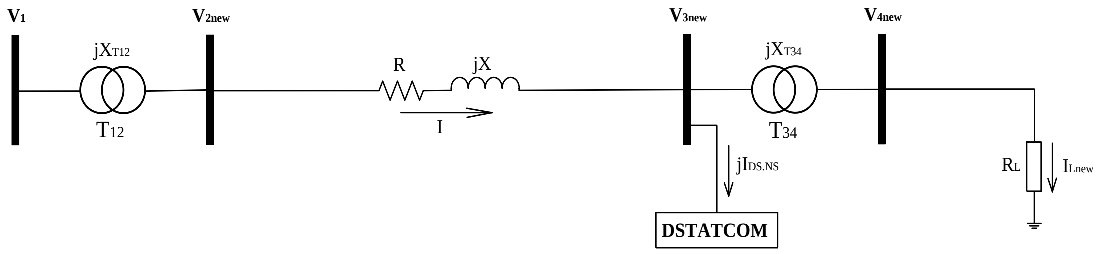


Figure 3.3: Single line diagram of a four bus SWER system including network side DSTATCOM.

3.3.2 Customer Side Voltage Support

A single line diagram of a four bus SWER system including a customer side DSTATCOM is shown in Figure 3.4. The injected current from customer side DSTATCOM $I_{DS.CS}$ will increase all bus voltages except V_1.

Voltage boost due to the customer side DSTATCOM at bus 4 is $\Delta|V_{4.CS}|$ will be calculated as below:

$$|V_{4newCS}| - |V_4| = \Delta|V_{4.CS}| \tag{3.5}$$

$$\Delta|V_{4.CS}| = |R_L(I_L - I_{LnewCS})| \tag{3.6}$$

$$|I_L - I_{Lnew}| = \left|\frac{jI_{DS.CS}(R + j(X_{T12} + X + X_{T34}))}{(R + R_L) + j(X_{T12} + X + X_{T34})}\right| \tag{3.7}$$

Substituting equation (3.7) in (3.6) will show the voltage change at bus 4 as follows:

$$\Delta|V_{4.CS}| = \left|R_L \cdot \frac{jI_{DS.CS}(R + j(X_{T12} + X + X_{T34}))}{(R + R_L) + j(X_{T12} + X + X_{T34})}\right| \tag{3.8}$$

As shown in equation (3.8), $\Delta|V_{4.CS}|$ is the voltage rise at bus 4 due to DSTATCOM injected current $I_{DS.CS}$ at bus 4.

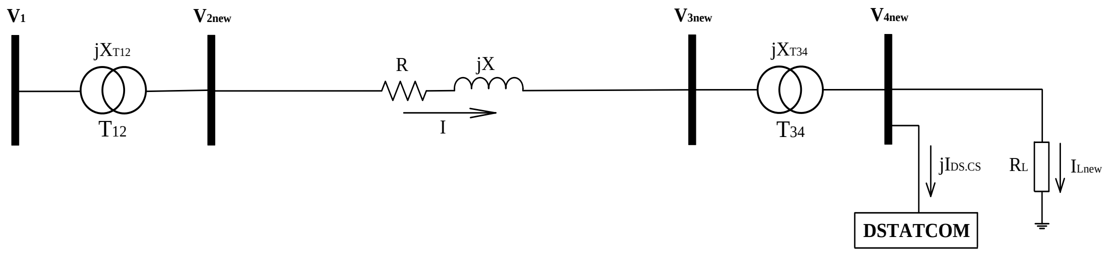


Figure 3.4: Single line diagram of a four bus SWER system including customer side DSTATCOM.

3.3.3 Comparison of Two Voltage Support Schemes

As the same size DSTATCOM is installed in two different locations, both injected currents are equal in magnitude, as per equation (3.9).

$$\left|I_{DS.CS}\right| = \left|I_{DS.NS}\right| \tag{3.9}$$

DSTATCOM injection currents are equal. In this case the only difference is the location of injection which could be either the network side or customer side. The magnitude of voltage boost achieved at bus 4 due to the network side DSTATCOM and customer side DSTATCOM are expressed in equations (3.4) and (3.8) respectively. To evaluate the effectiveness of both types of DSTATCOM placements in terms of voltage support, the ratio of the voltage rise due to customer side current injection over network side injection will be calculated as below:

$$\frac{\Delta\left|V_{4.CS}\right|}{\Delta\left|V_{4.NS}\right|} = \left|\frac{R + j(X_{T12} + X + X_{T34})}{R + j(X_{T12} + X)}\right| \tag{3.10}$$

From equation (3.10), as the nominator is greater than denominator, this ratio is always more than one. This implies both placements of DSTATCOM, either network side or customer side, will provide voltage boost, but it is a more pronounced boost when DSTATCOM is placed on the customer side due to the customer transformer reactance X_{T34}.

Network side DSTATCOM compensation current $I_{DS.NS}$ passes through isolating transformer reactance and SWER line reactance $j(X_{T12}+X)$ but customer side DSTATCOM compensation current $I_{DS.CS}$ passes through a larger reactance $j(X_{T12}+X+X_{T34})$. This compensation current produces a higher voltage boost when DSTATCOM is located on the customer side.

More importantly, this ratio will be affected by system impedance and SWER line R/X ratio while load and DSTATCOM size will not influence this value.

As shown in equation (3.11), the R/X ratio of the network side installed DSTATCOM is greater than the R/X ratio of the one placed on the customer side:

$$(R/X)_{N.S} > (R/X)_{C.S} \tag{3.11}$$

As a result, locating DSTATCOMs on the customer side of SWER lines to support the voltage will be more effective than on the network side.

3.4 Four Quadrant DSTATCOM

During light load conditions, the Q-only DSTATCOM might be a solution to tackle the voltage problem, but considering load growth, it would not be sufficient and an active power source (generator or energy storage elements such as battery) is required. When it comes to energy storage, cost would be the greatest challenge. Price reduction due to battery technology development is making the DSTATCOM solution more competitive compared to the SWER line upgrading option [3]. An example is the recently implemented Grid Utility Support System (GUSS) in Australia by Ergon Energy [126]. Future batteries will be smaller in size and cheaper in price. It gives researchers an opportunity to include them as a part of solution.

Using a source of active power, any kind, in DSTATCOM system makes it able to absorb or inject active power which means the extra ability of supporting voltage during a heavier load. Four-quadrant DSTATCOM operation will be introduced as voltage support equipment in a SWER system in section 3.6 where stability of the operating point on the P-Q plane is investigated.

3.5 SWER System Voltage Analysis

DSTATCOMs may have a role at network locations suffering from poor voltage regulation. Depending on the load and voltage level, DSTATCOM will operate at a different operating point to improve the voltage.

3.5.1 Single Line Diagram of Two Bus SWER System

A single line diagram of a simple SWER system, including DSTATCOM, is shown in Figure 3.5. The four-quadrant DSTATCOM is used for voltage support. For simplicity, isolating and customer transformer reactance are lumped with the SWER line reactance. The DSTATCOM (P_{DS2}+jQ_{DS2}) and the load (P_{L2}+jQ_{L2}) are connected to bus 2.

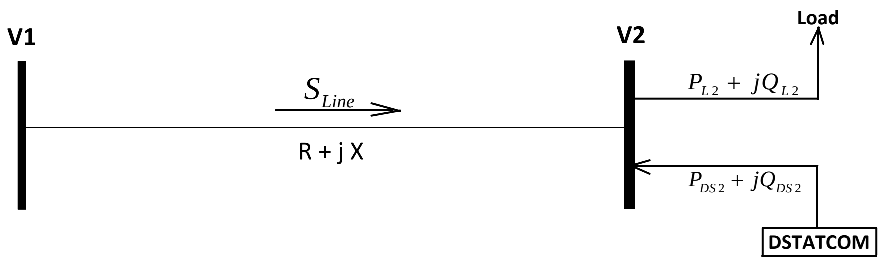


Figure 3.5: Single line diagram of a simple SWER system including four quadrant DSTATCOM.

3.5.2 Voltage Drop Analysis

The phasor diagram of the two bus SWER line is shown in Figure 3.6. As can be seen the customer voltage V_2 will drop due to current passing through SWER line R+jX. From phasor diagram the voltage drop is ΔV with real and imaginary components of ΔV_x and ΔV_y respectively.

Voltage V_1 will be expressed as:

$$V_1 = (V_2 + \Delta V_x) + j\Delta V_y \tag{3.12}$$

Voltage drop is expressed as:

$$\Delta V = \Delta V_x + j\Delta V_y \tag{3.13}$$

In the presence of DSTATCOM we have:

$$\Delta V_x = \frac{R(P_{L2} - P_{DS2}) + X(Q_{L2} - Q_{DS2})}{V_2} \tag{3.14}$$

$$\Delta V_y = \frac{X(P_{L2} - P_{DS2}) - R(Q_{L2} - Q_{DS2})}{V_2} \tag{3.15}$$

Substituting (3.14) and (3.15) in (3.13):

$$\Delta V = \frac{R(P_{L2} - P_{DS2}) + X(Q_{L2} - Q_{DS2})}{V_2} + j\frac{X(P_{L2} - P_{DS2}) - R(Q_{L2} - Q_{DS2})}{V_2} \tag{3.16}$$

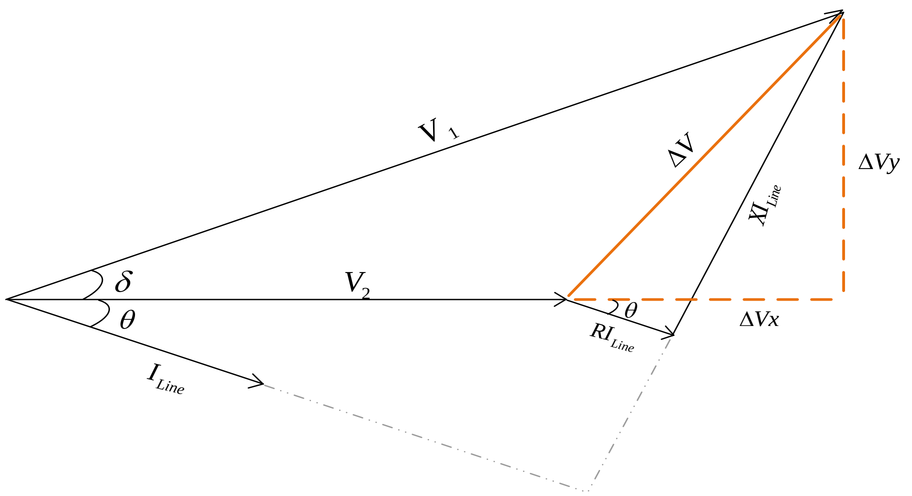


Figure 3.6: Phasor diagram of a two bus SWER system.

From the phasor diagram shown in Figure 3.6, the relationship between bus voltages and the voltage drop components is:

$$V_1^{\,2} = (V_2 + \Delta V_x)^2 + \Delta V_y^{\,2} \tag{3.17}$$

Substituting (3.14) and (3.15) in (3.17):

$$V_1^{\,2} = \left[V_2 + \frac{R(P_{L2} - P_{DS2}) + X\,(Q_{L2} - Q_{DS2})}{V_2} \right]^2 + \left[\frac{X\,(P_{L2} - P_{DS2}) - R(Q_{L2} - Q_{DS2})}{V_2} \right]^2 \tag{3.18}$$

Simplifying (3.18):

$$V_1^{\,2} = V_2^{\,2} + \frac{R^2(P_{L2} - P_{DS2})^2}{V_2^{\,2}} + \frac{X^{\,2}(Q_{L2} - Q_{DS2})^2}{V_2^{\,2}} + \frac{2RX\,(P_{L2} - P_{DS2})(Q_{L2} - Q_{DS2})}{V_2^{\,2}} + 2R(P_{L2} - P_{DS2}) + 2X\,(Q_{L2} - Q_{DS2}) +$$

$$+ \frac{X^{\,2}(P_{L2} - P_{DS2})^2}{V_2^{\,2}} + \frac{R^2(Q_{L2} - Q_{DS2})^2}{V_2^{\,2}} - \frac{2RX\,(P_{L2} - P_{DS2})(Q_{L2} - Q_{DS2})}{V_2^{\,2}} \tag{3.19}$$

$$V_1^{\,2} = \frac{V_2^{\,4} + R^2(P_{L2} - P_{DS2})^2 + X^{\,2}(Q_{L2} - Q_{DS2})^2 + 2RX\,(P_{L2} - P_{DS2})(Q_{L2} - Q_{DS2}) + 2V_2^{\,2}R(P_{L2} - P_{DS2})}{V_2^{\,2}} +$$

$$+ \frac{2V_2^{\,2}X\,(Q_{L2} - Q_{DS2}) + X^{\,2}(P_{L2} - P_{DS2})^2 + R^2(Q_{L2} - QDS2)^2 - 2RX\,(P_{L2} - P_{DS2})(Q_{L2} - Q_{DS2})}{V_2^{\,2}} \tag{3.20}$$

$$-V_1^{\,2}V_2^{\,2} + V_2^{\,4} + 2V_2^{\,2}R(P_{L2} - P_{DS2}) + 2V_2^{\,2}X\,(Q_{L2} - Q_{DS2}) + R^2(P_{L2} - P_{DS2})^2 + X^{\,2}(Q_{L2} - Q_{DS2})^2 + X^{\,2}(P_{L2} - P_{DS2})^2 +$$

$$+R^2(Q_{L2} - Q_{DS2})^2 + \left[2RX\,(P_{L2} - P_{DS2})(Q_{L2} - Q_{DS2})\right] - \left[2RX\,(P_{L2} - P_{DS2})(Q_{L2} - Q_{DS2})\right] = 0 \tag{3.21}$$

$$V_2^4 + 2V_2^2\left[-\frac{V_1^2}{2} + R(P_{L2} - P_{DS2}) + X(Q_{L2} - Q_{DS2})\right] + \left[(P_{L2} - P_{DS2})^2(R^2 + X^2) + (Q_{L2} - Q_{DS2})^2(R^2 + X^2)\right] = 0 \tag{3.22}$$

$$V_2^4 + V_2^2\, 2\left[R(P_{L2} - P_{DS2}) + X(Q_{L2} - Q_{DS2}) - \frac{V_1^2}{2}\right] + (R^2 + X^2)\left[(P_{L2} - P_{DS2})^2 + (Q_{L2} - Q_{DS2})^2\right] = 0 \tag{3.23}$$

Setting $V_2^2 = F$, (3.23) can be rewritten in the form of:

$$F^2 + 2F\left[R(P_{L2} - P_{DS2}) + X(Q_{L2} - Q_{DS2}) - \frac{V_1^2}{2}\right] + (R^2 + X^2)\left[(P_{L2} - P_{DS2})^2 + (Q_{L2} - Q_{DS2})^2\right] = 0 \tag{3.24}$$

In Figure 3.7, the voltage at bus 2 is shown as a function of DSTATCOM active power injection. The voltage change $|\Delta V_2|$ at the peak is zero where V_2 is V_{2Max} and P_{DS2} is P_{V2max}. The voltage at bus 2 reaches its maximum when the DSTATCOM active power injection is P_{V2max}. The vertex is the point (P_{V2max},V_{2Max}). In other words, if the DSTATCOM connected to bus 2 operates with active power injection of P_{V2max}, the maximum voltage support would be available. This means injecting active power greater than P_{V2max} will not improve the voltage any further (equation (3.24)).

From (3.23), V_2 can be expressed as (3.25).

$$V_2 = \sqrt{R(P_{DS2} - P_{L2}) + X(Q_{DS2} - Q_{L2}) + \frac{V_1^2}{2} + \sqrt{\frac{V_1^4}{4} + V_1^2\left[R(P_{DS2} - P_{L2}) + X(Q_{DS2} - Q_{L2})\right] - \left[X(P_{DS2} - P_{L2}) - R(Q_{DS2} - Q_{L2})\right]^2}} \tag{3.25}$$

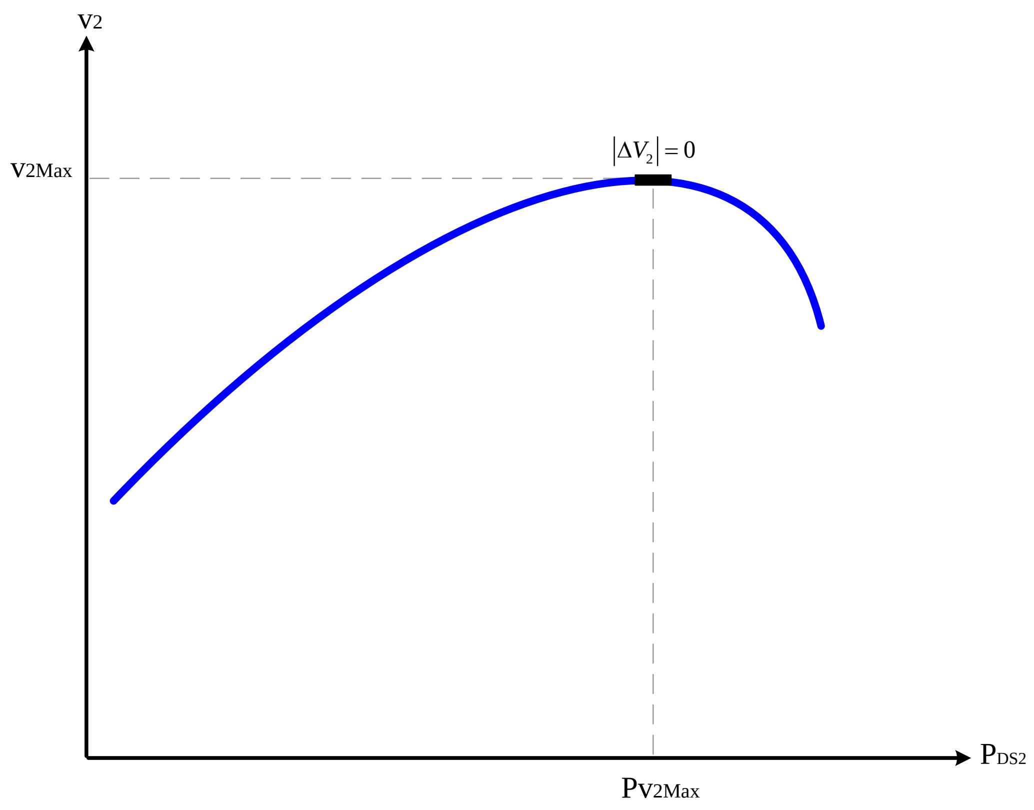


Figure 3.7: Maximum voltage and DSTATCOM active power at bus 2.

As shown in equation (3.25), the voltage at bus 2 is a function of DSTATCOM power, load size, system impedance (R+jX) and SWER system R/X ratio.

Defining net active and reactive power as:

$$P_2 = P_{DS2} - P_{L2} \tag{3.26}$$

$$Q_2 = Q_{DS2} - Q_{L2} \tag{3.27}$$

Equation (3.25) is simplified by substituting (3.26) and (3.27) as:

$$V_2 = \sqrt{RP_2 + XQ_2 + \frac{V_1^2}{2} + \sqrt{\frac{V_1^4}{4} + V_1^2\left[RP_2 + XQ_2\right] - \left[XP_2 - RQ_2\right]^2}} \tag{3.28}$$

The four quadrant DSTATCOM rated power diagram, including the active and reactive power constraints is shown in Figure 3.8. In addition, the operating point of DSTATCOM with size S_{DS2} is labeled. If the DSTATCOM is set to perform at ϕ_{DS2} operating point, it is able to inject active power P_{DS2} and reactive power Q_{DS2} in to the system.

3.6 DSTATCOM Operating Point Analysis

3.6.1 Operation Point Angle

Apparent power in terms of DSTATCOM active and reactive power is given by:

$$P_{DS2}^2 + Q_{DS2}^2 = S_{DS2}^2 \tag{3.29}$$

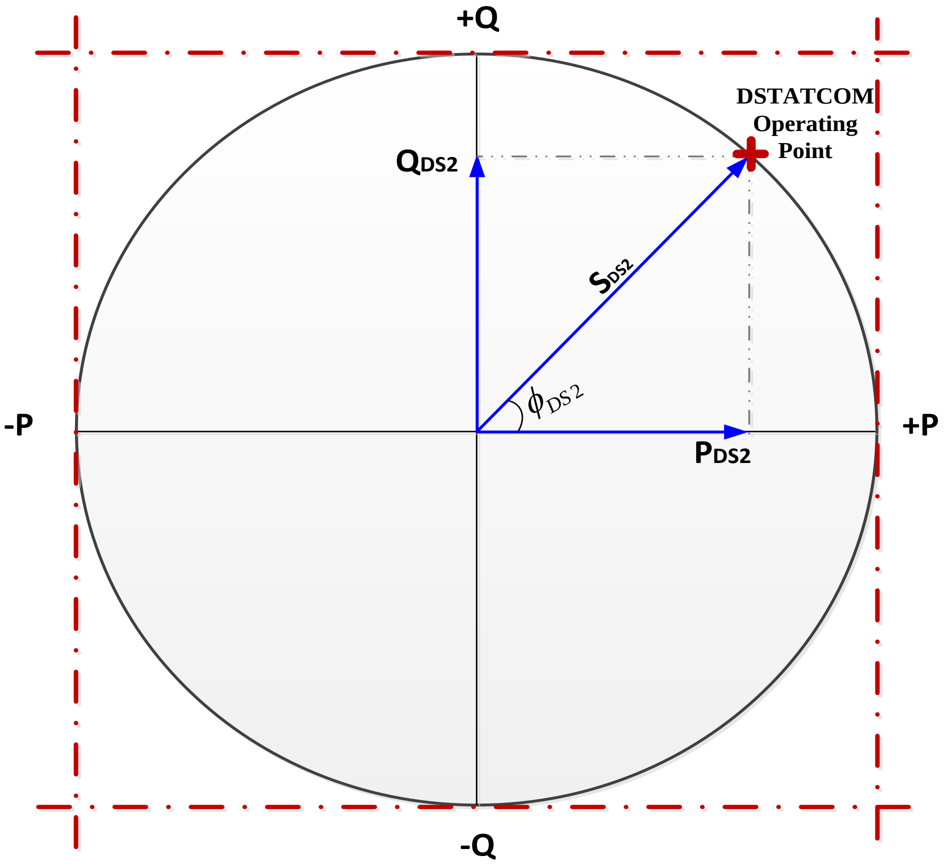


Figure 3.8: Rated power circle diagram of a four quadrant DSTATCOM.

The derivative of (3.29) with respect to Q is:

$$2P_{DS2}\frac{dP_{DS2}}{dQ_{DS2}} + 2Q_{DS2} = 0 \tag{3.30}$$

$$\frac{dP_{DS2}}{dQ_{DS2}} = -\frac{Q_{DS2}}{P_{DS2}} \tag{3.31}$$

The voltage for a given load can be expressed as a function of DSTATCOM active and reactive power that is:

$$V_2 = f(P_{DS2}, Q_{DS2}) \tag{3.32}$$

$$\left|\Delta V_2\right| = \Delta P_{DS2}\frac{\partial V_2}{\partial P_{DS2}} + \Delta Q_{DS2}\frac{\partial V_2}{\partial Q_{DS2}} \tag{3.33}$$

With respect to voltage change at the maximum point being zero, where V_2 is V_{2max} and P_{DS2} is P_{V2max}, an assumption of $\left|\Delta V_2\right| = 0$ will be made and equation (3.33) is rewritten as:

$$\Delta P_{DS2}\frac{\partial V_2}{\partial P_{DS2}} + \Delta Q_{DS2}\frac{\partial V_2}{\partial Q_{DS2}} = 0 \tag{3.34}$$

$$\frac{\Delta P_{DS2}}{\Delta Q_{DS2}} = -\frac{\partial V_2 / \partial Q_{DS2}}{\partial V_2 / \partial P_{DS2}} \tag{3.35}$$

On the other hand, if S_{DS2} is constant, then:

$$\frac{\Delta P_{DS2}}{\Delta Q_{DS2}} = \frac{dP_{DS2}}{dQ_{DS2}} \tag{3.36}$$

Substituting (3.31) and (3.36) in (3.35):

$$\frac{Q_{DS2}}{P_{DS2}} = \frac{\partial V_2 / \partial Q_{DS2}}{\partial V_2 / \partial P_{DS2}} \tag{3.37}$$

Applying (3.37) for a simple SWER system as Figure 3.5:

$$\frac{Q_{DS2}}{P_{DS2}} = \frac{Q_{V2\max}}{P_{V2\max}} = \frac{\partial V_2 / \partial Q_2}{\partial V_2 / \partial P_2} \tag{3.38}$$

Equation (3.38), plotted in Figure 3.9, shows that if DSTATCOM real and reactive power of P_{DS2} and Q_{DS2} are injected at the ratio of its connected node voltage sensitivity $(\partial V_2/\partial Q_2)/(\partial V_2/\partial P_2)$, the maximum voltage enhancement can be obtained.

For a given customer load distribution and at a given DSTATCOM apparent power output, system voltage first rises as active power injection is increased before reaching a maximum and then decreasing. This needs to be taken into consideration when designing the closed loop voltage control system of the DSTATCOM. A stability margin will be needed if the maximum system voltage is on unstable operating point. This point will be introduced as DSTATCOM Steady-state Stability Limit (DSSL) point. In this chapter, DSSL main function is as a DSTATCOM operating within the maximum voltage support range.

Figure 3.10 shows the DSSL lay-out, with the combination of three graphs as already shown in Figures 3.7, 3.8 and 3.9.

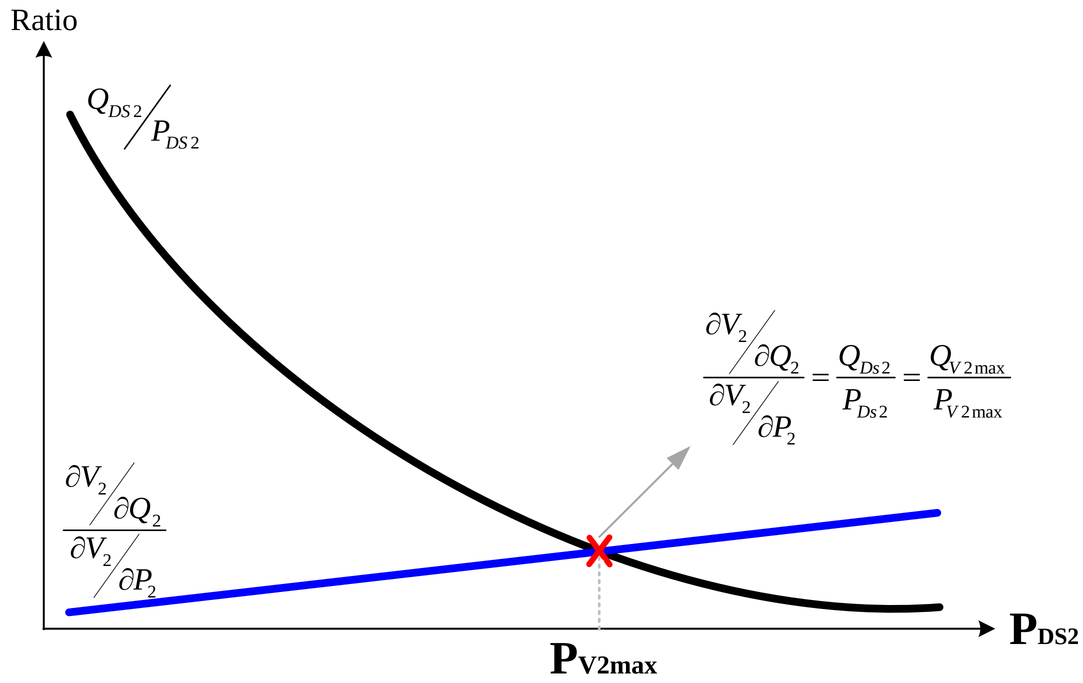


Figure 3.9: Relationship between power and sensitivity ratio, equation (3.38).

From rated apparent power:

$$\phi_{DSSL} = \tan^{-1}\left(\frac{Q_{DS2}}{P_{DS2}}\right) \tag{3.39}$$

Substituting (3.38) in (3.39):

$$\phi_{DSSL} = \tan^{-1}\left(\frac{\partial V_2/\partial Q_2}{\partial V_2/\partial P_2}\right) \tag{3.40}$$

Where: ϕ_{DSSL} is the DSSL angle. If the DSTATCOM at bus 2 operates at this angle the customer voltage will be raised to its maximum.

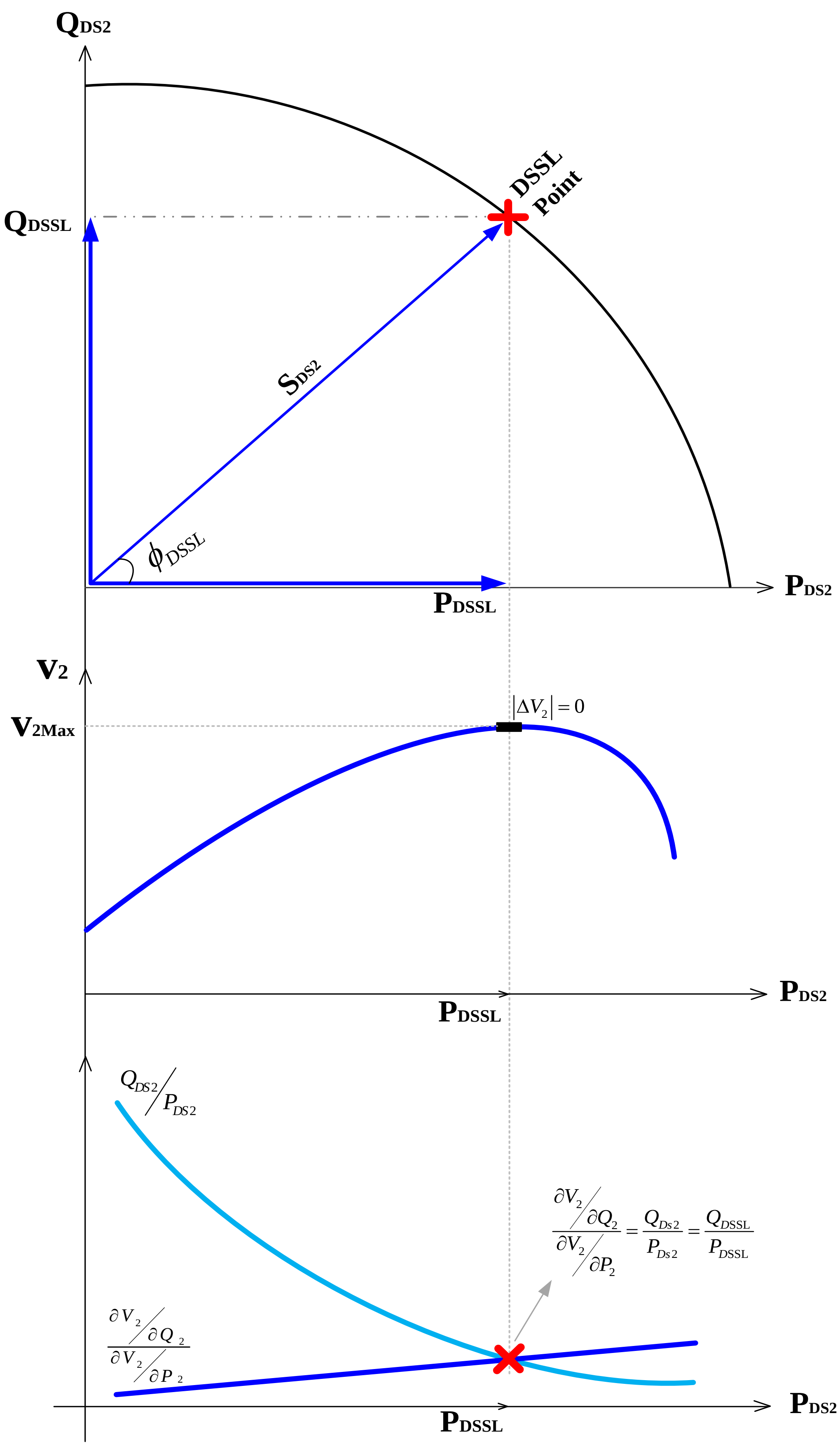


Figure 3.10: DSTATCOM Steady state Stability Limit (DSSL) Point lay out.

3.6.2 Voltage Sensitivity

The DSSL operating point is directly related to the voltage sensitivity of the SWER system. Therefore, before setting the DSTATCOM to its operating point, a sensitivity study should be performed.

Partial derivative of (3.25) with respect to P_{DS2} is:

$$\frac{\partial V_2}{\partial P_{DS2}} = \frac{R + \dfrac{V_1^2 R - 2X^2(P_{DS2} - P_{L2}) + 2RX(Q_{DS2} - Q_{L2})}{2\sqrt{\dfrac{V_1^4}{4} + V_1^2\left[R(P_{DS2} - P_{L2}) + X(Q_{DS2} - Q_{L2})\right] - \left[X(P_{DS2} - P_{L2}) - R(Q_{DS2} - Q_{L2})\right]^2}}}{2\sqrt{R(P_{DS2} - P_{L2}) + X(Q_{DS2} - Q_{L2}) + \dfrac{V_1^2}{2} + \sqrt{\dfrac{V_1^4}{4} + V_1^2\left[R(P_{DS2} - P_{L2}) + X(Q_{DS2} - Q_{L2})\right] - \left[X(P_{DS2} - P_{L2}) - R(Q_{DS2} - Q_{L2})\right]^2}}} \tag{3.41}$$

Partial derivative of (3.25) with respect to Q_{DS2} is:

$$\frac{\partial V_2}{\partial Q_{DS2}} = \frac{X + \dfrac{V_1^2 X - 2R^2(Q_{DS2} - Q_{L2}) + 2RX(P_{DS2} - P_{L2})}{2\sqrt{\dfrac{V_1^4}{4} + V_1^2\left[R(P_{DS2} - P_{L2}) + X(Q_{DS2} - Q_{L2})\right] - \left[X(P_{DS2} - P_{L2}) - R(Q_{DS2} - Q_{L2})\right]^2}}}{2\sqrt{R(P_{DS2} - P_{L2}) + X(Q_{DS2} - Q_{L2}) + \dfrac{V_1^2}{2} + \sqrt{\dfrac{V_1^4}{4} + V_1^2\left[R(P_{DS2} - P_{L2}) + X(Q_{DS2} - Q_{L2})\right] - \left[X(P_{DS2} - P_{L2}) - R(Q_{DS2} - Q_{L2})\right]^2}}} \tag{3.42}$$

Voltage sensitivity ratio is:

$$\frac{\dfrac{\partial V_2}{\partial Q_{DS2}}}{\dfrac{\partial V_2}{\partial P_{DS2}}} = \frac{X + \dfrac{V_1^2 X - 2R^2(Q_{DS2} - Q_{L2}) + 2RX(P_{DS2} - P_{L2})}{2\sqrt{\dfrac{V_1^4}{4} + V_1^2\left[R(P_{DS2} - P_{L2}) + X(Q_{DS2} - Q_{L2})\right] - \left[X(P_{DS2} - P_{L2}) - R(Q_{DS2} - Q_{L2})\right]^2}}}{R + \dfrac{V_1^2 R - 2X^2(P_{DS2} - P_{L2}) + 2RX(Q_{DS2} - Q_{L2})}{2\sqrt{\dfrac{V_1^4}{4} + V_1^2\left[R(P_{DS2} - P_{L2}) + X(Q_{DS2} - Q_{L2})\right] - \left[X(P_{DS2} - P_{L2}) - R(Q_{DS2} - Q_{L2})\right]^2}}} \tag{3.43}$$

$$\frac{\frac{\partial V_2}{\partial Q_{DS2}}}{\frac{\partial V_2}{\partial P_{DS2}}} = \frac{\frac{1}{2}XV_1^2 - R^2(Q_{DS2} - Q_{L2}) + RX(P_{DS2} - P_{L2}) + X\sqrt{\frac{V_1^4}{4} + V_1^2\left[R(P_{DS2} - P_{L2}) + X(Q_{DS2} - Q_{L2})\right] - \left[X(P_{DS2} - P_{L2}) - R(Q_{DS2} - Q_{L2})\right]^2}}{\frac{1}{2}RV_1^2 - X^2(P_{DS2} - P_{L2}) + RX(Q_{DS2} - Q_{L2}) + R\sqrt{\frac{V_1^4}{4} + V_1^2\left[R(P_{DS2} - P_{L2}) + X(Q_{DS2} - Q_{L2})\right] - \left[X(P_{DS2} - P_{L2}) - R(Q_{DS2} - Q_{L2})\right]^2}} \tag{3.44}$$

Net active and reactive power as (3.26) and (3.27) will be used to simplify the voltage sensitivity ratio.

Partial derivative of (3.28) with respect to P_2 is:

$$\frac{\partial V_2}{\partial P_2} = \frac{R + \frac{V_1^2 R - 2X^2 P_2 + 2RXQ_2}{2\sqrt{\frac{V_1^4}{4} + V_1^2\left[RP_2 + XQ_2\right] - \left[XP_2 - RQ_2\right]^2}}}{2\sqrt{RP_2 + XQ_2 + \frac{V_1^2}{2} + \sqrt{\frac{V_1^4}{4} + V_1^2\left[RP_2 + XQ_2\right] - \left[XP_2 - RQ_2\right]^2}}} \tag{3.45}$$

Partial derivative of (3.28) with respect to Q_2 is:

$$\frac{\partial V_2}{\partial Q_2} = \frac{X + \frac{V_1^2 X - 2R^2 Q_2 + 2RX(P_{DS2} - P_{L2})}{2\sqrt{\frac{V_1^4}{4} + V_1^2\left[RP_2) + XQ_2\right] - \left[XP_2 - RQ_2\right]^2}}}{2\sqrt{RP_2 + XQ_2 + \frac{V_1^2}{2} + \sqrt{\frac{V_1^4}{4} + V_1^2\left[RP_2 + XQ_2\right] - \left[XP_2 - RQ_2\right]^2}}} \tag{3.46}$$

Voltage sensitivity ratio is:

$$\frac{\frac{\partial V_2}{\partial Q_2}}{\frac{\partial V_2}{\partial P_2}} = \frac{\frac{1}{2}XV_1^2 - R^2 Q_2 + RXP_2 + X\sqrt{\frac{V_1^4}{4} + V_1^2\left[RP_2 + XQ_2\right] - \left[XP_2 - RQ_2\right]^2}}{\frac{1}{2}RV_1^2 - X^2 P_2 + RXQ_2 + R\sqrt{\frac{V_1^4}{4} + V_1^2\left[RP_2 + XQ_2\right] - \left[XP_2 - RQ_2\right]^2}} \tag{3.47}$$

As can be seen in equation (3.47), the voltage sensitivity ratio will be affected by load, SWER line impedance and system R/X ratio. The greater the voltage sensitivity $(\partial V2/\partial Q2)/(\partial V2/\partial P2)$, the less active power is needed in order to reach the DSSL point and maximize the voltage support.

The active and reactive power at DSSL point is to be calculated from (3.39) as:

$$P_{DSSL} = \frac{S_{DS2}}{\sqrt{1+\tan^2\phi_{DSSL}}} \tag{3.48}$$

$$Q_{DSSL} = P_{DSSL}\tan\phi_{DSSL} \tag{3.49}$$

Where: S_{DS2} is known as a size of DSTATCOM, P_{DSSL} is DSTATCOM active power when it is operating at DSSL point, Q_{DSSL} is DSTATCOM reactive power when it is operating at DSSL point and ϕ_{DSSL} can be calculated from equation (3.40).

Generally, the governing equation of voltage in node 2 as given in (3.25), can be written for DSSL point as:

$$V_{2Max} = \sqrt{R(P_{DSSL}-P_{L2})+X(Q_{DSSL}-Q_{L2})+\frac{V_1^2}{2}+\sqrt{\frac{V_1^4}{4}+V_1^2\left[R(P_{DSSL}-P_{L2})+X(Q_{DSSL}-Q_{L2})\right]-\left[X(P_{DSSL}-P_{L2})-R(Q_{DSSL}-Q_{L2})\right]^2}} \tag{3.50}$$

3.6.3 Load Flow Study

For a realistic SWER system with more customers and equipment, finding the voltage sensitivity as in equations (3.45) and (3.46) will be complicated, and that is where the load flow study becomes important. Load flow calculations are fast and precise and widely used in research [127-129]. In order to determine the DSSL point and find sensitivity for all the load buses, the Newton Raphson load flow approach will be used.

The inverse power flow Jacobian relates changes in power injections to changes in angles and voltages, that is:

$$\begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix} = J^{-1}.\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \tag{3.51}$$

Equation (3.51) shows the angle and voltage amplitude values for all nodes resulting from active and reactive power changes. The inverse of a Jacobian, shown in (3.52), will be the key point in load flow study. In equation (3.52), the elements of Jacobian inverse matrix are shown. As can be seen, it is divided into four sub matrices. The $[J^{-1}]_{11}$ and $[J^{-1}]_{12}$ elements show the voltage angle change due to active and reactive power changes. Also, the $[J^{-1}]_{21}$ and $[J^{-1}]_{22}$ elements show the magnitude of the voltage changes due to active and reactive power changes. For each node in the system, there is an associated real power sensitivity of $\partial V/\partial P$ and reactive power sensitivity of $\partial V/\partial Q$. The diagonal elements of the inverse Jacobian matrix represent the sensitivity of one bus voltage magnitude to the injection of power at the same bus, whereas the off diagonal elements represent the sensitivity to power injected at other buses [4]. Instead of applying equations (3.45) and (3.46), the diagonal elements of $[J^{-1}]_{21}$ and $[J^{-1}]_{22}$ with the values of $\partial V_N/\partial P_N$ and $\partial V_N/\partial Q_N$ for node N will be used to find the voltage sensitivity for each customer.

$$J^{-1} = \left[\begin{array}{ccc|ccc} \frac{\partial\delta_1}{\partial P_1} & \cdots & \frac{\partial\delta_1}{\partial P_N} & \frac{\partial\delta_1}{\partial Q_1} & \cdots & \frac{\partial\delta_1}{\partial Q_N} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \frac{\partial\delta_N}{\partial P_1} & \cdots & \frac{\partial\delta_N}{\partial P_N} & \frac{\partial\delta_N}{\partial Q_1} & \cdots & \frac{\partial\delta_N}{\partial Q_N} \\ \hline \frac{\partial V_1}{\partial P_1} & \cdots & \frac{\partial V_1}{\partial P_N} & \frac{\partial V_1}{\partial Q_1} & \cdots & \frac{\partial V_1}{\partial Q_N} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \frac{\partial V_N}{\partial P_1} & \cdots & \frac{\partial V_N}{\partial P_N} & \frac{\partial V_N}{\partial Q_1} & \cdots & \frac{\partial V_N}{\partial Q_N} \end{array}\right] = \left[\begin{array}{c|c} \left[J^{-1}\right]_{11} & \left[J^{-1}\right]_{12} \\ \hline \left[J^{-1}\right]_{21} & \left[J^{-1}\right]_{22} \end{array}\right] \tag{3.52}$$

3.6.4 Q-Priority

The DG operation with Q priority is the most economical, as it requires less generation energy and reduces the fuel consumption for the same level of voltage requirement.

For low levels of voltage correction, it has been found beneficial for the DG to firstly operate before real power injection, varying reactive power injection from minimum to maximum. At higher levels of voltage correction, it is best to operate the DG at full rating with real and reactive injection. The DG controller needs to increase real power injection and decrease reactive injection slowly and will settle at the point of maximum voltage sensitivity [11].

The DSTATCOM operation and power injection based on Q-priority strategy is shown in Figure 3.11. If reactive power injection is able to support the voltage, no active power will be applied. But, if reactive power injection reached its limitation (to be DSTATCOM size, thermal limitation or stability issues) and the voltage problem still remains, the active power will be used to improve the voltage. In this study the DSTATCOM size is considered as a reactive power compensation limitation. It has to be noted that to keep the DSTATCOM operating point on the power circle, as the active power injected raises, the reactive power is reduced as shown in step 2, 3 and 4 in Figure 3.11. The DSTATCOM operating point angle starts from 90º (ϕ_1) which corresponds to maximum Q and zero P injection. In this chapter the DSTATCOM will be operating following the Q-priority strategy.

3.7 Case Study

In this section two sample networks will be studied. The four node SWER system is shown in Figure 3.12, and a real one with 126 nodes is shown in Figure 3.23.

3.7.1 Simple Four Bus SWER System

The single line diagram of a simple SWER system including four nodes, network side and customer side DSTATCOM and load is shown in Figure 3.12. Customer loads and customer transformers are lumped.

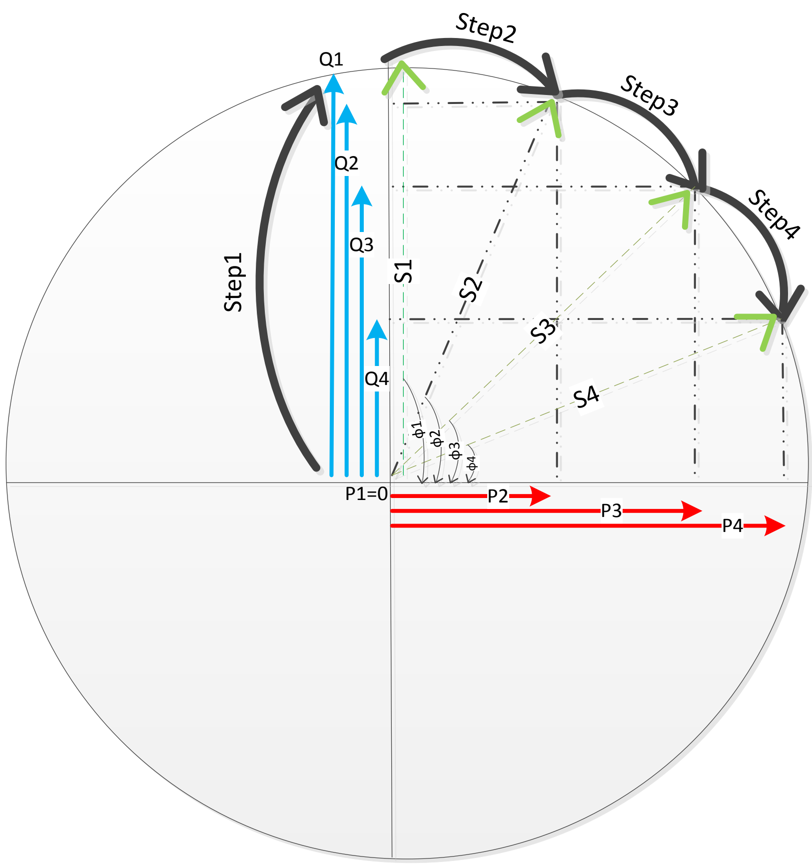


Figure 3.11: Operation of DSTATCOM and power injection based on Q-priority strategy.

The switch $S_{DS.NS}$ connects the DSTATCOM from the network side to the SWER system at bus 3 and switch $S_{DS.CS}$ connects the DSTATCOM from customer side to the SWER system at bus 4. The voltage level of DSTATCOM at bus 4 will be the same as customer voltage V_4, but the network side DSTATCOM voltage needs a step up transformer to increase its voltage to the voltage of the SWER line at bus 3 (it is assumed that a step up transformer is included within the DSTATCOM system). The load is considered to be $P_{L4}+jQ_{L4}$. The DSTATCOM for both sides has the ability to inject or absorb the same amount of reactive power $Q_{DS.NS}$ and $Q_{DS.CS}$. SWER line length L with impedance of $R_{23}+jX_{23}$ is shown, also isolating and customer transformer reactance are jX_{T12} and jX_{T34} respectively.

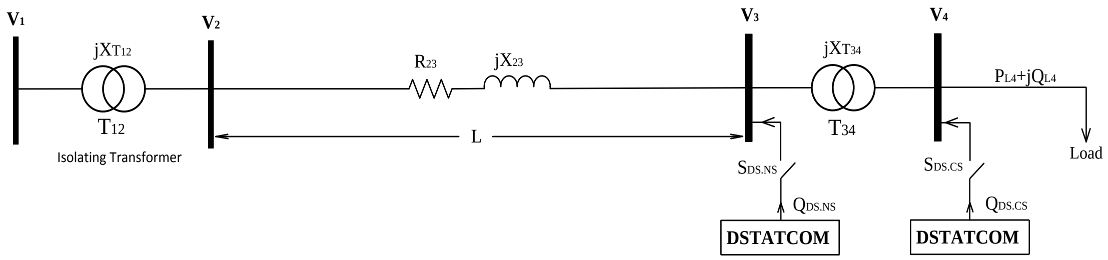


Figure 3.12: Single line diagram of a simple SWER system including four nodes, network side and customer side DSTATCOM and a load.

Table 3.1 shows the simple SWER system specifications that will be used as a first case study.

Table 3.1: Simple SWER system specifications

Isolating transformer	400kVA
Customer transformer	200 kVA
SWER line length	120 km
Conductor type	BANANA
System impedance ($Z_{1\_2}+Z_{2\_3}+Z_{3\_4}$)	0.1524+j0.1526
Load size (%60 of Transformer size)	120kVA
Load power factor	0.9

The magnitude of voltage at bus 4 (V_4) when there is no DSTATCOM connected to the system is calculated to be 0.859pu using equation (3.25). Bus number one is assumed to be an infinite bus with voltage magnitude of 1pu. In this case, three different sizes of DSTATCOM as a percentage of customer transformer size will be considered:

- 60kVAr as 30% of customer transformer rating
- 120kVAr as 60% of customer transformer rating
- 180kVAr as 90% of customer transformer rating

Table 3.2 shows the customer voltage boost $\Delta|V_4|$ due to DSTATCOM reactive power injection for different sizes and locations. The voltage level at bus 4 with network side and customer side DSTATCOM reactive power injection is defined as $V_{4.NS}$ and $V_{4.CS}$ respectively. As can be seen, regardless of the DSTATCOM size, the customer side DSTATCOM improved the voltage to the higher level than the network side one. It means the voltage rise due to VAr compensation at bus 4 through DSTATCOM customer side, $\Delta|V_{4.CS}|$, is greater than that on the network side, $\Delta|V_{4.NS}|$. The ratio of DSTATCOM customer side voltage boost over the network side, $\Delta|V_{4.CS}|/\Delta|V_{4.NS}|$, has not been affected by the DSTATCOM size. As shown in equation (3.10), this ratio will be affected by system impedance and R/X ratio. In this case, $\Delta|V_{4.CS}|/\Delta|V_{4.NS}|$ is more than 1.2 which means, using DSTATCOM at customer side as voltage support, equipment is more effective than network side by more than 20%.

Table 3.2: Customer (lumped) voltage boost due to different DSTATCOM sizes and locations

DSTATCOM kVAr	**V_4 pu**	**$V_{4.NS}$ pu**	**$V_{4.CS}$ pu**	**$\Delta\|V_{4.NS}\|$**	**$\Delta\|V_{4.CS}\|$**	**$\Delta\|V_{4.CS}\| / \Delta\|V_{4.NS}\|$**
60	0.8059	0.8778	0.896	0.0719	0.0901	1.23
120	0.8059	0.9363	0.9671	0.1304	0.1612	1.24
180	0.8059	0.9864	1.0271	0.1805	0.2212	1.25

The SWER line R/X ratio plays an important role in terms of voltage support. The following part investigates its effect on the ratio of voltage change due to DSTATCOM customer side and network side injection. It is assumed that in the case of changing the R/X ratio of line, the impedance remains constant.

Figure 3.13 shows the effect of SWER feeder R/X ratio on the voltage improvement due to DSTATCOM VAr injection at the customer side over the network side for three different DSTATCOM sizes. Load size is fixed at 60% of customer transformer rating. As can be seen the voltage boost is not affected by the size of DSTATCOM, but more so by line R/X ratio. Depending on the R/X ratio of the SWER line, using DSTATCOM at the customer side is more effective than on the network side, up to 70% in this case. The more resistive the system is, the more effective the customer side VAr compensation gets. This means that as the system becomes more resistive the effect of customer transformer reactance becomes more significant in terms of voltage support via reactive power injection.

The effect of load on the system voltage improvement due to DSTATCOM customer side over network side VAr injection in three different sizes is shown in Figure 3.14. As can be seen, it has not been affected by load and DSTATCOM size.

The DSTATCOM with the ability to inject and absorb active and reactive power will be analysed in this part of the study. The focus is on investigating the effect of location and size on the operating point of DSTATCOM in terms of voltage support. Two different possible locations to install the DSTATCOMs are the network side and customer side. Three different DSTATCOM sizes as a percentage of customer transformer size will be used.

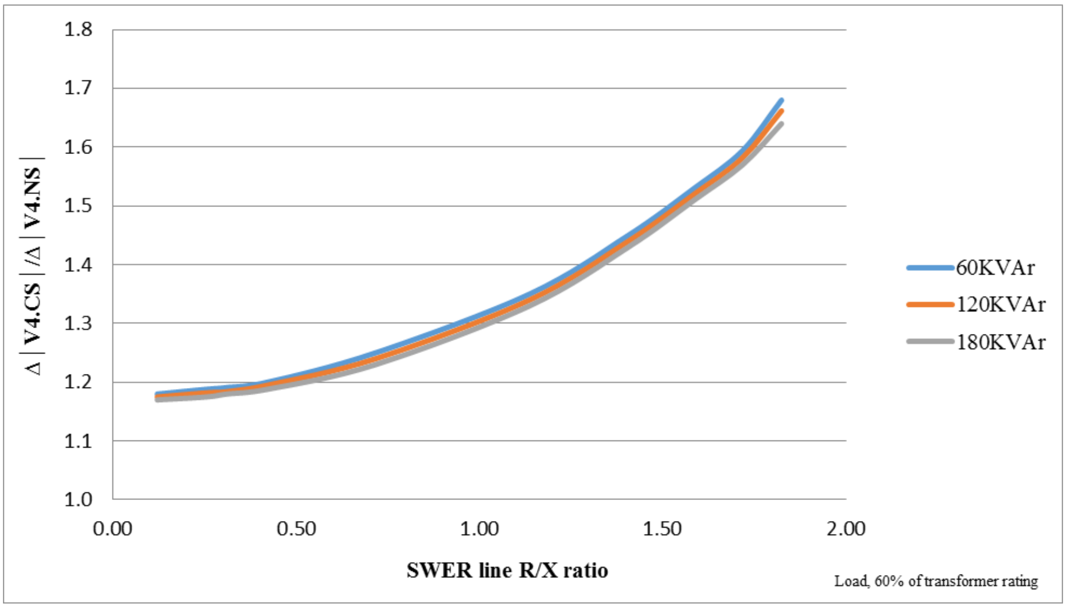


Figure 3.13: The effect of SWER line R/X ratio on the voltage improvement due to DSTATCOM customer side and network side VAr injection in three different sizes.

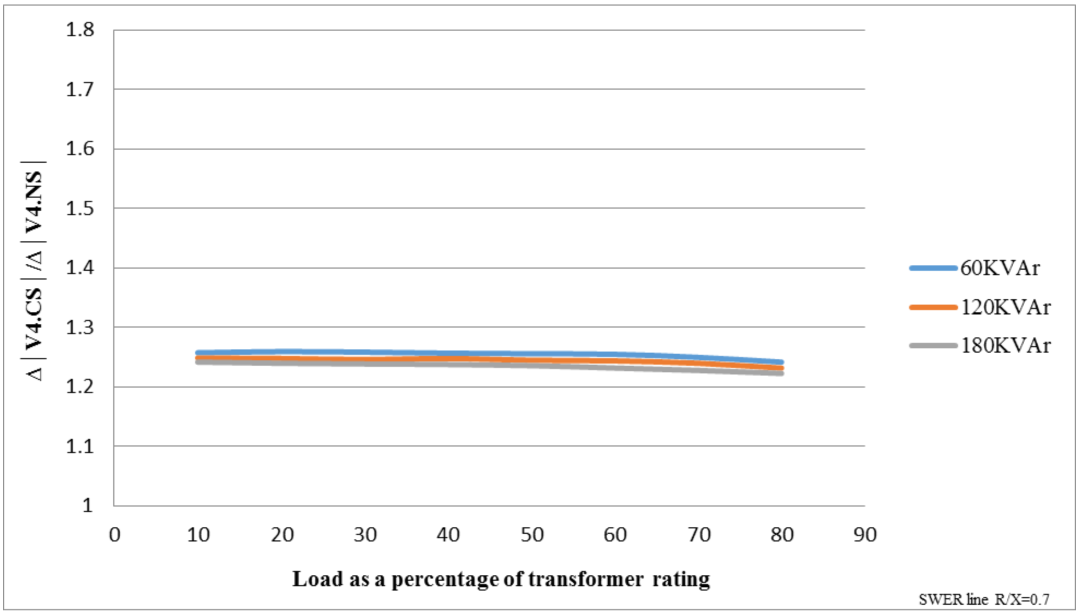


Figure 3.14: The effect of load on the ratio of voltage improvement due to DSTATCOM customer side over network side VAr injection in three different sizes.

Table 3.3 shows the location and size effect of DSTATCOM on DSSL point. As can be seen, DSSL point is not affected by the DSTATCOM rating but it is by location. Regardless of the size of DSTATCOM, the maximum voltage support due to installing the DSTATCOM at the customer side is higher compared to the network side. The DSTATCOM rating effects on the DSSL point when it is located at the customer side and network side are shown in Figure 3.15 and 3.16 respectively. The DSSL angle is not affected by the size of DSTATCOM and it is kept at 42° for network side injection and 35° for customer side. In this case, the DSTATCOM is always operating at this angle to provide the maximum voltage support at the DSSL point, but it is higher when the support is provided at the customer side, as is shown in Figure 3.17.

Table 3.3: Location and size effect of DSTATCOM on DSSL point

DSTATCOM kVA	**V_4** pu	**(∂V/∂Q)/(∂V/∂P)**	**$\phi°_{DSSL}$**		**P_{DS}** kW		**Q_{DS}** kVAr		**V_{4Max}** pu	
			NS	**CS**	**NS**	**CS**	**NS**	**CS**	**NS**	**CS**
60	0.8059	1.14	35	42	50	45	35	40	0.9181	0.9342
120	0.8059	1.14	35	42	99	90	69	80	0.9755	1.003
180	0.8059	1.14	35	42	148	134	104	120	1.0269	1.0638

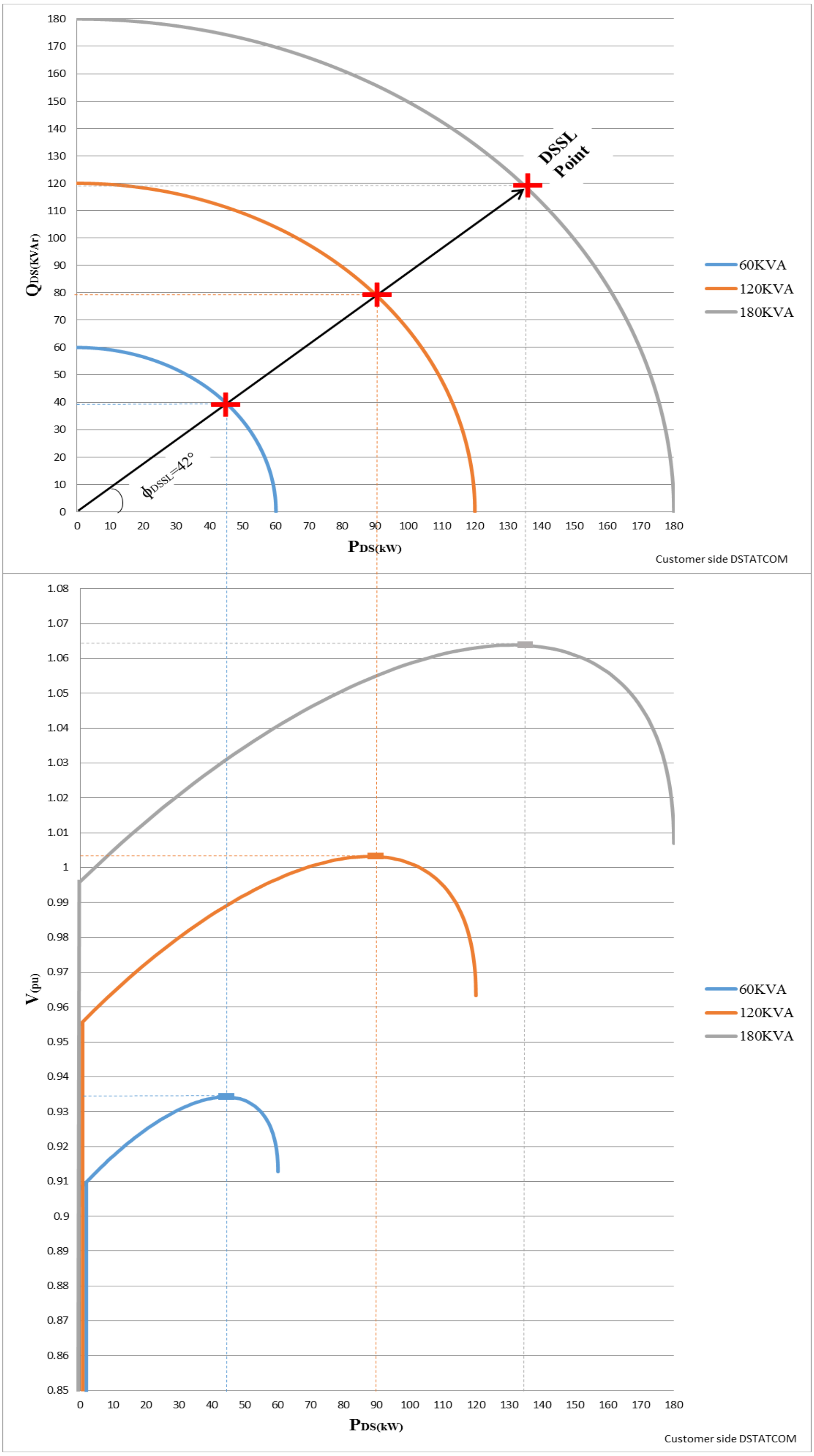


Figure 3.15: DSTATCOM size effect on customer side DSSL point.

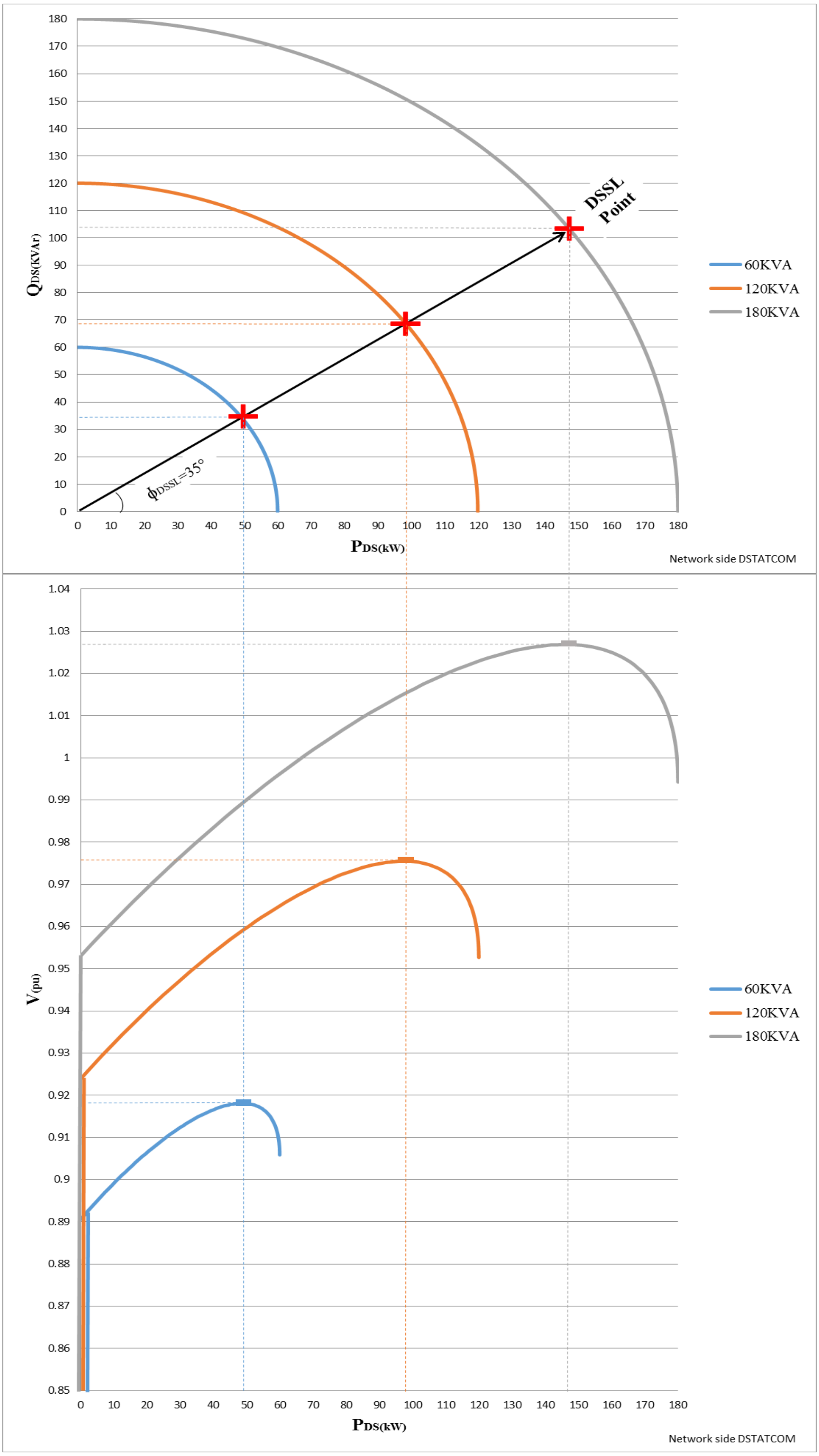


Figure 3.16: DSTATCOM size effect on network side DSSL point.

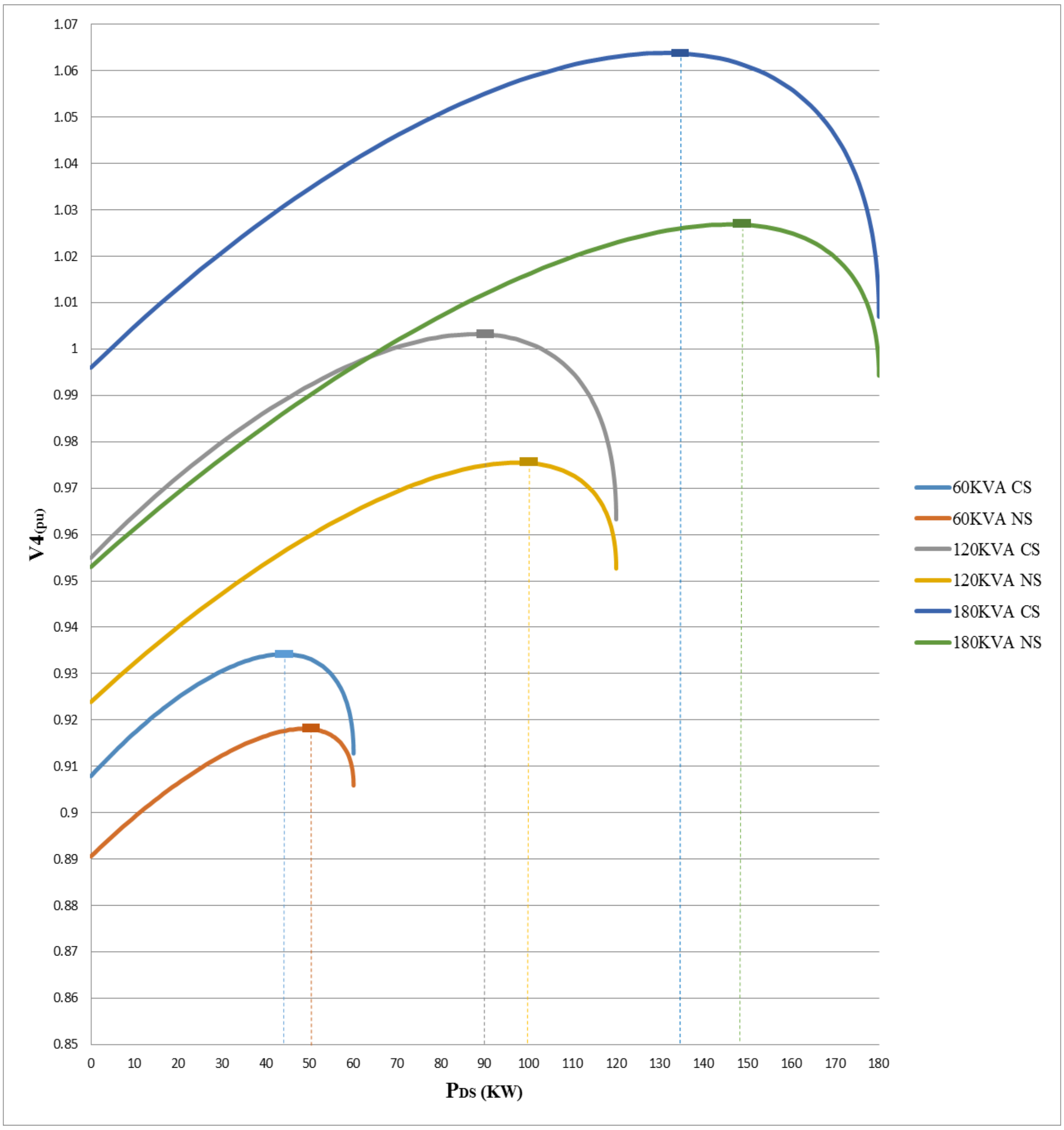


Figure 3.17: DSTATCOM location effect on DSSL point.

From equation (3.44), it is obvious that voltage sensitivity $(\partial V/\partial Q)/(\partial V/\partial P)$ varies depending on the system R/X ratio and load. The effects of these will be investigated in this part of study. Figure 3.18 shows the effect of R/X ratio on DSSL point. As the SWER line R/X ratio increased, the DSSL active power level increased which means that more active power is needed to reach the maximum voltage support. The higher the R/X ratio is the lower value of the voltage sensitivity $(\partial V/\partial Q)/(\partial V/\partial P)$ and ϕ_{DSSL} for each customer. In other words, the higher the R/X ratio, the more active power is needed to reach the DSSL point and to improve the voltage level.

Another factor that affects the DSSL point is the load. It is changing all the time, not only during the day, but in the future considering load growth. In this part of study, the relationship between the load sizes on DSSL point will be analysed.

Figure 3.19 represents the effect of load size on the DSSL point. The load size is assumed as a percentage of each customer's transformer rating from 10% to 80%. As it is obviously seen, the DSSL point active power increases with the load size. Larger loads will reduce the value of voltage sensitivity $(\partial V/\partial Q)/(\partial V/\partial P)$ and ϕ_{DSSL} for each customer. The bigger the load, the more the active power is needed in order to reach the DSSL point.

In Figure 3.20, two different R/X ratios are considered to examine their effects on the DSSL point. The load and DSTATCOM sizes are 60% and 30% of the transformer rating respectively. As can be seen, ϕ_{DSSL1} for R/X equal to 0.3 is operating on 67° with active and reactive power of 24kW and 55kVAr. As the R/X ratio is increased to 1.8 at DSSL2, ϕ_{DSSL2} reduced to 28°, with increased active and reactive power to 53kW and 28kVAr respectively.

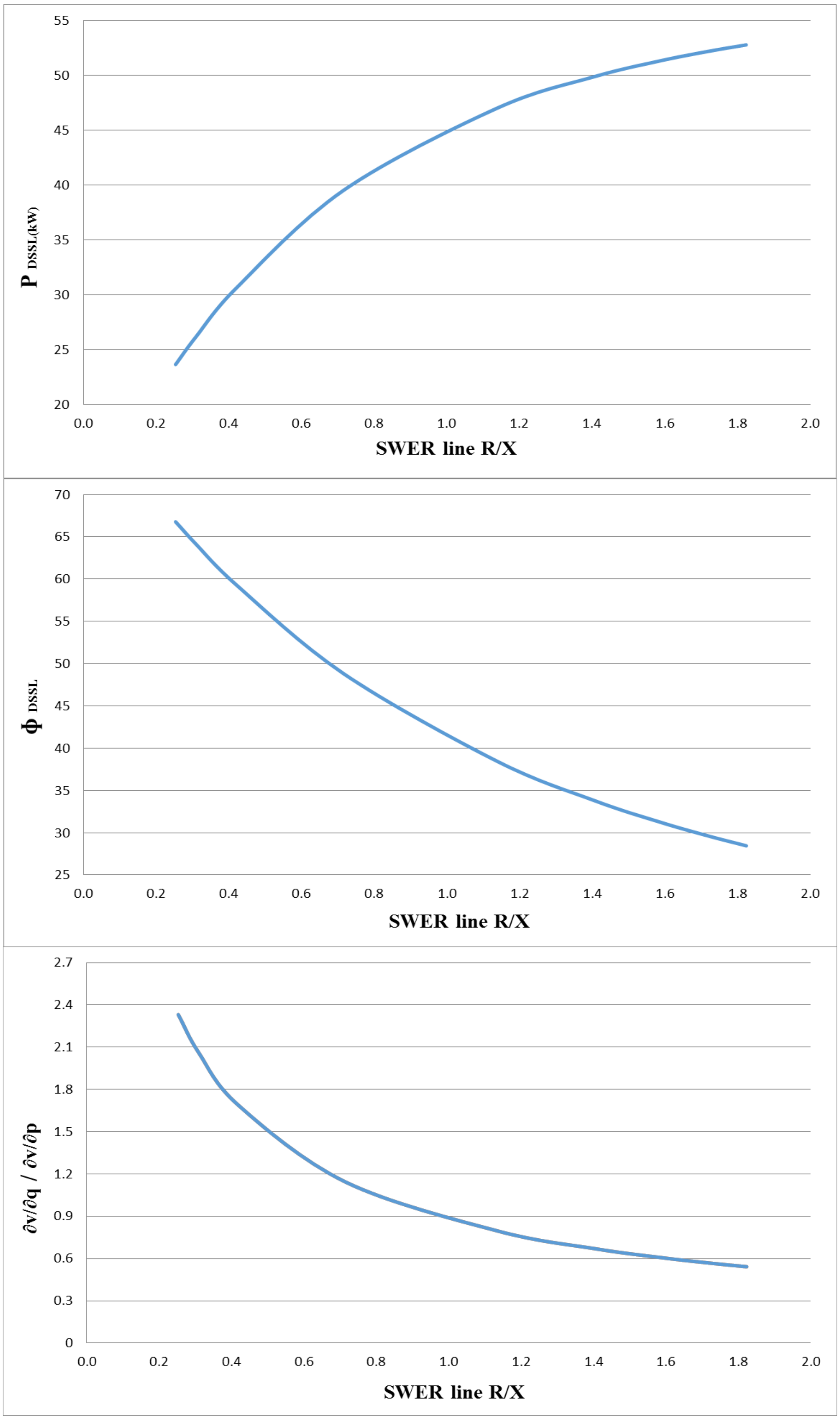


Figure 3.18: The effect of SWER line R/X ratio on DSSL point.

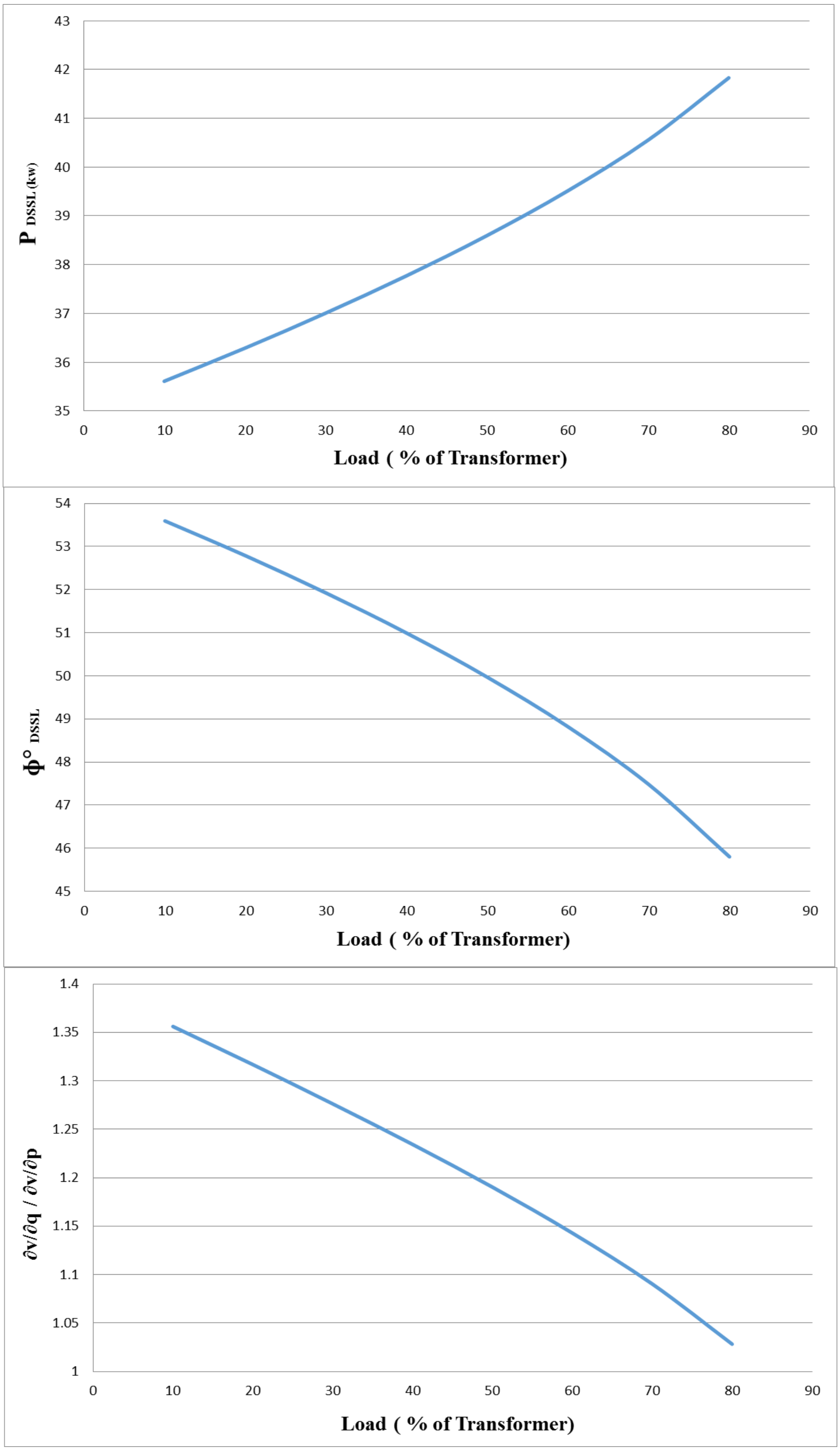


Figure 3.19: The effect of load size on DSSL point.

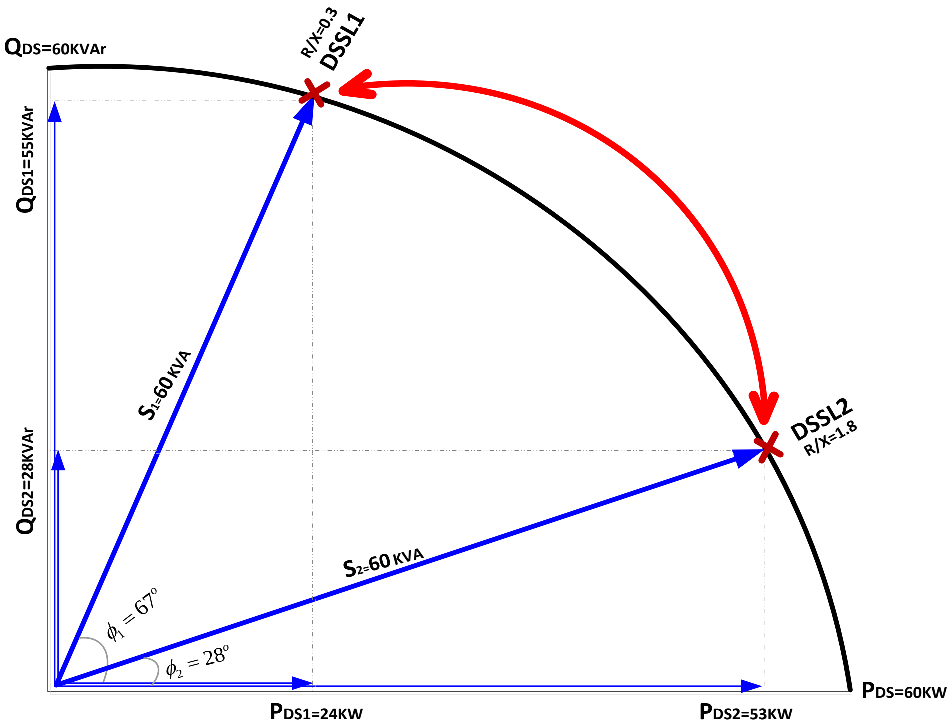


Figure 3.20: The SWER line R/X ratio effect on DSSL point (Load is 60% & DSTATCOM is 30% of transformer rating).

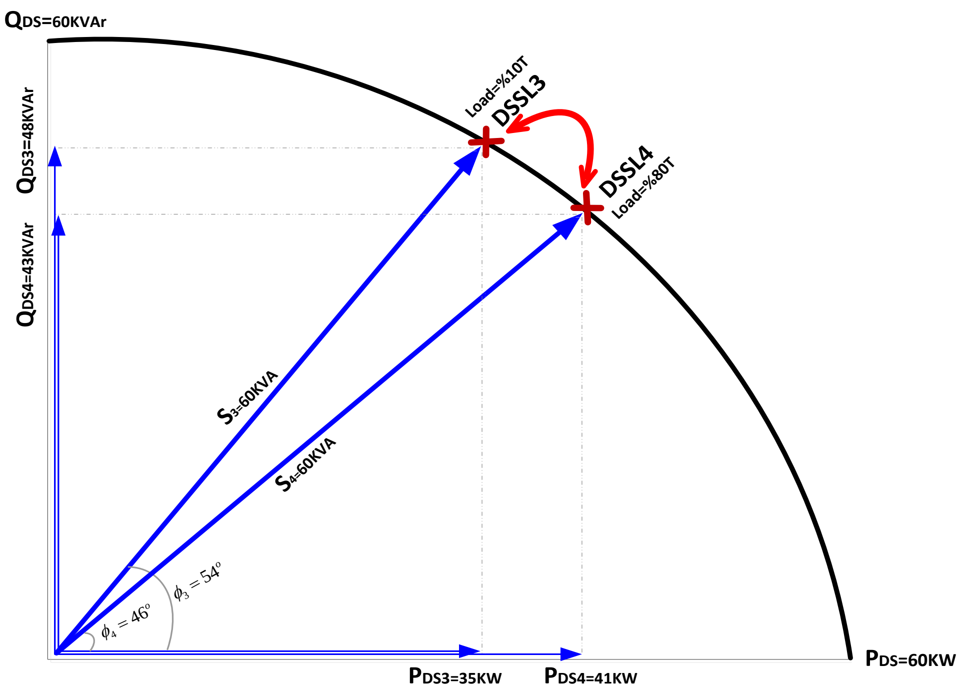


Figure 3.21: The load size effect on DSSL point (DSTATCOM is 30% of transformer rating & R/X=0.7).

In Figure 3.21, the effect of load change on the DSSL point is shown. SWER line R/X ratio is considered to be 0.7, with the same DSTATCOM size of 60kVA. As can be seen, the DSSL3 defined when the load was 10% of transformer size (20kVA). At this point, ϕ_{DSSL3} is operating at 54° with 35kW and 48kVAr. If the load is increased to 80% of transformer rating (160kVA), the ϕ_{DSSL4} only reduces by 8°. Active and reactive power for DSSL4 is raised to 41kW and 43kVAr. Clearly it can be seen that change of R/X ratio reduced the ϕ_{DSSL} by 39°, but change of load dropped it by 8°. It can be concluded that the SWER line R/X ratio and load have the same effects on the DSSL point but the R/X ratio is more pronounced.

3.7.2 Richmond SWER Line

In this study, a load flow model of a SWER line is developed using MATLAB®. The Richmond SWER line model proposed in this study is based on one phase of the Richmond triplex system. It originates at Richmond 66/33/19.1kV zone substation and is located in Central Queensland, Australia as shown in Figure 3.22. The Richmond system comprises of 126 nodes with 49 customers. The single line diagram of the Richmond SWER line is shown at Figure 3.23. All the data is available in the appendix. Uniform loads and DSTATCOMs are considered for all customers in the study. All the sizes will be based on a percentage of installed customer transformer capacity. Single phase transformers with standard ratings of 10kVA or 25 kVA are installed at customer locations. Out of all 49 customers, only 13 are using 25kVA and the rest use the smaller size which is 10kVA.

In this case, the load size is considered to be 35% of the customer transformer size. In addition, all customers have DSTATCOM with 45% transformer size installed at the network side or customer side. These 49 DSTATCOMs are only able to inject or absorb reactive power to support the voltage. Newton Raphson load flow was used to find the voltage of all locations. As shown in Figure 3.24, for the given load all the customers were suffering from low voltage problems (less than 0.94pu).

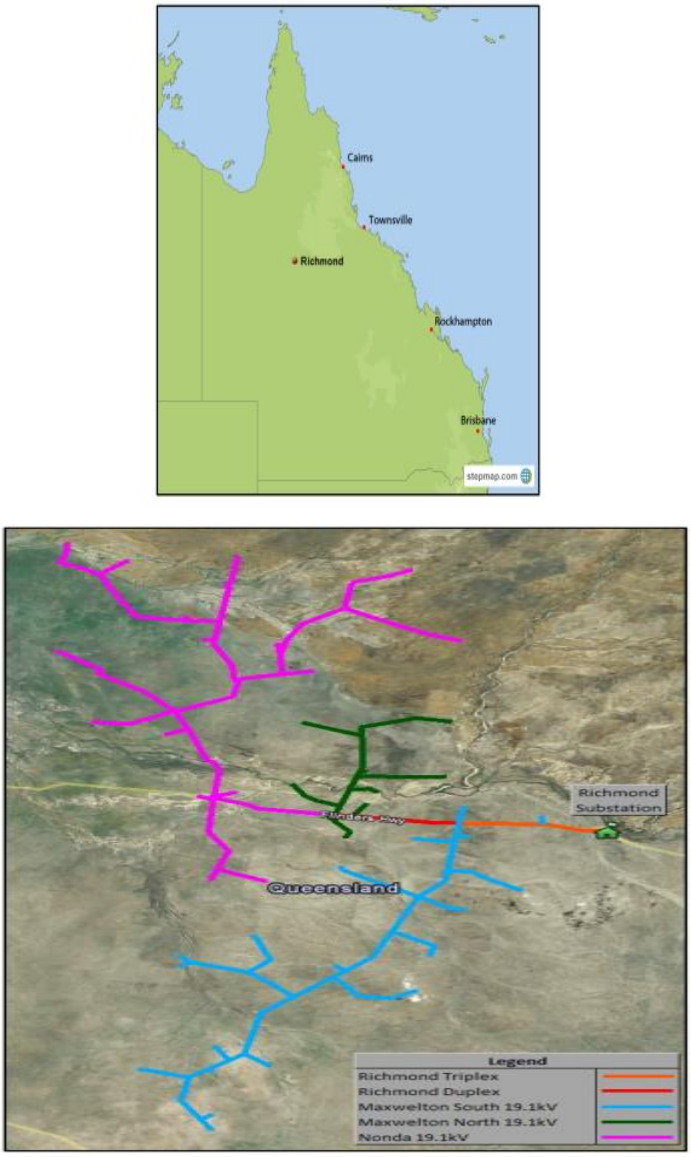


Figure 3.22: Location of Richmond SWER line system [2].

To improve the voltage profile of the system in two different scenarios, the same size of DSTATCOM will be placed at the network side and customer side. It has been assumed they are only able to inject or absorb reactive power. As already discussed, the amount of voltage rise is expected to be different based on DSTATCOM location.

As can be seen in Figure 3.24, voltage level improved due to maximum possible VAr injection of DSTATCOM at the network side, but still some of the customers suffered from a low voltage. On the other hand, by installing DSTATCOM at the customer side, the voltage will be fully supported at all customer locations and operating within nominal limits.

Richmond customers' voltage change due to different DSTATCOM location is shown in Table 3.4. As can be seen, the effectiveness of VAr injection using the same DSTATCOM at the customer side is greater than on the network side by 14% to16%. Depending on the R/X ratio of SWER systems this percentage could be up to 70% as discussed in the first case study.

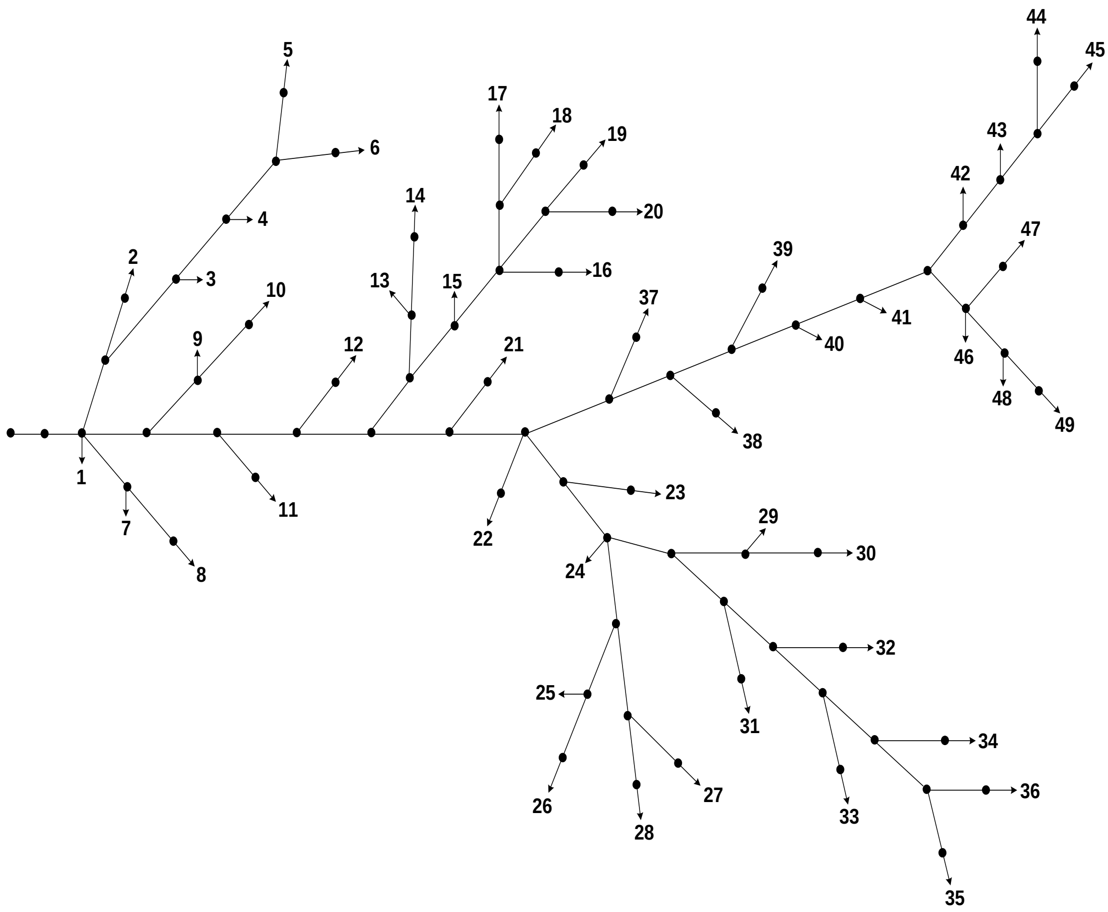


Figure 3.23: Single line diagram of Richmond SWER line with 126 nodes and 49 customers [2].

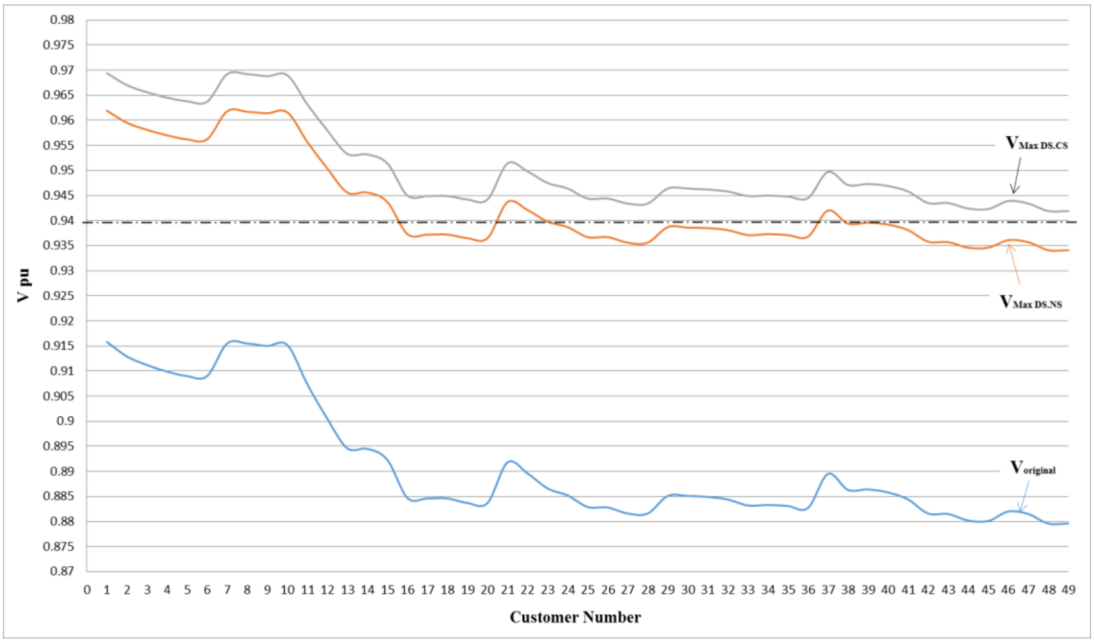


Figure 3.24: Network side and customer side DSTATCOM effect on all customers' voltage profile (Load & DSTATCOM size 35% & 45% of transformer rating; only Q injection is considered).

In the previous section of this study, all customers were considered to have consumed 35% of its transformer rating, which is a light load. As already discussed, the low voltage problem has been addressed by reactive power injection using DSTATCOM at the customer side. Considering peak load and load growth, reactive power injection is not a sufficient solution. Four-quadrant DSTATCOM installation, with the ability of injecting and absorbing active and reactive power, will be studied now.

Figure 3.25 shows the maximum possible voltage due to DSTATCOM operation at DSSL point in network side and customer side. The load and DSTATCOM are 65% and 45% of transformer rating (6.5kVA and 4.5 kVA). The minimum voltage when there is no DSTATCOM connected in to the system is calculated to be 0.7334pu, which belongs to customer 49 at the end of the line. As can be seen, all customers are suffering from low voltage issues, and having DSTATCOM on the customer side has improved all voltages above 0.94pu.

Table 3.4: Richmond customers' voltage change due to different DSTATCOM location

Customr No.	V pu	$V_{DS.NS}$	$V_{DS.CS}$	ΔV_{NS}	ΔV_{CS}	$\Delta V_{CS} / \Delta V_{NS}$
1	0.9158	0.9619	0.9694	0.0461	0.0536	1.16
2	0.9129	0.9595	0.967	0.0466	0.0541	1.16
3	0.9112	0.9581	0.9656	0.0469	0.0544	1.16
4	0.9099	0.957	0.9645	0.0471	0.0546	1.16
5	0.909	0.9562	0.9638	0.0472	0.0548	1.16
6	0.909	0.9562	0.9637	0.0472	0.0547	1.16
7	0.9155	0.9618	0.9692	0.0463	0.0537	1.16
8	0.9155	0.9617	0.9692	0.0462	0.0537	1.16
9	0.915	0.9614	0.9688	0.0464	0.0538	1.16
10	0.9152	0.9616	0.969	0.0464	0.0538	1.16
11	0.9074	0.9557	0.9632	0.0483	0.0558	1.16
12	0.9005	0.9504	0.958	0.0499	0.0575	1.15
13	0.8946	0.9456	0.9533	0.051	0.0587	1.15
14	0.8945	0.9456	0.9532	0.0511	0.0587	1.15
15	0.8923	0.9437	0.9514	0.0514	0.0591	1.15
16	0.8847	0.9373	0.945	0.0526	0.0603	1.15
17	0.8846	0.9372	0.9449	0.0526	0.0603	1.15
18	0.8846	0.9372	0.9449	0.0526	0.0603	1.15
19	0.8837	0.9365	0.9442	0.0528	0.0605	1.15
20	0.8837	0.9365	0.9442	0.0528	0.0605	1.15
21	0.8918	0.9437	0.9514	0.0519	0.0596	1.15
22	0.8896	0.9421	0.9498	0.0525	0.0602	1.15
23	0.8866	0.9398	0.9475	0.0532	0.0609	1.14
24	0.8852	0.9387	0.9464	0.0535	0.0612	1.14
25	0.8829	0.9367	0.9444	0.0538	0.0615	1.14
26	0.8828	0.9367	0.9444	0.0539	0.0616	1.14
27	0.8816	0.9356	0.9434	0.054	0.0618	1.14
28	0.8816	0.9356	0.9434	0.054	0.0618	1.14
29	0.8851	0.9387	0.9464	0.0536	0.0613	1.14
30	0.8851	0.9386	0.9464	0.0535	0.0613	1.15
31	0.8849	0.9385	0.9462	0.0536	0.0613	1.14
32	0.8844	0.9381	0.9458	0.0537	0.0614	1.14
33	0.8832	0.9371	0.9449	0.0539	0.0617	1.14
34	0.8833	0.9373	0.945	0.054	0.0617	1.14
35	0.8831	0.9371	0.9448	0.054	0.0617	1.14
36	0.8827	0.9368	0.9445	0.0541	0.0618	1.14
37	0.8895	0.942	0.9497	0.0525	0.0602	1.15
38	0.8863	0.9394	0.9471	0.0531	0.0608	1.15
39	0.8864	0.9396	0.9473	0.0532	0.0609	1.14
40	0.8858	0.9392	0.9469	0.0534	0.0611	1.14
41	0.8844	0.9381	0.9458	0.0537	0.0614	1.14
42	0.8816	0.9358	0.9435	0.0542	0.0619	1.14
43	0.8815	0.9357	0.9435	0.0542	0.062	1.14
44	0.8802	0.9346	0.9424	0.0544	0.0622	1.14
45	0.8801	0.9346	0.9423	0.0545	0.0622	1.14
46	0.882	0.9361	0.9439	0.0541	0.0619	1.14
47	0.8815	0.9357	0.9434	0.0542	0.0619	1.14
48	0.8796	0.9341	0.9419	0.0545	0.0623	1.14
49	0.8796	0.9341	0.9419	0.0545	0.0623	1.14

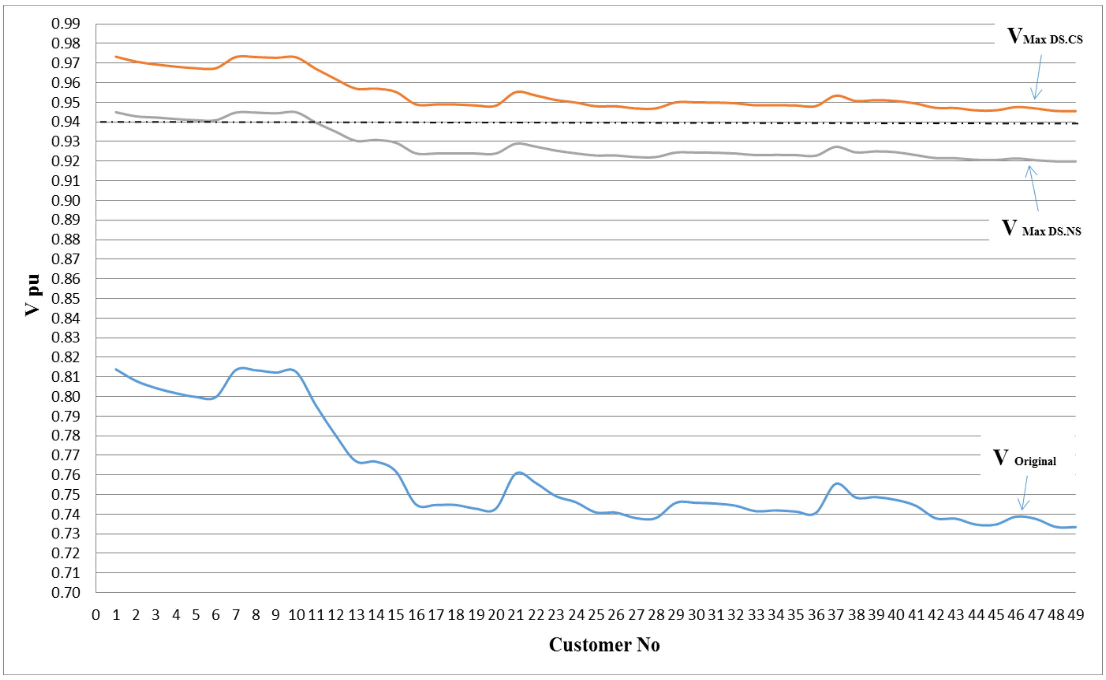


Figure 3.25: Maximum possible voltage due DSSL point in Network side and customer side (load 65% transformer size, DSTATCOM 45% of transformer size).

The voltage profile without DSTATCOM (second column in Table 3.4) clearly justifies the need for voltage support. The voltage profile of customer 49 with load and DSTATCOM of 65% and 45% of transformer rating (6.5kVA and 4.5 kVA) is shown in Figure 3.26. The DSTATCOM is located at two different locations, customer side and network side. According to the Q priority strategy, the voltage changes due to 4.5 kVAr injected reactive power in to the system are shown by the vertical orange and blue colour for network side and customer side locations respectively. As can be seen, only Q injection will boost the voltage level, but it is not enough to fully support the voltage. The next step is injecting active power into the system to improve customer voltage to an acceptable level. It is clear that customer side DSTATCOM has corrected the voltage while the network side DSTATCOM has not been able to solve the voltage issues. The same situation is shown for customer 47 in Figure 3.27, with a different size of DSTATCOM as it is a proportion of customer transformer rating.

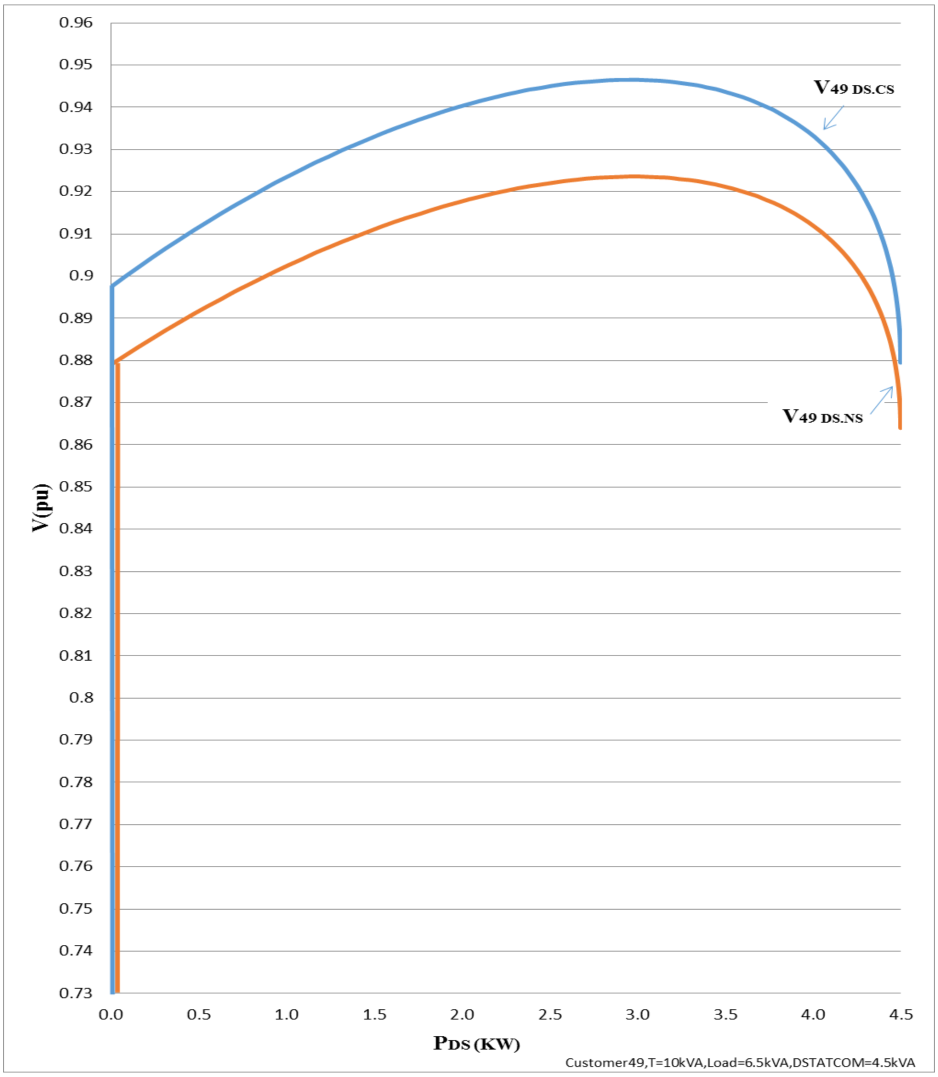


Figure 3.26: The effect of DSTATCOM location on maximum voltage support at customer 49.

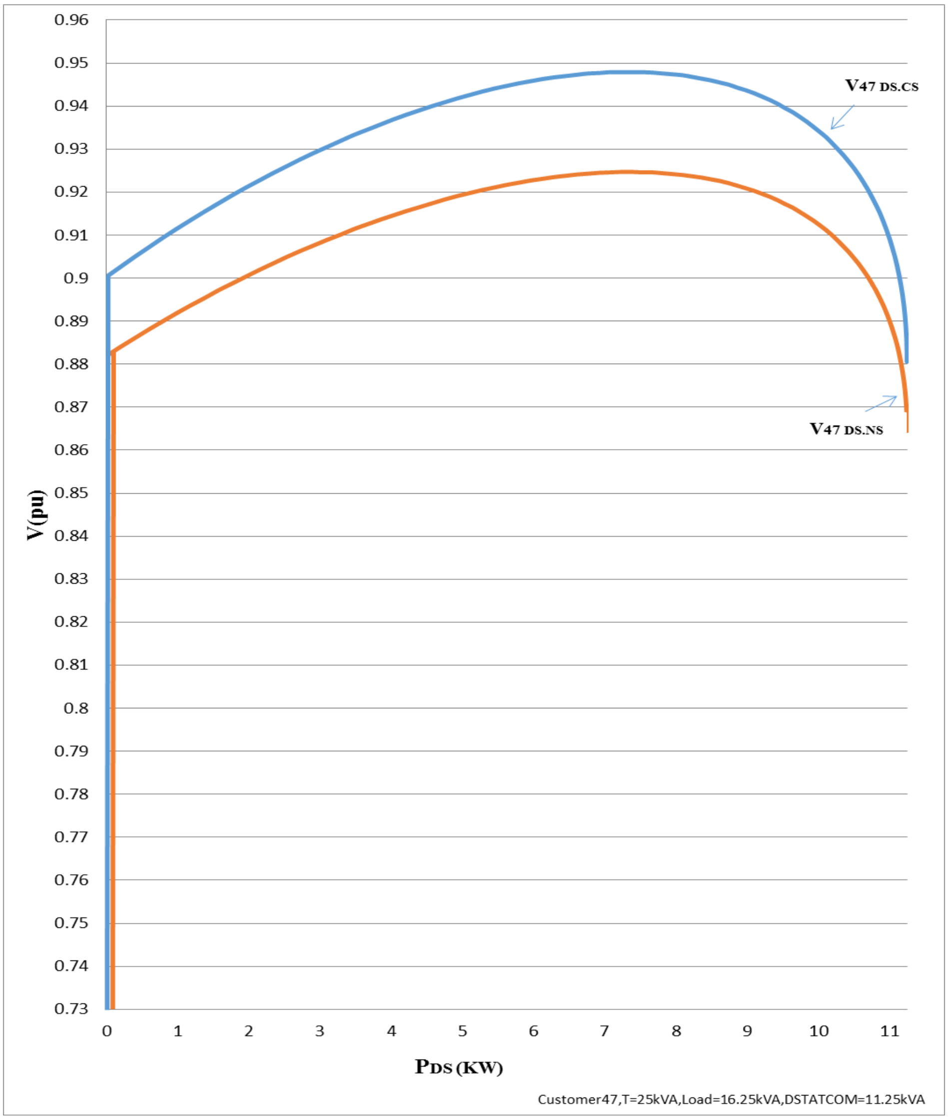


Figure 3.27: The effect of DSTATCOM location on maximum voltage support at customer 47.

Customer side and network side voltage sensitivity with respect to active and reactive power change are shown in Figure 3.28 and 3.29 respectively. As can be seen, the voltage sensitivity for both active and reactive power changes is higher at the customer side for all the customers. In the case of customer side support and due to transformer inductance, the voltage sensitivity of reactive power change is more than that of active power change.

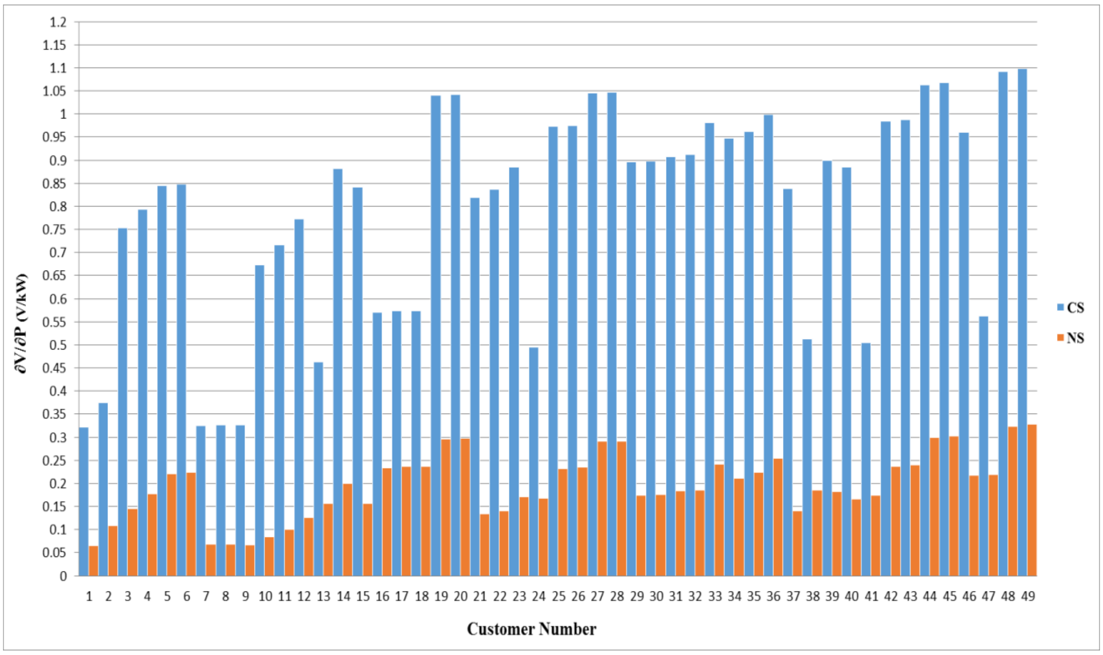


Figure 3.28: Customer side and network side voltage sensitivity with respect to active power change.

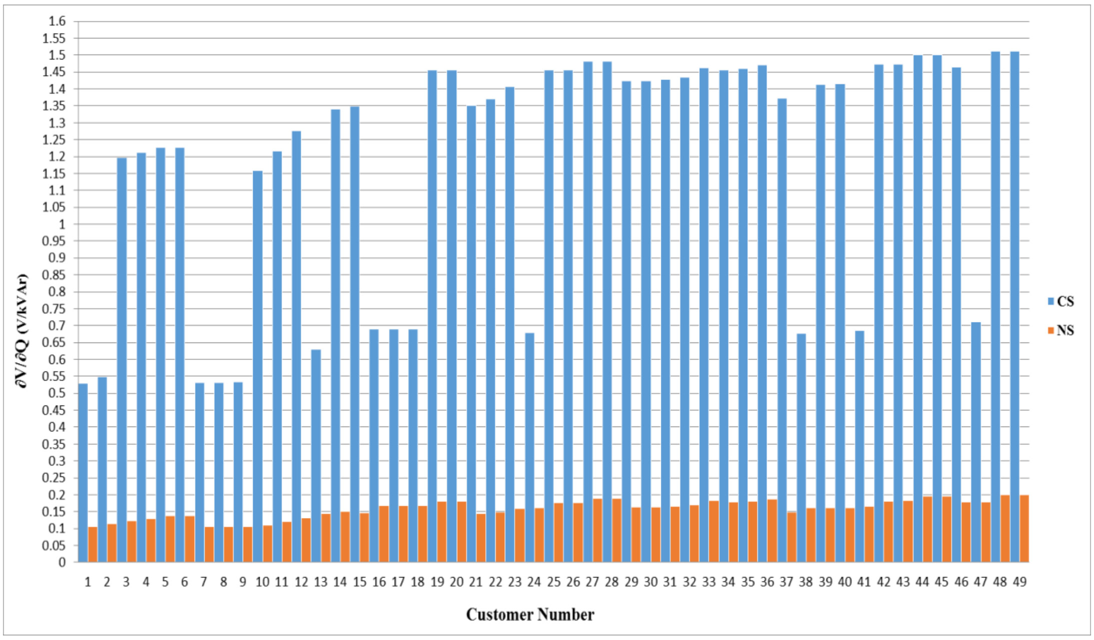


Figure 3.29: Customer side and network side voltage sensitivity with respect to reactive power change.

The voltage for all 49 customers due to different DSTATCOM operating angles, is shown in Figure 3.30. As expected, the maximum voltage occurs when DSTATCOM operates on its DSSL point. Figure 3.31 shows a system voltage profile due to different DSTATCOM operating angles and locations. As can be seen, customer side DSTATCOM voltage support is more effective than that on the network side.

Figure 3.32 shows the location effects on the voltage sensitivity ratio. As can be seen, voltage sensitivity ratio on the customer side is always greater than the network side for all the customers.   In other words, the DSTATCOM reaches its DSSL point with less amount of P than Q when it is located on the customer side.

The network side and customer side DSSL angle, voltage sensitivity ratio and maximum voltage support for all customers are shown in Table 3.5 and 3.6 respectively.

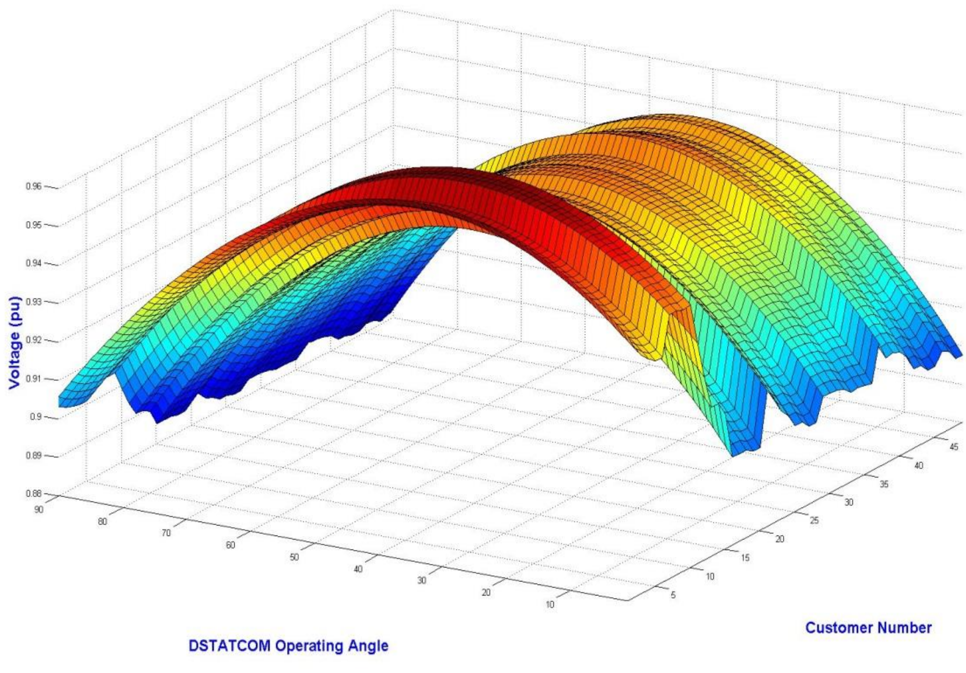


Figure 3.30: System voltage profile due to different customer side DSTATCOM operating angle.

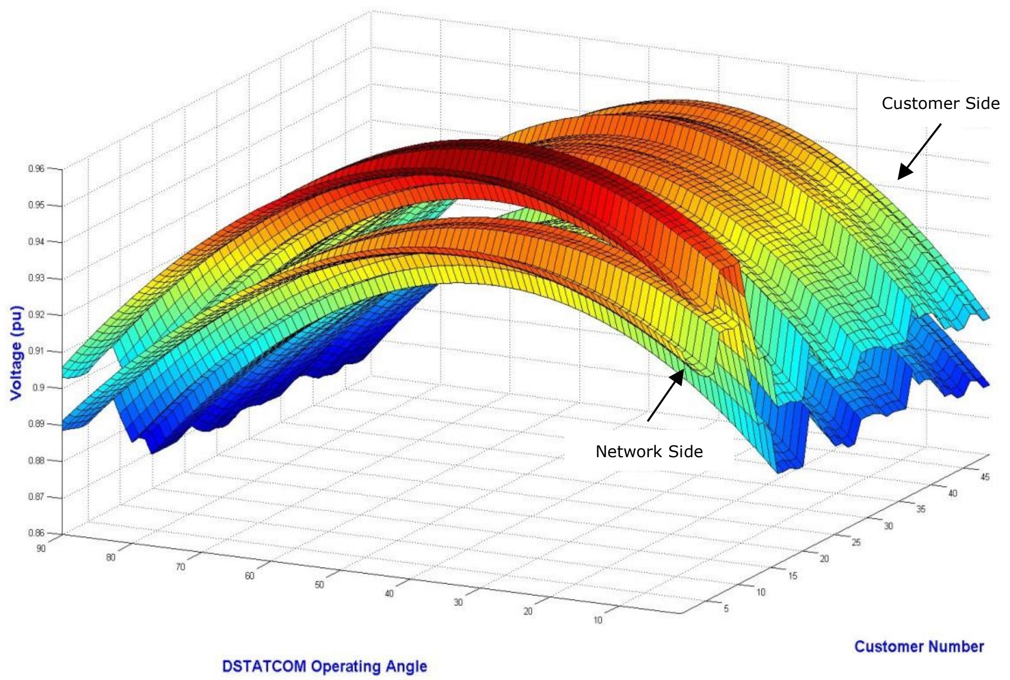


Figure 3.31: System voltage profile due to different DSTATCOM operating angle and location.

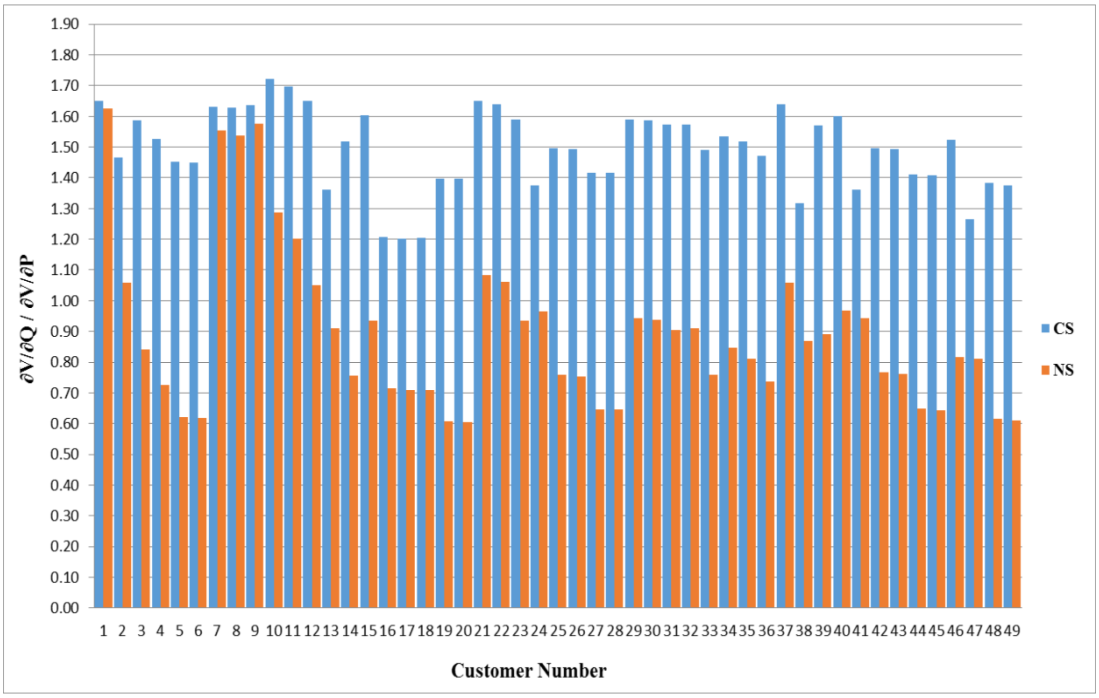


Figure 3.32: Location effects on the voltage sensitivity ratio

Table 3.5: Network side DSSL angle and maximum voltage support for all customers

Customr No.	V_{NS} (pu)	$\partial v/\partial q$ / $\partial v/\partial p$	$\phi_{DS.NS}$	$PF_{DS.NS}$	DSTATCOM (kVA)	$P_{DS.NS}$ (kW)	$Q_{DS.NS}$ (kVAr)	V_{MAX} (pu)
1	0.81	1.62	58	0.52	11.25	5.90	9.58	0.945
2	0.81	1.06	47	0.69	11.25	7.72	8.18	0.943
3	0.80	0.84	40	0.77	4.5	3.44	2.90	0.942
4	0.80	0.73	36	0.81	4.5	3.64	2.64	0.942
5	0.80	0.62	32	0.85	4.5	3.82	2.38	0.941
6	0.80	0.62	32	0.85	4.5	3.83	2.36	0.941
7	0.81	1.55	57	0.54	11.25	6.09	9.46	0.945
8	0.81	1.54	57	0.55	11.25	6.13	9.43	0.945
9	0.81	1.58	58	0.54	11.25	6.03	9.50	0.944
10	0.81	1.29	52	0.61	4.5	2.76	3.55	0.945
11	0.80	1.20	50	0.64	4.5	2.88	3.46	0.940
12	0.78	1.05	46	0.69	4.5	3.10	3.26	0.935
13	0.77	0.91	42	0.74	11.25	8.31	7.58	0.930
14	0.77	0.76	37	0.80	4.5	3.59	2.71	0.931
15	0.76	0.94	43	0.73	4.5	3.29	3.07	0.929
16	0.75	0.72	36	0.81	11.25	9.15	6.55	0.924
17	0.74	0.71	35	0.82	11.25	9.18	6.51	0.924
18	0.74	0.71	35	0.82	11.25	9.17	6.52	0.924
19	0.74	0.61	31	0.85	4.5	3.85	2.33	0.924
20	0.74	0.60	31	0.86	4.5	3.85	2.33	0.924
21	0.76	1.08	47	0.68	4.5	3.05	3.31	0.929
22	0.76	1.06	47	0.69	4.5	3.09	3.27	0.927
23	0.75	0.94	43	0.73	4.5	3.29	3.07	0.925
24	0.75	0.97	44	0.72	11.25	8.09	7.81	0.924
25	0.74	0.76	37	0.80	4.5	3.59	2.72	0.923
26	0.74	0.75	37	0.80	4.5	3.60	2.71	0.923
27	0.74	0.65	33	0.84	4.5	3.78	2.44	0.922
28	0.74	0.65	33	0.84	4.5	3.78	2.44	0.922
29	0.75	0.94	43	0.73	4.5	3.27	3.09	0.924
30	0.75	0.94	43	0.73	4.5	3.28	3.08	0.924
31	0.75	0.90	42	0.74	4.5	3.34	3.02	0.924
32	0.74	0.91	42	0.74	4.5	3.33	3.03	0.924
33	0.74	0.76	37	0.80	4.5	3.58	2.72	0.923
34	0.74	0.85	40	0.76	4.5	3.44	2.91	0.923
35	0.74	0.81	39	0.78	4.5	3.49	2.84	0.923
36	0.74	0.74	36	0.80	4.5	3.62	2.67	0.923
37	0.76	1.06	47	0.69	4.5	3.09	3.27	0.927
38	0.75	0.87	41	0.76	11.25	8.50	7.37	0.925
39	0.75	0.89	42	0.75	4.5	3.36	2.99	0.925
40	0.75	0.97	44	0.72	4.5	3.24	3.13	0.925
41	0.74	0.94	43	0.73	11.25	8.18	7.72	0.923
42	0.74	0.77	37	0.79	4.5	3.57	2.74	0.922
43	0.74	0.76	37	0.80	4.5	3.58	2.72	0.922
44	0.73	0.65	33	0.84	4.5	3.78	2.45	0.921
45	0.73	0.64	33	0.84	4.5	3.78	2.44	0.921
46	0.74	0.82	39	0.77	4.5	3.49	2.84	0.921
47	0.74	0.81	39	0.78	11.25	8.74	7.08	0.921
48	0.73	0.62	32	0.85	4.5	3.83	2.36	0.920
49	0.73	0.61	31	0.85	4.5	3.84	2.34	0.920

Table 3.6: Customer side DSSL angle and maximum voltage support for all customers

Customr No.	V_{CS} (pu)	$\partial v/\partial q$ / $\partial v/\partial p$	$\phi_{DS.CS}$	$PF_{DS.CS}$	DSTATCOM (kVA)	$P_{DS.CS}$ (kW)	$Q_{DS.CS}$ (kVAr)	V_{MAX} (pu)
1	0.81	1.65	59	0.52	11.25	5.83	9.62	0.973
2	0.81	1.46	56	0.56	11.25	6.34	9.29	0.971
3	0.80	1.59	58	0.53	4.5	2.40	3.81	0.969
4	0.80	1.53	57	0.55	4.5	2.47	3.76	0.968
5	0.80	1.45	55	0.57	4.5	2.55	3.71	0.967
6	0.80	1.45	55	0.57	4.5	2.56	3.70	0.967
7	0.81	1.63	59	0.52	11.25	5.88	9.59	0.973
8	0.81	1.63	58	0.52	11.25	5.89	9.59	0.973
9	0.81	1.64	59	0.52	11.25	5.86	9.60	0.973
10	0.81	1.72	60	0.50	4.5	2.26	3.89	0.973
11	0.80	1.70	59	0.51	4.5	2.28	3.88	0.967
12	0.78	1.65	59	0.52	4.5	2.33	3.85	0.962
13	0.77	1.36	54	0.59	11.25	6.66	9.07	0.957
14	0.77	1.52	57	0.55	4.5	2.47	3.76	0.957
15	0.76	1.60	58	0.53	4.5	2.38	3.82	0.955
16	0.75	1.21	50	0.64	11.25	7.17	8.67	0.949
17	0.74	1.20	50	0.64	11.25	7.19	8.65	0.949
18	0.74	1.20	50	0.64	11.25	7.19	8.65	0.949
19	0.74	1.40	54	0.58	4.5	2.62	3.66	0.948
20	0.74	1.40	54	0.58	4.5	2.62	3.66	0.948
21	0.76	1.65	59	0.52	4.5	2.33	3.85	0.955
22	0.76	1.64	59	0.52	4.5	2.34	3.84	0.954
23	0.75	1.59	58	0.53	4.5	2.40	3.81	0.951
24	0.75	1.37	54	0.59	11.25	6.62	9.10	0.950
25	0.74	1.50	56	0.56	4.5	2.50	3.74	0.948
26	0.74	1.49	56	0.56	4.5	2.50	3.74	0.948
27	0.74	1.42	55	0.58	4.5	2.60	3.68	0.947
28	0.74	1.42	55	0.58	4.5	2.60	3.68	0.947
29	0.75	1.59	58	0.53	4.5	2.40	3.81	0.950
30	0.75	1.59	58	0.53	4.5	2.40	3.81	0.950
31	0.75	1.57	58	0.54	4.5	2.41	3.80	0.950
32	0.74	1.57	58	0.54	4.5	2.42	3.80	0.950
33	0.74	1.49	56	0.56	4.5	2.51	3.74	0.949
34	0.74	1.54	57	0.55	4.5	2.46	3.77	0.949
35	0.74	1.52	57	0.55	4.5	2.48	3.76	0.948
36	0.74	1.47	56	0.56	4.5	2.53	3.72	0.948
37	0.76	1.64	59	0.52	4.5	2.34	3.84	0.953
38	0.75	1.32	53	0.60	11.25	6.80	8.96	0.951
39	0.75	1.57	58	0.54	4.5	2.42	3.80	0.951
40	0.75	1.60	58	0.53	4.5	2.38	3.82	0.951
41	0.74	1.36	54	0.59	11.25	6.66	9.06	0.949
42	0.74	1.50	56	0.56	4.5	2.50	3.74	0.947
43	0.74	1.49	56	0.56	4.5	2.51	3.74	0.947
44	0.73	1.41	55	0.58	4.5	2.60	3.67	0.946
45	0.73	1.41	55	0.58	4.5	2.61	3.67	0.946
46	0.74	1.52	57	0.55	4.5	2.47	3.76	0.948
47	0.74	1.26	52	0.62	11.25	6.98	8.82	0.947
48	0.73	1.38	54	0.59	4.5	2.64	3.65	0.946
49	0.73	1.38	54	0.59	4.5	2.65	3.64	0.946

3.8 Conclusions

This chapter addresses the voltage regulation problems in SWER systems. DSTATCOMs in Q-only mode as a source of reactive power, and four-quadrant mode including active power injection have been proposed to support the voltage. Two possible locations for voltage support equipment, the network side of the distribution transformer or the customer side have been studied. In addition, the DSTATCOM operating point and its effect on system voltage support was analyzed. Two SWER networks, a simple one with only 4 nodes and a real one with 126 nodes load at Richmond, Australia, have been modeled using MATLAB®.

It is shown that having DSTATCOM on the customer side as a source of reactive power is much more effective than on the network side to support the voltage due to customer transformer reactance. Customer side DSTATCOMs are likely to be more cost effective because they operate a standard low voltage. Network side DSTATCOMs may not be cost effective because either they have to operate at high voltage or would need a transformer. In addition, system losses are generally less while the DSTATCOM is mounted as voltage support equipment at the customer side than network side. This is even more significant for systems with higher R/X ratio, which means that as the system becomes more resistive, the effect of customer transformer reactance becomes more significant in terms of voltage support.

Considering load growth, as VAr compensation alone is insufficient to solve the future voltage issues, having voltage support equipment with a source of active power would be advantageous. Four-quadrant DSTATCOMs with the ability to inject or absorb active and reactive power has been proposed for voltage support.

The operating point of a DSTATCOM and its effectiveness on SWER system voltage improvement has been studied in this part. The focus was on determining the DSTATCOM operating point to have the maximum possible support during heavy load. The maximum voltage support (DSSL point) includes more reactive power than active power when the DSTATCOM is located at the customer side compared with a location on the network side. In fact, the DSSL point for each customer depends on its voltage sensitivity ratio which will be affected by load, SWER line impedance and system R/X ratio. The less the voltage sensitivity $(\partial V2/\partial Q2)/(\partial V2/\partial P2)$, the more active power is needed to meet the DSSL point.

The important thing to be noted is that the DSTATCOM excessive P injection will not raise the voltage. DSTATCOM steady state stability limit point introduced as DSSL is the point to provide maximum voltage support in SWER network. The optimal size is determined based on the DSSL index. Exceeding the DSSL optimum point will not raise the voltage but also may have some stability margin issues. For a given customer load distribution and at a given DSTATCOM apparent power level, system voltage will first rise with increasing active power injection, reach a maximum and then decrease. This needs to be taken into consideration when designing the closed loop voltage control system that the DSTATCOM is part of. A stability margin will be needed if that maximum system voltage is in an unstable operating region.

The operating mode to allow DSTATCOM to support the voltage is the next issue to be considered for SWER systems. The parallel operation of DSTATCOMs in such a system, and the necessary load sharing strategy, is a new challenge to be studied. In coming chapters, different types of DSTATCOM operating mode with reference to SWER network voltage support will be analysed.

Ideally, the cost of DSTATCOMs being proposed should be shared between the customers and the network service provider. Sharing of cost is fair because the DSTATCOMs provide benefits to both the customers and network service providers.

CHAPTER 4

Q_ONLY DSTATCOM OPERATING MODE

4.1 Introduction

As discussed in chapter 3, the best place to install DSTATCOM as voltage support equipment would be on the customer side. Assuming DSTATCOM is to be placed on the customer side to support the voltage, four different operating modes: Q-only; Q-priority; load power factor follow and load power factor correction mode will be discussed in coming chapters.

This chapter studies Q-only DSTATCOM operating mode which means only reactive power can be injected or absorbed. The aim is to support the voltage using DSTATCOMs that are able to perform in Q-only mode while it is active. Typical reactive power voltage droop characteristics will be used on DSTATCOMs and in addition a modified one will be proposed. Due to DSTATCOM installation as voltage support equipment, reactive power (VAr) circulation is a possibility. How to minimise this effect in a SWER systems will also be analysed. Finally, the SWER system model is developed, using MATLAB, to study DSTATCOM operation in Q-only mode and the possibility of VAr circulation.

4.2 DSTATCOM Q-only Mode Operation

In this part of the study, it has been assumed that if the DSTATCOM is ON, it is operating in reactive power only mode. In other words, the voltage in the system will be maintained only via injecting or absorbing VArs using DSTATCOM.

Figure 4.1 represents a simple AC system including a four-quadrant DSTATCOM and its power diagram. The DSTATCOM is able to operate in four quadrants but in this chapter it is on Q-only operating mode. In this case, the operating point of the DSTATCOM is always located somewhere on the reactive power axis as is highlighted.

4.3 Droop Characteristics

4.3.1 Droop Control Techniques

The droop control method is a popular way for power sharing in an electrical system. It is used to obtain DSTATCOM parallel operation and proper reactive power sharing between them.

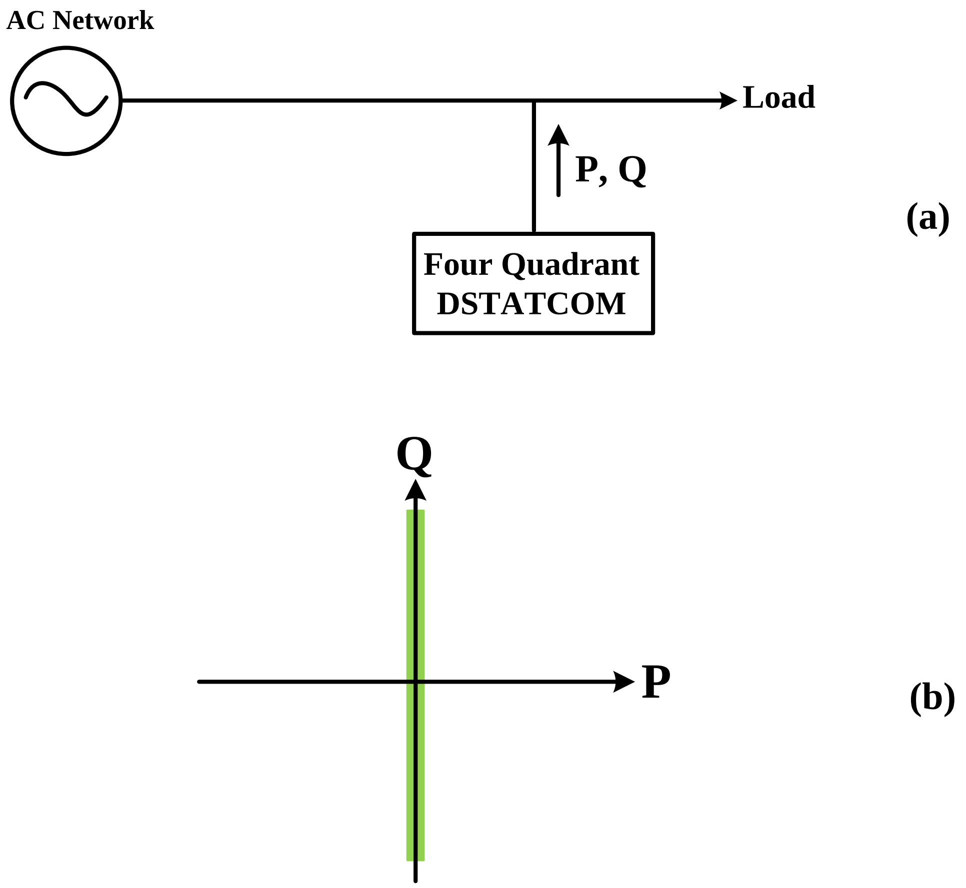


Figure 4.1: (a) A simple AC system including four quadrant DSTATCOM and (b) its power diagram.

The DSTATCOM reactive power-voltage droop characteristic (Q_s-V) is represented at Figure 4.2. The droop control equation is defined as:

$$Q_{si} = K_{qi}(V_{ref} - |V_i|) \tag{4.1}$$

Where: Q_{si} is the calculated DSTATCOM reactive power amount to be injected or absorbed, K_{qi} is a constant, V_{ref} is the reference voltage and $|V_i|$ is the amplitude of the voltage at bus number *i*. The reference voltage is a fixed value, but customer voltage will change with the varying load conditions.

Depending upon the amplitude of V_i, the control action will be as follows:

a) $|V_i|<V_{ref}$, low voltage problem is detected, Q_{si} is positive and VArs to be injected

b) $|V_i|>V_{ref}$, high voltage problem is detected, Q_{si} is negative and VArs have to be absorbed

c) $|V_i|=V_{ref}$, system is operating on a normal situation, no action is needed

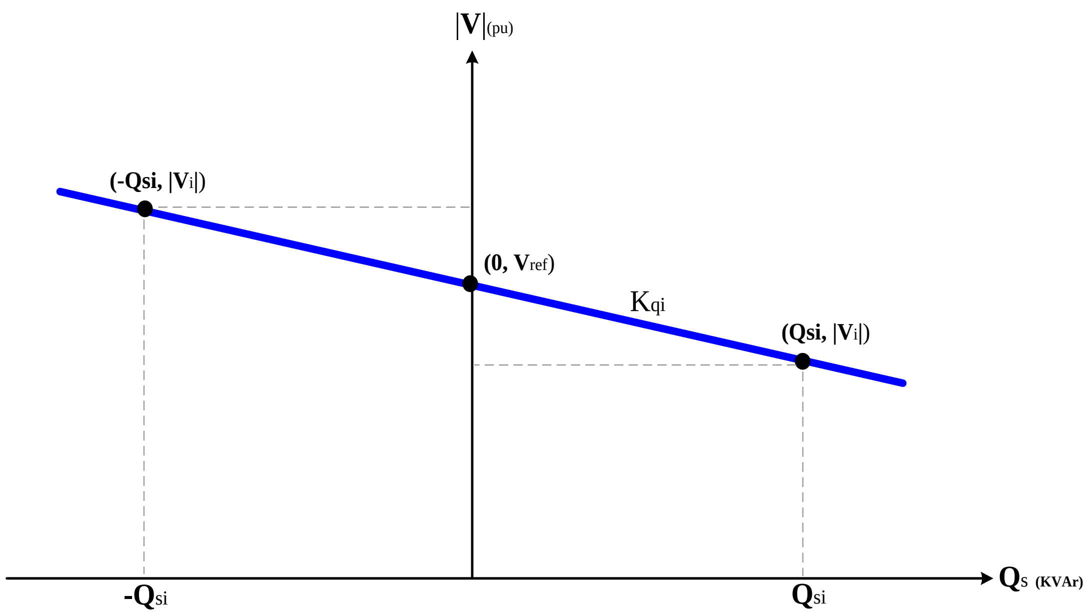


Figure 4.2: Reactive power-voltage droop characteristics (Qs-V).

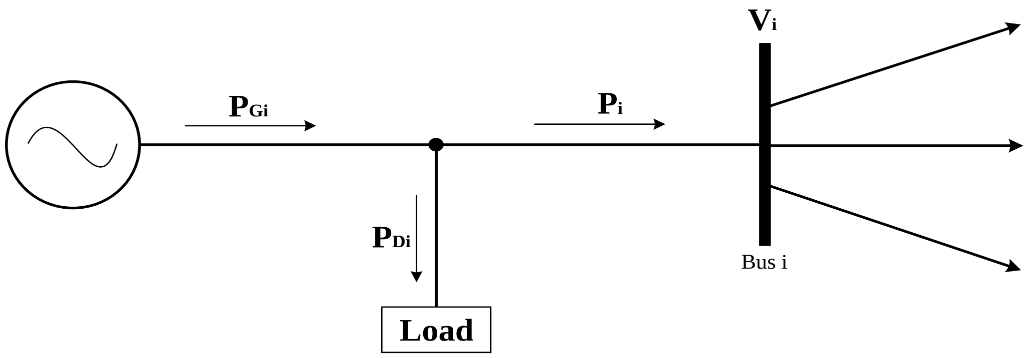
If the bus voltage is less than the reference voltage, it means the customer has a low voltage problem and reactive power Q_{si} is calculated to be positive referring to equation (4.1). In this case, DSTATCOM reactive power Q_{si} has to be injected to raise the voltage V_i up to V_{ref} as is shown at Figure 4.2. On the other hand, high voltage problems will be detected when voltage V_i is greater than V_{ref} and Q_{si} will be negative. This negative sign of Q_{si} indicates that reactive power has to be absorbed to push the voltage down toward V_{ref} as is illustrated at Figure 4.2.

4.3.2 Droop Implementation in Load Flow Study

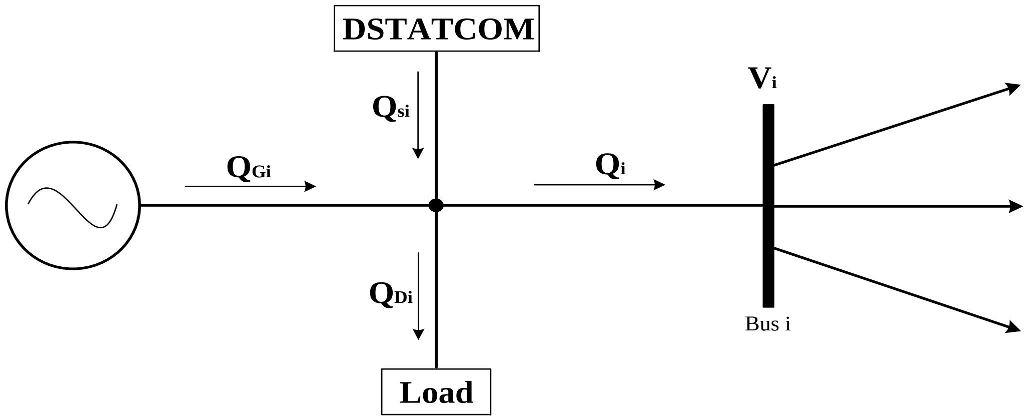
There are several different methods of solving the resulting nonlinear system of equations. One of the most popular is the Newton–Raphson method. This method starts with initial guesses of all unknown variables: voltage magnitudes and angles at load buses; and the angle of the voltage at generator buses. In this study, Q_s-V droop will be implemented in the load flow equations to compute the DSTATCOM reactive power Q_{si} while it is operating in Q-only mode. A modified Newton Raphson method is proposed to solve the power flow problem for power networks. This is achieved using a simple approach in which the droop control of the DSTATCOM is combined with the conventional Newton Raphson method. The presented method provides a simple, easy to implement, and accurate approach to solve the power flow equations for SWER lines.

4.3.3 Modified Jacobian Matrix Elements

Implementing DSTATCOM as a source of reactive power in the SWER system will change the matrix [J] that is consists of partial derivatives known as a Jacobian matrix. The first step to be considered is to review the active and reactive power at bus *i*, while a DSTATCOM with Q-only mode operation is connected to it, as is shown at Figure 4.3. Considering the mentioned mode for connected DSTATCOM at bus *i*, makes its active power P_s to be zero in this case, Figure 4.3(a). Further, the DSTATCOM reactive power connected to bus *i* will be Q_{si} as is represented at Figure 4.3(b).



(a)



(b)

Figure 4.3: (a) Active and (b) reactive power flow at bus *i* including DSTATCOM operating in Q-only mode.

From Figure 4.3, net active and reactive power P_i and Q_i will be calculated as:

$$P_i = P_{Gi} - P_{Di} \tag{4.2}$$

$$Q_i = (Q_{Gi} - Q_{Di}) + Q_{si} \tag{4.3}$$

The total P and Q flowing into bus *i*, for a converged solution is:

$$f_{P,i}(\delta,V) = (P_{Gi} - P_{Di}) - \sum_{k=1}^{n} |V_k||V_i|[G_{ik}\cos(\delta_k - \delta_i) - B_{ik}\sin(\delta_k - \delta_i)] = 0 \quad (4.4)$$

$$f_{Q,i}(\delta,V) = (Q_{Gi} - Q_{Di}) + K_{qi}(V_{ref} - |V_i|) + \sum_{k=1}^{n} |V_k||V_i|[B_{ik}\cos(\delta_k - \delta_i) + G_{ik}\sin(\delta_k - \delta_i)] = 0 \quad (4.5)$$

The Jacobian matrix [J] contains the partial derivatives of the expressions for P and Q flowing into each bus. These partial derivatives fall into four categories and [J] is often partitioned into four submatrices described as follows:

$$J = \left[\begin{array}{ccc|ccc} \frac{\partial P_1}{\partial \delta_1} & \cdots & \frac{\partial P_1}{\partial \delta_N} & \frac{\partial P_1}{\partial |V_1|} & \cdots & \frac{\partial P_1}{\partial |V_N|} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \frac{\partial P_N}{\partial \delta_1} & \cdots & \frac{\partial P_N}{\partial \delta_N} & \frac{\partial P_N}{\partial |V_1|} & \cdots & \frac{\partial P_N}{\partial |V_N|} \\ \hline \frac{\partial Q_1}{\partial \delta_1} & \cdots & \frac{\partial Q_1}{\partial \delta_N} & \frac{\partial Q_1}{\partial |V_1|} & \cdots & \frac{\partial Q_1}{\partial |V_N|} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \frac{\partial Q_N}{\partial \delta_1} & \cdots & \frac{\partial Q_N}{\partial \delta_N} & \frac{\partial Q_N}{\partial |V_1|} & \cdots & \frac{\partial Q_N}{\partial |V_N|} \end{array}\right] = \left[\begin{array}{c|c} J_{11} & J_{12} \\ \hline J_{21} & J_{22} \end{array}\right] \quad (4.6)$$

The partials derivatives can be obtained from the equations 4.4 and 4.5 for P_i and Q_i. Diagonal and off-diagonal terms will be calculated in 8 different equations as follows.

Main-diagonal and off-diagonal terms of submatrix J_{11} are determined to be as:

$$\frac{\partial f_{Pi}}{\partial \delta_i} = (Q_{Gi} - Q_{Di}) + K_{qi}(V_{ref} - |V_i|)) + |V_i|^2 B_{ii} \tag{4.7}$$

$$\frac{\partial f_{Pi}}{\partial \delta_k} = |V_k||V_i|[G_{ik} \sin(\delta_k - \delta_i) + B_{ik} \cos(\delta_k - \delta_i)] \tag{4.8}$$

Main-diagonal and off-diagonal elements of submatrix J_{12} are determined to be as:

$$\frac{\partial f_{Pi}}{\partial |V_i|} = [-(P_{Gi} - P_{Di}) - |V_i|^2 G_{ii}] / |V_i| \tag{4.9}$$

$$\frac{\partial f_{Pi}}{\partial |V_k|} = -|V_i|[G_{ik} \cos(\delta_k - \delta_i) - B_{ik} \sin(\delta_k - \delta_i)] \tag{4.10}$$

Main-diagonal and off-diagonal terms of submatrix J_{21} are determined to be as:

$$\frac{\partial f_{Qi}}{\partial \delta_i} = -(P_{Gi} - P_{Di}) + |V_i|^2 G_{ii} \tag{4.11}$$

$$\frac{\partial f_{Qi}}{\partial \delta_k} = -|V_k||Vi|[B_{ik} \cos(\delta_k - \delta_i) + G_{ik} \sin(\delta_k - \delta_i)] \tag{4.12}$$

Main-diagonal and off-diagonal elements of submatrix J_{22} are determined to be as:

$$\frac{\partial f_{Qi}}{\partial |V_i|} = K_{qi} - [(Q_{Gi} - Q_{Di}) + K_{qi}(V_{ref} - |V_i|) - |V_i|^2 B_{ii}] / |V_i| \tag{4.13}$$

$$\frac{\partial f_{Qi}}{\partial |V_k|} = |V_i|[B_{ik} \cos(\delta_k - \delta_i) + G_{ik} \sin(\delta_k - \delta_i)] \tag{4.14}$$

Compared with a normal Jacobian matrix, a DSTATCOM that is able to operate in Q-only mode at bus *i* with reactive power of Q_{si}, only change the diagonal elements of J_{11} and J_{22} as shown above at equations 4.7 and 4.13. Running a load flow with this new Jacobian matrix will calculate the amount of DSTATCOM reactive power considering typical droop Q_{si}-V_i for a given load of P_{Di} and Q_{Di} to raise the voltage.

4.4 Modified Droop Characteristics

New droop characteristics will be proposed in this part of the study. Firstly, a hysteresis control loop for DSTATCOM Q-only mode will be defined. Following the loop forces the DSTATCOM to be switched ON or OFF based on the amplitude of the voltage calculated at bus *i* via the load flow study. The expecting outcome of this control component is minimising VAr circulation and reducing the amount of reactive power that is needed to support the voltage in a SWER network.

4.4.1 VAr Circulation

The voltage issues experienced at the customers placed downstream and relatively far from the source is more significant than others. The more serious the voltage problem is, the greater the reactive power is needed to support the voltage. The injected reactive power into the network will not only correct the voltage locally, but may affect other customers, including upstream ones that are close to the power system back bone with minor voltage issues. As a result, it may cause overstepping the voltage of these customers above the reference voltage. In this case, the control system detects a high voltage problem and attempts to push the voltage down via applying (Q_{si}-V_i) droop characteristics and absorbing reactive power Q_{si}. In other words, the reactive power injected in one part of the system to boost the voltage will be absorbed in another part as it causes a high voltage problem. This circulating reactive power in the system will be termed VAr circulation. To minimise the possibility of VAr circulation occurring a modified droop characteristics as a part of the DSTATCOM control system will be proposed.

4.4.2 Hysteresis Control Loop for Q-only Mode

The general idea of this part is to minimise VAr circulation and avoid unnecessary reactive power circulating in the system while it is operating in within an acceptable voltage range. The hysteresis control loop will be introduced to control the state of DSTATCOM with respect to the defined voltage boundaries. It is obvious that the lower and upper voltage thresholds can be set at any value, depending on the standard voltage levels and system specifications.

The DSTATCOM state will be inactive if the customer voltage is operating within the nominal range. If the voltage reaches its lower level, the DSTATCOM will be activated and operating in Q-only mode to improve the network voltage by injecting reactive power. If the system voltage some time later, reaches the top limit of the nominal range, a high voltage event will be detected and reactive power will be absorbed to reduce the voltage. The hysteresis band control for Q-only mode, including the DSTATCOM switching with respect to the defined voltage limits, is shown at Figure 4.4. As can be seen, the voltage at each costumer is the only input used to control the state of the DSTATCOM. The DSTATCOM state changes from OFF to ON and Q_s has to be injected when the voltage reaches its lower limit of 0.94pu (Line AB).

The high voltage system scenario that activates the DSTATCOM is when the voltage reaches the upper band of 1.06pu and a high voltage event will be detected (Line GH). In this case the voltage will be reduced by Q_s absorption. The reactive power control will be terminated only when the voltage is operating within the normal range, in this example at 0.99pu the DSTATCOM will be switched OFF (Line DE). On the other hand, absorbing VArs will be stopped by switching OFF the DSTATCOM when the voltage is down to 1.01pu, i.e. within the nominal range (Line JF). The state of customer voltage, DSTATCOM and Q_s based on the amplitude of voltage and hysteresis loop controller is shown in detail in Table 4.1.

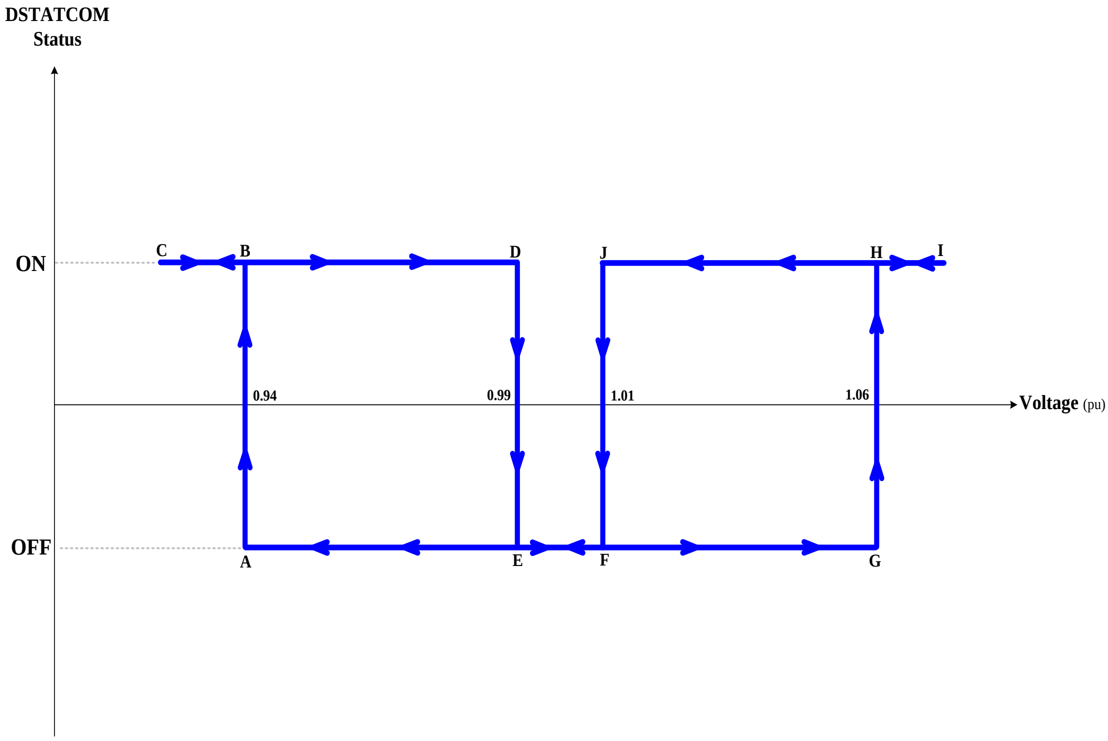


Figure 4.4: The hysteresis control loop for Q-only mode including DSTATCOM switching ON or OFF position.

Table 4.1: Detailed hysteresis control loop of DSTATCOM Q_only mode corresponded with Figure 4.4

Position on Hysteresis Loop	**Voltage** pu	**Customer Voltage Status**	**DSTATCOM Status**	**Q_s Status**
AB	0.94	Low Voltage	OFF → ON	To be injected
BD	0.94–0.99	Allowable range	ON	Is injecting
DE	0.99	Normal	ON → OFF	Injection terminated
EA	0.99–0.94	Allowable range	OFF	No injection/ absorption
EF/FE	0.99–1.01	Allowable range	OFF	No injection/ absorption
FG	1.01– 1.06	Allowable range	OFF	No injection/ absorption
GH	1.06	High Voltage	OFF → ON	To be absorbed
HJ	1.06–1.01	Allowable range	ON	Is absorbing
JF	1.01	Normal	ON → OFF	Absorption terminated

4.5 Modified Droop Characteristics Including Hysteresis Control Loop

Improving the load sharing of networks is usually based on modifications of the typical droop control method. In this section, a modified droop characteristic with respect to the proposed hysteresis control loop will be introduced.

The outcome of applying the hysteresis control loop shown in Figure 4.4 with a typical Q_{si}-V_i droop characteristic as shown in Figure 4.2, with modifications is shown in Figure 4.5 (Please note that V_{ref} is set to 1pu).

Firstly assume that the voltage at bus *i*, which is located on line EA with DSTATCOM state OFF, is 0.96pu. If the load increases then the voltage will drop accordingly and when it reaches 0.94pu (point A), the DSTATCOM will be switched ON (from point A to B). The reactive power Q_s will be injected into the system via DSTATCOM and as a result the voltage will rise. From point B to D the system performs as a typical droop controller. When it reaches point D with a voltage of 0.99pu, the DSTATCOM will be switched OFF (from point D to E). The DSTATCOM may be deactivated, e.g. when the voltage goes down, reaching 0.96pu.

The path of ABDEA will be introduced as a VAr injecting cycle. On the other hand, if this path goes upward, DSTATCOM will remain OFF until the voltage increases to 1.06pu (point G), and will then be switched ON (from point G to H). While it is operating from point H to J, the reactive power will be absorbed and the voltage will be reduced following a typical droop characteristic. When it reaches point J the DSTATCOM will be switched OFF (from point J to F). From point F, depending on the load changes, the voltage can go up or down. If it goes up, the same cycle will be repeated and FGHJF will be introduced as a VAr absorbing cycle. But if it goes down again the VAr injecting cycle will be operated that as previously discussed.

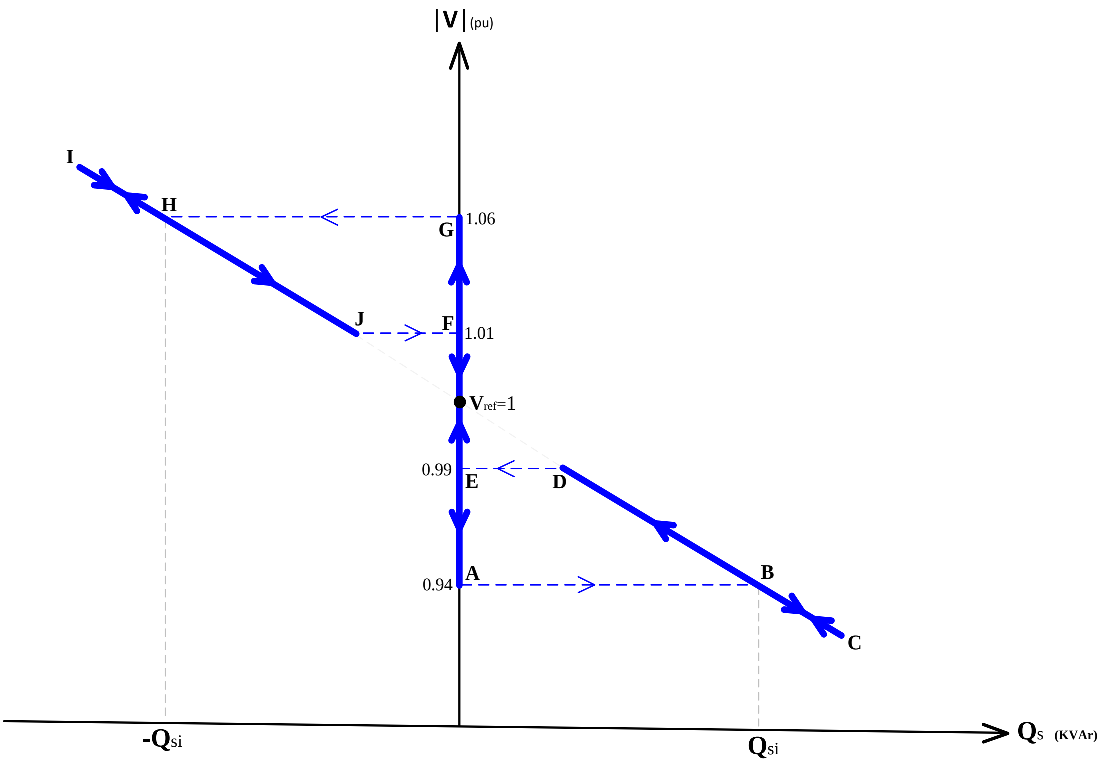


Figure 4.5: Modified droop characteristics including hysteresis control loop.

4.5.1 DSTATCOM Q-only Mode Flowchart

Q-only mode of DSTATCOM operation has been described in detail in a flowchart shown in Figure 4.6. As can be seen, it includes droop implementation in load flow, Jacobian matrix elements modification and lower and upper voltage boundary switching limits of DSTATCOMs.

4.6 Case study

In this section Richmond SWER network with 126 nodes shown in Figure 3.23 will be studied.

4.6.1 Load Growth

The average energy usage growth rate for rural and residential regions in Australia is about 3% [3]. The maximum Australian SWER networks asset life most often depends on the life of the species of hardwood pole, whose replacement life is up to 70 years [26]. Ergon Energy's SWER network in Queensland ranges in age between 25 – 45 years [29]. In this study the 24hr load cycle over a 70 year period of time with 5 year intervals will be considered.

Figures 4.7 and 4.8 show the typical 24hr load profile for the 70 years period, assuming 3% annual load growth for two different types of customers with rated transformers of 10 and 25 kVA respectively. In this case, the load has two peaks during the day, the lighter one in the morning at around 7:00hrs and a heavier one in the evening at time 19:00hrs.

4.6.2 Results and Discussions

The 24 hours voltage profiles of customers 47 and 49 with load profiles shown in Figures 4.7 and 4.8 are displayed in Figures 4.9 and 4.10 respectively. As can be seen in both figures the voltage is down to around 0.65pu at peak times of 19:00 of year 70.

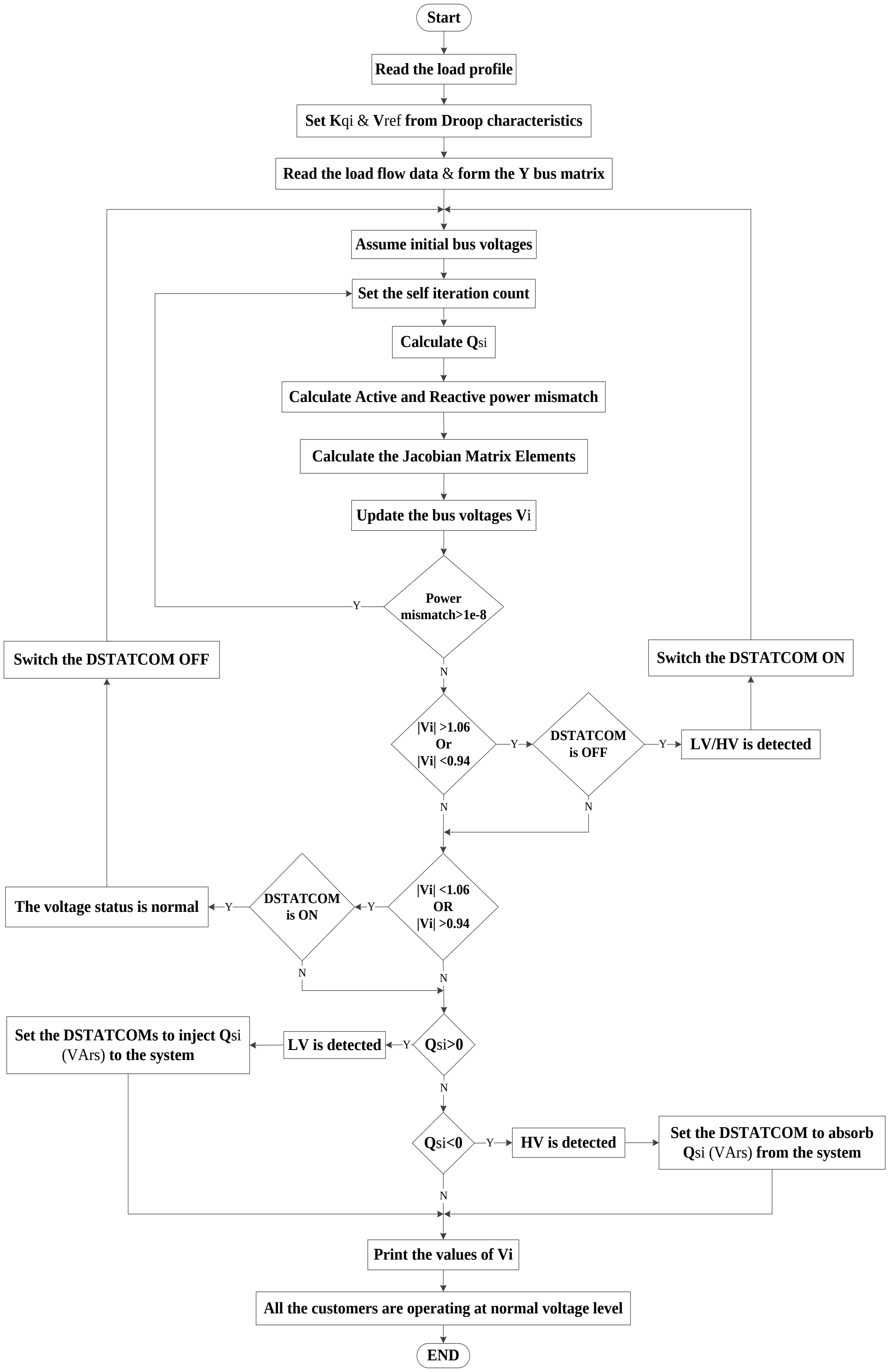


Figure 4.6: DSTATCOM Q-only mode flowchart.

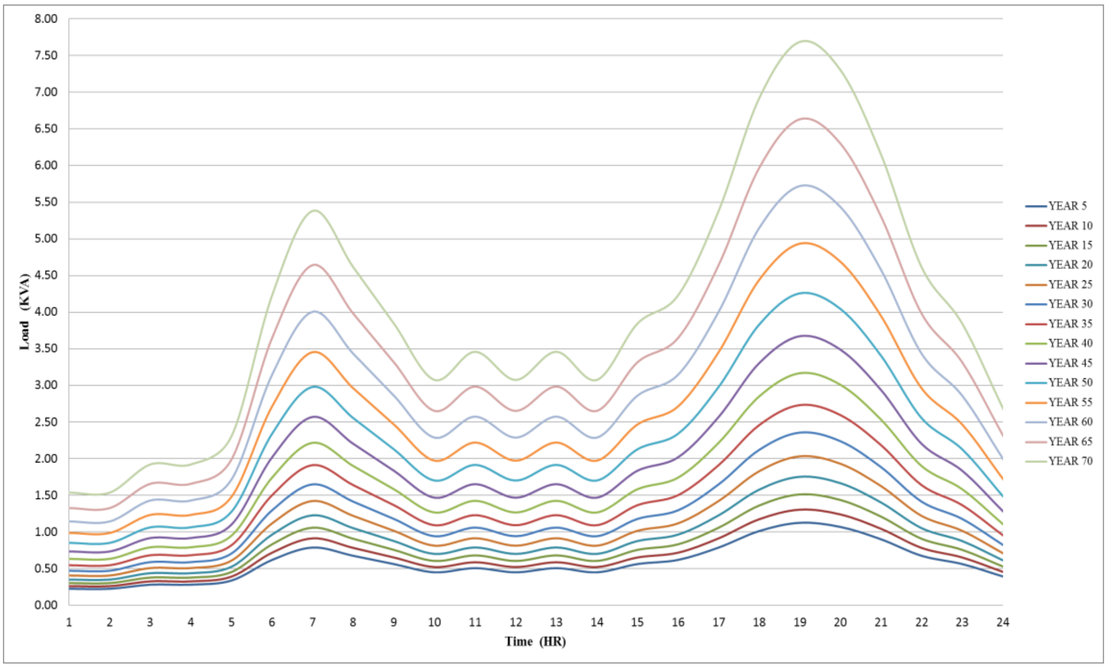


Figure 4.7: A typical 24 hours load profile in 70 years period of time considering 3% annual load growth for customer 49 (rated transformer of 10 kVA).

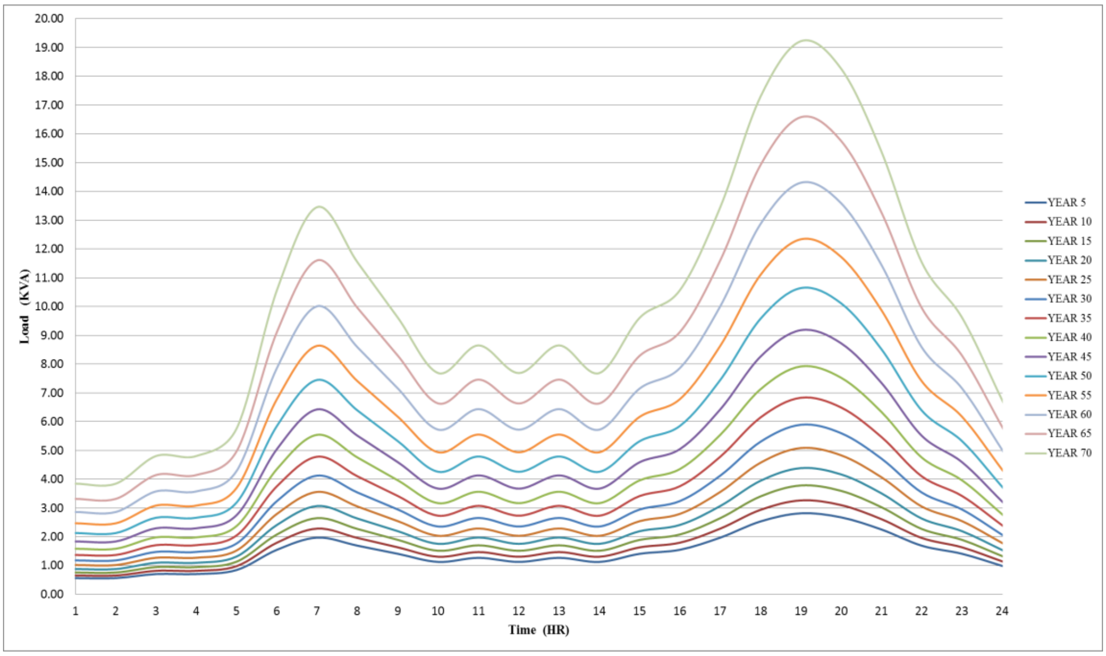


Figure 4.8: A typical 24 hours load profile in 70 years period of time considering 3% annual load growth for customer 47 (rated transformer of 25 kVA).

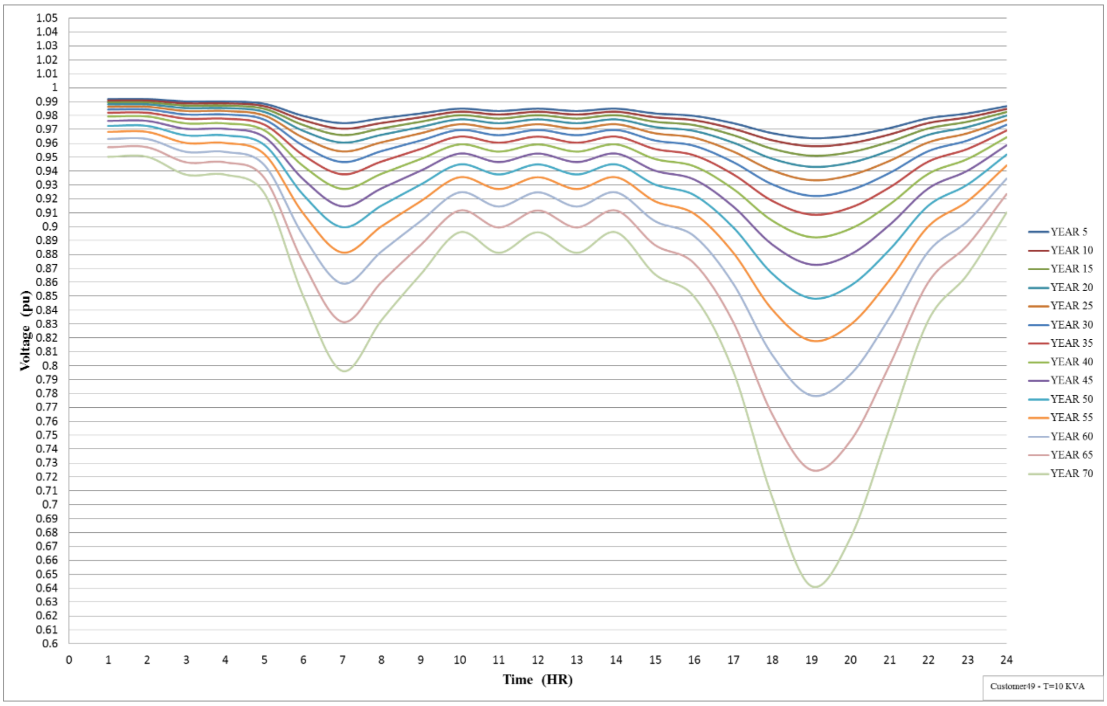


Figure 4.9: The 24 hours voltage profile of customer 49 corresponded with the load at Figure 4.7.

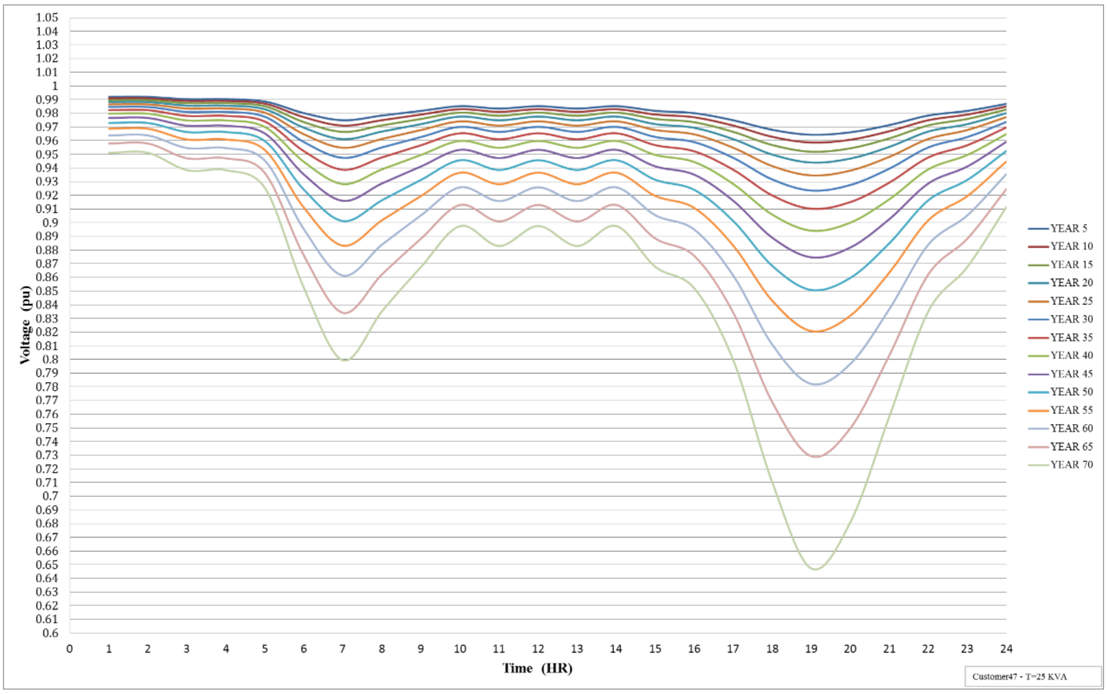


Figure 4.10: The 24 hours voltage profile of the customer 47 corresponded with the load at Figure 4.8.

In Figure 4.11, the voltage profile of all 49 customers at peak time (19:00) over the 70 year period is shown. Depending on the customer location and load size the voltage is operates at different levels. As expected, customers located at the far end of the network suffer from more serious voltage problems than others. At year 25 some of the customers' voltages dropped lower than 0.94pu and as time goes on more customers suffering from voltage issues. It is obvious that at year 35 all 49 customers are dealing with low voltage issues and the system is operating below the required standard voltage level. Taking into account that the loading in this instance is at its peak, meaning this voltage level is the worst daily outcome over the annual period for each year studied.

The droop characteristic of reactive power-voltage control, as shown in Figure 4.2, was implemented in a load flow study for the Richmond network. The DSTATCOM is operating in Q-only mode, with K_{qi} fixed for all DSTATCOMs and V_{ref} is set at 1pu. The voltage profile of all 49 customers at peak demand (19:00) over the 70 year period using Q_{si}-V_i droop characteristic is represented at Figure 4.12. The outcomes of the load flow show that applying droop resulted in full system voltage correction as expected. It shows all the customers performing at voltage levels close to V_{ref} which is 1pu.

The DSTATCOM reactive power of Qs to be injected or absorbed for all customers at time 1:00 of year 5 is shown at Figure 4.13. As expected VAr circulation has occurred at customers located along the back bone of the system close to the source without a serious voltage problem. As previously discussed, due to VAr injection at other customer nodes, the voltage on these 5 customers increased above 1pu, and the control system detects this as a high voltage problem, engaging DSTATCOMs to absorb VArs.

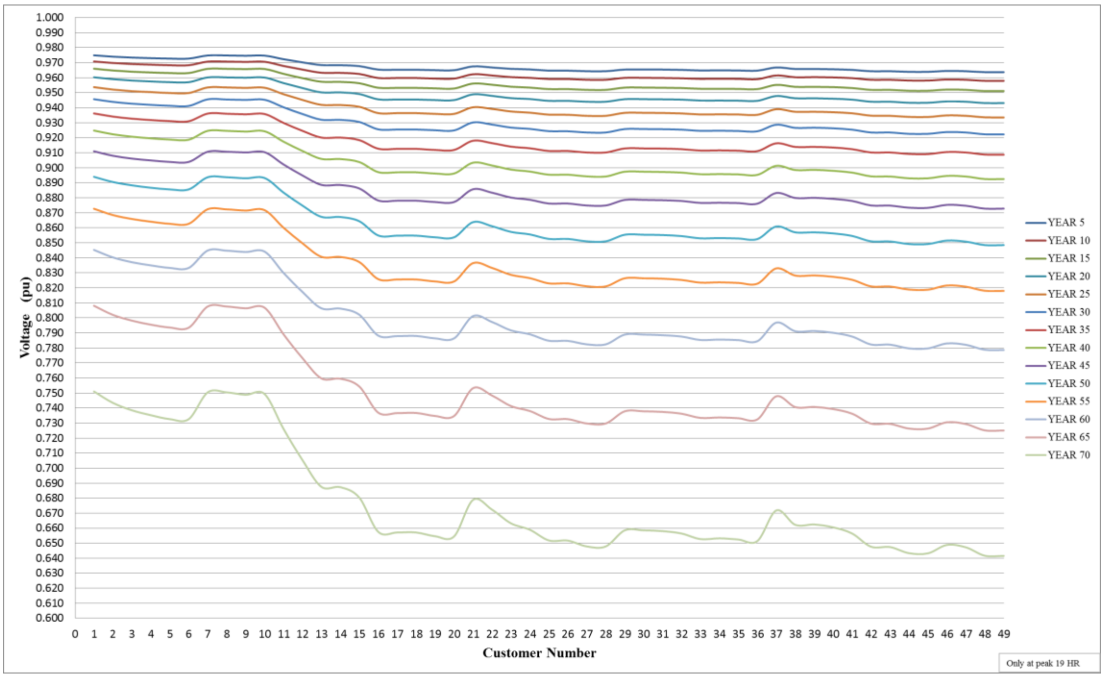


Figure 4.11: The voltage profile of all 49 customers at peak time 19:00 in 70 years period of time.

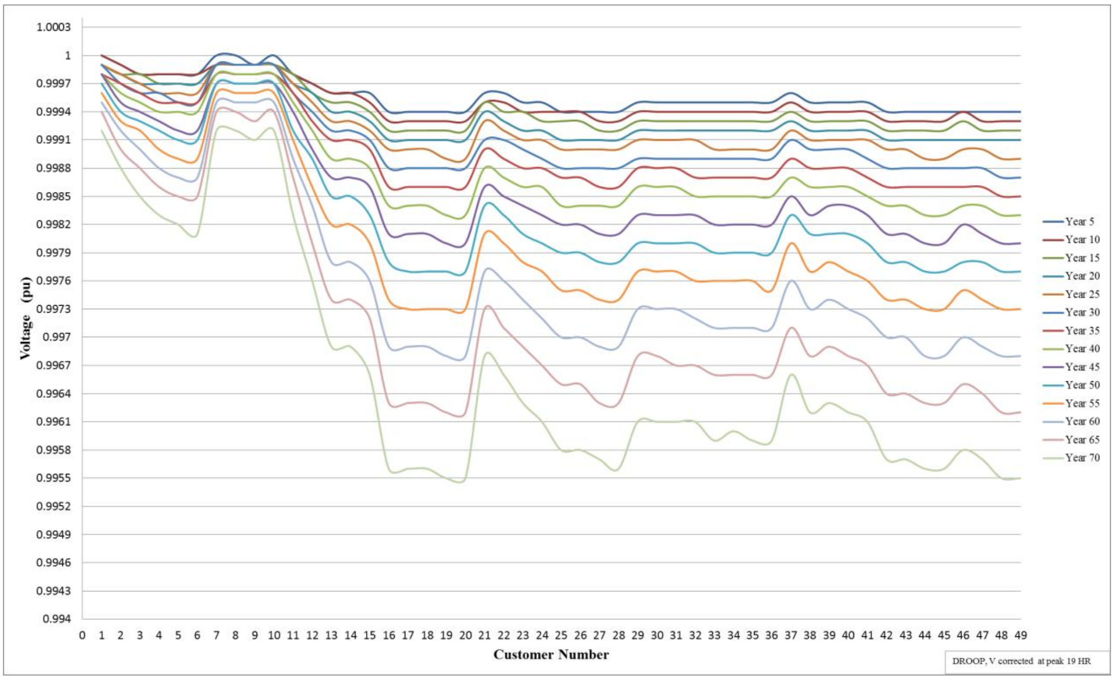


Figure 4.12: The voltage profile of all 49 customers at peak time 19:00 in 70 years period of time, using Q_s-V droop characteristic as at Figure 4.2.

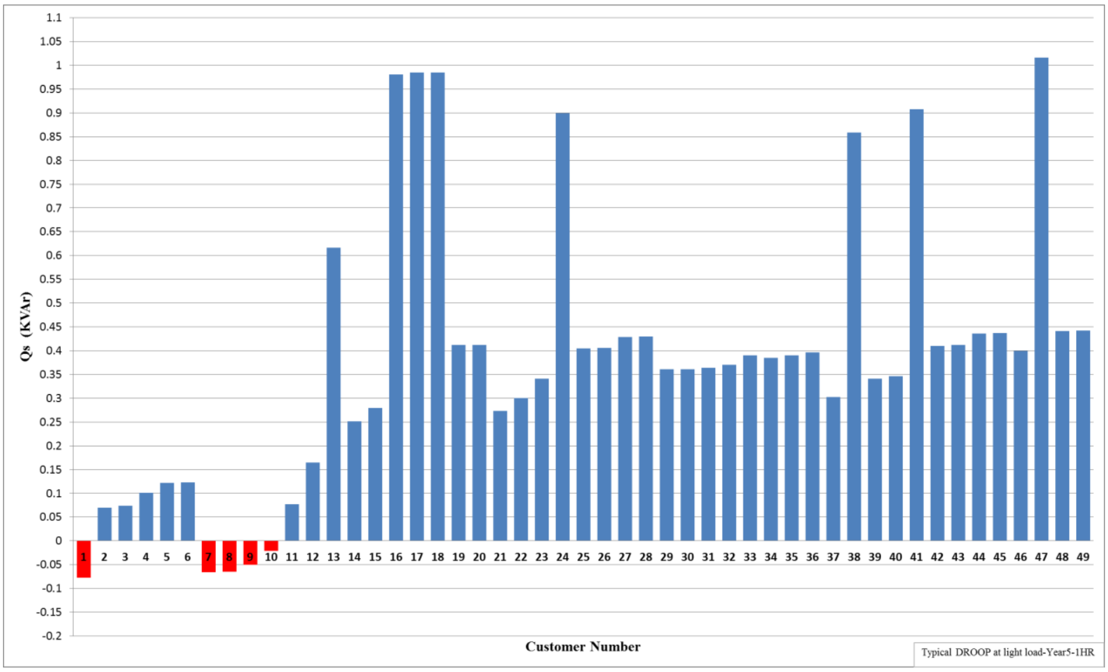


Figure 4.13: The DSTATCOM reactive power Qs to be injected or absorbed for all customers at time 1:00 of year 5, using Q_s-V droop characteristic as at Figure 4.2.

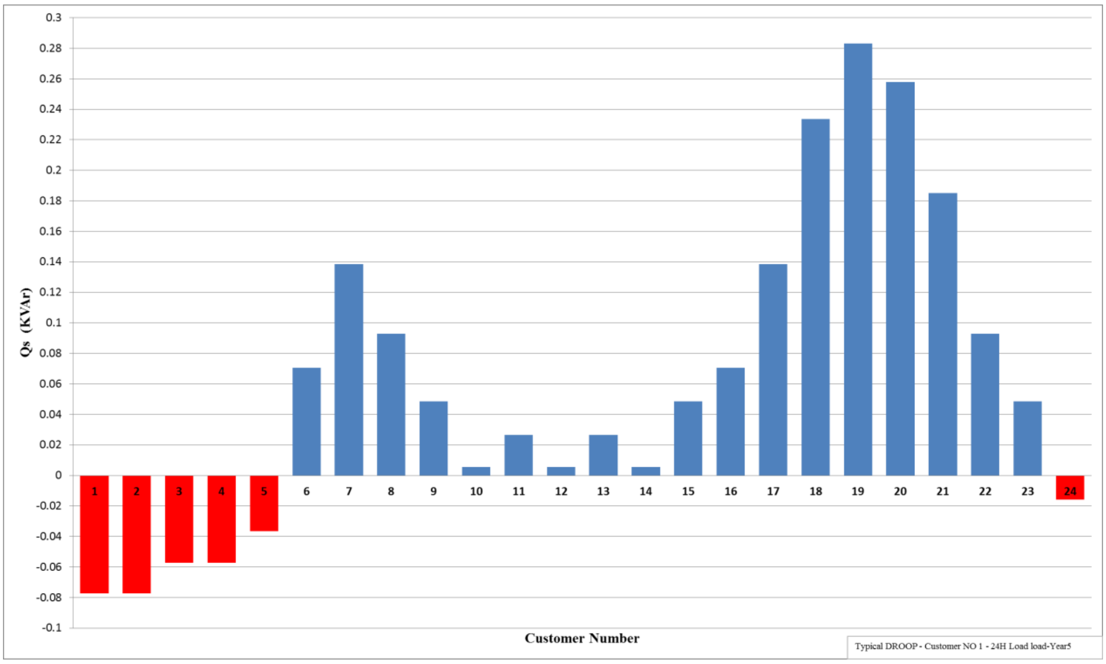


Figure 4.14: The DSTATCOM reactive power Qs to be injected or absorbed at customer 1 in 24 hours of year 5, using Q_s-V droop characteristic as at Figure 4.2.

The DSTATCOM reactive power of Qs to be injected or absorbed at customer one in the 24 hours period of time of year 5 is illustrated in Figure 4.14. The calculated Q_s is negative during the lightly loaded hours, which means the voltage has been detected to be above V_{ref} and VArs have to be absorbed to correct the voltage. Both Figures 4.13 and 4.14 show evidence of VAr circulation. In the system with droop control implemented into load flow it was necessary to address such a problem by modifying the droop control.

Typical and modified droop characteristics (Figures 4.2 and 4.5) have been implemented in load flow to calculate the needed DSTATCOM reactive power Q_s in terms of voltage support. The DSTATCOM reactive power Q_s for all customers at peak time of 19:00 for a 70 year period, using both types of Q_s-V droop characteristic is shown in Figure 4.15. As can be seen, using the modified droop method not only supports the voltage with less reactive power injection and minimises the possibility of VAr circulation, but also reduced the number of customers needing to install a DSTATCOM. In this case, 9 out of 49 existing customers do not need any voltage support equipment to be installed.

The voltage profile of all 49 customers corresponding to the injected DSTATCOM reactive power Q_s in Figure 4.15 is shown in Figure 4.16. In both cases the voltages have been fully supported and the system is operating within normal tolerances during the peak period.

It has to be noted that the voltage profile in Figure 4.16 is only showing year 70. The voltage profile of all customers at the peak time (19:00) in the 70 years period with the modified droop characteristics including hysteresis control loop is shown in Figure 4.17. It is obvious that the voltage of all the customers during the 70 years period have been fully supported and operating above the lower voltage threshold that is set to 0.94pu.

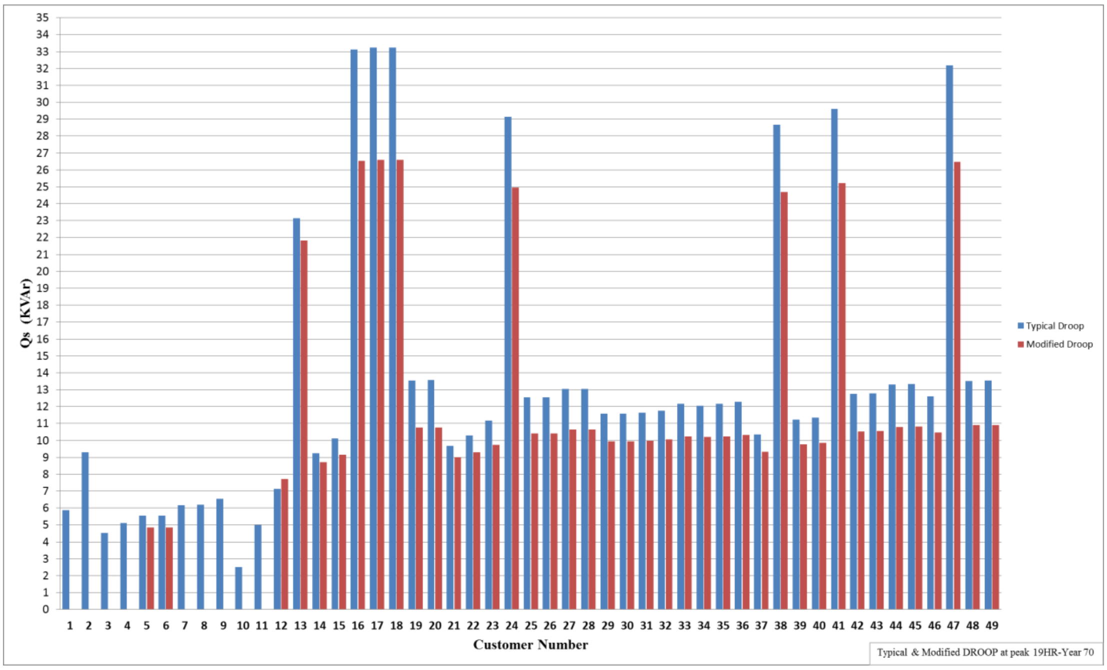


Figure 4.15: The DSTATCOM reactive power Q_s for all customers at peak time 19:00 of year 70 using typical and modified Q_s-V droop characteristic as at Figures 4.2 and 4.5.

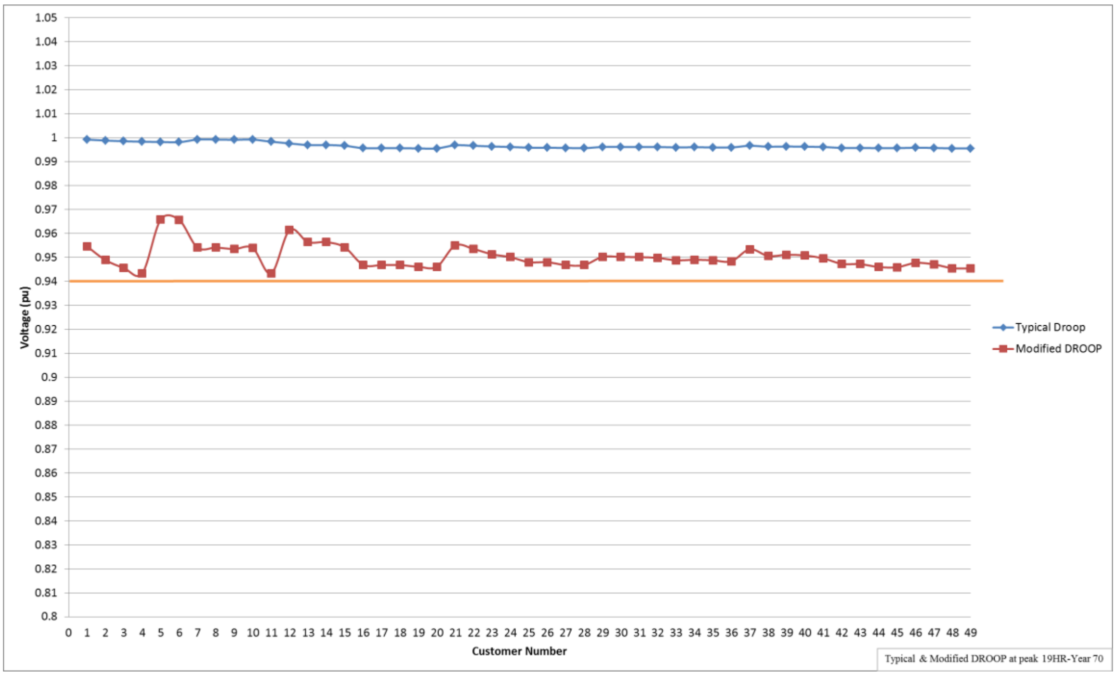


Figure 4.16: The voltage profile of all 49 customers corresponded with injected DSTATCOM reactive power Q_s shown at Figure 4.15.

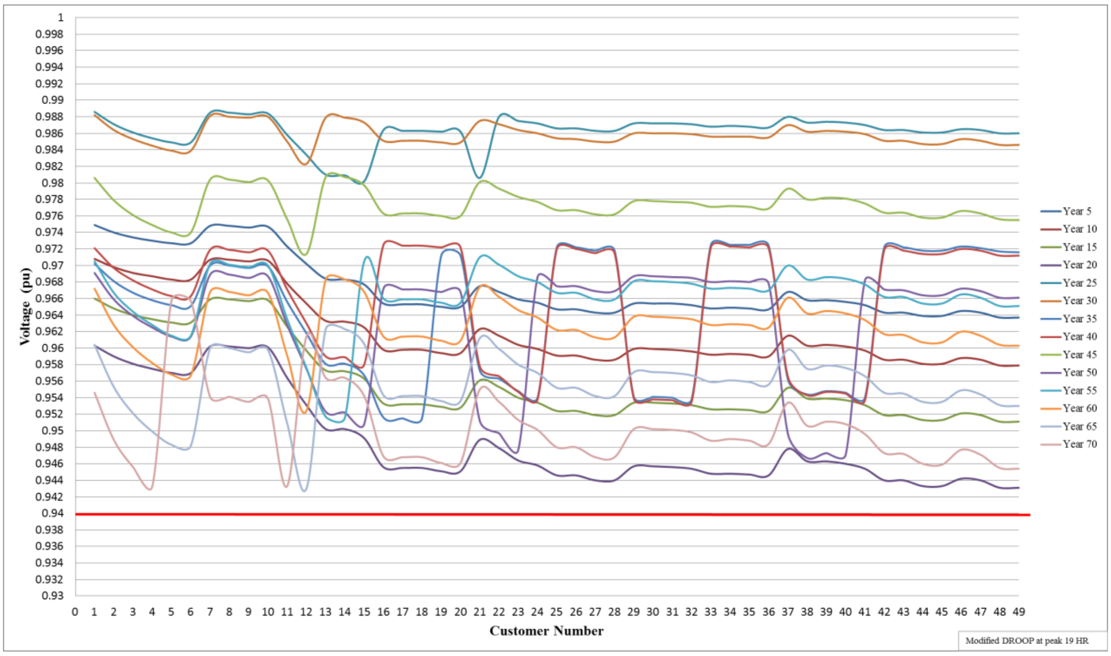


Figure 4.17: The voltage profile of all 49 customers at peak time 19:00 in 70 years period of time, using modified droop characteristics as at Figure 4.5.

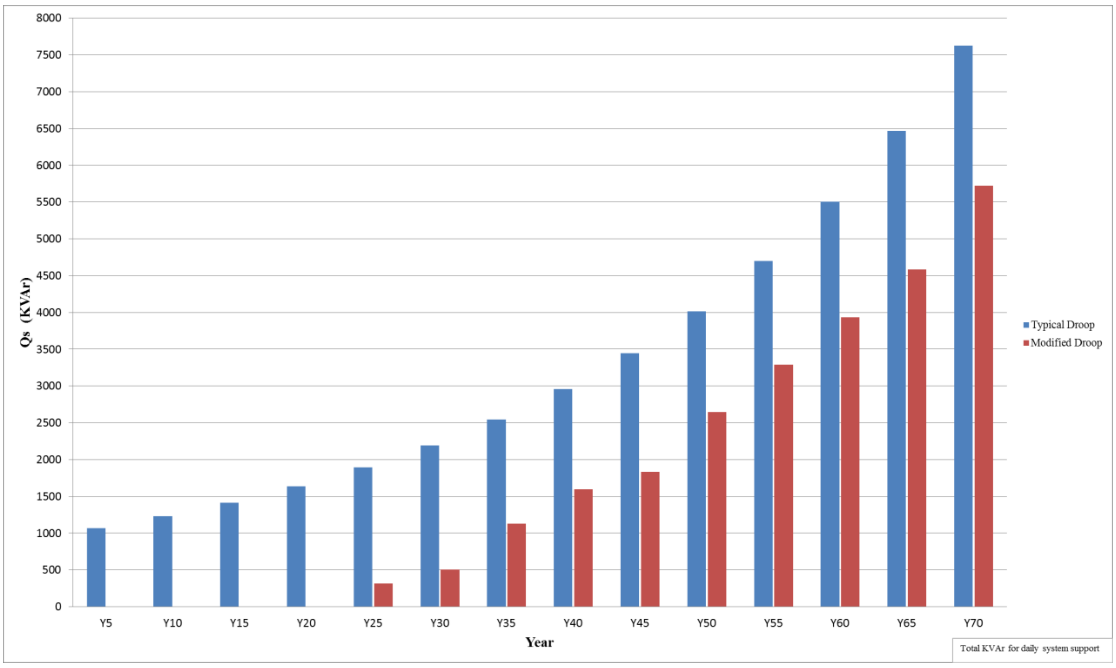


Figure 4.18: The needed DSTATCOM reactive power Q_s to support the voltage in 70 years period of time using typical and modified Q_s-V droop characteristics.

The required DSTATCOM reactive power Q_s to support the voltage in 70 years period of time using typical and modified Q_s-V droop characteristics is represented in Figure 4.18. As can be seen, the modified droop method not only supports from year 25, but also lowers amount of kVAr that has to be injected compared to the typical droop. The saved kVAr following from modified droop can be more than 25%, irrespective of the 20year delay in commencement of voltage support.

The 24 hours DSTATCOM operating status in years 25 and 70 to support the voltage are shown at Tables 4.2 and 4.3 respectively. It has to be considered that, if it is showing “OFF”, it means voltage is fine and no support is needed but if it is showing “Q”, it means that customer suffering from either high or low voltage problem, DSTATCOM status is ON and operating on Q-only mode to support the voltage.

The 24hr voltage profile of all 49 customers in years 25 and 70 corresponding to Tables 4.2 and 4.3 are shown at Figures 4.19 and 4.20 respectively. As can be seen, the voltage level for all customers is above the lower voltage threshold and the system has been fully supported. The voltage of some customers in year 25 at time 18:00 dropped very close to 0.94pu and as for the next hour the load would be increasing, with a low voltage event likely to happen. Table 4.2 shows some of the DSTATCOMs switched ON to improve the voltage at time 19:00.

Table 4.4 shows the DSTATCOM usage for all the customers over the 70 years period. It includes the year of DSTATCOM installation and when it reaches its maximum capacity to support the voltage. As can be seen, 9 of the customers which are located closer to the back bone and not far from the source do not need any DSTATCOMs to be installed in this period of time. However, the system requires DSTATCOMs to be installed from year 25 and considering load growth more customers would be involved by year 70. In addition, the DSTATCOM of customer 47 reaches its maximum capacity from year 40 and more DSTATCOMS reach this limitation in following years. As can be seen, the DSTATCOM with Q-only operating mode is a solution to support the voltage for limited period of time depending on the load size and location.

Table 4.2: 24 hours DSTATCOM operating status in year 25 to support the voltage

HR / CUS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
2	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
3	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
4	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
5	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
6	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
7	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
8	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
9	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
10	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
11	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
12	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
13	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
14	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
15	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
16	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	OFF	OFF	OFF
17	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	OFF	OFF	OFF
18	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	OFF	OFF	OFF
19	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
20	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
21	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
22	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
23	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
24	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	OFF	OFF	OFF
25	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
26	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
27	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	OFF	OFF	OFF
28	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	OFF	OFF	OFF
29	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	OFF	OFF	OFF
30	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	OFF	OFF	OFF
31	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	OFF	OFF	OFF
32	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	OFF	OFF	OFF
33	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	OFF	OFF	OFF
34	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	OFF	OFF	OFF
35	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	OFF	OFF	OFF
36	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	OFF	OFF	OFF
37	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
38	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	OFF	OFF	OFF
39	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	OFF	OFF	OFF
40	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	OFF	OFF	OFF
41	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	OFF	OFF	OFF
42	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	OFF	OFF	OFF
43	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	OFF	OFF	OFF
44	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	OFF	OFF	OFF
45	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	OFF	OFF	OFF
46	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	OFF	OFF	OFF
47	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	OFF	OFF	OFF
48	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	OFF	OFF	OFF
49	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	OFF	OFF	OFF

Table 4.3: 24 hours DSTATCOM operating state in year 70 to support voltage

CUS \ HR	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
2	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
3	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
4	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
5	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q
6	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q
7	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
8	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
9	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
10	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
11	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
12	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q
13	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
14	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
15	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
16	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
17	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
18	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
19	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
20	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
21	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
22	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
23	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
24	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
25	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
26	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
27	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
28	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
29	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
30	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
31	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
32	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
33	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
34	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
35	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
36	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
37	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
38	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
39	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
40	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
41	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
42	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
43	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
44	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
45	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
46	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
47	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
48	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
49	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q

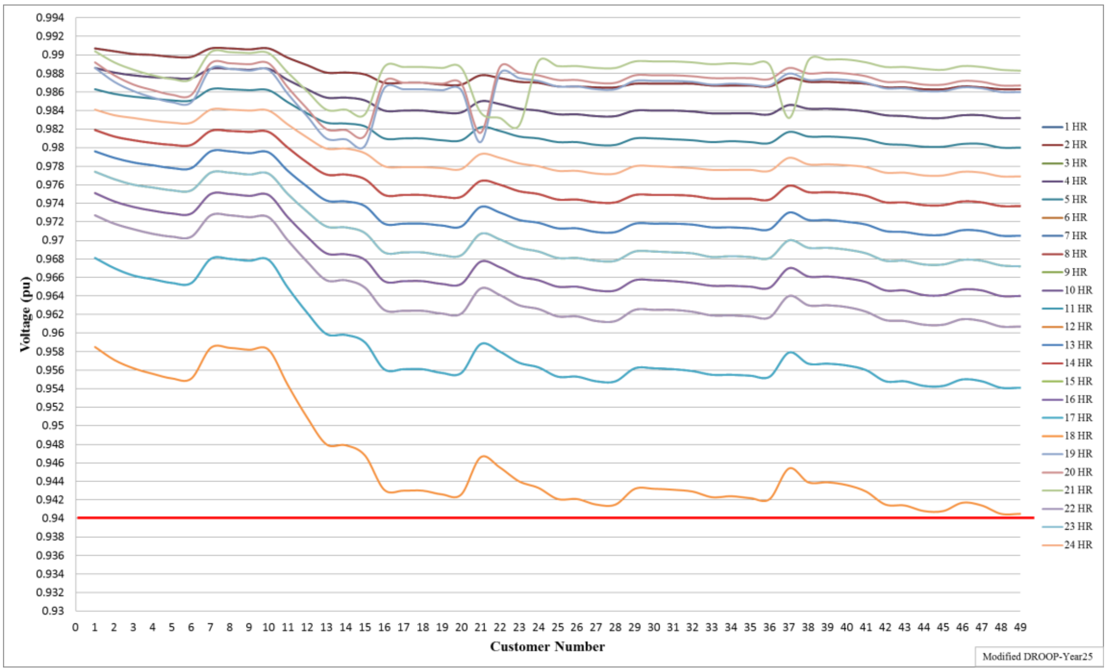


Figure 4.19: 24 hours voltage profile of all 49 customers in year 25 corresponding to Table 4.2.

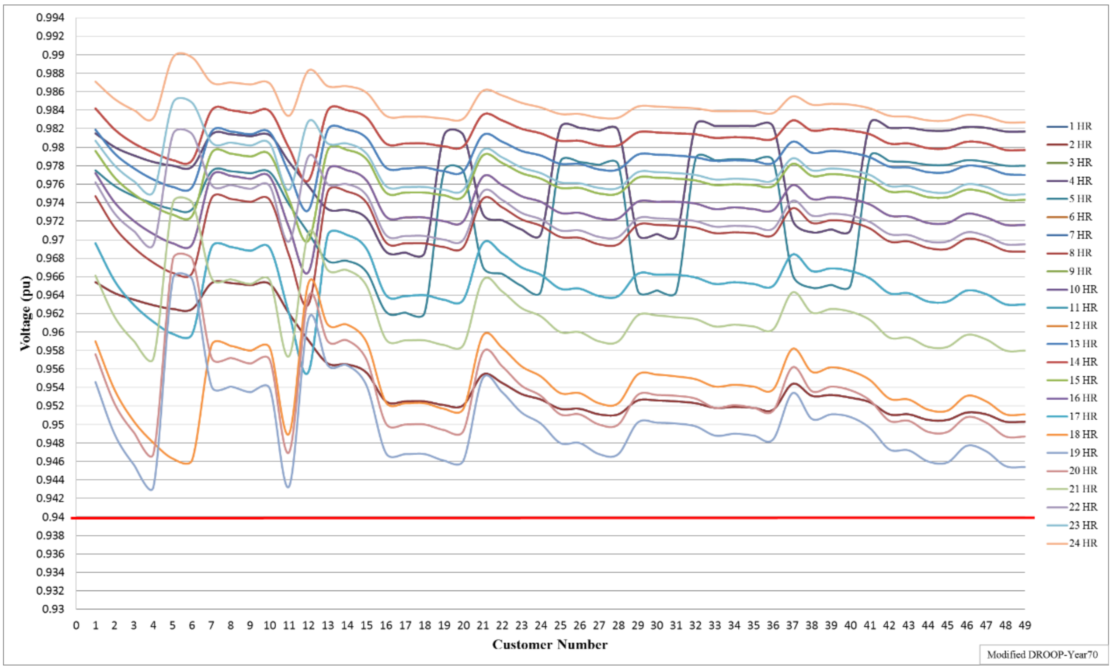


Figure 4.20: 24 hours voltage profile of all 49 customers in year 70 corresponding to Table 4.3.

Table 4.4: DSTATCOM usage for all customers over a 70 years period

Customer Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Year DSTATCOM is needed	---	---	---	---	70	70	---	---	---	---
Year DSTATCOM reaches its maximum	---	---	---	---	---	---	---	---	---	---
Customer Number	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Year DSTATCOM is needed	---	60	45	55	55	25	25	25	50	45
Year DSTATCOM reaches its maximum	---	---	55	70	70	45	45	45	60	55
Customer Number	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**
Year DSTATCOM is needed	55	55	55	25	35	40	25	25	25	25
Year DSTATCOM reaches its maximum	70	70	60	50	50	55	50	55	55	55
Customer Number	**31**	**32**	**33**	**34**	**35**	**36**	**37**	**38**	**39**	**40**
Year DSTATCOM is needed	25	25	25	25	25	25	30	25	25	25
Year DSTATCOM reaches its maximum	60	60	60	50	50	50	55	45	55	55
Customer Number	**41**	**42**	**43**	**44**	**45**	**46**	**47**	**48**	**49**	---
Year DSTATCOM is needed	25	25	25	25	25	25	25	25	25	---
Year DSTATCOM reaches its maximum	45	60	60	55	55	55	40	50	50	---

4.7 Conclusions

This chapter presented a Q-only operating mode for DSTATCOM to support the voltage in a SWER network, by either absorbing or injecting VArs to reduce or increase the voltage to the desired level. The operation of the DSTATCOMs in the system as voltage support equipment was able to be controlled using a traditional reactive power-voltage droop. Moreover, the Jacobian matrix was modified due to implementation of droop with a Newton Raphson load flow. To minimise the possibility of VAr circulation and reduce the quantity of reactive power required to support the voltage, a modified droop method was implemented. This was done by considering a hysteresis control loop that could control the state of the DSTATCOM, either ON or OFF, absorbing or injecting VArs.

The results demonstrated that using a typical droop control may cause VAr circulation in the system but that the modified droop, with hysteresis control loop included, not only minimised the VAr circulation possibility, but also reduced the amount of reactive power required to support the system voltage. Furthermore, it has reduced the required number of DSTATCOMs needed to be installed in the system as voltage support equipment.

In reality there is a limit for the use of VAr compensation (transformer rating, stability issues and thermal limitation). In this study, the VAr compensation is considered to be limited by the DSTATCOM size with maximum of the transformer rating. In such a system the use of DSTATCOMs with Q-only operation is a solution for a limited time period, as shown in Table 4.4. Another type of DSTATCOM operating mode will be introduced in next chapter as a solution to support the voltage for a longer period of time when the DSTATCOM reaches its VAr compensation limit.

CHAPTER 5

Q_PRIORITY DSTATCOM OPERATING MODE

5.1 Introduction

Another type of DSTATCOM operation mode, namely Q-priority, will be studied in this chapter. Applying reactive power as much as possible to support the system voltage in this mode is given priority and in the cases where the voltage issue can not be addressed by reactive power support alone, then active power is included. When the DSTATCOM is OFF it means no voltage support equipment is operating in the system and the voltage is within standard tolerances of supply. On the other hand, when it is ON it means that a voltage issue, either low or high, has been detected and the system voltage has to be pushed back to within tolerance boundaries. In this case, depending on deviation from the normal tolerances the DSTATCOM might be operating in Q-only mode or P-Q mode. In order to achieve this functionality a new droop characteristic that allows the DSTATCOM able to operate in the Q-only mode or P-Q mode will be proposed. The introduced droop characteristic for the DSTATCOM as voltage support equipment will be verified by load flow studies. MATLAB is used to study the DSTATCOM Q-priority mode for a SWER system.

5.2 DSTATCOM Q-Priority Mode Operation

In this chapter the DSTATCOM will be operating in Q-priority mode. The priority of this voltage support method is to inject or absorb reactive power, but in the cases where Q only is not able to correct the voltage, active power injection can also be included. This means the DSTATCOM will be operating in either Q-only mode or P-Q mode. The DSTATCOM operating point sits on the reactive power axis when it is in Q-only mode and on a power circle when operating in P-Q mode.

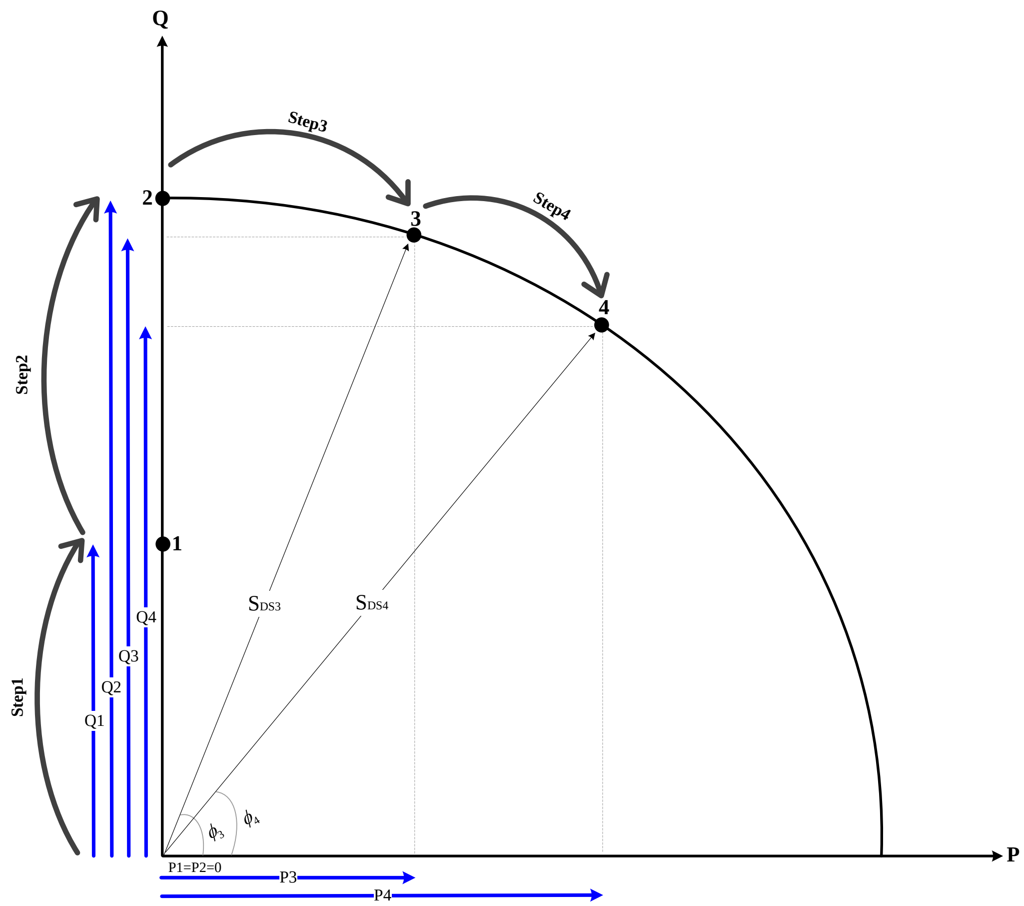


Figure 5.1: The DSTATCOM power injection in Q-priority mode operation.

Figure 5.1 shows the DSTATCOM power injection in Q-priority mode operation for four different system operating conditions.

As illustrated in figure 5.1, the operating point may either be located on the Q axis (steps 1 and 2) or on the power circle (steps 3 and 4). The first 2 steps are Q-only mode as per Figure 4.1 in the previous chapter. Assuming the DSTATCOM is operating at point 2 and due to a variation in load conditions the corresponding voltage will drop. Due to DSTATCOM size limitations, it is not able to inject more reactive power and step 3 will be taken. As can be seen, instead of going further up and injecting more VArs, the operating point will sit on the P-Q circle with a DSTATCOM active and reactive power of P_3 and Q_3 respectively.

As the DSTATCOM rating is assumed to be fixed, the operating point would be somewhere on the circle with the same S_{DS}. Considering future load increment step 4 would be taken and a new DSTATCOM operating point adjusts at point 4. To improve the voltage in the network more active power is needed, but to stay on the circle the reactive power will be reduced.

5.3 Droop Characteristics

Two different types of droop can be used while the DSTATCOM is operating on Q-priority mode. If only reactive power is enough to support the voltage, the Q_s-V droop will be used as like the previous chapter. But, if active power is included and P_s and Q_s applied to support the voltage of the system, the new type of droop that named active power-voltage droop (P_S-V) will be used.

5.3.1 DSTATCOM Reactive Power-Voltage Droop

In this case only reactive power will be used to support the voltage and the corresponding droop characteristic is shown in Figure 5.2(a). As can be seen, if the DSTATCOM operating point sits on the Q axis, (Figure 5.2, point A), the Q_s-V droop will be used. The droop control equation has already been defined at previous chapter as equation (4.1). It is obvious that the P_s, DSTATCOM active power, is zero.

5.3.2 DSTATCOM Active Power-Voltage Droop

When the load is too heavy, the system voltage will drop and in order to support it, injection of active power needs to be considered. The DSTATCOM operating point will sit on the P-Q circle and in this case new droop characteristics will be introduced. Figure 5.2(b) shows the active power-voltage droop characteristics when the DSTATCOM is required to inject or absorb active and reactive power (operating point B).

The new droop control equation for P_{si}-V_i droop characteristics is defined as:

$$P_{si} = K_{pi}(V_{ref} - |V_i|) \tag{5.1}$$

$$Q_{si} = \sqrt{S_{DSi}^2 - P_{si}^2} \tag{5.2}$$

$$Cos\phi_{DSi} = \frac{P_{Si}}{S_{DSi}} \tag{5.3}$$

Where: P_{si} and Q_{si} are respectively the DSTATCOM active and reactive power injected and S_{DSi} is the rated VA of the DSTATCOM. In this case the DSTATCOM will be operating at a power factor of Cos ϕ_{DSi}.

5.3.3 Load Flow Study Droop Implementation

Implementing the Q-Priority droop controls for a Newton Raphson load flow will be studied in this section. Depending on the system load and DSTATCOM operating point two different situations with different droop characteristics will be considered as per Figures 5.2(a) and 5.2(b). The first will be used with only reactive power supporting the voltage and DSTATCOM operating on the Q axis in Q-only mode. In this case, Q_s-V droop will be implemented in the load flow equations to compute the required DSTATCOM reactive power Q_{si}. The second droop characteristic will be used when active and reactive powers are included with the DSTATCOM operating on the P-Q power circle. The new droop characteristics, P_{si}-V_i, will be implemented in the load flow and the respective DSTATCOM active and reactive power at bus *i*, P_{si} and Q_{si}, will be calculated.

5.3.4 Modified Jacobian Matrix Elements

The implementation of the DSTATCOM in Q-priority mode as a source of active and reactive power in the load flow will change the Jacobian matrix elements. Figure 5.3 represents the power at bus *i*, for the DSTATCOM operating in Q-priority mode. With the DSTATCOM operating with reactive power, the power connection in Figure 5.3 (a1) and (b) will be considered, which has already been discussed in the previous chapter. On the other hand, when active power is included, Figure 5.3 (a2) and (b) will be considered where P_{si} is the DSTATCOM active power to be injected in to bus *i*.

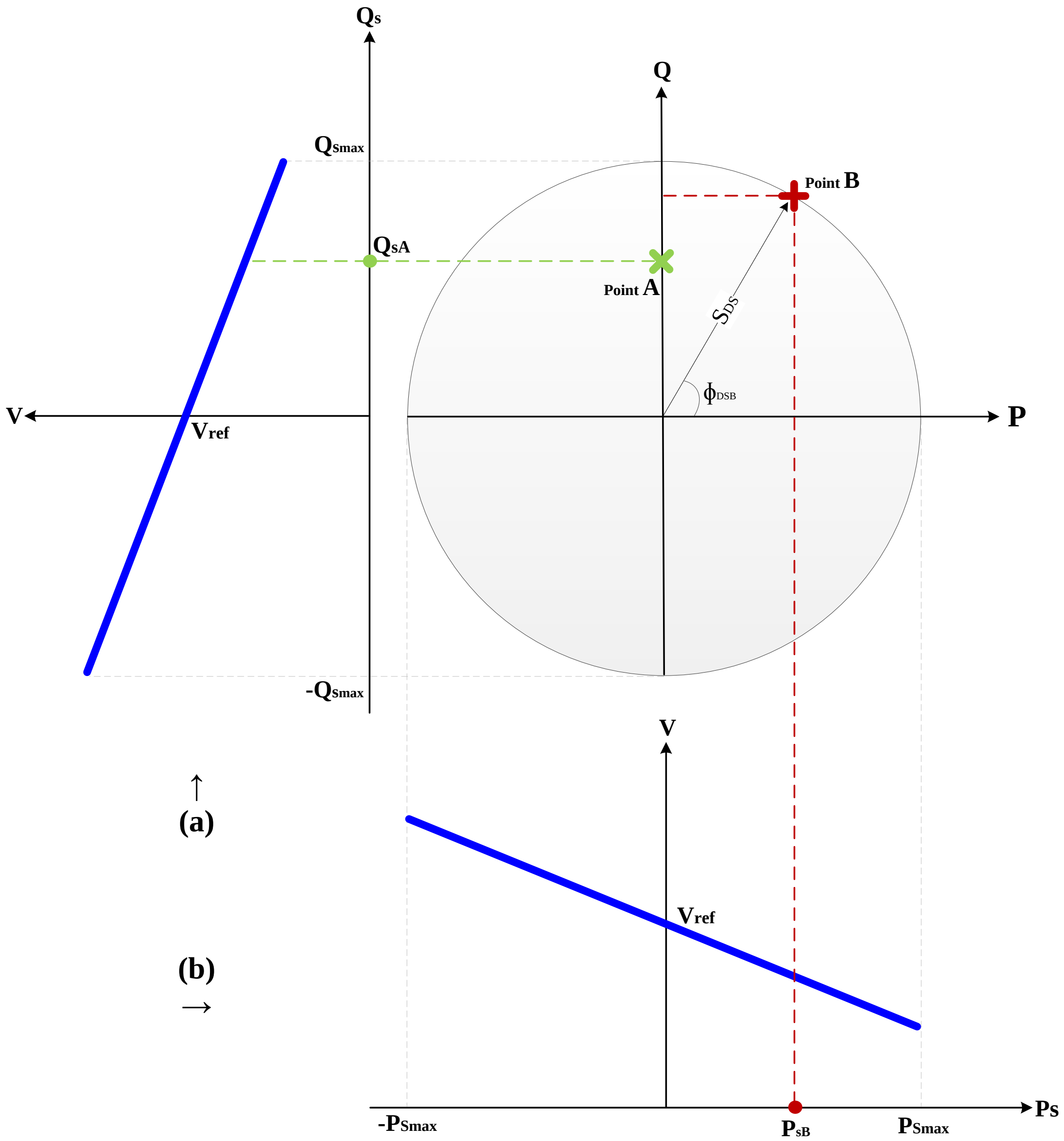


Figure 5.2: P-Q circle, Q_s-V and P_S-V droop control relationship.

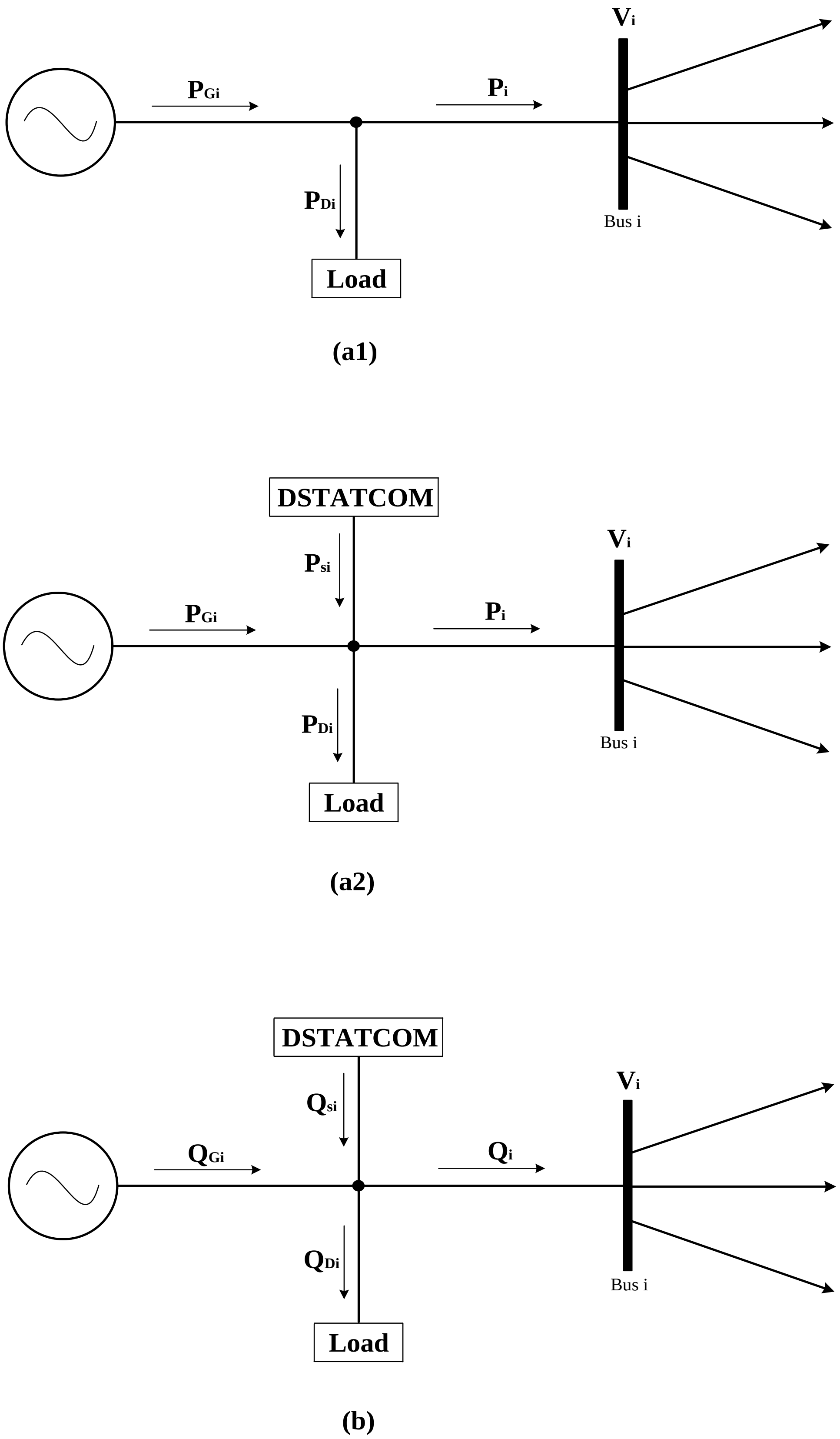


Figure 5.3: (a1) and (a2) Active and (b) Reactive power flow at bus *i* with DSTATCOM operating in Q-priority mode.

From the Figure 5.3 (a2) and (b), net active and reactive power will be calculated as:

$$P_i = K_{pi}(V_{ref} - |V_i|) + (P_{Gi} - P_{Di}) \quad (5.4)$$

$$Q_i = \sqrt{S_{DSi}^2 - K_{pi}^2 (V_{ref} - |V_i|)^2} + (Q_{Gi} - Q_{Di}) \quad (5.5)$$

Where: P_i and Q_i are the respective net active and reactive powers injected at bus i.

The total P and Q flowing in to bus i, for a converged solution are:

$$f_{P,i}(\delta, V) = K_{pi}(V_{ref} - |V_i|) + (P_{Gi} - P_{Di}) - \sum_{k=1}^{n} |V_k||V_i|[G_{ik}\cos(\delta_k - \delta_i) - B_{ik}\sin(\delta_k - \delta_i)] = 0 \quad (5.6)$$

$$f_{Q,i}(\delta, V) = \sqrt{S_{DSi}^2 - K_{pi}^2 (V_{ref} - |V_i|)^2} + (Q_{Gi} - Q_{Di}) + \sum_{k=1}^{n} |V_k||V_i|[B_{ik}\cos(\delta_k - \delta_i) + G_{ik}\sin(\delta_k - \delta_i)] = 0 \quad (5.7)$$

The Jacobian matrix diagonal and off-diagonal terms will be calculated as follows:

Main-diagonal and off-diagonal terms of submatrix J_{11} are determined to be as:

$$\frac{\partial f_{Pi}}{\partial \delta_i} = \sqrt{S_{DSi}^2 - K_{pi}^2 (V_{ref} - |V_i|)^2} + (Q_{Gi} - Q_{Di}) + |V_i|^2 B_{ii} \quad (5.8)$$

$$\frac{\partial f_{Pi}}{\partial \delta_k} = |V_k||V_i|[G_{ik}\sin(\delta_k - \delta_i) + B_{ik}\cos(\delta_k - \delta_i)] \quad (5.9)$$

Main-diagonal and off-diagonal elements of submatrix J_{12} are determined to be as:

$$\frac{\partial f_{Pi}}{\partial |V_i|} = K_{pi} + [-(K_{pi}(V_{ref} - |V_i|) + (P_{Gi} - P_{Di})) - |V_i|^2 G_{ii}] / |V_i| \quad (5.10)$$

$$\frac{\partial f_{Pi}}{\partial |V_k|} = -|V_i|[G_{ik}\cos(\delta_k - \delta_i) - B_{ik}\sin(\delta_k - \delta_i)] \quad (5.11)$$

Main-diagonal and off-diagonal terms of submatrix J_{21} are determined to be as:

$$\frac{\partial f_{Qi}}{\partial \delta_i} = -[K_{pi}(V_{ref} - |V_i|)) + (P_{Gi} - P_{Di})] + |V_i|^2 G_{ii} \tag{5.12}$$

$$\frac{\partial f_{Qi}}{\partial \delta_k} = -|V_k||Vi|[B_{ik} \cos(\delta_k - \delta_i) + G_{ik} \sin(\delta_k - \delta_i)] \tag{5.13}$$

Main-diagonal and off-diagonal elements of submatrix J_{22} are determined to be as:

$$\frac{\partial f_{Qi}}{\partial |V_i|} = -[S_{DSi}^2 - K_{pi}^2 (V_{ref} - |V_i|)^2]^{-1/2} (V_{ref} - |V_i|) K_{pi}^2 - |V_i|^2 B_{ii}] / |V_i| \tag{5.14}$$

$$\frac{\partial f_{Qi}}{\partial |V_k|} = |V_i|[B_{ik} \cos(\delta_k - \delta_i) + G_{ik} \sin(\delta_k - \delta_i)] \tag{5.15}$$

As can be seen from the above equations, having a DSTATCOM installed in bus *i* operating in Q-priority mode will change the diagonal elements of all 4 Jacobian submatrices. Running a load flow with Q-priority mode implemented will calculate the required amount of active and reactive power for DSTATCOM to support the voltage for given system load values of P_{Di} and Q_{Di} .

5.4 Modified Droop Characteristics

In this part of the study a hysteresis control loop for DSTATCOM Q-priority mode control will be defined. This loop controls the DSTATCOM operation i.e. ON or OFF, based on the amplitude of the voltage calculated at bus *i* via the load flow study. Whether the DSTATCOM is ON, depends on its respective operating point on either the Q_s-V or P_s-V droop characteristic being applied.

5.4.1 Hysteresis Control Loops for Q-priority Mode

The new hysteresis control loop with respect to the Q-priority mode of DSTATCOM will be defined in this part of the study. It will control the state of the DSTATCOM based on defined upper and lower voltage boundaries. The hysteresis control loop for Q-priority mode including the DSTATCOM mode switching boundaries is shown in Figure 5.4. Compared with the Q-only mode, the new control approach includes active power injection as the voltage reaches 0.92pu, which means the reactive power injection could not solely solve the voltage problem. In this case, active power injection is required and the DSTATCOM will be able to support the voltage via injection of both P and Q elements. As can be seen, when the voltage reaches 0.94pu (point A) the DSTATCOM will be switched ON and operate in Q-only mode (line AB). After this point, there are two possibilities, firstly, that the voltage increases due to VAr injection and secondly, that voltage decreases due to rising load. The first possibility has been already discussed in Q-only mode, but the question is how the DSTATCOM will react if the voltage dropped (line BC) as VAr is injected. When the system voltage reaches 0.92pu (point C) the Q-only control mode of the DSTATCOM will be switched OFF (line CK) and the P-Q mode will be turned ON (line KM). When the DSTATCOM is operating in P-Q mode, as in point B of Figure 5.2, active and reactive power will be injected into the system and the voltage will increase (line MN). This operating mode will continue until the voltage reaches the upper control band of 0.99pu (point N). Operating at the voltage of 0.99pu will be detected as a normal condition and the DSTATCOM P-Q mode will be switched OFF (line NE).

All the logical possibilities related to DSTATCOM operational state for all possible customer voltage amplitude scenarios, along with the defined control boundaries from Figure 5.4 are detailed in Table 5.1.

5.4.2 DSTATCOM Q-Priority Mode Flowchart

The Q-priority mode of DSTATCOM operation has been explained in a flowchart in Figure 5.5. As can be seen, it includes two different droop control implementations in a load flow as shown in Figure 5.2. Modified elements of the Jacobian matrix, with upper and lower voltage boundaries and switching conditions of the DSTATCOMs respective operating modes are also given.

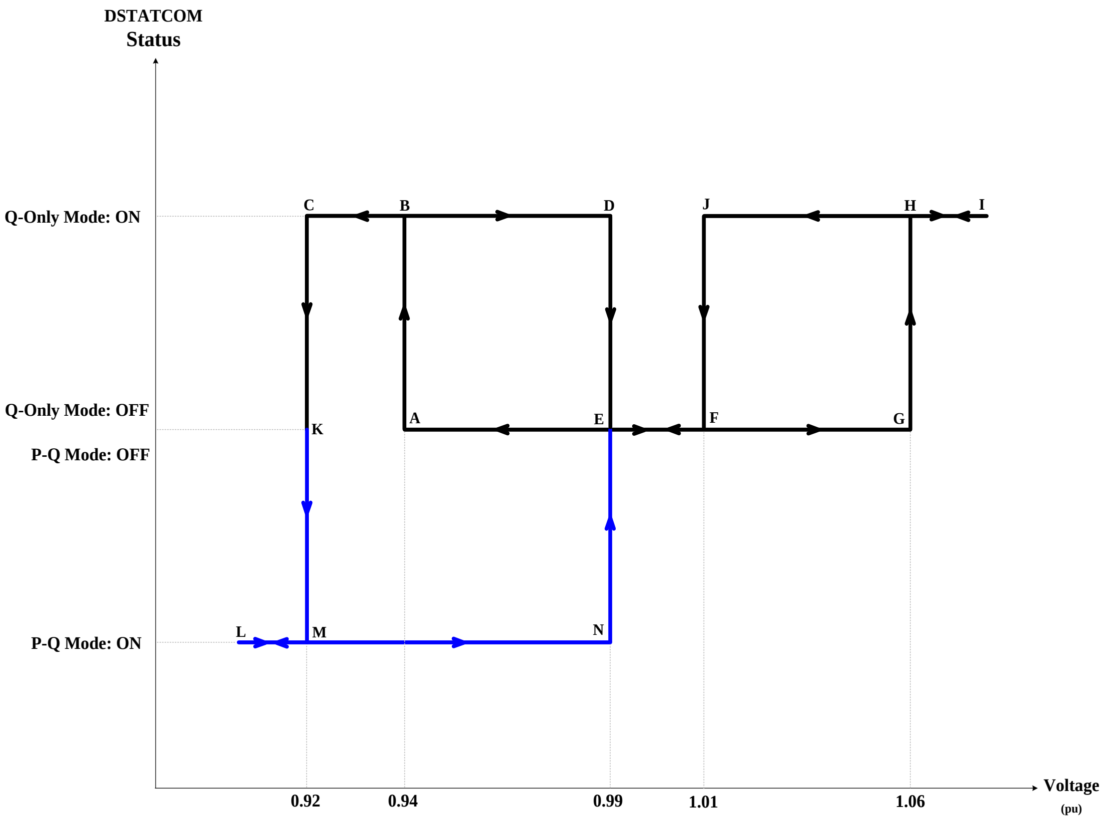


Figure 5.4: Hysteresis control loop for Q-priority mode showing DSTATCOM state.

Table 5.1: Hysteresis control loop details for DSTATCOM Q-priority mode as per Figure 5.4

Hysteresis Loop Position	**Voltage** (pu)	**Customer Voltage Status**	**DSTATCOM**		**Q_s / P_s Status**
			Mode	**State**	
AB	0.94	Low voltage	Q-only	OFF→ON	Q_s to be injected
BD	0.94–0.99	Allowable range	Q-only	ON	Q_s is injecting
DE	0.99	Normal	Q-only	ON→OFF	Q_s injection terminated
EA	0.99–0.94	Allowable range	Q-only/P-Q	OFF	No injection/absorption
EF/FE	0.99–1.01	Allowable range	Q-only/P-Q	OFF	No injection/absorption
FG	1.01–1.06	Allowable range	Q-only/P-Q	OFF	No injection/absorption
GH	1.06	High voltage	Q-only	OFF→ON	Q_s to be absorbed
HJ	1.06–1.01	Allowable range	Q-only	ON	Q_s is absorbing
JF	1.01	Normal	Q-only	ON→OFF	Q_s absorption terminated
BC	0.94–0.92	Allowable range	Q-only	ON	Q_s is injecting
CK	0.92	Low voltage	Q-only	ON→OFF	Q_s injection terminated
KM	0.92	Low voltage	P-Q	OFF→ON	Q_s&P_s to be injected
MN	0.92–0.99	Allowable range	P-Q	ON	Q_s&P_s are injecting
NE	0.99	Normal	P-Q	ON→OFF	Q_s&P_s injection terminated

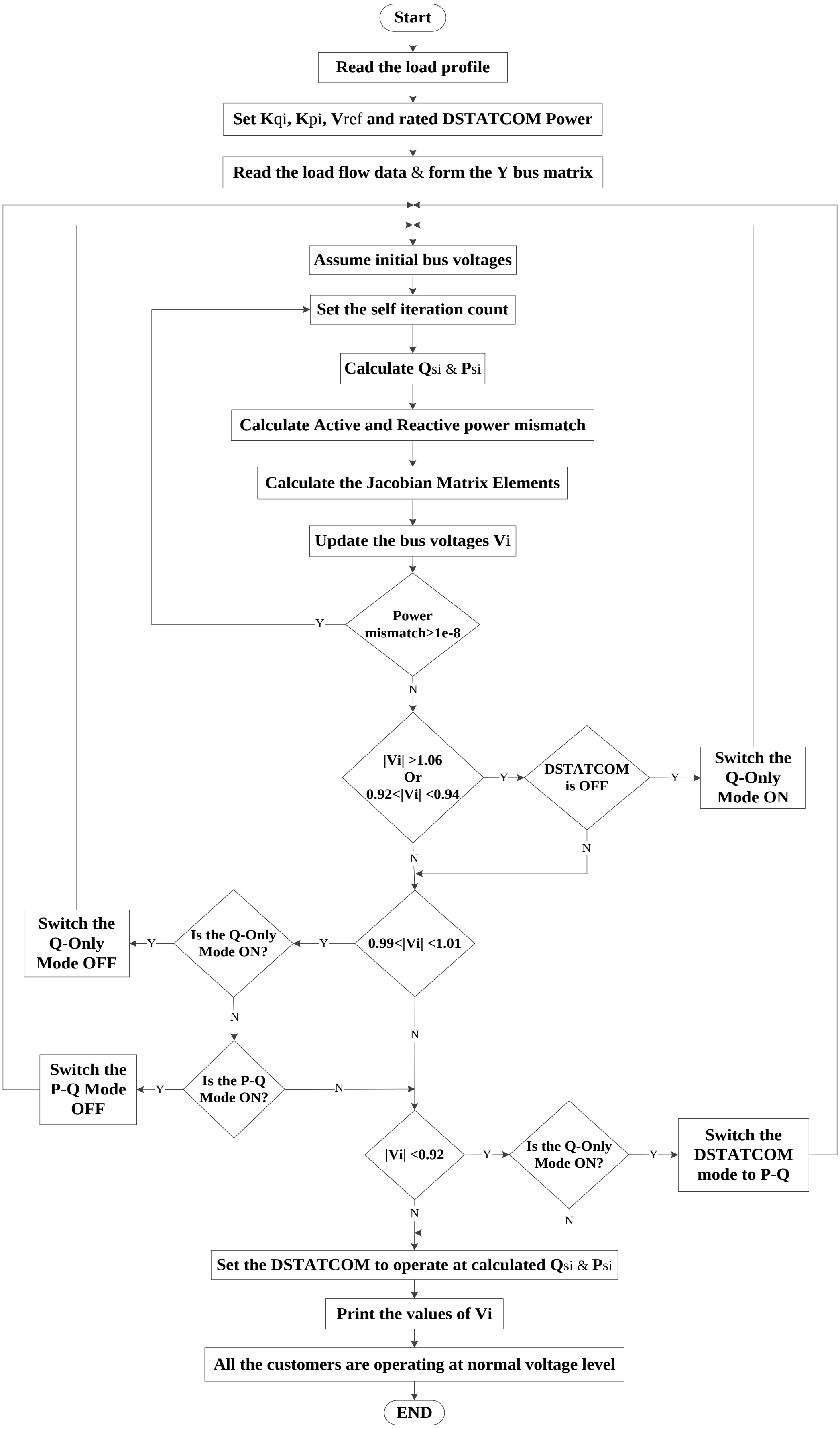


Figure 5.5: DSTATCOM Q-priority mode flowchart.

5.5 Case Study

In this section the Richmond SWER network in Central Queensland with 126 nodes as represented in Figure 3.23 will be studied.

5.6 Results and Discussions

The DSTATCOM operation in Q-priority mode at time 7:00 in year 70 for all 49 customers is shown in Figure 5.6. As can be seen, the DSTATCOMs located at the first 11 customers have not been activated at all and for the remaining 38 customers the system voltage is supported via reactive power injection alone. This is explained by the fact that the load during the morning peak is not a heavy one, and none of the DSTATCOMs needed to operate in P-Q mode. The system voltage profile corresponding to DSTATCOM operation of Figure 5.6 is represented in Figure 5.7.

During the afternoon peak when the load increases to its maximum the DSTATCOM will not be able to operate only in Q-only mode. The DSTATCOM operation of all customers at time 19:00 in year 70 is shown in Figure 5.8. The amount of active and reactive power needed to support the voltage by the DSTATCOM has been shown as P_s and Q_s. Only at customer 1 the DSTATCOM is never being used and 7 customers operated in P-Q mode. The other 41 customers' voltages are supported solely through reactive power injection. The DSTATCOMs at four of these customers (13, 20, 28 and 34) appear on the limit of allowable reactive power injection and if the load increase continues they will switch to P-Q mode operation. The system voltage was fully supported via the DSTATCOMs and is shown in Figure 5.9.

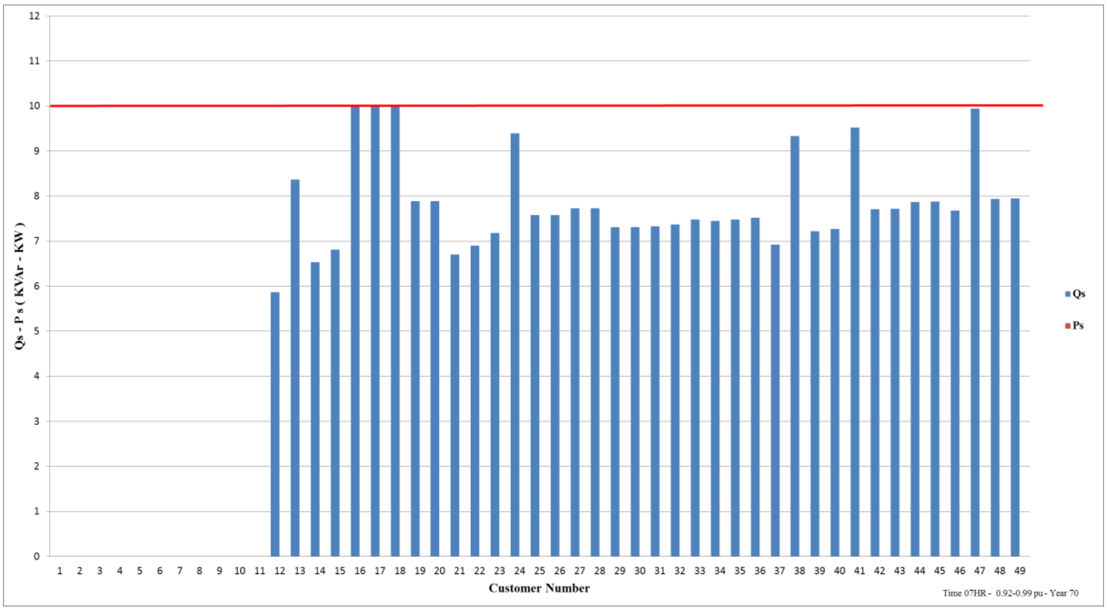


Figure 5.6: Q-Priority DSTATCOM operation, time 7:00, year 70, P-Q mode limits: 0.92pu-0.99pu.

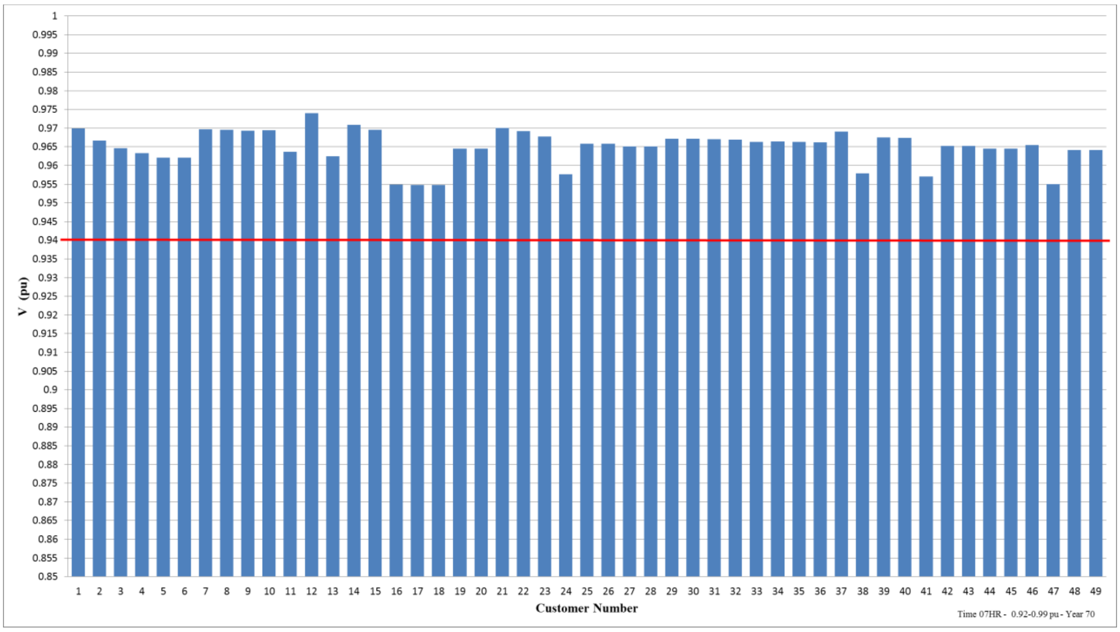


Figure 5.7: System voltage profile, time 7:00, year 70 with DSTATCOM operating in Q-priority mode.

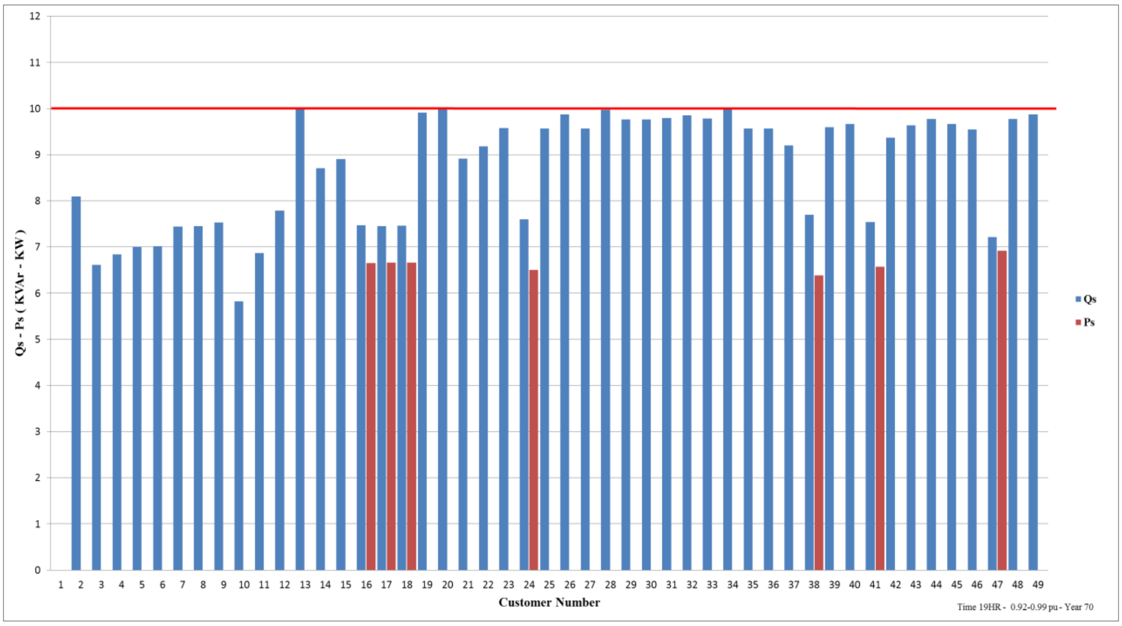


Figure 5.8: DSTATCOM operation in Q-priority mode, time 19:00, year 70, P-Q mode limits: 0.92-0.99pu.

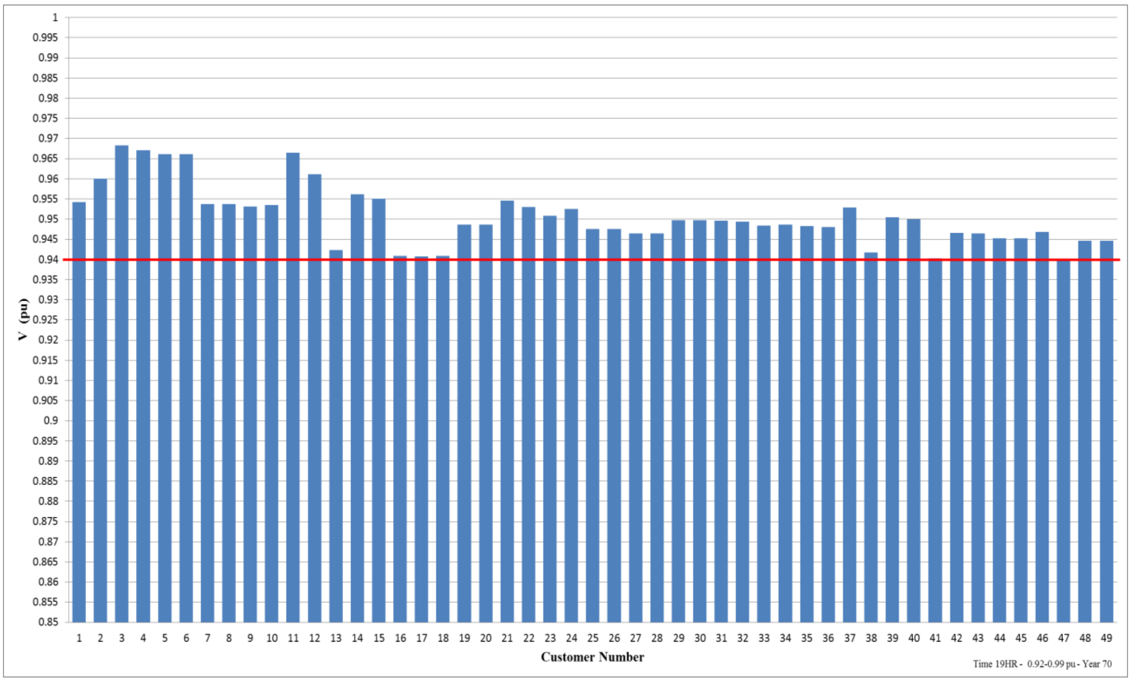


Figure 5.9: System voltage profile, 19:00, year 70 for DSTATCOM operating in Q-priority mode.

The DSTATCOM operation of a random customer, number 41, has been picked to show the results for a 24 hours period of time in Figure 5.10. As can be seen, this customer's DSTATCOM is operating for all but 2 hours in the day, operating either in Q-only mode or P-Q mode. During the day it is operated in Q-only mode, coming close to the limit value of VAr injection during the morning peak. At 18:00 the maximum possible reactive power injection was reached and the DSTATCOM operation changed to P-Q mode with values of active and reactive power of P_s and Q_s respectively. The voltage was fully supported during these 24 hours as shown in Figure 5.11.

In Table 5.2, the DSTATCOM operating mode of all customers with rated power of 10kVA over a 24 hour period in year 70 is shown. The DSTATCOM switched ON at 0.94 to operate at Q-only mode and changed to P-Q mode at the voltage of 0.92pu. In both modes when the voltage increased to 0.99pu it will be switched OFF.

The DSTATCOM mode will change its operation to P-Q mode when the voltage drops to 0.92pu. It has to be considered that this lower boundary can be modified based on how much the system is allowed to operate under 0.94pu. In this part, the voltage limit used for switching the DSTATCOM mode from Q-only to P-Q will change to 0.93pu instead of 0.92pu. As the DSTATCOM is switched to this mode earlier, it is expected that the DSTATCOM will be operating in P-Q mode for a longer period over the same time frame. In the other words, the system will incorporate the active power injection earlier than before in order to support the system voltage. The effect of such a change on the operation of the DSTATCOM is more significant for a lighter load than a heavier load. The operation of the Q-priority mode for all customers at time 7:00 in year 70, switching the P-Q mode ON at 0.93pu is shown in Figure 5.12. As can be seen, 15 of the customers have their DSTATCOM operating in P-Q mode compared to the 0.92pu level scenario shown in Figure 5.6, where none of the customers used active power to support the voltage. The voltage is completely supported by the new switching voltage value as shown in Figure 5.13.

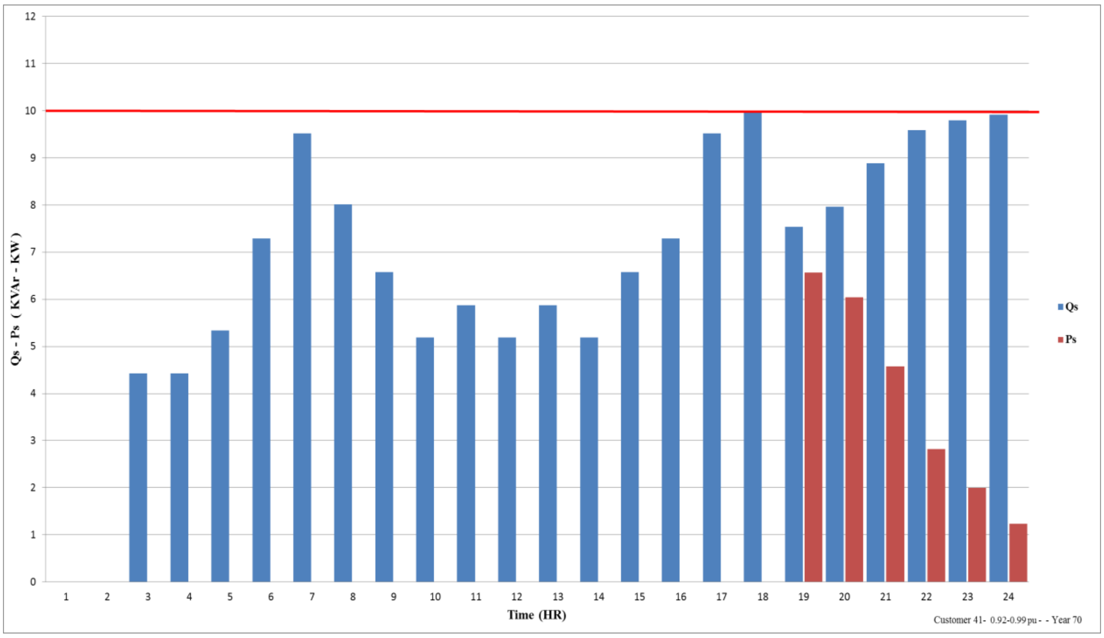


Figure 5.10: DSTATCOM customer 41 daily operations profile, year 70, P-Q mode limits: 0.92-0.99pu.

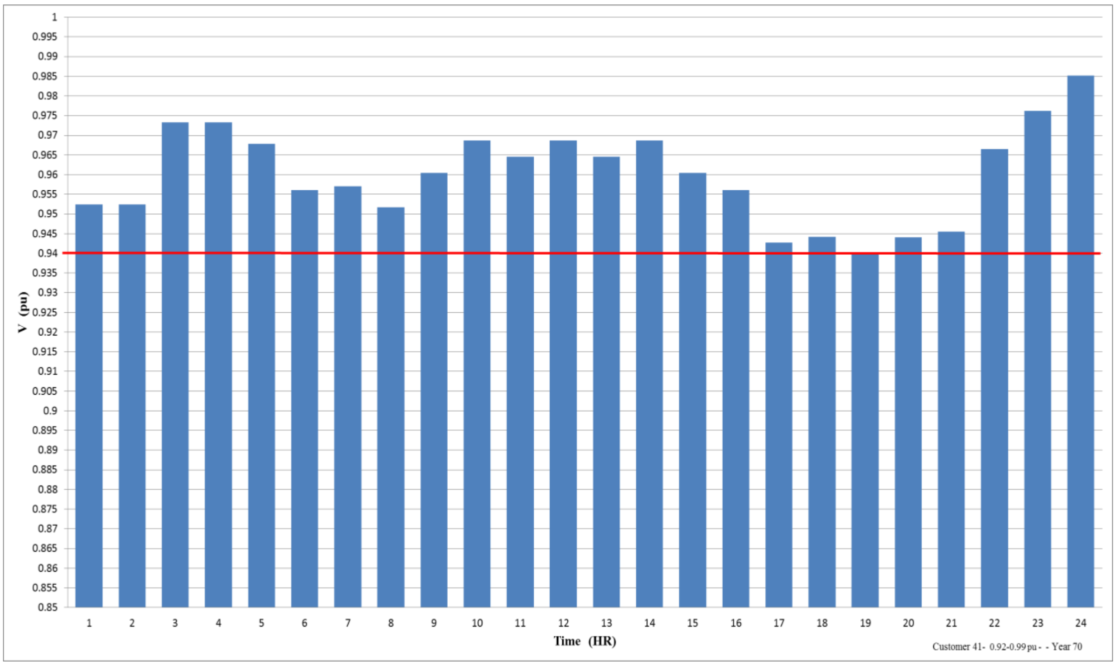


Figure 5.11: Daily voltage profile of customer 41, year 70.

Table 5.2: DSTATCOM operations, S_{DS}=10 kVA, year 70, Q-only mode: 0.94-0.99pu; P-Q mode limits: 0.92-0.99pu

CUS \ HR	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
2	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q
3	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q
4	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q
5	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q
6	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q
7	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q
8	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q
9	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q
10	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q
11	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q
12	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
13	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
14	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
15	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
16	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
17	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
18	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
19	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
20	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
21	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
22	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
23	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
24	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	P-Q	P-Q	P-Q	P-Q	P-Q	Q
25	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
26	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
27	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
28	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
29	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
30	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
31	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
32	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
33	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
34	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
35	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
36	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
37	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
38	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	P-Q	P-Q	P-Q	P-Q	P-Q	Q
39	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
40	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
41	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
42	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
43	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
44	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
45	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
46	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
47	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
48	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
49	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q

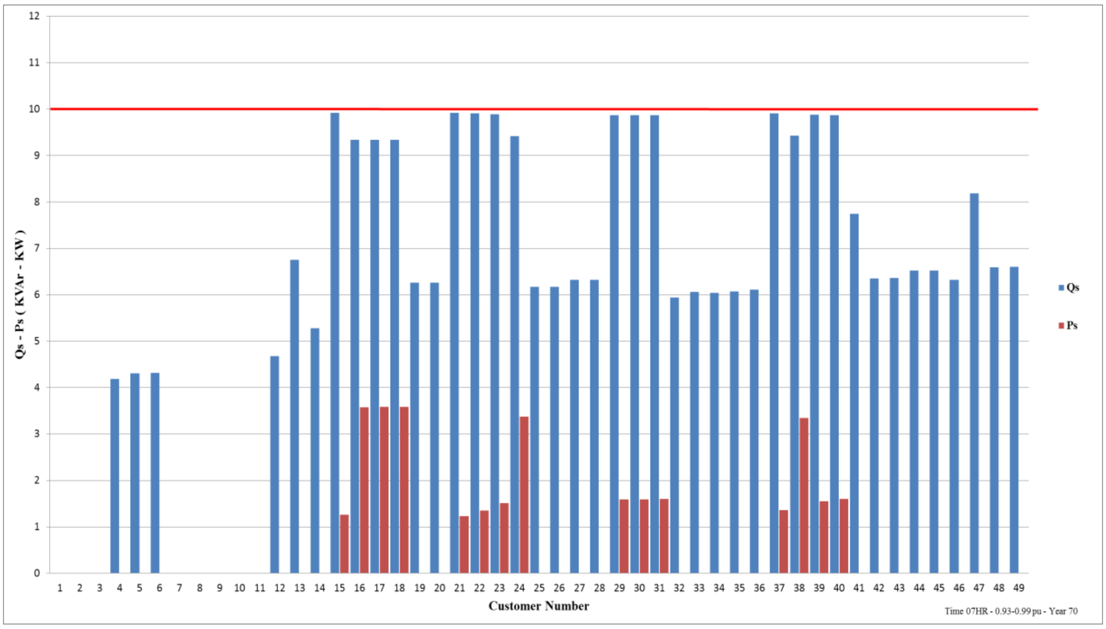


Figure 5.12: DSTATCOM Q-priority mode, time 7:00, year 70, P-Q mode limits: 0.93pu-0.99pu.

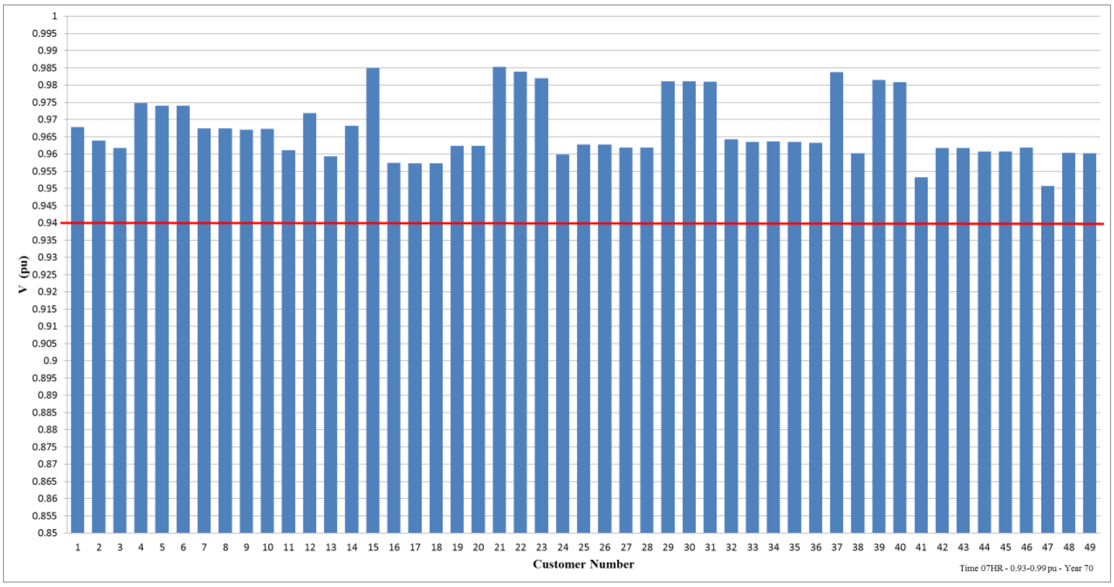


Figure 5.13: System voltage profile, time 7:00, year 70, DSTATCOM operating in Q-priority mode.

The operation of the DSTATCOM in Q-priority mode at time 19:00 in year 70, switching P-Q mode ON at 0.93pu and OFF at 0.99pu and the system voltage profile are shown in Figures 5.14 and 5.15 respectively. As expected the results changed slightly during peak load periods compared to the previous switching states as shown in Figure 5.8.

Figure 5.16 shows the DSTATCOM operation of customer 41 for a 24 hours period in year 70, switching P-Q mode ON at 0.93pu and OFF at 0.99pu. By comparison with Figure 5.10, if the DSTATCOM switched to P-Q mode while at 0.93pu, active power will be applied one hour earlier from 18:00 and be switched OFF at time 23:00. The supported system voltage profile is shown in Figure 5.17.

The DSTATCOM operations for all customers with rated power of 10 kVA over a 24 hours period in year 70 are shown in Table 5.3. The DSTATCOM is switched ON at 0.94pu to operate in Q-only mode and changed to P-Q mode at a voltage of 0.93pu. In both modes when the voltage increased to 0.99pu the DSTATCOM will be switched OFF. As expected the P-Q mode started earlier and ran for a longer time during the day. The results show that more active power is needed to support the system voltage if the DSTATCOM switches to P-Q mode at a voltage of 0.93pu.

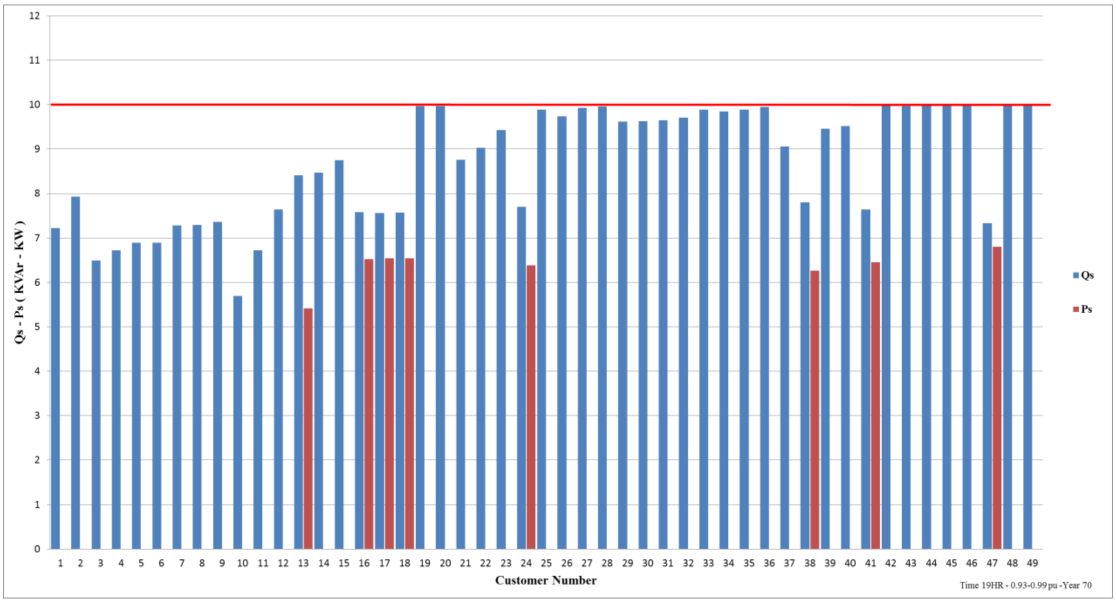


Figure 5.14: DSTATCOM Q-priority mode operations, time 19:00, year 70, P-Q mode limits: 0.93pu-0.99pu.

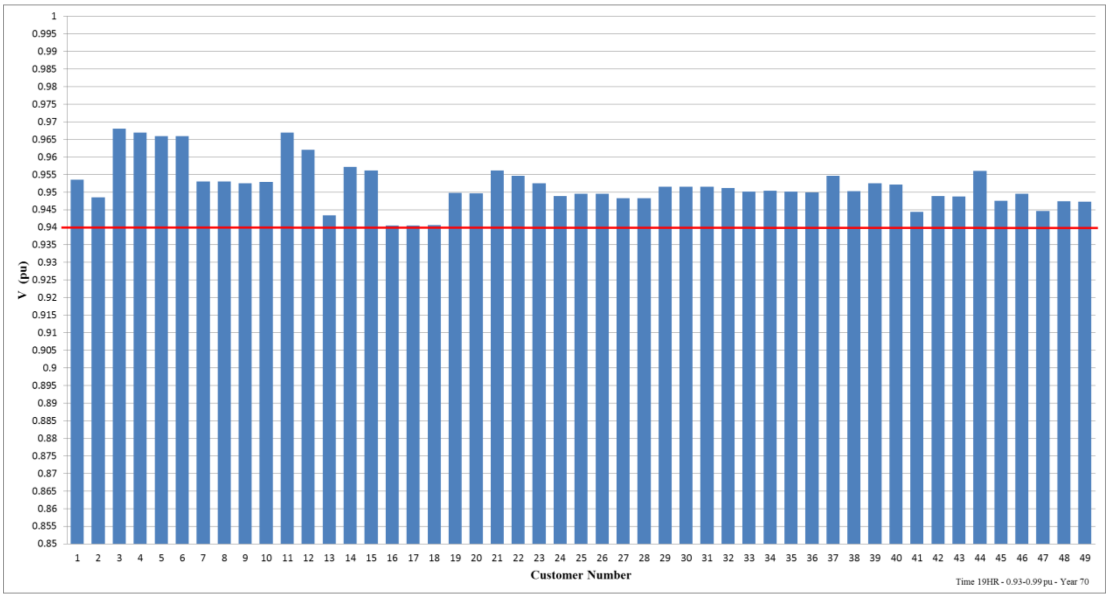


Figure 5.15: System Voltage profile, time 19:00, year 70, DSTATCOM operating in Q-priority mode.

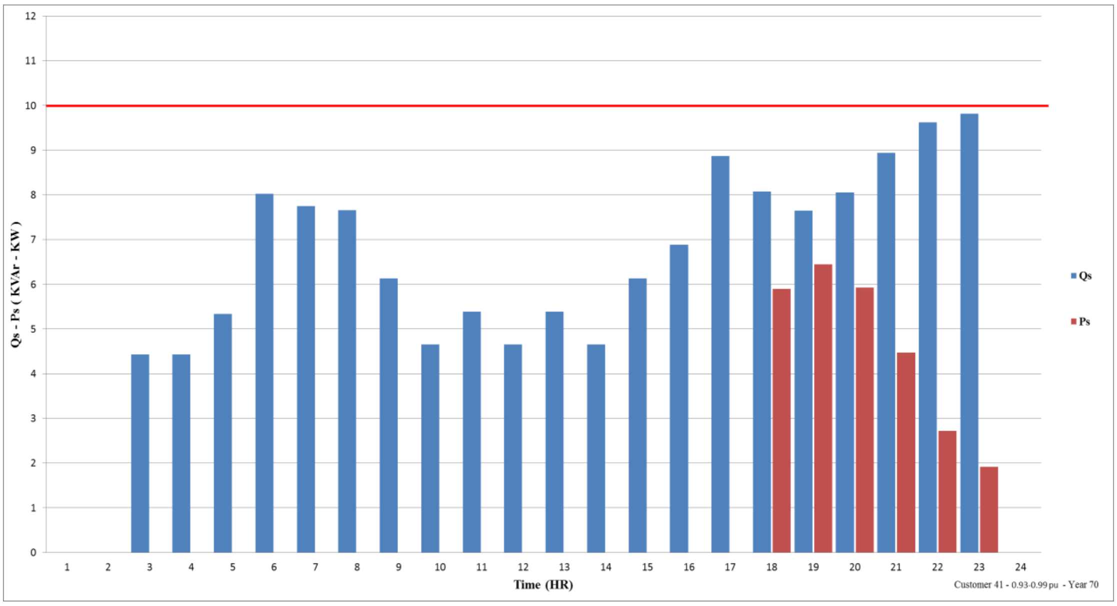


Figure 5.16: DSTATCOM operation of customer 41 over a 24 hours period, year 70, P-Q mode limits: 0.93pu-0.99pu.

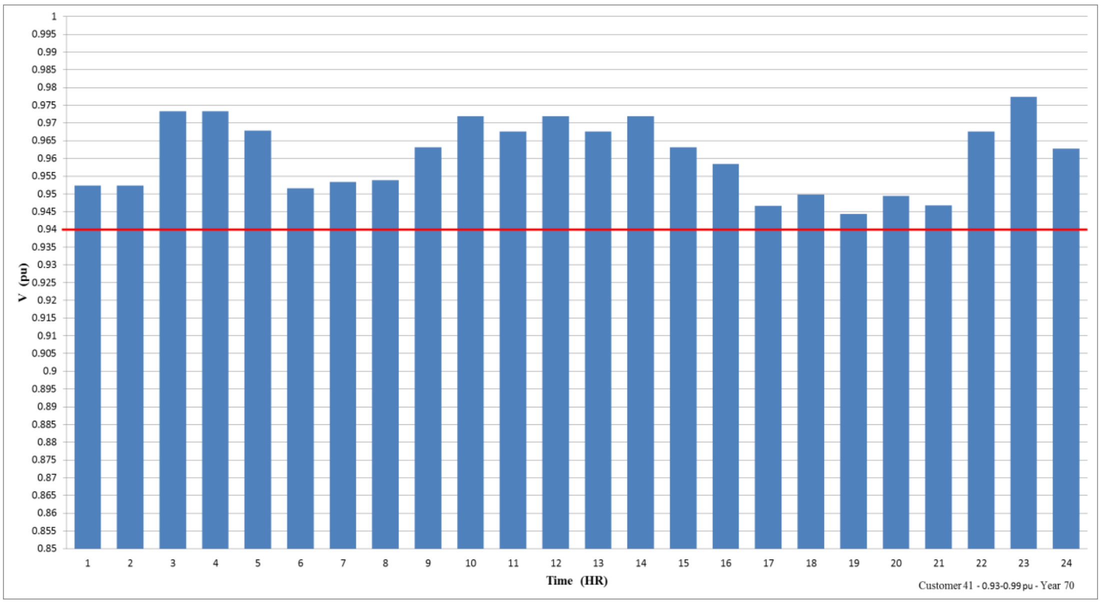


Figure 5.17: Voltage profile of customer 41 over a 24 hours period, year 70, Q-priority mode.

Table 5.3: DSTATCOM mode operation: S_{DS}=10 kVA, year 70, Q-only mode limits: 0.94-0.99pu; P-Q mode limits: 0.93-0.99pu

CUS \ HR	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	OFF
2	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	OFF
3	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	OFF
4	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	OFF
5	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	OFF
6	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	OFF
7	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	OFF
8	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	OFF
9	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	OFF
10	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	OFF
11	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	OFF
12	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
13	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	P-Q	P-Q	P-Q	P-Q	P-Q	OFF
14	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
15	OFF	OFF	OFF	OFF	OFF	OFF	P-Q	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q
16	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	OFF
17	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	OFF
18	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	OFF
19	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
20	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
21	OFF	OFF	OFF	OFF	OFF	OFF	P-Q	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q
22	OFF	OFF	OFF	OFF	OFF	OFF	P-Q	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q
23	OFF	OFF	OFF	OFF	OFF	OFF	P-Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
24	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	OFF
25	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
26	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
27	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
28	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
29	OFF	OFF	OFF	OFF	OFF	OFF	P-Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
30	OFF	OFF	OFF	OFF	OFF	OFF	P-Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
31	OFF	OFF	OFF	OFF	OFF	OFF	P-Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
32	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
33	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
34	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
35	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
36	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
37	OFF	OFF	OFF	OFF	OFF	OFF	P-Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
38	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	OFF
39	OFF	OFF	OFF	OFF	OFF	OFF	P-Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
40	OFF	OFF	OFF	OFF	OFF	OFF	P-Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
41	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	OFF
42	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
43	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
44	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
45	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
46	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
47	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
48	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
49	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q

As already discussed in this chapter, the P-Q mode operations begin when the voltage falls to either 0.92pu or 0.93pu and ceases operations at a voltage of 0.99pu. Active and reactive power is used to support the voltage until it rises to 0.99pu and then the DSTATCOM will be switched OFF. An alternative control scenario is that the DSTATCOM P-Q mode could be switched OFF at a voltage of 0.97pu. This will save more active power from being used when supporting the network voltage. The results for such a scenario, P-Q mode ON at 0.92pu and OFF at 0.97pu, is shown in Table 5.4. Comparing these results with those in Table 5.2, the DSTATCOM P-Q mode has been switched OFF 2 hours earlier, significantly reducing the active power required to support the system voltage.

The DSTATCOM operating point for all customers over a 24 hours period in year 70 with P-Q mode switching ON at 0.92pu and 0.93pu are shown in Figures 5.18 and 5.19 respectively. As can be seen in Figure 5.19, more DSTATCOMs are operating on the P-Q circle while the P-Q mode is being applied with a higher amount of active power injection used for voltage support.

Table 5.4: DSTATCOM with S_{DS}=10kVA, year 70, Q-only mode limits: 0.94-0.97pu; P-Q mode limits: 0.92-0.97pu

CUS \ HR	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
2	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	OFF	OFF
3	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q
4	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q
5	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q
6	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q
7	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q
8	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q
9	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q
10	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q
11	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q
12	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
13	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
14	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
15	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
16	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	P-Q	P-Q	P-Q	P-Q	P-Q	OFF	OFF
17	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	P-Q	P-Q	P-Q	P-Q	P-Q	OFF	OFF
18	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	P-Q	P-Q	P-Q	P-Q	P-Q	OFF	OFF
19	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
20	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
21	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
22	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
23	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
24	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	P-Q	P-Q	P-Q	P-Q	OFF	OFF
25	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
26	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
27	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
28	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
29	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
30	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
31	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
32	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
33	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
34	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
35	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
36	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
37	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
38	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	P-Q	P-Q	P-Q	P-Q	OFF	OFF
39	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
40	OFF	OFF	OFF	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
41	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	P-Q	P-Q	P-Q	P-Q	OFF	OFF
42	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
43	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
44	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
45	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
46	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
47	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	P-Q	P-Q	P-Q	P-Q	OFF	OFF
48	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q
49	OFF	OFF	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q	Q

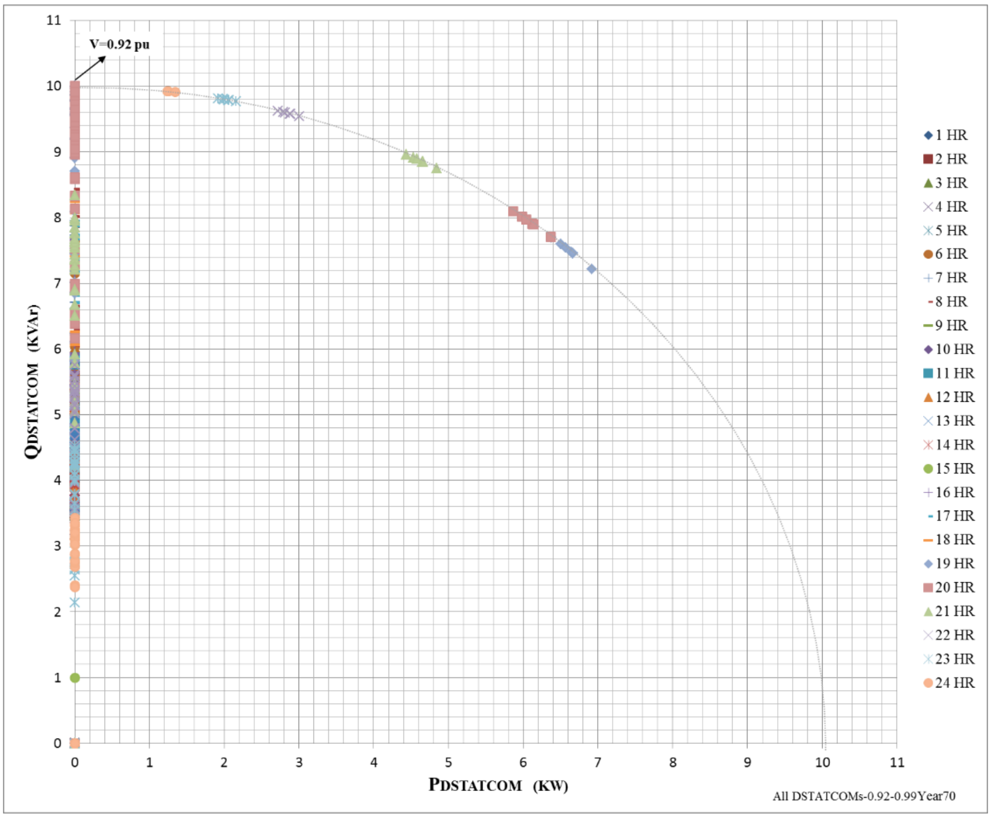


Figure 5.18: Daily DSTATCOM operations, year 70, P-Q mode limits: 0.92-0.99pu.

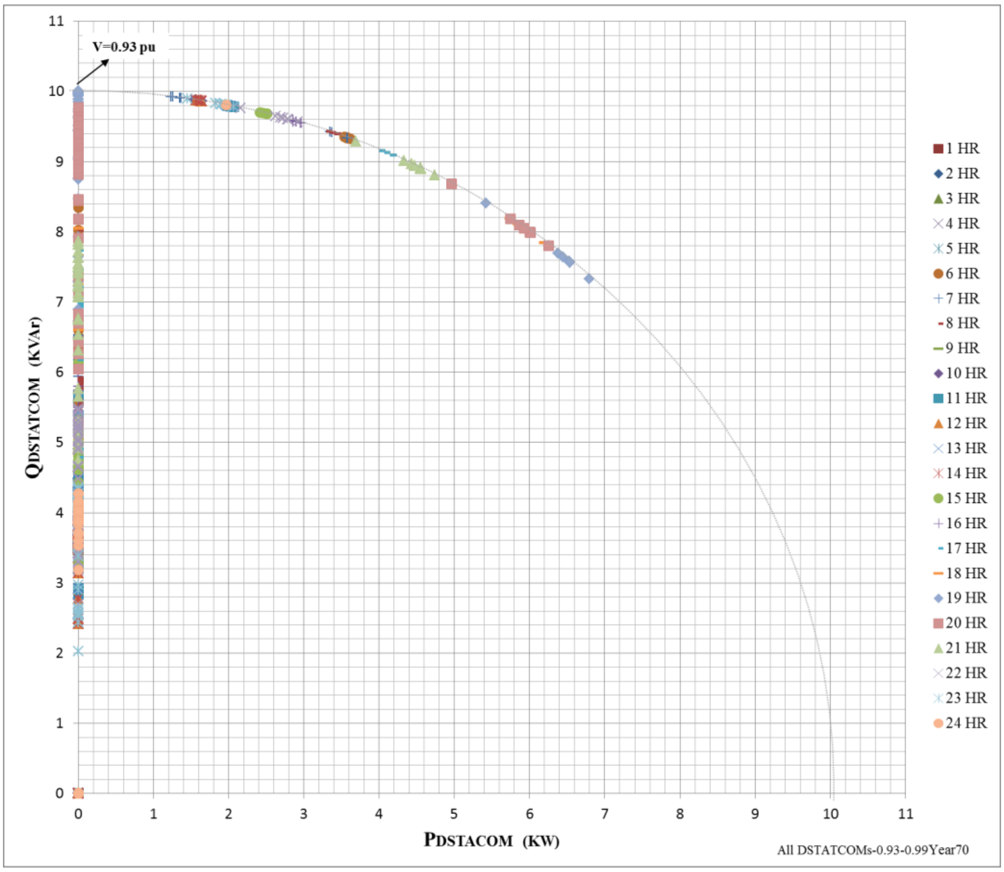


Figure 5.19: Daily DSTATCOM operation for all customers, year 70, P-Q mode limits: 0.93-0.99pu.

5.7 Conclusions

Q-priority mode for the DSTATCOM voltage support of a SWER system was presented in this chapter. Operating in this mode allows the DSTATCOM to use reactive power as the preferred option and inject active power as needed to maintain the voltage within the prescribed levels. The DSTATCOM is based on the newly proposed droop characteristics, Q_s-V to operate in Q-only mode and P_S-V to operate in P-Q mode. Newton Raphson load flows have been modified to consider the newly proposed droop characteristics allowing control of the system voltage. A hysteresis control loop has been added to minimise the possibility of VAr circulation, as discussed in previous chapters to reduce the need for active and reactive power.

The results presented using the new droop characteristics including hysteresis control and subsequent implementation with a DSTATCOM in load flows show that the system voltage is supported for all of the different load conditions. The Q-priority mode operates properly and corrects the voltage by applying reactive power only during lightly loaded periods and then uses active power injection when the voltage issues are more significant during heavy load periods.

It has been shown that a system with DSTATCOM installed for voltage support operating in Q-priority mode can be a practical solution if islanding is not an issue. Even so, there are some solutions available such as communications between the DSTATCOMs and circuit breakers. Other solutions to avoid islanding are to use the DSTATCOMs with schemes named load power factor follow and correction modes, which will be studied in the next chapter.

CHAPTER 6

LOAD POWER FACTOR FOLLOW AND CORRECTION DSTATCOM OPERATING MODES

6.1 Introduction

Different types of DSTATCOM operating modes, namely Q-Only and Q-Priority, have been discussed and analysed in the last two chapters. The Q-Priority mode which can operate in Q-only or P-Q modes depending on the load conditions is a practical solution to support the SWER system. An added issue to be considered regarding this type of operation is communication. As there is no communication between Circuit Breakers (CBs) and DSTATCOMs in the network, the possibility of islanding in the system is an issue. Even in the case of intentional islanding the identification of frequency reference for phasor calculations of real and reactive power may be an issue. To avoid islanding in the SWER system another type of DSTATCOM operating mode will be introduced, i.e. load power factor follow mode. In this mode the DSTATCOM system follows the load power factor and will not allow P and Q to be injected to the grid under islanded conditions. As the load PF will be changing during the day, the DSTATCOM will follow it, with active and reactive power injected proportional to the load. Furthermore, another type of DSTATCOM operating scheme will be introduced as load power factor correction mode. In this scheme, the net power factor seen from the source will be improved via DSTATCOM operating at PF correction mode. Therefore, there is no active power to be injected to support the voltage and the DSTATCOM will be used as a source of reactive power to improve the net power factor.

6.2 DSTATCOM Load PF Follow Mode Operation

The DSTATCOM operating mode considered in this part is the load power factor follow. In this type of operating mode the DSTATCOM monitors the load power factor and will adjust the operating point accordingly. As the amount of active and reactive power to be injected never exceeds that of the load there is no need to be concerned about islanding of the system. In terms of safety, detecting an islanding mode is an important issue for the control system and as all the DSTATCOMs are operating at the power factor of load, there is no possibility of injecting P and Q to the network while islanding.

The DSTATCOM power injection in load PF follow mode operation is shown in Figure 6.1. The DSTATCOM operating point is always located on a line at the load power factor angle. To have the DSTATCOM operating on the above mentioned mode, the following condition applies:

$$\phi_{Load} = \phi_{DS} \tag{6.1}$$

Where: ϕ_{Load} and ϕ_{DS} are the load and DSTATCOM operating angles respectively.

The only difference between the load and the DSTATCOM output is magnitude. The operating point will change under different load conditions but the active and reactive power components are always smaller than that of the load. As illustrated in Figure 6.1, load has increased and the DSTATCOM operating point with respect to P_{DS} and Q_{DS} components has changed accordingly to support the load voltage. To avoid islanding issues in this mode, there are also two other conditions that have to be met:

$$P_{DS(Max)} < P_{Load(Max)} \tag{6.2}$$

$$Q_{DS(Max)} < Q_{Load(Max)} \tag{6.3}$$

Where: $P_{DS(Max)}$ is the maximum DSTATCOM active power output while the respective load active power is $P_{Load(Max)}$. $Q_{DS(Max)}$ is the maximum DSTATCOM reactive power output while the load reactive power maximum is $Q_{Load(Max)}$. Applying the above two conditions means that the amount of DSTATCOM active and reactive power to be injected in to the system is not permitted to exceed that of the load.

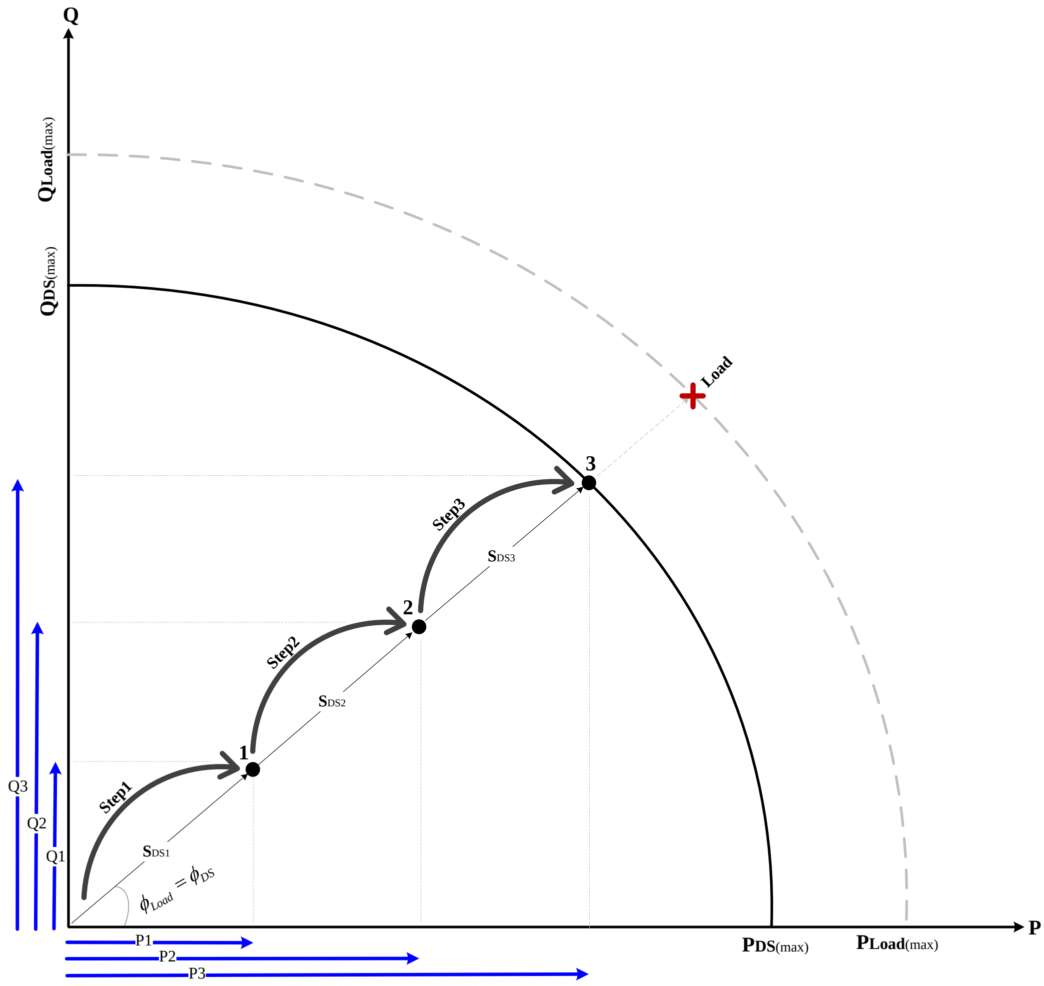


Figure 6.1: DSTATCOM power injection in load PF follow mode of operation.

6.3 Droop Characteristics

Considering that the DSTATCOM is operating in load PF follow mode, regardless of the load size or how small the voltage problem is, the active and reactive power injection will be applied at all times to support the voltage. The active and reactive power to be injected to the system via DSTATCOM will be calculated individually using its own droop characteristics.

6.3.1 DSTATCOM Active Power -Voltage Droop

The active power-voltage (P_s-V) droop characteristic of the DSTATCOM load PF follow mode is shown in Figure 6.2. It is significantly different compared to that of the typical droop characteristics in terms of slope. The slope is a function of load size (P_{Di}) and as the load is increases, the DSTATCOM active power P_{si} increases correspondingly.

The droop control equation for active power voltage control is defined as:

$$P_{si} = K_{Spi}(V_{ref} - |V_i|).P_{Di} \tag{6.4}$$

Where: P_{Di} is the active power demand at customer number *i* and K_{SPi} is a coefficient.

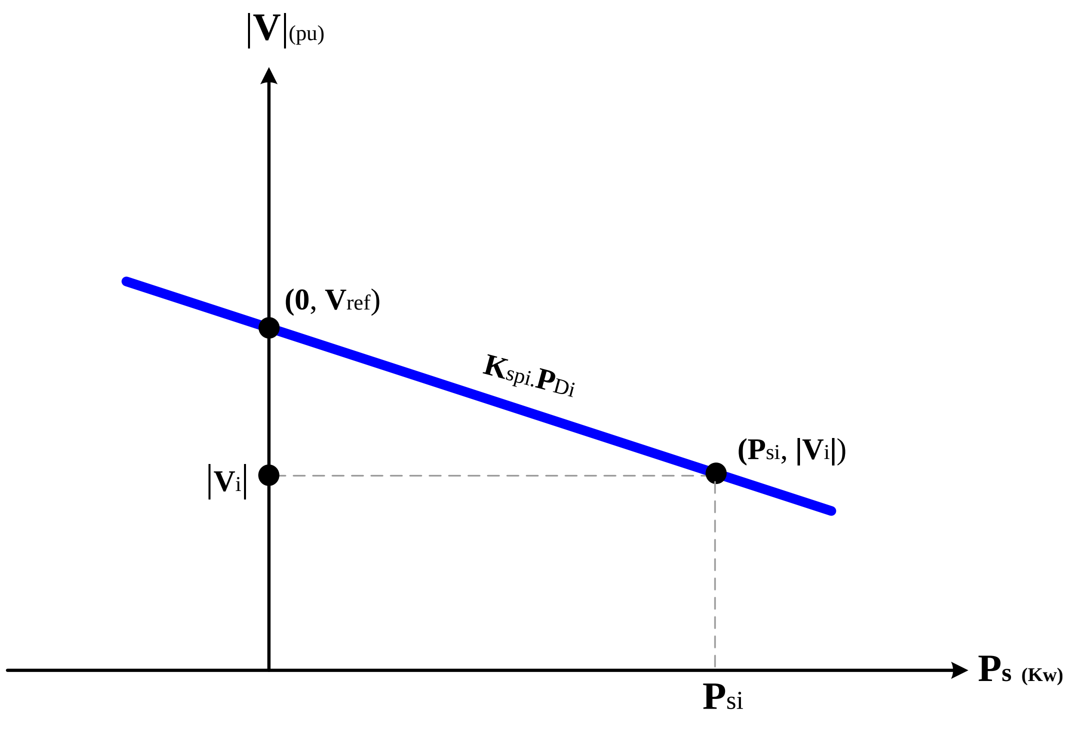


Figure 6.2: Active power-voltage (P_s-V) droop characteristics.

6.3.2 DSTATCOM Reactive Power-Voltage Droop

In Figure 6.3 the reactive power-voltage (Q_s-V) droop characteristics of DSTATCOM operating in load PF follow mode is shown. As can be seen the slope of the droop is a function of load size (Q_{Di}) and the DSTATCOM injected reactive power Q_{si}, which will increase as the load grows.

The droop equation for reactive power voltage control is defined as:

$$Q_{si} = K_{Sqi}(V_{ref} - |V_i|).Q_{Di} \tag{6.5}$$

Where: Q_{Di} is the reactive power demand of customer *i* and K_{Sqi} is a coefficient.

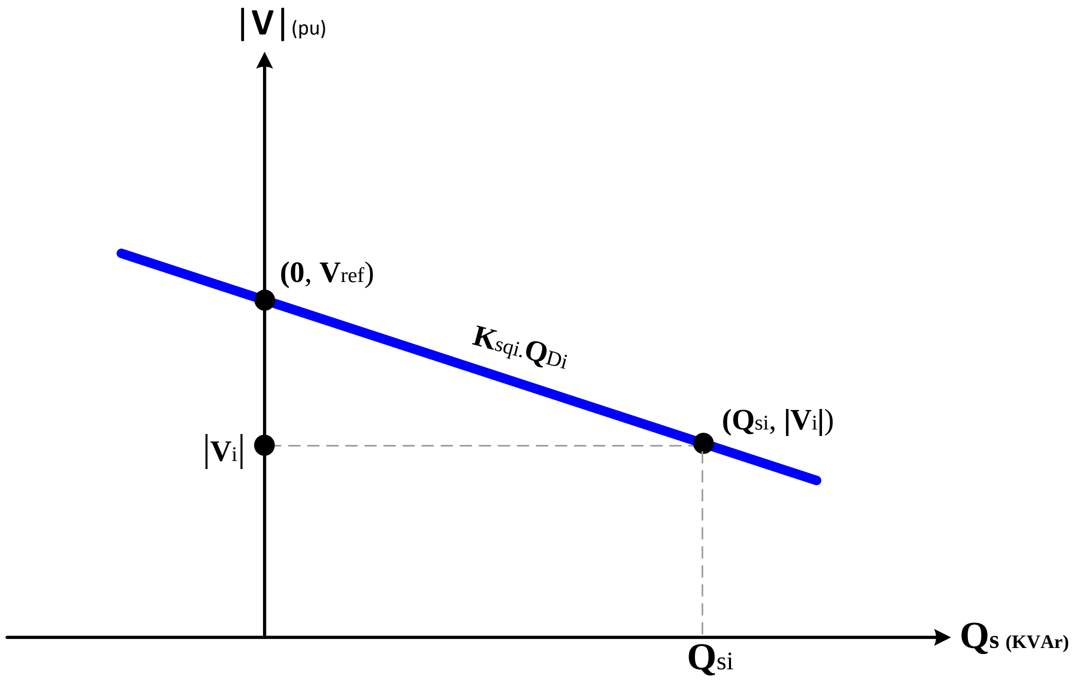


Figure 6.3: Reactive power-voltage (Q_s-V) droop characteristics.

6.3.3 Load Flow Study with Droop Implementation

The droop characteristic implementation of DSTATCOM load PF follow mode with the Newton Raphson method will be studied in this section. Two different droop characteristics, active power voltage (P_s-V) and reactive power voltage (Q_s-V) as shown in Figures 6.2 and 6.3 will be implemented in a load flow simulation. As the DSTATCOM has to follow the load power factor in this mode, active and reactive power to be injected to the system is a function of demand. To calculate the DSTATCOM active power injected (P_{si}) and reactive power injected (Q_{si}) in the load flow, equations (6.4) and (6.5) will be used.

6.3.4 Modified Jacobian Matrix Elements

As a result of installing the DSTATCOM as a new system power source, the Jacobian matrix elements need to be modified. The active and reactive power at bus *i* including the DSTATCOM operating in load PF follow mode are shown in Figures 6.4 (a) and (b) respectively.

In the above mentioned figure, the net active and reactive power at bus *i* will be calculated as follows:

$$P_i = (P_{Gi} - P_{Di}) + K_{Spi}(V_{ref} - |V_i|).P_{Di} \tag{6.6}$$

$$Q_i = (Q_{Gi} - Q_{Di}) + K_{Sqi}(V_{ref} - |V_i|).Q_{Di} \tag{6.7}$$

The total P and Q flowing in to bus *i*, for a converged solution are:

$$f_{P,i}(\delta, V) = (P_{Gi} - P_{Di}) + K_{Spi}(V_{ref} - |V_i|).P_{Di} - \sum_{k=1}^{n} |V_k||V_i|[G_{ik}\cos(\delta_k - \delta_i) - B_{ik}\sin(\delta_k - \delta_i)] = 0 \tag{6.8}$$

$$f_{Q,i}(\delta, V) = (Q_{Gi} - Q_{Di}) + K_{Sqi}(V_{ref} - |V_i|).Q_{Di} + \sum_{k=1}^{n} |V_k||V_i|[B_{ik}\cos(\delta_k - \delta_i) + G_{ik}\sin(\delta_k - \delta_i)] = 0 \tag{6.9}$$

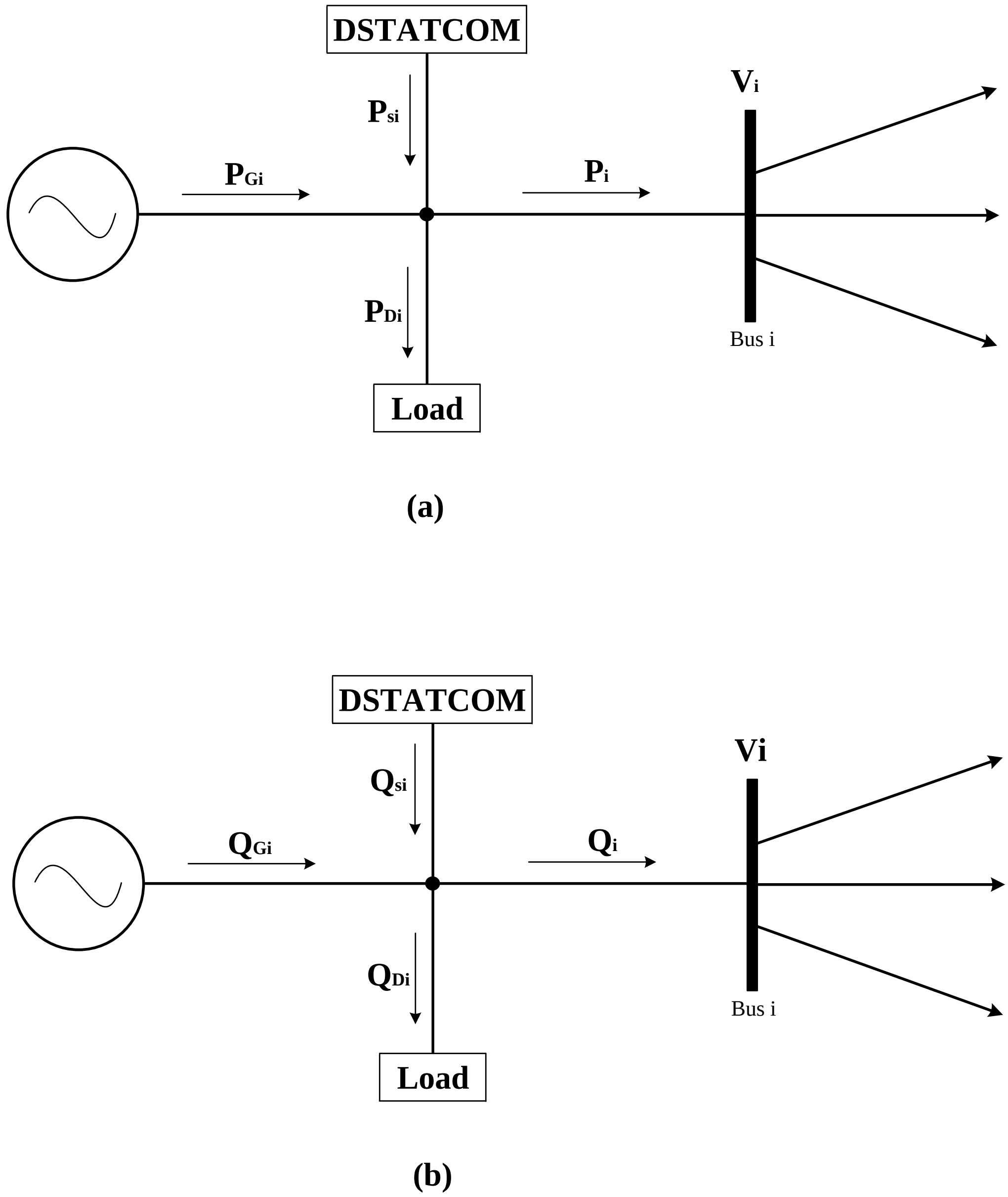


Figure 6.4: (a) Active and (b) reactive power flow at bus *i* for DSTATCOM load PF follow mode.

The diagonal and off diagonal terms of Jacobian matrix will be calculated as follows:

Main-diagonal and off-diagonal terms of submatrix J_{11} are determined to be as:

$$\frac{\partial f_{Pi}}{\partial \delta_i} = (Q_{Gi} - Q_{Di}) + K_{Sqi}(V_{ref} - |V_i|).Q_{Di} + |V_i|^2 B_{ii} \tag{6.10}$$

$$\frac{\partial f_{Pi}}{\partial \delta_k} = |V_k||V_i|[G_{ik}\sin(\delta_k - \delta_i) + B_{ik}\cos(\delta_k - \delta_i)] \tag{6.11}$$

Main-diagonal and off-diagonal elements of submatrix J_{12} are determined to be as:

$$\frac{\partial f_{Pi}}{\partial |V_i|} = [K_{Spi} - (P_{Gi} - P_{Di}) - |V_i|^2 G_{ii}] / |V_i| \tag{6.12}$$

$$\frac{\partial f_{Pi}}{\partial |V_k|} = -|V_i|[G_{ik}\cos(\delta_k - \delta_i) - B_{ik}\sin(\delta_k - \delta_i)] \tag{6.13}$$

Main-diagonal and off-diagonal terms of submatrix J_{21} are determined to be as:

$$\frac{\partial f_{Qi}}{\partial \delta_i} = -(P_{Gi} - P_{Di}) + |V_i|^2 G_{ii} \tag{6.14}$$

$$\frac{\partial f_{Qi}}{\partial \delta_k} = -|V_k||Vi|[B_{ik}\cos(\delta_k - \delta_i) + G_{ik}\sin(\delta_k - \delta_i)] \tag{6.15}$$

Main-diagonal and off-diagonal elements of submatrix J_{22} are determined to be as:

$$\frac{\partial f_{Qi}}{\partial |V_i|} = [K_{Sqi} - (Q_{Gi} - Q_{Di}) + K_{Sqi}(V_{ref} - |V_i|).Q_{Di} - |V_i|^2 B_{ii}] / |V_i| \tag{6.16}$$

$$\frac{\partial f_{Qi}}{\partial |V_k|} = |V_i|[B_{ik}\cos(\delta_k - \delta_i) + G_{ik}\sin(\delta_k - \delta_i)] \tag{6.17}$$

With respect to the above equations, a load flow analysis will calculate the active and reactive power to be injected via DSTATCOM required to support the network voltage.

6.4 Hysteresis Control Loop for Load Flow PF Follow Mode

A hysteretic control loop will be proposed for a DSTATCOM operating in load PF follow mode. The state of the DSTATCOM will be based on the value of the voltage at each customer, with defined upper and lower voltage boundaries. The hysteresis control loop for load PF follow mode including DSTATCOM state is illustrated in Figure 6.5. As can be seen, the lower threshold is 0.94pu which switches the DSTATCOM load PF follow mode ON. The DSTATCOM will be switched OFF at a voltage value of 0.99pu, as it is considered to be within normal tolerances. By contrast with the other two introduced hysteresis control loops described in the last two chapters, which considered the issue of high voltage, in this loop the DSTATCOM will only follow the load and therefore no power is absorbed.

The hysteresis control loop details for DSTATCOM load PF follow mode corresponding to Figure 6.5 is shown in Table 6.1.

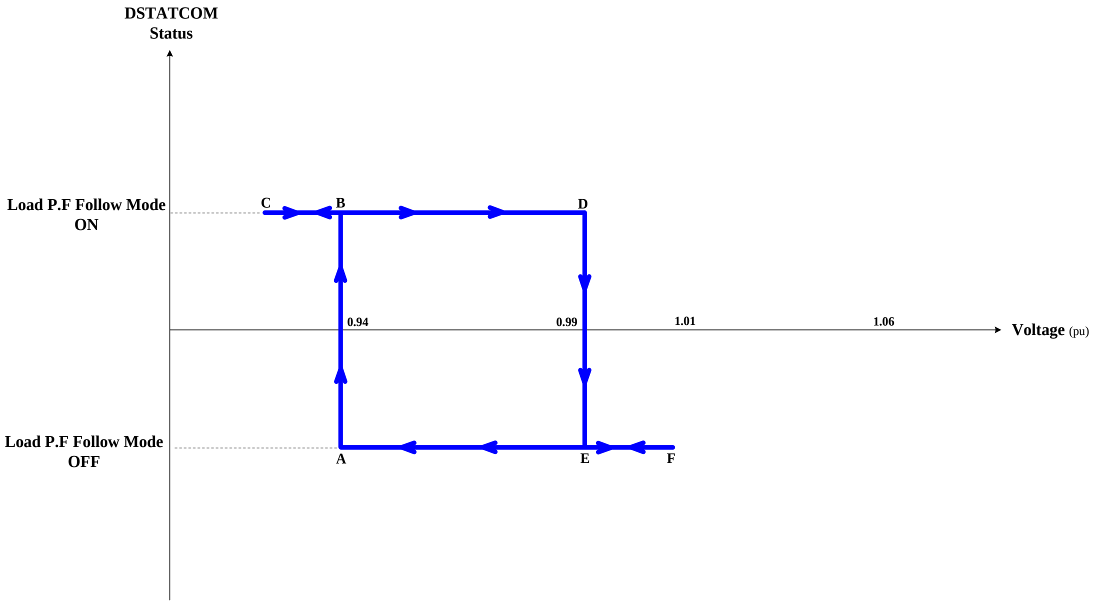


Figure 6.5: Hysteresis control loop for load PF follow mode showing DSTATCOM state.

Table 6.1: Hysteresis control loop of DSTATCOM load PF follow corresponding with Figure 6.5

Position on Hysteresis Loop	**Voltage** (pu)	**Customer Voltage Status**	**DSTATCOM Status**	**Q_s & P_s Status**
AB	0.94	Low Voltage	OFF → ON	To be injected
BD	0.94–0.99	Allowable range	ON	Is injecting
DE	0.99	Normal	ON → OFF	Injection terminated
EA	0.90–0.94	Allowable range	OFF	No injection

6.5 DSTATCOM Load Flow PF Follow Mode Flowchart

The DSTATCOM load PF follow mode flowchart is shown in Figure 6.6. as expected there are similarities with Figures 4.6 and 5.5 the main difference in this case is the use of load power factor information to determine the operating point of the DSTATCOM.

6.6 Hysteresis Control Loop for Load Flow PF Correction Mode

The load PF follow scheme is an effective DSTATCOM operation mode to support the voltage but an expensive solution. In this part of study another type of DSTATCOM operating scheme will be introduced. In this mode the DSTATCOM will be used as a source of reactive power and the net power factor will be improved. Correcting load power factor in SWER network is one of the ways to increase the voltage and this scheme of operation will be considered as a voltage support mode. Comparing to load PF follow mode, in this scheme everything will stay the same except K_{SPi} is equal to zero as there is no injection of active power to improve the load power factor.

A hysteretic control loop will be proposed for a DSTATCOM operating in load PF correction mode. The state of the DSTATCOM will be based on the value of the voltage at each customer, with defined upper and lower voltage boundaries. The hysteresis control loop for load PF correction scheme including DSTATCOM state is illustrated in Figure 6.7. As can be seen, the lower threshold is 0.94pu which activates the DSTATCOM load PF correction mode and the load power factor will be improved. The DSTATCOM will be deactivated at a voltage value of 0.99pu, as it is considered to be within normal tolerances.

The hysteresis control loop details for DSTATCOM load PF correction mode corresponding to Figure 6.7 is shown in Table 6.2.

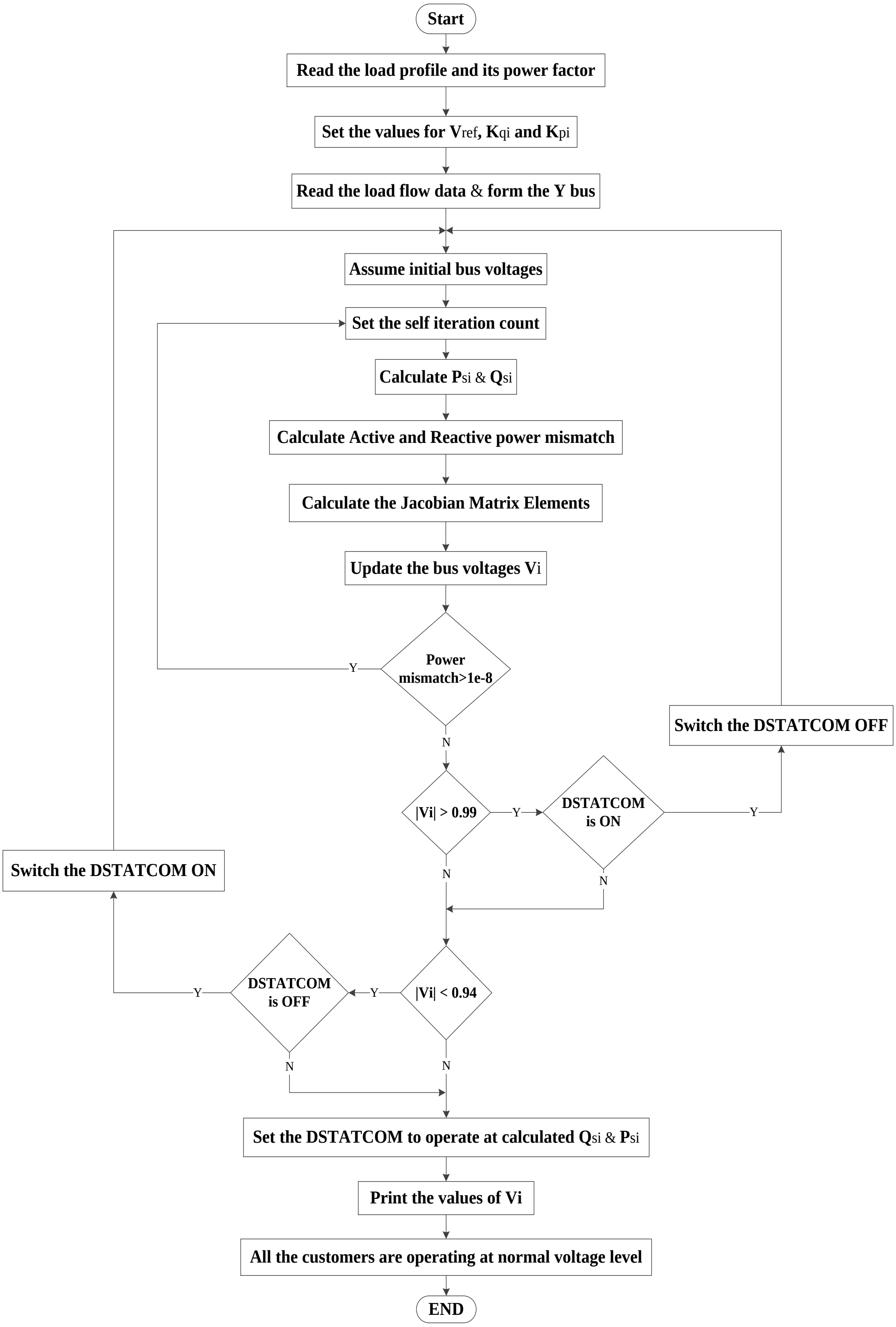


Figure 6.6: DSTATCOM load PF follow mode flowchart.

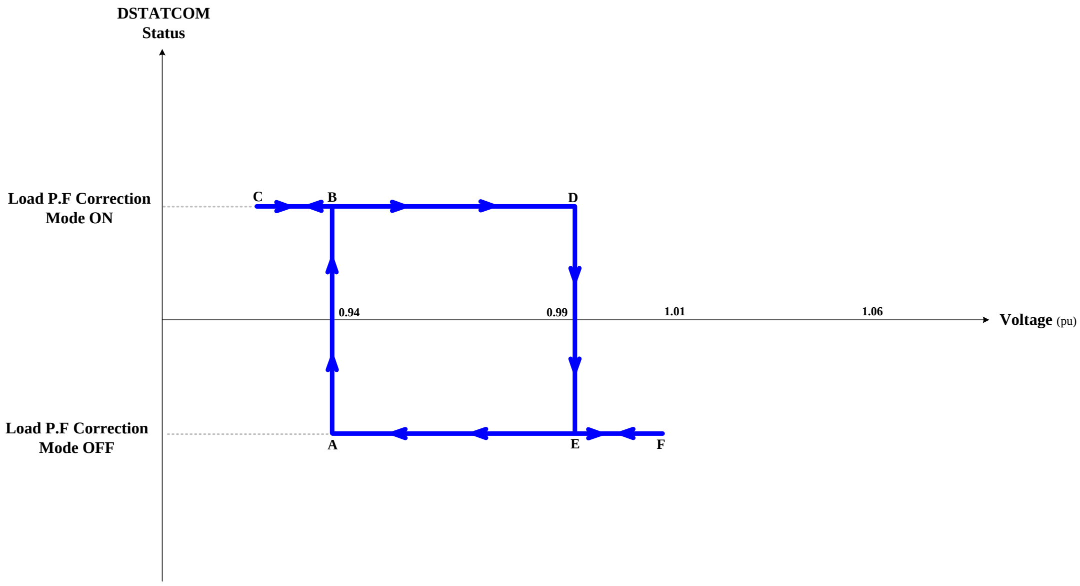


Figure 6.7: Hysteresis control loop for load PF correction mode showing DSTATCOM state.

Table 6.2: Hysteresis control loop of DSTATCOM load PF correction corresponding with Figure 6.7

Position on Hysteresis Loop	**Voltage** (pu)	**Customer Voltage Status**	**DSTATCOM Status**	**Load Power Factor Status**
AB	0.94	Low Voltage	OFF → ON	To be corrected
BD	0.94–0.99	Allowable range	ON	Is correcting
DE	0.99	Normal	ON → OFF	Correction terminated
EA	0.90–0.94	Allowable range	OFF	No correction

6.7 Case Study

An existing SWER system in Richmond, Queensland, Australia with 126 nodes and 49 customers is shown in Figure 3.23 and will be studied in this section.

6.7.1 Load PF Follow Mode Results

The DSTATCOM will be operating at a given load power factor but always at a lower output level than the load. The two conditions for the rated active and reactive power injected for DSTATCOM from equations (6.3) and (6.4) will be considered as:

$$P_{si} \leq 80\%.P_{Di} \qquad (6.18)$$

$$Q_{si} \leq 80\%.Q_{Di} \quad (6.19)$$

Results for DSTATCOM operation at customer 41 for a 24 hours period in year 70 with a given power factor of 0.9 is shown in Figure 6.8. The load power (shown with a blue bar) is always followed by The DSTATCOM output power (shown with a red bar) while it is switched ON. During the first 4 hours of the day the load is light and the voltage is operating within normal tolerances (Figure 6.9), the DSTATCOM has been switched OFF and there is no supporting power injection. The morning load rose from time 5:00; where the voltage dropped below the lower band level of 0.94pu and the DSTATCOM switched ON to load PF follow mode. The corresponding system voltages with and without the DSTATCOM as per Figure 6.8 are shown in Figure 6.9.

To study the operation of the DSTATCOM, another customer that is located at the end of the SWER line, customer 49, with more significant voltage issues will be studied. The results are shown in Figures 6.10 and 6.11. As can be seen, the voltage corrections now start 2 hours earlier due to the effects of this customer. The voltage in this case has to be supported for the whole day via DSTATCOM to be kept within tolerances.

The loads of all customers without and with DSTATCOM over a 24 hours period with three different power factors, 0.9, 0.8 and 0.7, in year 70 are illustrated in Figures 6.12 and 6.13 respectively. All the customers have been fully supported from a voltage point of view via DSTATCOM operating in load PF follow mode with no islanding potential.

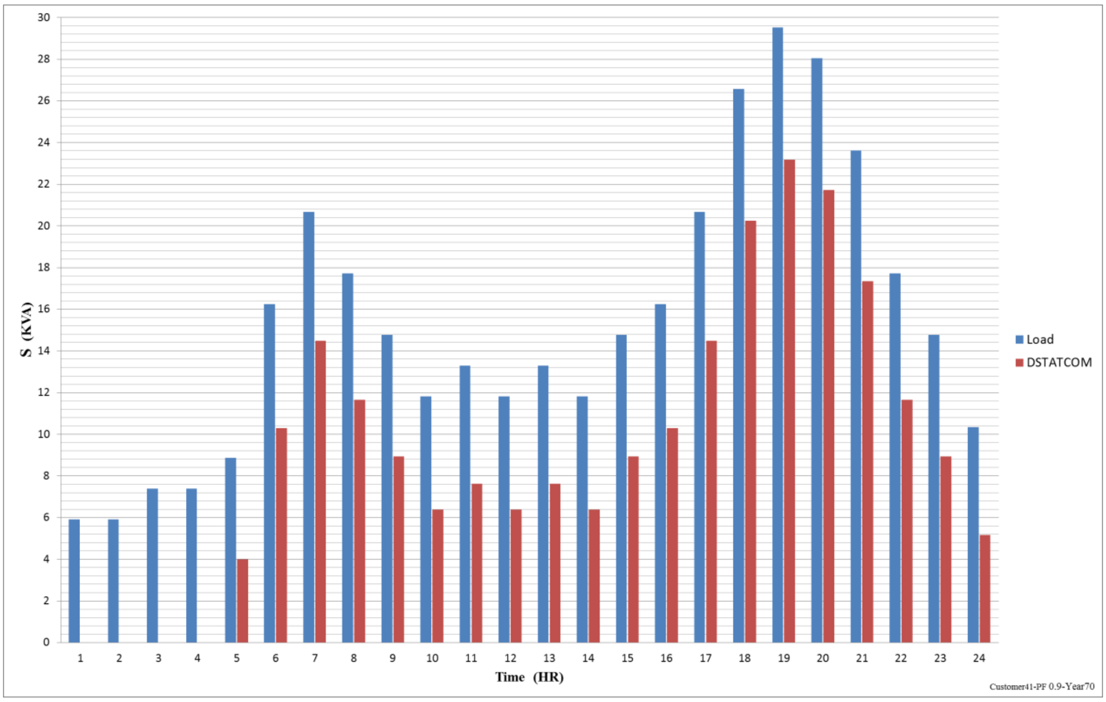


Figure 6.6: Daily load profile and DSTATCOM operation with PF 0.9 of customer 41 in year 70 (Load PF follow mode).

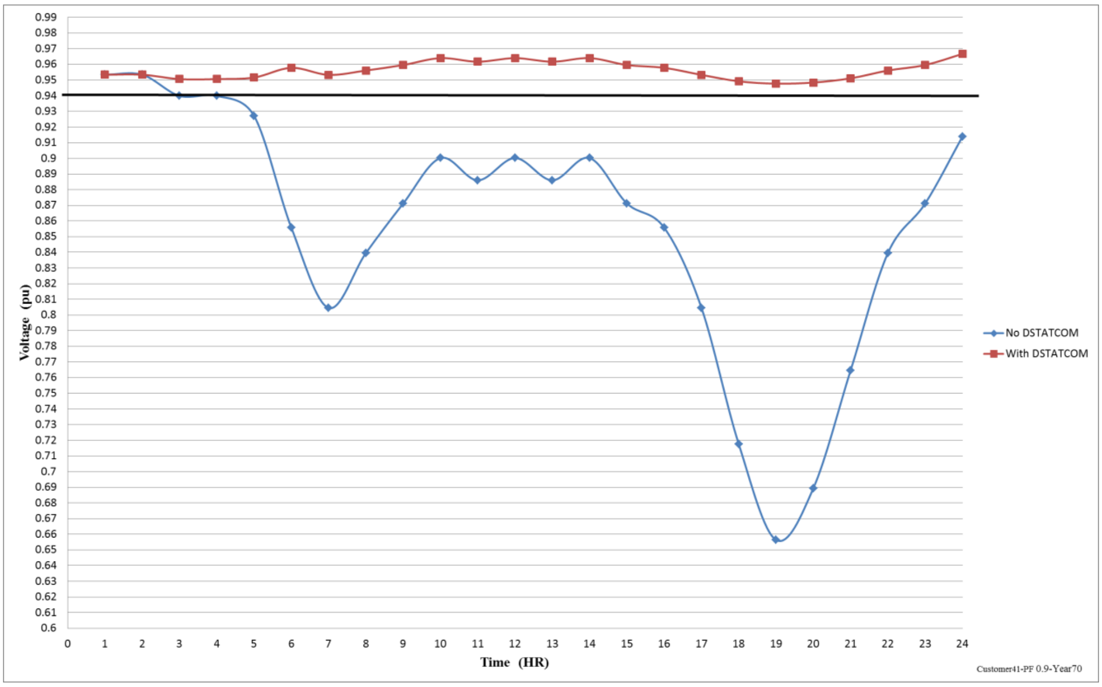


Figure 6.7: The system voltage with and without DSTATCOM operating at load PF follow mode for 24 hours at customer 41 in year 70 with PF of 0.9.

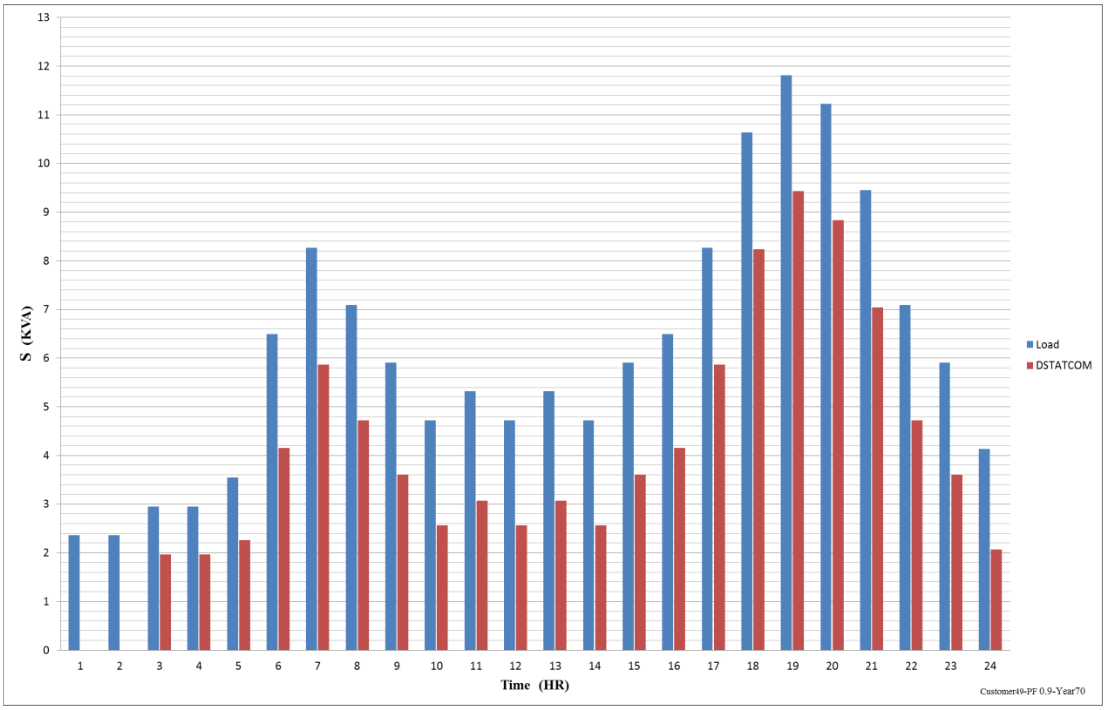


Figure 6.8: The 24 hours of load and DSTATCOM operation with PF 0.9 at customer 49 in year 70 (Load PF follow mode).

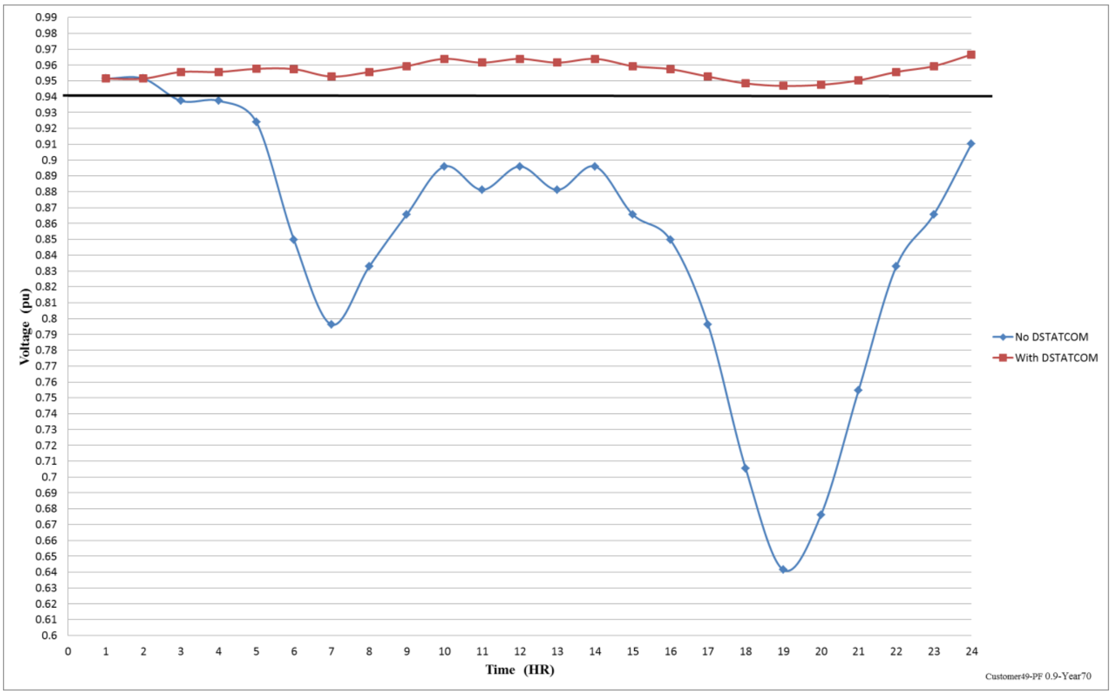


Figure 6.9: System voltage with and without DSTATCOM operating in load PF follow mode for 24 hours period of customer 49 in year 70 with PF of 0.9.

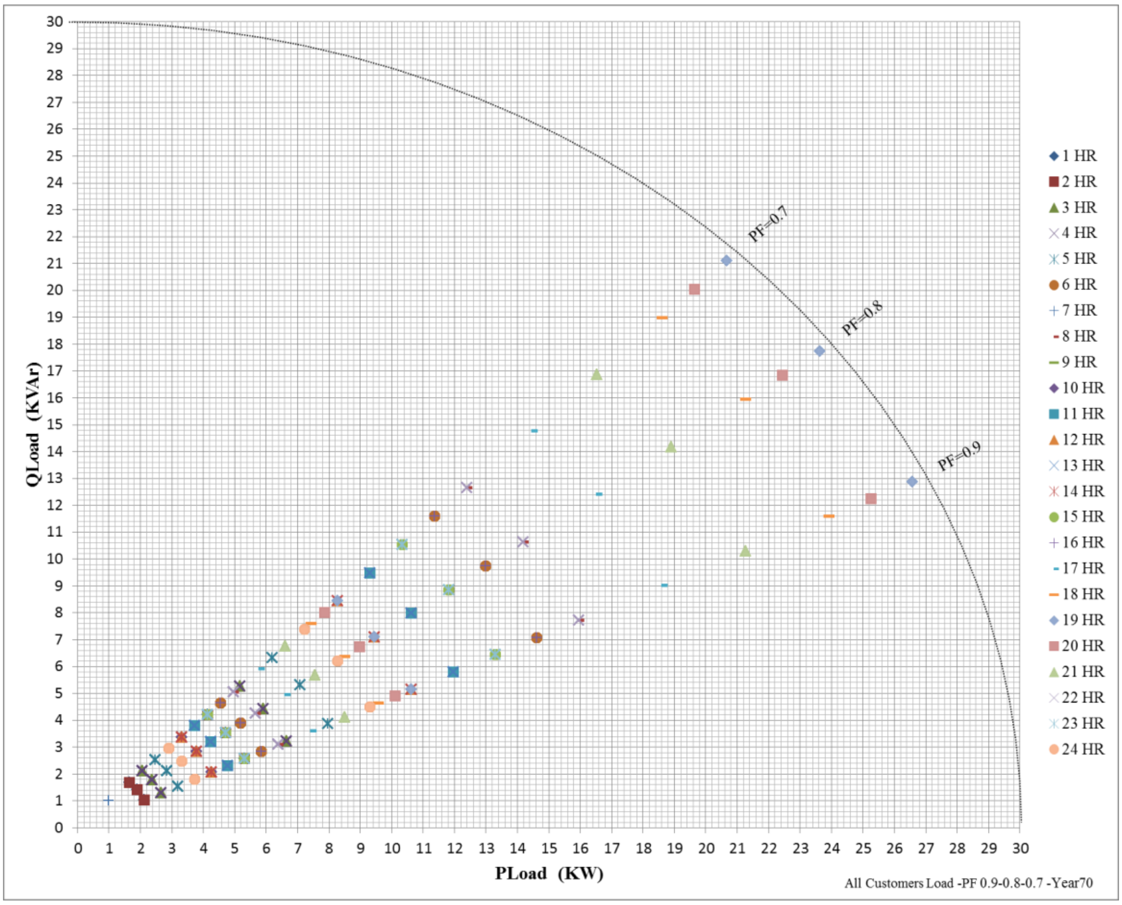


Figure 6.10: Daily load conditions of all customers with three different power factors, 0.9, 0.8 and 0.7, year 70 with no DSTATCOMs in the network.

The state of the DSTATCOMs in load PF follow mode for all 49 customers in three different load power factors, 0.9, 0.8 and 0.7 over a 24 hours period in year 70 are shown in Tables 6.3, 6.4 and 6.5 respectively. The OFF state means there is no voltage issue in the system and there is no need to run any voltage support equipment. The P-Q situation shows that a voltage problem is detected and that the DSTATCOM is switched ON to tackle the issue.

6.7.2 Load PF Correction Mode Results

The DSTATCOM will be operating at load PF correction scheme but always at a lower reactive power output level than the reactive power of the load. The condition for the rated reactive power injected for DSTATCOM from equation (6.4) will be considered as:

$$Q_{si} \leq Q_{Di} \qquad (6.20)$$

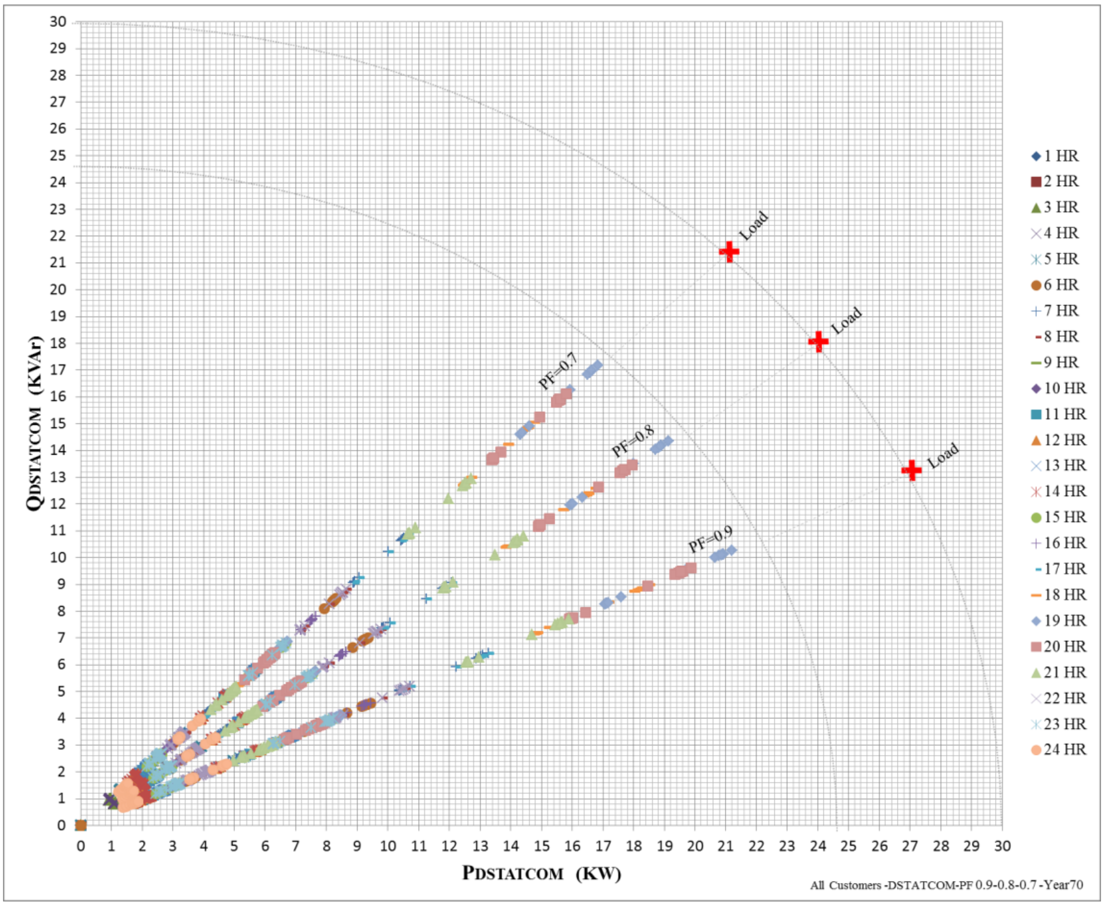


Figure 6.11: Daily DSTATCOM operation, load PF follow mode, all customers with three different load power factors, 0.9, 0.8 and 0.7, year 70.

Results for the system load power factor using DSTATCOM operating at load PF correction scheme in 24 hours of year 40 for three different power factors of 0.9, 0.8 and 0.7 are shown in Tables 6.6, 6.8 and 6.10 respectively. System voltage profile with DSTATCOM operating in load PF correction mode corresponded with above mentioned Tables are shown in Tables 6.7, 6.9 and 6.11 respectively. As can be seen the net power factor at year 40 has been improved and the voltage is fully supported in this scheme while the DSTATCOM has been activated. It has to be noted that this scheme has been only effective by year 40 and will not be able to support the voltage after that which shows its limited effectiveness.

Table 6.3: DSTATCOM state, load PF follow mode, year 70, load PF of 0.9

CUS \ HR	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
2	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
3	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
4	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
5	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
6	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
7	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
8	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
9	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
10	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
11	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
12	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
13	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
14	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
15	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
16	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
17	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
18	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
19	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
20	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
21	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
22	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
23	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
24	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
25	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
26	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
27	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
28	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
29	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
30	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
31	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
32	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
33	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
34	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
35	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
36	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
37	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
38	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
39	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
40	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
41	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
42	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
43	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
44	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
45	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
46	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
47	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
48	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
49	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q

Table 6.4: DSTATCOM state, load PF follow mode, year 70, load PF of 0.8

CUS \ HR	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	OFF	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
2	OFF	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
3	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
4	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
5	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
6	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
7	OFF	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
8	OFF	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
9	OFF	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
10	OFF	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
11	OFF	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
12	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
13	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
14	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
15	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
16	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
17	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
18	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
19	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
20	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
21	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
22	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
23	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
24	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
25	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
26	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
27	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
28	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
29	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
30	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
31	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
32	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
33	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
34	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
35	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
36	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
37	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
38	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
39	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
40	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
41	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
42	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
43	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
44	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
45	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
46	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
47	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
48	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
49	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q

Table 6.5: DSTATCOM state, load PF follow mode, year 70, load PF of 0.7

CUS \ HR	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	OFF	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
2	OFF	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
3	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
4	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
5	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
6	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
7	OFF	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
8	OFF	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
9	OFF	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
10	OFF	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
11	OFF	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
12	OFF	OFF	OFF	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
13	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
14	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
15	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
16	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
17	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
18	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
19	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
20	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
21	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
22	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
23	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
24	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
25	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
26	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
27	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
28	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
29	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
30	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
31	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
32	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
33	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
34	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
35	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
36	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
37	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
38	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
39	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
40	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
41	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
42	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
43	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
44	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
45	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
46	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
47	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
48	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q
49	OFF	OFF	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q	P-Q

Table 6.6: System load power factor using DSTATCOM load PF correction mode, year 40, load PF 0.9

HR / CUS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
2	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
3	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
4	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
5	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
6	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
7	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
8	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
10	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
11	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
12	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
13	0.9	0.9	0.9	0.9	0.9	0.9	0.99	0.98	0.97	0.96	0.97	0.96	0.97	0.96	0.97	0.98	0.99	1.00	1.00	1.00	0.99	0.98	0.97	0.95
14	0.9	0.9	0.9	0.9	0.9	0.9	0.99	0.98	0.97	0.96	0.96	0.96	0.96	0.96	0.97	0.97	0.99	0.99	1.00	1.00	0.99	0.98	0.97	0.95
15	0.9	0.9	0.9	0.9	0.9	0.9	0.99	0.98	0.97	0.96	0.97	0.96	0.97	0.96	0.97	0.98	0.99	1.00	1.00	1.00	0.99	0.98	0.97	0.96
16	0.9	0.9	0.9	0.9	0.9	0.9	0.99	0.98	0.98	0.97	0.97	0.97	0.97	0.97	0.98	0.98	0.99	1.00	1.00	1.00	1.00	0.98	0.98	0.96
17	0.9	0.9	0.9	0.9	0.9	0.9	0.99	0.99	0.98	0.97	0.97	0.97	0.97	0.97	0.98	0.98	0.99	1.00	1.00	1.00	1.00	0.99	0.98	0.96
18	0.9	0.9	0.9	0.9	0.9	0.9	0.99	0.99	0.98	0.97	0.97	0.97	0.97	0.97	0.98	0.98	0.99	1.00	1.00	1.00	1.00	0.99	0.98	0.96
19	0.9	0.9	0.9	0.9	0.9	0.9	0.99	0.98	0.98	0.97	0.97	0.97	0.97	0.97	0.98	0.98	0.99	1.00	1.00	1.00	1.00	0.98	0.98	0.96
20	0.9	0.9	0.9	0.9	0.9	0.9	0.99	0.98	0.98	0.97	0.97	0.97	0.97	0.97	0.98	0.98	0.99	1.00	1.00	1.00	1.00	0.98	0.98	0.96
21	0.9	0.9	0.9	0.9	0.9	0.9	0.99	0.98	0.97	0.96	0.97	0.96	0.97	0.96	0.97	0.98	0.99	1.00	1.00	1.00	0.99	0.98	0.97	0.96
22	0.9	0.9	0.9	0.9	0.9	0.9	0.99	0.98	0.97	0.96	0.97	0.96	0.97	0.96	0.97	0.98	0.99	1.00	1.00	1.00	0.99	0.98	0.97	0.96
23	0.9	0.9	0.9	0.9	0.9	0.9	0.99	0.98	0.97	0.96	0.97	0.96	0.97	0.96	0.97	0.98	0.99	1.00	1.00	1.00	0.99	0.98	0.97	0.96
24	0.9	0.9	0.9	0.9	0.9	0.9	0.99	0.98	0.98	0.97	0.97	0.97	0.97	0.97	0.98	0.98	0.99	1.00	1.00	1.00	1.00	0.98	0.98	0.96
25	0.9	0.9	0.9	0.9	0.9	0.9	0.99	0.98	0.98	0.97	0.97	0.97	0.97	0.97	0.98	0.98	0.99	1.00	1.00	1.00	1.00	0.98	0.98	0.96
26	0.9	0.9	0.9	0.9	0.9	0.9	0.99	0.98	0.98	0.97	0.97	0.97	0.97	0.97	0.98	0.98	0.99	1.00	1.00	1.00	1.00	0.98	0.98	0.96
27	0.9	0.9	0.9	0.9	0.9	0.9	0.99	0.99	0.98	0.97	0.97	0.97	0.97	0.97	0.98	0.98	0.99	1.00	1.00	1.00	1.00	0.99	0.98	0.96
28	0.9	0.9	0.9	0.9	0.9	0.9	0.99	0.99	0.98	0.97	0.97	0.97	0.97	0.97	0.98	0.98	0.99	1.00	1.00	1.00	1.00	0.99	0.98	0.96
29	0.9	0.9	0.9	0.9	0.9	0.9	0.99	0.98	0.97	0.96	0.97	0.96	0.97	0.96	0.97	0.98	0.99	1.00	1.00	1.00	0.99	0.98	0.97	0.96
30	0.9	0.9	0.9	0.9	0.9	0.9	0.99	0.98	0.97	0.96	0.97	0.96	0.97	0.96	0.97	0.98	0.99	1.00	1.00	1.00	0.99	0.98	0.97	0.96
31	0.9	0.9	0.9	0.9	0.9	0.9	0.99	0.98	0.98	0.96	0.97	0.96	0.97	0.96	0.98	0.98	0.99	1.00	1.00	1.00	0.99	0.98	0.98	0.96
32	0.9	0.9	0.9	0.9	0.9	0.9	0.99	0.98	0.98	0.96	0.97	0.96	0.97	0.96	0.98	0.98	0.99	1.00	1.00	1.00	0.99	0.98	0.98	0.96
33	0.9	0.9	0.9	0.9	0.9	0.9	0.99	0.98	0.98	0.97	0.97	0.97	0.97	0.97	0.98	0.98	0.99	1.00	1.00	1.00	1.00	0.98	0.98	0.96
34	0.9	0.9	0.9	0.9	0.9	0.9	0.99	0.98	0.98	0.97	0.97	0.97	0.97	0.97	0.98	0.98	0.99	1.00	1.00	1.00	1.00	0.98	0.98	0.96
35	0.9	0.9	0.9	0.9	0.9	0.9	0.99	0.98	0.98	0.97	0.97	0.97	0.97	0.97	0.98	0.98	0.99	1.00	1.00	1.00	1.00	0.98	0.98	0.96
36	0.9	0.9	0.9	0.9	0.9	0.9	0.99	0.98	0.98	0.97	0.97	0.97	0.97	0.97	0.98	0.98	0.99	1.00	1.00	1.00	1.00	0.98	0.98	0.96
37	0.9	0.9	0.9	0.9	0.9	0.9	0.99	0.98	0.97	0.96	0.97	0.96	0.97	0.96	0.97	0.98	0.99	1.00	1.00	1.00	0.99	0.98	0.97	0.96
38	0.9	0.9	0.9	0.9	0.9	0.9	0.99	0.98	0.98	0.96	0.97	0.96	0.97	0.96	0.98	0.98	0.99	1.00	1.00	1.00	0.99	0.98	0.98	0.96
39	0.9	0.9	0.9	0.9	0.9	0.9	0.99	0.98	0.97	0.96	0.97	0.96	0.97	0.96	0.97	0.98	0.99	1.00	1.00	1.00	0.99	0.98	0.97	0.96
40	0.9	0.9	0.9	0.9	0.9	0.9	0.99	0.98	0.97	0.96	0.97	0.96	0.97	0.96	0.97	0.98	0.99	1.00	1.00	1.00	0.99	0.98	0.97	0.96
41	0.9	0.9	0.9	0.9	0.9	0.9	0.99	0.98	0.98	0.97	0.97	0.97	0.97	0.97	0.98	0.98	0.99	1.00	1.00	1.00	1.00	0.98	0.98	0.96
42	0.9	0.9	0.9	0.9	0.9	0.9	0.99	0.99	0.98	0.97	0.97	0.97	0.97	0.97	0.98	0.98	0.99	1.00	1.00	1.00	1.00	0.99	0.98	0.96
43	0.9	0.9	0.9	0.9	0.9	0.9	0.99	0.99	0.98	0.97	0.97	0.97	0.97	0.97	0.98	0.98	0.99	1.00	1.00	1.00	1.00	0.99	0.98	0.96
44	0.9	0.9	0.9	0.9	0.9	0.9	0.99	0.99	0.98	0.97	0.97	0.97	0.97	0.97	0.98	0.98	0.99	1.00	1.00	1.00	1.00	0.99	0.98	0.96
45	0.9	0.9	0.9	0.9	0.9	0.9	0.99	0.99	0.98	0.97	0.97	0.97	0.97	0.97	0.98	0.98	0.99	1.00	1.00	1.00	1.00	0.99	0.98	0.96
46	0.9	0.9	0.9	0.9	0.9	0.9	0.99	0.99	0.98	0.97	0.97	0.97	0.97	0.97	0.98	0.98	0.99	1.00	1.00	1.00	1.00	0.99	0.98	0.96
47	0.9	0.9	0.9	0.9	0.9	0.9	0.99	0.99	0.98	0.97	0.97	0.97	0.97	0.97	0.98	0.98	0.99	1.00	1.00	1.00	1.00	0.99	0.98	0.96
48	0.9	0.9	0.9	0.9	0.9	0.9	0.99	0.99	0.98	0.97	0.97	0.97	0.97	0.97	0.98	0.98	0.99	1.00	1.00	1.00	1.00	0.99	0.98	0.96
49	0.9	0.9	0.9	0.9	0.9	0.9	0.99	0.99	0.98	0.97	0.97	0.97	0.97	0.97	0.98	0.98	0.99	1.00	1.00	1.00	1.00	0.99	0.98	0.96

Table 6.7: System voltage profile with DSTATCOM operating in load PF correction mode, year 40, load PF 0.9

CUS \ HR	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	0.99	0.99	0.98	0.98	0.98	0.96	0.97	0.97	0.97	0.98	0.98	0.98	0.98	0.98	0.97	0.97	0.97	0.96	0.95	0.95	0.96	0.97	0.97	0.98
2	0.99	0.99	0.98	0.98	0.98	0.96	0.96	0.97	0.97	0.98	0.98	0.98	0.98	0.98	0.97	0.97	0.96	0.95	0.95	0.95	0.96	0.97	0.97	0.98
3	0.99	0.99	0.98	0.98	0.98	0.96	0.96	0.97	0.97	0.98	0.97	0.98	0.97	0.98	0.97	0.97	0.96	0.95	0.95	0.95	0.96	0.97	0.97	0.98
4	0.99	0.99	0.98	0.98	0.98	0.96	0.96	0.97	0.97	0.98	0.97	0.98	0.97	0.98	0.97	0.97	0.96	0.95	0.95	0.95	0.96	0.97	0.97	0.98
5	0.98	0.98	0.98	0.98	0.98	0.96	0.96	0.97	0.97	0.98	0.97	0.98	0.97	0.98	0.97	0.97	0.96	0.95	0.95	0.95	0.96	0.97	0.97	0.98
6	0.98	0.98	0.98	0.98	0.98	0.96	0.96	0.97	0.97	0.98	0.97	0.98	0.97	0.98	0.97	0.97	0.96	0.95	0.95	0.95	0.96	0.97	0.97	0.98
7	0.99	0.99	0.98	0.98	0.98	0.96	0.96	0.97	0.97	0.98	0.98	0.98	0.98	0.98	0.97	0.97	0.96	0.96	0.95	0.95	0.96	0.97	0.97	0.98
8	0.99	0.99	0.98	0.98	0.98	0.96	0.96	0.97	0.97	0.98	0.98	0.98	0.98	0.98	0.97	0.97	0.96	0.96	0.95	0.95	0.96	0.97	0.97	0.98
9	0.99	0.99	0.98	0.98	0.98	0.96	0.96	0.97	0.97	0.98	0.98	0.98	0.98	0.98	0.97	0.97	0.96	0.96	0.95	0.95	0.96	0.97	0.97	0.98
10	0.99	0.99	0.98	0.98	0.98	0.96	0.96	0.97	0.97	0.98	0.98	0.98	0.98	0.98	0.97	0.97	0.96	0.96	0.95	0.95	0.96	0.97	0.97	0.98
11	0.98	0.98	0.98	0.98	0.98	0.96	0.96	0.97	0.97	0.98	0.97	0.98	0.97	0.98	0.97	0.97	0.96	0.95	0.95	0.95	0.96	0.97	0.97	0.98
12	0.98	0.98	0.98	0.98	0.98	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.96	0.95	0.94	0.94	0.95	0.96	0.97	0.98
13	0.98	0.98	0.98	0.98	0.97	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.95	0.96	0.97	0.98
14	0.98	0.98	0.98	0.98	0.97	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.96	0.95	0.94	0.95	0.95	0.96	0.97	0.98
15	0.98	0.98	0.98	0.98	0.97	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.95	0.96	0.97	0.98
16	0.98	0.98	0.98	0.98	0.97	0.95	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
17	0.98	0.98	0.98	0.98	0.97	0.95	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
18	0.98	0.98	0.98	0.98	0.97	0.95	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
19	0.98	0.98	0.98	0.98	0.97	0.95	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
20	0.98	0.98	0.98	0.98	0.97	0.95	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
21	0.98	0.98	0.98	0.98	0.97	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.95	0.96	0.97	0.98
22	0.98	0.98	0.98	0.98	0.97	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.94	0.94	0.94	0.95	0.96	0.97	0.98
23	0.98	0.98	0.98	0.98	0.97	0.95	0.95	0.96	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.97	0.97
24	0.98	0.98	0.98	0.98	0.97	0.95	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
25	0.98	0.98	0.98	0.98	0.97	0.95	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
26	0.98	0.98	0.98	0.98	0.97	0.95	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
27	0.98	0.98	0.98	0.98	0.97	0.95	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
28	0.98	0.98	0.98	0.98	0.97	0.95	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
29	0.98	0.98	0.98	0.98	0.97	0.95	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
30	0.98	0.98	0.98	0.98	0.97	0.95	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
31	0.98	0.98	0.98	0.98	0.97	0.95	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
32	0.98	0.98	0.98	0.98	0.97	0.95	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
33	0.98	0.98	0.98	0.98	0.97	0.95	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
34	0.98	0.98	0.98	0.98	0.97	0.95	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
35	0.98	0.98	0.98	0.98	0.97	0.95	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
36	0.98	0.98	0.98	0.98	0.97	0.95	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
37	0.98	0.98	0.98	0.98	0.97	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.94	0.94	0.94	0.95	0.96	0.97	0.98
38	0.98	0.98	0.98	0.98	0.97	0.95	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
39	0.98	0.98	0.98	0.98	0.97	0.95	0.95	0.96	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.97	0.97
40	0.98	0.98	0.98	0.98	0.97	0.95	0.95	0.96	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.97	0.97
41	0.98	0.98	0.98	0.98	0.97	0.95	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
42	0.98	0.98	0.98	0.98	0.97	0.95	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
43	0.98	0.98	0.98	0.98	0.97	0.95	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
44	0.98	0.98	0.98	0.98	0.97	0.94	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.94	0.96	0.96	0.97
45	0.98	0.98	0.98	0.98	0.97	0.94	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.94	0.96	0.96	0.97
46	0.98	0.98	0.98	0.98	0.97	0.95	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
47	0.98	0.98	0.98	0.98	0.97	0.95	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.94	0.96	0.96	0.97
48	0.98	0.98	0.97	0.97	0.97	0.94	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.94	0.96	0.96	0.97
49	0.98	0.98	0.97	0.97	0.97	0.94	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.94	0.96	0.96	0.97

Table 6.8: System load power factor using DSTATCOM load PF correction mode, year 40, load PF 0.8

CUS \ HR	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
2	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
3	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
4	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
5	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
6	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
7	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
9	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
10	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
11	0.8	0.8	0.8	0.8	0.8	0.8	0.95	0.94	0.92	0.90	0.91	0.90	0.91	0.90	0.92	0.93	0.95	0.97	0.98	0.98	0.96	0.94	0.92	0.89
12	0.8	0.8	0.8	0.8	0.8	0.8	0.96	0.94	0.93	0.91	0.92	0.91	0.92	0.91	0.93	0.94	0.96	0.98	0.99	0.98	0.97	0.94	0.93	0.90
13	0.8	0.8	0.8	0.8	0.8	0.8	0.97	0.95	0.94	0.92	0.93	0.92	0.93	0.92	0.94	0.95	0.97	0.99	0.99	0.99	0.98	0.95	0.94	0.90
14	0.8	0.8	0.8	0.8	0.8	0.8	0.97	0.95	0.93	0.91	0.92	0.91	0.92	0.91	0.93	0.94	0.97	0.99	0.99	0.99	0.98	0.95	0.93	0.90
15	0.8	0.8	0.8	0.8	0.8	0.8	0.97	0.95	0.94	0.92	0.93	0.92	0.93	0.92	0.94	0.95	0.97	0.99	0.99	0.99	0.98	0.95	0.94	0.91
16	0.8	0.8	0.8	0.8	0.8	0.8	0.98	0.97	0.95	0.93	0.94	0.93	0.94	0.93	0.95	0.96	0.98	1.00	1.00	1.00	0.99	0.97	0.95	0.91
17	0.8	0.8	0.8	0.8	0.8	0.8	0.98	0.97	0.95	0.93	0.94	0.93	0.94	0.93	0.95	0.96	0.98	1.00	1.00	1.00	0.99	0.97	0.95	0.91
18	0.8	0.8	0.8	0.8	0.8	0.8	0.98	0.97	0.95	0.93	0.94	0.93	0.94	0.93	0.95	0.96	0.98	1.00	1.00	1.00	0.99	0.97	0.95	0.91
19	0.8	0.8	0.8	0.8	0.8	0.8	0.98	0.96	0.95	0.93	0.94	0.93	0.94	0.93	0.95	0.96	0.98	1.00	1.00	1.00	0.99	0.96	0.95	0.91
20	0.8	0.8	0.8	0.8	0.8	0.8	0.98	0.96	0.95	0.93	0.94	0.93	0.94	0.93	0.95	0.96	0.98	1.00	1.00	1.00	0.99	0.96	0.95	0.91
21	0.8	0.8	0.8	0.8	0.8	0.8	0.97	0.95	0.94	0.92	0.93	0.92	0.93	0.92	0.94	0.95	0.97	0.99	0.99	0.99	0.98	0.95	0.94	0.91
22	0.8	0.8	0.8	0.8	0.8	0.8	0.97	0.96	0.94	0.92	0.93	0.92	0.93	0.92	0.94	0.95	0.97	0.99	1.00	0.99	0.98	0.96	0.94	0.91
23	0.8	0.8	0.8	0.8	0.8	0.8	0.97	0.96	0.94	0.92	0.93	0.92	0.93	0.92	0.94	0.95	0.97	0.99	1.00	1.00	0.98	0.96	0.94	0.91
24	0.8	0.8	0.8	0.8	0.8	0.8	0.98	0.96	0.95	0.93	0.94	0.93	0.94	0.93	0.95	0.96	0.98	0.99	1.00	1.00	0.99	0.96	0.95	0.91
25	0.8	0.8	0.8	0.8	0.8	0.8	0.98	0.96	0.95	0.93	0.94	0.93	0.94	0.93	0.95	0.96	0.98	0.99	1.00	1.00	0.99	0.96	0.95	0.91
26	0.8	0.8	0.8	0.8	0.8	0.8	0.98	0.96	0.95	0.93	0.94	0.93	0.94	0.93	0.95	0.96	0.98	1.00	1.00	1.00	0.99	0.96	0.95	0.91
27	0.8	0.8	0.8	0.8	0.8	0.8	0.98	0.97	0.95	0.93	0.94	0.93	0.94	0.93	0.95	0.96	0.98	1.00	1.00	1.00	0.99	0.97	0.95	0.92
28	0.8	0.8	0.8	0.8	0.8	0.8	0.98	0.97	0.95	0.93	0.94	0.93	0.94	0.93	0.95	0.96	0.98	1.00	1.00	1.00	0.99	0.97	0.95	0.92
29	0.8	0.8	0.8	0.8	0.8	0.8	0.98	0.96	0.94	0.92	0.93	0.92	0.93	0.92	0.94	0.95	0.98	0.99	1.00	1.00	0.99	0.96	0.94	0.91
30	0.8	0.8	0.8	0.8	0.8	0.8	0.98	0.96	0.94	0.92	0.93	0.92	0.93	0.92	0.94	0.95	0.98	0.99	1.00	1.00	0.99	0.96	0.94	0.91
31	0.8	0.8	0.8	0.8	0.8	0.8	0.98	0.96	0.94	0.92	0.93	0.92	0.93	0.92	0.94	0.95	0.98	0.99	1.00	1.00	0.99	0.96	0.94	0.91
32	0.8	0.8	0.8	0.8	0.8	0.8	0.98	0.96	0.95	0.92	0.94	0.92	0.94	0.92	0.95	0.95	0.98	0.99	1.00	1.00	0.99	0.96	0.95	0.91
33	0.8	0.8	0.8	0.8	0.8	0.8	0.98	0.96	0.95	0.93	0.94	0.93	0.94	0.93	0.95	0.96	0.98	0.99	1.00	1.00	0.99	0.96	0.95	0.91
34	0.8	0.8	0.8	0.8	0.8	0.8	0.98	0.96	0.95	0.93	0.94	0.93	0.94	0.93	0.95	0.96	0.98	0.99	1.00	1.00	0.99	0.96	0.95	0.91
35	0.8	0.8	0.8	0.8	0.8	0.8	0.98	0.96	0.95	0.93	0.94	0.93	0.94	0.93	0.95	0.96	0.98	0.99	1.00	1.00	0.99	0.96	0.95	0.91
36	0.8	0.8	0.8	0.8	0.8	0.8	0.98	0.96	0.95	0.93	0.94	0.93	0.94	0.93	0.95	0.96	0.98	0.99	1.00	1.00	0.99	0.96	0.95	0.91
37	0.8	0.8	0.8	0.8	0.8	0.8	0.97	0.96	0.94	0.92	0.93	0.92	0.93	0.92	0.94	0.95	0.97	0.99	1.00	0.99	0.98	0.96	0.94	0.91
38	0.8	0.8	0.8	0.8	0.8	0.8	0.98	0.96	0.95	0.92	0.94	0.92	0.94	0.92	0.95	0.95	0.98	0.99	1.00	1.00	0.99	0.96	0.95	0.91
39	0.8	0.8	0.8	0.8	0.8	0.8	0.97	0.96	0.94	0.92	0.93	0.92	0.93	0.92	0.94	0.95	0.97	0.99	1.00	1.00	0.99	0.96	0.94	0.91
40	0.8	0.8	0.8	0.8	0.8	0.8	0.98	0.96	0.94	0.92	0.93	0.92	0.93	0.92	0.94	0.95	0.98	0.99	1.00	1.00	0.99	0.96	0.94	0.91
41	0.8	0.8	0.8	0.8	0.8	0.8	0.98	0.96	0.95	0.93	0.94	0.93	0.94	0.93	0.95	0.96	0.98	0.99	1.00	1.00	0.99	0.96	0.95	0.91
42	0.8	0.8	0.8	0.8	0.8	0.8	0.98	0.97	0.95	0.93	0.94	0.93	0.94	0.93	0.95	0.96	0.98	1.00	1.00	1.00	0.99	0.97	0.95	0.92
43	0.8	0.8	0.8	0.8	0.8	0.8	0.98	0.97	0.95	0.93	0.94	0.93	0.94	0.93	0.95	0.96	0.98	1.00	1.00	1.00	0.99	0.97	0.95	0.92
44	0.8	0.8	0.8	0.8	0.8	0.8	0.98	0.97	0.95	0.93	0.94	0.93	0.94	0.93	0.95	0.96	0.98	1.00	1.00	1.00	0.99	0.97	0.95	0.92
45	0.8	0.8	0.8	0.8	0.8	0.8	0.98	0.97	0.95	0.93	0.94	0.93	0.94	0.93	0.95	0.96	0.98	1.00	1.00	1.00	0.99	0.97	0.95	0.92
46	0.8	0.8	0.8	0.8	0.8	0.8	0.98	0.97	0.95	0.93	0.94	0.93	0.94	0.93	0.95	0.96	0.98	1.00	1.00	1.00	0.99	0.97	0.95	0.91
47	0.8	0.8	0.8	0.8	0.8	0.8	0.98	0.97	0.95	0.93	0.94	0.93	0.94	0.93	0.95	0.96	0.98	1.00	1.00	1.00	0.99	0.97	0.95	0.92
48	0.8	0.8	0.8	0.8	0.8	0.8	0.98	0.97	0.95	0.93	0.94	0.93	0.94	0.93	0.95	0.96	0.98	1.00	1.00	1.00	0.99	0.97	0.95	0.92
49	0.8	0.8	0.8	0.8	0.8	0.8	0.98	0.97	0.95	0.93	0.94	0.93	0.94	0.93	0.95	0.96	0.98	1.00	1.00	1.00	0.99	0.97	0.95	0.92

Table 6.9: System voltage profile with DSTATCOM operating in load PF correction mode, year 40, load PF 0.8

HR / CUS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	0.98	0.98	0.98	0.98	0.98	0.96	0.96	0.97	0.97	0.98	0.97	0.98	0.97	0.98	0.97	0.97	0.96	0.96	0.95	0.95	0.96	0.97	0.97	0.98
2	0.98	0.98	0.98	0.98	0.98	0.96	0.96	0.97	0.97	0.98	0.97	0.98	0.97	0.98	0.97	0.97	0.96	0.95	0.95	0.95	0.96	0.97	0.97	0.98
3	0.98	0.98	0.98	0.98	0.98	0.95	0.96	0.97	0.97	0.98	0.97	0.98	0.97	0.98	0.97	0.97	0.96	0.95	0.95	0.95	0.96	0.97	0.97	0.98
4	0.98	0.98	0.98	0.98	0.98	0.95	0.96	0.96	0.97	0.98	0.97	0.98	0.97	0.98	0.97	0.97	0.96	0.95	0.95	0.95	0.96	0.96	0.97	0.98
5	0.98	0.98	0.98	0.98	0.98	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.96	0.95	0.95	0.95	0.95	0.96	0.97	0.98
6	0.98	0.98	0.98	0.98	0.98	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.96	0.95	0.95	0.95	0.95	0.96	0.97	0.98
7	0.98	0.98	0.98	0.98	0.98	0.96	0.96	0.97	0.97	0.98	0.97	0.98	0.97	0.98	0.97	0.97	0.96	0.95	0.95	0.95	0.96	0.97	0.97	0.98
8	0.98	0.98	0.98	0.98	0.98	0.96	0.96	0.97	0.97	0.98	0.97	0.98	0.97	0.98	0.97	0.97	0.96	0.95	0.95	0.95	0.96	0.97	0.97	0.98
9	0.98	0.98	0.98	0.98	0.98	0.96	0.96	0.97	0.97	0.98	0.97	0.98	0.97	0.98	0.97	0.97	0.96	0.95	0.95	0.95	0.96	0.97	0.97	0.98
10	0.98	0.98	0.98	0.98	0.98	0.96	0.96	0.97	0.97	0.98	0.97	0.98	0.97	0.98	0.97	0.97	0.96	0.95	0.95	0.95	0.96	0.97	0.97	0.98
11	0.98	0.98	0.98	0.98	0.97	0.95	0.96	0.97	0.97	0.98	0.97	0.98	0.97	0.98	0.97	0.97	0.96	0.96	0.95	0.95	0.96	0.97	0.97	0.98
12	0.98	0.98	0.98	0.98	0.97	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.96	0.95	0.95	0.95	0.96	0.96	0.97	0.98
13	0.98	0.98	0.98	0.98	0.97	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.95	0.95	0.96	0.97	0.98
14	0.98	0.98	0.98	0.98	0.97	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.95	0.95	0.96	0.97	0.98
15	0.98	0.98	0.98	0.98	0.97	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.95	0.96	0.97	0.98
16	0.98	0.98	0.97	0.97	0.97	0.94	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
17	0.98	0.98	0.97	0.97	0.97	0.94	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
18	0.98	0.98	0.97	0.97	0.97	0.94	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
19	0.98	0.98	0.97	0.97	0.97	0.94	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
20	0.98	0.98	0.97	0.97	0.97	0.94	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
21	0.98	0.98	0.98	0.98	0.97	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.95	0.96	0.97	0.98
22	0.98	0.98	0.98	0.98	0.97	0.94	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.95	0.96	0.97	0.97
23	0.98	0.98	0.97	0.97	0.97	0.94	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
24	0.98	0.98	0.97	0.97	0.97	0.94	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
25	0.98	0.98	0.97	0.97	0.97	0.94	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
26	0.98	0.98	0.97	0.97	0.97	0.94	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
27	0.98	0.98	0.97	0.97	0.97	0.94	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
28	0.98	0.98	0.97	0.97	0.97	0.94	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
29	0.98	0.98	0.97	0.97	0.97	0.94	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
30	0.98	0.98	0.97	0.97	0.97	0.94	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
31	0.98	0.98	0.97	0.97	0.97	0.94	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
32	0.98	0.98	0.97	0.97	0.97	0.94	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
33	0.98	0.98	0.97	0.97	0.97	0.94	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
34	0.98	0.98	0.97	0.97	0.97	0.94	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
35	0.98	0.98	0.97	0.97	0.97	0.94	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
36	0.98	0.98	0.97	0.97	0.97	0.94	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
37	0.98	0.98	0.98	0.98	0.97	0.94	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.95	0.96	0.97	0.97
38	0.98	0.98	0.97	0.97	0.97	0.94	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
39	0.98	0.98	0.97	0.97	0.97	0.94	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
40	0.98	0.98	0.97	0.97	0.97	0.94	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
41	0.98	0.98	0.97	0.97	0.97	0.94	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
42	0.98	0.98	0.97	0.97	0.97	0.94	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
43	0.98	0.98	0.97	0.97	0.97	0.94	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
44	0.98	0.98	0.97	0.97	0.97	0.94	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
45	0.98	0.98	0.97	0.97	0.97	0.94	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
46	0.98	0.98	0.97	0.97	0.97	0.94	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
47	0.98	0.98	0.97	0.97	0.97	0.94	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
48	0.98	0.98	0.97	0.97	0.97	0.94	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
49	0.98	0.98	0.97	0.97	0.97	0.94	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97

Table 6.10: System load power factor using DSTATCOM load PF correction mode, year 40, load PF 0.7

CUS \ HR	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
2	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
3	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
4	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
5	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
6	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
8	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
9	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
10	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
11	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
12	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
13	0.7	0.7	0.7	0.7	0.7	0.7	0.94	0.92	0.89	0.86	0.88	0.86	0.88	0.86	0.89	0.91	0.94	0.98	0.99	0.98	0.96	0.92	0.89	0.85
14	0.7	0.7	0.7	0.7	0.7	0.7	0.94	0.92	0.89	0.86	0.88	0.86	0.88	0.86	0.89	0.91	0.94	0.97	0.99	0.98	0.96	0.92	0.89	0.84
15	0.7	0.7	0.7	0.7	0.7	0.7	0.95	0.92	0.90	0.86	0.88	0.86	0.88	0.86	0.90	0.91	0.95	0.98	0.99	0.98	0.96	0.92	0.90	0.85
16	0.7	0.7	0.7	0.7	0.7	0.7	0.96	0.94	0.91	0.88	0.89	0.88	0.89	0.88	0.91	0.92	0.96	0.99	1.00	0.99	0.98	0.94	0.91	0.86
17	0.7	0.7	0.7	0.7	0.7	0.7	0.96	0.94	0.91	0.88	0.89	0.88	0.89	0.88	0.91	0.93	0.96	0.99	1.00	0.99	0.98	0.94	0.91	0.86
18	0.7	0.7	0.7	0.7	0.7	0.7	0.96	0.94	0.91	0.88	0.89	0.88	0.89	0.88	0.91	0.93	0.96	0.99	1.00	0.99	0.98	0.94	0.91	0.86
19	0.7	0.7	0.7	0.7	0.7	0.7	0.96	0.94	0.91	0.88	0.89	0.88	0.89	0.88	0.91	0.92	0.96	0.99	1.00	0.99	0.98	0.94	0.91	0.86
20	0.7	0.7	0.7	0.7	0.7	0.7	0.96	0.94	0.91	0.88	0.89	0.88	0.89	0.88	0.91	0.92	0.96	0.99	1.00	0.99	0.98	0.94	0.91	0.86
21	0.7	0.7	0.7	0.7	0.7	0.7	0.95	0.92	0.90	0.86	0.88	0.86	0.88	0.86	0.90	0.91	0.95	0.98	0.99	0.98	0.96	0.92	0.90	0.85
22	0.7	0.7	0.7	0.7	0.7	0.7	0.95	0.93	0.90	0.87	0.88	0.87	0.88	0.87	0.90	0.91	0.95	0.98	0.99	0.99	0.97	0.93	0.90	0.85
23	0.7	0.7	0.7	0.7	0.7	0.7	0.95	0.93	0.90	0.87	0.89	0.87	0.89	0.87	0.90	0.92	0.95	0.98	0.99	0.99	0.97	0.93	0.90	0.85
24	0.7	0.7	0.7	0.7	0.7	0.7	0.96	0.94	0.91	0.88	0.89	0.88	0.89	0.88	0.91	0.92	0.96	0.99	1.00	0.99	0.98	0.94	0.91	0.86
25	0.7	0.7	0.7	0.7	0.7	0.97	0.96	0.94	0.91	0.88	0.89	0.88	0.89	0.88	0.91	0.92	0.96	0.99	1.00	0.99	0.98	0.94	0.91	0.86
26	0.7	0.7	0.7	0.7	0.7	0.97	0.96	0.94	0.91	0.88	0.89	0.88	0.89	0.88	0.91	0.92	0.96	0.99	1.00	0.99	0.98	0.94	0.91	0.86
27	0.7	0.7	0.7	0.7	0.7	0.97	0.96	0.94	0.91	0.88	0.90	0.88	0.90	0.88	0.91	0.93	0.96	0.99	1.00	0.99	0.98	0.94	0.91	0.86
28	0.7	0.7	0.7	0.7	0.7	0.97	0.96	0.94	0.91	0.88	0.90	0.88	0.90	0.88	0.91	0.93	0.96	0.99	1.00	0.99	0.98	0.94	0.91	0.86
29	0.7	0.7	0.7	0.7	0.7	0.7	0.96	0.93	0.91	0.87	0.89	0.87	0.89	0.87	0.91	0.92	0.96	0.99	0.99	0.99	0.97	0.93	0.91	0.86
30	0.7	0.7	0.7	0.7	0.7	0.7	0.96	0.93	0.91	0.87	0.89	0.87	0.89	0.87	0.91	0.92	0.96	0.99	0.99	0.99	0.97	0.93	0.91	0.86
31	0.7	0.7	0.7	0.7	0.7	0.7	0.96	0.93	0.91	0.87	0.89	0.87	0.89	0.87	0.91	0.92	0.96	0.99	0.99	0.99	0.97	0.93	0.91	0.86
32	0.7	0.7	0.7	0.7	0.7	0.7	0.96	0.94	0.91	0.87	0.89	0.87	0.89	0.87	0.91	0.92	0.96	0.99	1.00	0.99	0.97	0.94	0.91	0.86
33	0.7	0.7	0.7	0.7	0.7	0.97	0.96	0.94	0.91	0.88	0.89	0.88	0.89	0.88	0.91	0.92	0.96	0.99	1.00	0.99	0.98	0.94	0.91	0.86
34	0.7	0.7	0.7	0.7	0.7	0.97	0.96	0.94	0.91	0.88	0.89	0.88	0.89	0.88	0.91	0.92	0.96	0.99	1.00	0.99	0.98	0.94	0.91	0.86
35	0.7	0.7	0.7	0.7	0.7	0.97	0.96	0.94	0.91	0.88	0.89	0.88	0.89	0.88	0.91	0.92	0.96	0.99	1.00	0.99	0.98	0.94	0.91	0.86
36	0.7	0.7	0.7	0.7	0.7	0.97	0.96	0.94	0.91	0.88	0.89	0.88	0.89	0.88	0.91	0.92	0.96	0.99	1.00	0.99	0.98	0.94	0.91	0.86
37	0.7	0.7	0.7	0.7	0.7	0.7	0.95	0.93	0.90	0.87	0.88	0.87	0.88	0.87	0.90	0.91	0.95	0.98	0.99	0.99	0.97	0.93	0.90	0.85
38	0.7	0.7	0.7	0.7	0.7	0.7	0.96	0.93	0.91	0.87	0.89	0.87	0.89	0.87	0.91	0.92	0.96	0.99	0.99	0.99	0.97	0.93	0.91	0.86
39	0.7	0.7	0.7	0.7	0.7	0.7	0.95	0.93	0.90	0.87	0.89	0.87	0.89	0.87	0.90	0.92	0.95	0.98	0.99	0.99	0.97	0.93	0.90	0.85
40	0.7	0.7	0.7	0.7	0.7	0.7	0.96	0.93	0.91	0.87	0.89	0.87	0.89	0.87	0.91	0.92	0.96	0.99	0.99	0.99	0.97	0.93	0.91	0.85
41	0.7	0.7	0.7	0.7	0.7	0.7	0.96	0.94	0.91	0.88	0.89	0.88	0.89	0.88	0.91	0.92	0.96	0.99	1.00	0.99	0.98	0.94	0.91	0.86
42	0.7	0.7	0.7	0.7	0.7	0.97	0.96	0.94	0.91	0.88	0.90	0.88	0.90	0.88	0.91	0.93	0.96	0.99	1.00	0.99	0.98	0.94	0.91	0.86
43	0.7	0.7	0.7	0.7	0.7	0.97	0.96	0.94	0.91	0.88	0.90	0.88	0.90	0.88	0.91	0.93	0.96	0.99	1.00	0.99	0.98	0.94	0.91	0.86
44	0.7	0.7	0.7	0.7	0.7	0.97	0.96	0.94	0.91	0.88	0.90	0.88	0.90	0.88	0.91	0.93	0.96	0.99	1.00	1.00	0.98	0.94	0.91	0.86
45	0.7	0.7	0.7	0.7	0.7	0.97	0.96	0.94	0.91	0.88	0.90	0.88	0.90	0.88	0.91	0.93	0.96	0.99	1.00	1.00	0.98	0.94	0.91	0.86
46	0.7	0.7	0.7	0.7	0.7	0.97	0.96	0.94	0.91	0.88	0.90	0.88	0.90	0.88	0.91	0.93	0.96	0.99	1.00	0.99	0.98	0.94	0.91	0.86
47	0.7	0.7	0.7	0.7	0.7	0.97	0.96	0.94	0.91	0.88	0.90	0.88	0.90	0.88	0.91	0.93	0.96	0.99	1.00	1.00	0.98	0.94	0.91	0.86
48	0.7	0.7	0.7	0.7	0.7	0.97	0.96	0.94	0.92	0.88	0.90	0.88	0.90	0.88	0.92	0.93	0.96	0.99	1.00	1.00	0.98	0.94	0.92	0.86
49	0.7	0.7	0.7	0.7	0.7	0.97	0.96	0.94	0.92	0.88	0.90	0.88	0.90	0.88	0.92	0.93	0.96	0.99	1.00	1.00	0.98	0.94	0.92	0.86

Table 6.11: System voltage profile with DSTATCOM operating in load PF correction mode, year 40, load PF 0.7

CUS \ HR	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	0.98	0.98	0.98	0.98	0.98	0.96	0.96	0.97	0.97	0.98	0.97	0.98	0.97	0.98	0.97	0.97	0.96	0.95	0.95	0.95	0.96	0.97	0.97	0.98
2	0.98	0.98	0.98	0.98	0.97	0.96	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.96	0.95	0.95	0.95	0.96	0.96	0.97	0.98
3	0.98	0.98	0.98	0.98	0.97	0.96	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.96	0.95	0.95	0.95	0.95	0.96	0.97	0.98
4	0.98	0.98	0.98	0.98	0.97	0.96	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.96	0.95	0.95	0.95	0.95	0.96	0.97	0.98
5	0.98	0.98	0.98	0.98	0.97	0.96	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.96	0.95	0.94	0.95	0.95	0.96	0.97	0.98
6	0.98	0.98	0.98	0.98	0.97	0.96	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.96	0.95	0.94	0.95	0.95	0.96	0.97	0.98
7	0.98	0.98	0.98	0.98	0.98	0.96	0.96	0.97	0.97	0.98	0.97	0.98	0.97	0.98	0.97	0.97	0.96	0.95	0.95	0.95	0.96	0.97	0.97	0.98
8	0.98	0.98	0.98	0.98	0.98	0.96	0.96	0.97	0.97	0.98	0.97	0.98	0.97	0.98	0.97	0.97	0.96	0.95	0.95	0.95	0.96	0.97	0.97	0.98
9	0.98	0.98	0.98	0.98	0.98	0.96	0.96	0.97	0.97	0.98	0.97	0.98	0.97	0.98	0.97	0.97	0.96	0.95	0.95	0.95	0.96	0.97	0.97	0.98
10	0.98	0.98	0.98	0.98	0.98	0.96	0.96	0.97	0.97	0.98	0.97	0.98	0.97	0.98	0.97	0.97	0.96	0.95	0.95	0.95	0.96	0.97	0.97	0.98
11	0.98	0.98	0.98	0.98	0.97	0.96	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.96	0.95	0.94	0.95	0.95	0.96	0.97	0.98
12	0.98	0.98	0.98	0.98	0.97	0.95	0.95	0.96	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.96	0.95	0.95	0.94	0.94	0.95	0.96	0.97	0.97
13	0.98	0.98	0.98	0.98	0.97	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.95	0.95	0.96	0.97	0.97
14	0.98	0.98	0.98	0.98	0.97	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.95	0.95	0.96	0.97	0.97
15	0.98	0.98	0.97	0.97	0.97	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.95	0.95	0.96	0.97	0.97
16	0.98	0.98	0.97	0.97	0.97	0.95	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
17	0.98	0.98	0.97	0.97	0.97	0.95	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
18	0.98	0.98	0.97	0.97	0.97	0.95	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
19	0.98	0.98	0.97	0.97	0.97	0.95	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
20	0.98	0.98	0.97	0.97	0.97	0.95	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
21	0.98	0.98	0.97	0.97	0.97	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.95	0.95	0.96	0.97	0.97
22	0.98	0.98	0.97	0.97	0.97	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.95	0.96	0.97	0.97
23	0.98	0.98	0.97	0.97	0.97	0.95	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
24	0.98	0.98	0.97	0.97	0.97	0.95	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
25	0.98	0.98	0.97	0.97	0.97	0.95	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
26	0.98	0.98	0.97	0.97	0.97	0.95	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
27	0.98	0.98	0.97	0.97	0.97	0.95	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
28	0.98	0.98	0.97	0.97	0.97	0.95	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
29	0.98	0.98	0.97	0.97	0.97	0.95	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
30	0.98	0.98	0.97	0.97	0.97	0.95	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
31	0.98	0.98	0.97	0.97	0.97	0.95	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
32	0.98	0.98	0.97	0.97	0.97	0.95	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
33	0.98	0.98	0.97	0.97	0.97	0.95	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
34	0.98	0.98	0.97	0.97	0.97	0.95	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
35	0.98	0.98	0.97	0.97	0.97	0.95	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
36	0.98	0.98	0.97	0.97	0.97	0.95	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
37	0.98	0.98	0.97	0.97	0.97	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.95	0.96	0.97	0.97
38	0.98	0.98	0.97	0.97	0.97	0.95	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
39	0.98	0.98	0.97	0.97	0.97	0.95	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
40	0.98	0.98	0.97	0.97	0.97	0.95	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
41	0.98	0.98	0.97	0.97	0.97	0.95	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
42	0.98	0.98	0.97	0.97	0.97	0.95	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
43	0.98	0.98	0.97	0.97	0.97	0.95	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
44	0.98	0.98	0.97	0.97	0.97	0.95	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
45	0.98	0.98	0.97	0.97	0.97	0.95	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
46	0.98	0.98	0.97	0.97	0.97	0.95	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
47	0.98	0.98	0.97	0.97	0.97	0.95	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
48	0.98	0.98	0.97	0.97	0.97	0.95	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97
49	0.98	0.98	0.97	0.97	0.97	0.95	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.95	0.94	0.94	0.94	0.95	0.96	0.96	0.97

6.8 Conclusions

The load PF follow mode and load PF correction mode of DSTATCOM operation were introduced in this chapter. The load PF follow mode operates at the load power factor in order to support the system voltage, but does not export P and Q into the grid. The DSTATCOM control applied was with active power-voltage and reactive power-voltage droop characteristics that were implemented in a load flow study with modified Jacobian matrix elements. The droop characteristic has been applied in a hysteretic control loop based on load voltage level. In addition, the load PF correction scheme uses the DSTATCOM as a source of reactive power to improve the net power factor seen from the source and as a result support the voltage of the network.

The results indicate that the SWER network voltage was fully supported via DSTATCOM operation in load PF follow scheme for 70 years which shows its effectiveness but it is an expensive solution. The load PF correction scheme is a cheaper solution and supported the voltage up to year 40 but not beyond.

CHAPTER 7

DISCUSSION AND CONCLUSIONS

7.1 Research Outcomes

The aim of this research project was to explore the effectiveness of DSTATCOMs at improving under-voltage problems due to load growth in dispersed rural SWERs. The reason for the focus on SWER networks is the high cost of upgrading them in the traditional way to solve voltage regulation problems that result from load growth. The following aspects of DSTATCOM installation and operation were explored in detail: (a) their location (b) VAr circulation avoidance (c) reactive power prioritising (d) four quadrant operation and (e) the timing of installation and operation.

7.1.1 DSTATCOM Location

From a simplified analysis presented in Chapter 3, involving a Thevenin source, a load and a reactive power only DSTATCOM, it is clear that placement of the DSTATCOM on the customer side of the SWER distribution transformer is significantly more effective than placing it on the network side of the transformer. The fundamental reason for this is the effect of the leakage reactance of the transformer. It effectively provides a voltage boost for the load when capacitive current from the DSTATCOM flows through it. While an analytical formula was derived to demonstrate this advantage for the case of a single load, it is not possible to extend that formula for the case of a more realistic SWER line with typically tens of customers on multiple branches of the line. However a simulation carried out for a real SWER line with forty-nine customers confirmed that about fifteen percent additional voltage boost is possible with the DSTATCOMs on the customer side.

It must be pointed that the extent of the advantage obtained by the DSTACOMs being installed on the customer side depends on a number of factors including the difference in R/X impedance ratios of the Thevenin impedance on the network side and on the customer side and on the number and location of customers. Quantitative evaluation of the benefits of customer side DSTATCOMs compared to network side DSTATCOMs should be done on a case by case basis as was done in Chapter 3 by means of detailed load flow studies. Similarly, cost comparisons should be done on a case by case basis.

This research has provided conclusive proof that less DSTATCOM total capacity is required if the DSTATCOMs are located on the customer side. However it could be argued that, unlike the case for the DSTATCOMs on the customer side, those on the network side could be combined into higher capacity DSTATCOMs which could be cheaper per kVAr. But that is not necessarily the case because of the cost of the required dedicated isolation transformer and earthing. Network losses are generally less if the DSTACOMs are located on the customer side. It should also be noted that a single higher capacity DSTATCOM is not necessarily cheaper per kVAr compared with a number of smaller DSTATCOM with the same total capacity. While the former may have the advantage of economies of scale, the latter may have the advantage of mass production.

7.1.2 VAr Circulation Avoidance

VAr circulation, if not avoided, effectively results in some of the capacity of installed DSTATCOMs being consumed without any positive effect on voltage regulation. It occurs when one or more DSTATCOMs inject reactive power into the network and simultaneously one or more DSTATCOMs somewhere else in the network absorbs reactive power. In practice there are two reasons that may cause VAr circulation. These are voltage sensing errors and the remote effect.

A scenario where voltage sensing error might cause problems is as follows: Assume that the target voltage for DSTATCOM A and DSTATCOM B is 1 per unit (pu) and the voltage is actually 1pu. This means that both DSTATCOM A and DSTATCOM B should neither inject nor absorb VArs. However if the DSTATCOM A’s voltage sensor reads the voltage as less than 1pu and DSTATCOM B's voltage sensor reads the voltage as more than 1pu, then DSTATCOM A unnecessarily produces reactive power which is absorbed by DSTATCOM B specially if the two DSTATCOMS are electrically close.

A scenario where VAr circulation occurs due to the remote effect is as follows: Assume that without the action of the DSTATCOMs, the voltage at DSTATCOM A's location is 1.0pu and the voltage at DSTATCOM B's location is 0.98pu. To bring the voltage at its location to 1pu DSTATCOM B injects reactive power into the network. This causes the voltage at DSTATCOMs A's location to increase to a level higher than 1pu and it therefore absorbs reactive power to bring its voltage back to 1pu.

It has been demonstrated, by load flow studies, in Chapter 4, that the use of droop control together with hysteretic control, avoids VAr circulation. The hysteretic band adopted was 0.94pu – 0.99pu for VAr injection and 1.01pu to 1.06pu for VAr absorption. The DSTATCOMs were represented in the load flow studies by their droop characteristics. This required modification of the Jacobian used in the classical Newton-Raphson based load flow problem.

7.1.3 Q Priority

Generally a DSTATCOM can regulate AC supply voltage by operating as a 4-quadrant device on the P-Q plane. However since cost per kVAr is much less than cost per kW, voltage regulation by reactive power injection or absorption is preferred compared to the use of active power for the same purpose. In other words operating DSTATCOMs in Q-only mode is given priority. As illustrated in Chapters 4 and 5, typically when a DSTATCOM is brought into service and is in Q-only mode, its operating point would remain on the vertical axis of the P-Q plane (P=0). This operating point shifts vertically upwards as the DSTATCOM supplies more and more reactive power.

Eventually, the injected reactive power will reach some maximum allowable limit. That could be due to the thermal rating of a plant item, a voltage stability limit or the rating of the DSTATCOM itself with the maximum size of customer transformer. In Chapter 5 it is assumed that the limit reached is the DSTATCOM rating. Once that limit is reached the DSTATCOM is made to operate at rated kVA but with increasing active power. In other words the operating point is now in the first quadrant of the P-Q plane and shifts along the rated kVA circle as more active power is injected.

A clear outcome of this research has been the identification of a point on the rated kVA circle that represents a peak achievable voltage. Analytical proof of the existence of that peak voltage is provided in Chapter 3 for the case of a single load. It is also confirmed that such a voltage peak exists for each DSTATCOM installed on a realistic SWER line. There is a simple physical interpretation for this phenomenon. As the operating point of the DSTATCOM shifts clockwise, injected active power goes up and injected reactive power comes down. At first when injected active power is small the voltage rise due to active power is more than the reduced voltage due to the drop in injected reactive power. However as the operating point shifts further clockwise on the rated kVA circle a point is reached where the incremental voltage rise per injected kW of active power matches the fall in voltage due to the drop in injected reactive power. Beyond that point there is a net drop in voltage. This is an important conclusion because it predicts that any closed loop voltage control system based on shifting the DSTATCOM operating point along its rated kVA circle on the P-Q plane will experience instability at the point where the voltage peaks.

7.1.4 The Possibility of Unwanted Islanding

Part of a distribution system may become isolated by deliberate opening of isolators by field staff or by operation of fuses or other protection equipment such as reclosers or circuit breakers. In rare cases operation as an “island” may continue if generation of active and reactive power by sources embedded in that isolated part respectively match the active and reactive power demand.

Distribution networks in general and SWER lines in particular are not designed to operate in “island” mode. However increased embedded generation including rooftop solar is increasing the likelihood of unwanted islanding. DSTATCOMs operating as sources of active and/or reactive power will increase that likelihood further.
Chapter 6 considers the case where DSTATCOM operation is arranged so that there is no net injection of either active power or reactive power back into the network, thus

removing the possibility of the DSTATCOMs contributing to islanding. In other words active and/or reactive power outputs of the DSTATCOMs are consumed by the local load. It has been demonstrated that if both active and reactive power is supplied by the DSTATCOM, this mode of operation can be very effective at regulating voltage. However the cost of the DSTATCOMs and their operation would most likely be prohibitive especially if batteries are used. It has also been demonstrated that if the DSTATCOMs are restricted to supply reactive power only, such that they only correct load power factor, then their effect on voltage regulation is significant but far from adequate.

7.1.5 Timing of DSTATCOM Installation and Operation

Part of the research question was "when and where should DSTATCOMs be installed on a SWER line?". A general approach has been proposed to address this question. A real SWER line has been used to illustrate the proposed approach which is based on:

(a) An assumed load demand growth rate for all consumers;
(b) a representative "worse case" daily demand profile for each year of operation being considered; and
(c) a control scheme for the DSTATCOMs.

In practice demand growth rate is a complex function of a number of factors, is generally different for different consumers and is not easy to predict. For simplicity demand has been assumed to grow uniformly at 3% per year and to be the same for all consumers. The 24-hour load profile corresponding to a particular year was taken to be representative of the highest peak demand for that year.

The 24-hour load profile representing peak demand for a particular year was made up of hourly demand intervals. A load flow solution was determined for each demand interval and depending on the calculated customer voltage and chosen control scheme, DSTATCOMs at each customer location was either automatically left off-line, brought on-line, left on-line or brought off-line. Different control schemes have been trialled and these were the Q-only scheme (Chapter 4), the Q-priority scheme (Chapter 5), the load power factor follow scheme (Chapter 6) and the load power factor correction scheme (Chapter 6). Each control scheme was based on a DSTATCOM droop characteristic and hysteretic band. Incorporation of the droop characteristic required modification of the standard load flow formulation. In particular the Jacobian had to be modified.

The modified load flow studies as described above was run for a real SWER line with a total length of 365 km and 49 customers over a period ranging from year zero to year 70. The following were automatically deduced:

(a) For each customer, the year that a DSTSTCOM first becomes necessary;
(b) For each customer and for each year, the kVAr and kW output of the DSTATCOM;
(c) For each customer and for each year, the number of kWh (and KVArh) delivered by the DSTATCOM on the representative peak demand day.

The load flow studies described above can be used to plan installation of the DSTATCOMs as they are needed. For example for the SWER line considered, the results in table 4.4 suggest that, if Q-only DSTATCOMs are used then beyond the 25th year up to the 70th, one to three additional DSTATCOMs need to be installed every five years to maintain customer voltage above 0.94pu. Other results in Chapters 5 and 6 quantify kWh requirements if four quadrant DSTATCOMs are used.

7.2 Further Work

The question of Q- priority has only been analysed in the case where the kVA rating of the DSTATCOM is reached as more and more reactive power is injected with active power output being zero. Given the relatively low cost of kVAr injection relative to kW injection, it is very likely that a more economical approach would be to have DSTATCOMs rated so that Q-injection is not limited by the rating of the DSTATCOMs. More investigations are needed to explore DSTATCOM control schemes that accommodate Q-injection limits (Q_{max}) that are not due to the rating of the DSTATCOM being reached. Such limits may be due to the thermal rating of some other electrical plant or to stability. Once that limit is reached, operation will change from pure Q-injection to a mix of Q-injection and P-injection. The question to be explored is:

What would be the best trajectory of the DSTATCOM operating point after the Q-only operating point limit (Q_{max}) is reached?

Unintentional islanding is regarded as a serious concern because of potential damage to equipment and risk to safety. Yet, with the increased prominence of embedded generation, the full benefit of Q-injection cannot be realised without a small risk of unwanted islanding. The question to be explored is how to minimise this risk. Communication between DSTATCOMs and between DSTATCOMs and isolators will most probably play a key role in avoiding unwanted islanding.

There is currently a lot of interest in micro-grids. There may be benefits in operating a part of a SWER line as a micro-grid that is connected to the main network for selected periods of time and in island mode for the rest of the time. In other words, a feature of some micro-grids is intentional islanding. A research question can focus on the role of DSTATCOMs in a SWER line section that operates as a micro-grid.

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APPENDIX A

This appendix provides Richmond SWER line data in Table A1 and Figure A1 as it has been used for case study in this thesis.

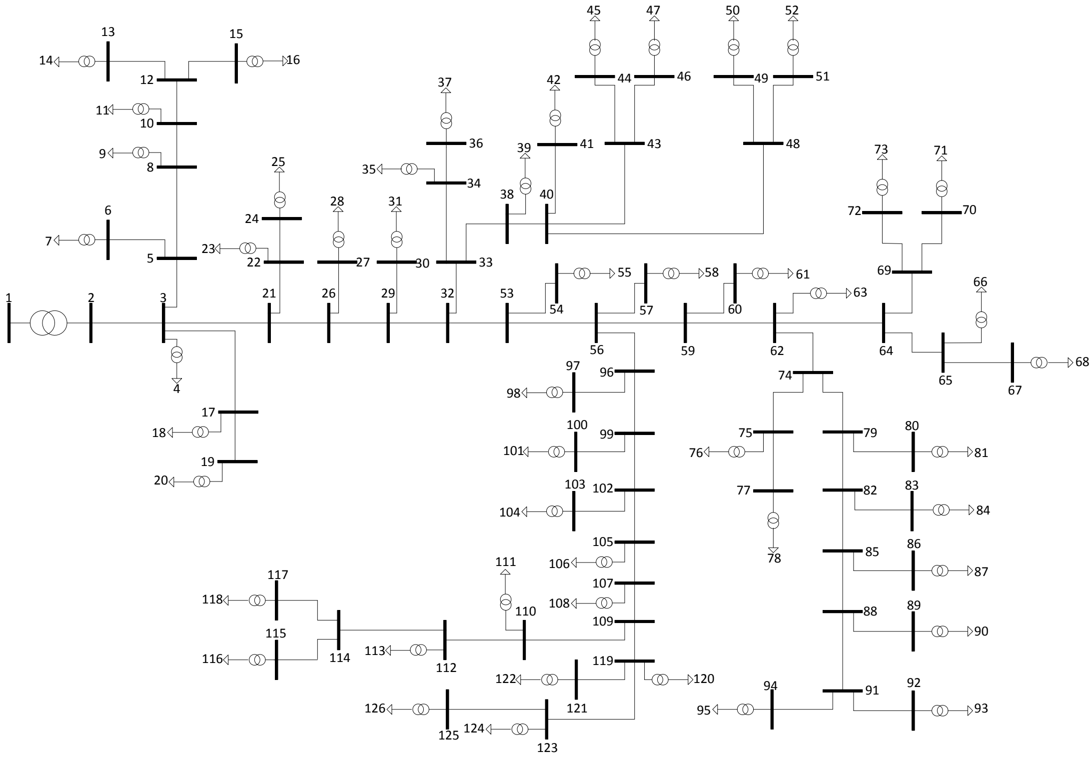

Figure A1: Single line diagram of Richmond SWER line with 126 nodes and 49 customers [2]

TableA1: Richmond SWER network data

Line Number	Line Specification
Line 1-2	400KVA Transformer
Line 2-3	47.655km BAN conductor
Line 3-4	25KVA Transformer
Line 3-5	5.454km SCAC conductor
Line 3-17	0.686km SCAC conductor
Line 3-21	0.947km SUL conductor
Line 5-6	3.075km SCAC conductor
Line 5-8	10.319km SCAC conductor
Line 6-7	25KVA Transformer
Line 8-9	10KKVA Transformer
Line 8-10	6.163km SCAC conductor
Line 10-11	10KVA Transformer
Line 10-12	5.431km SCAC conductor
Line 12-13	3.075km SCAC conductor
Line 13-14	10KVA Transformer
Line 12-15	3.512km SCAC conductor
Line 15-16	10KVA Transformer
Line 17-18	25KKVA Transformer
Line 17-19	0.160km SCAC conductor
Line 19-20	25KVA Transformer
Line 21-22	0.252km SCAC conductor
Line 21-26	11.149km SUL conductor
Line 22-23	25KKVA Transformer
Line 22-24	3.651km SCAC conductor
Line 24-25	10KVA Transformer
Line 26-27	3.075km SCAC conductor
Line 27-28	10KVA Transformer
Line 26-29	9.936km SUL conductor
Line 29-30	4.484km SCAC conductor
Line 30-31	10KVA Transformer
Line 29-32	5.635km SUL conductor
Line 32-33	0.240km SCAC conductor
Line 32-53	10.740km SUL conductor
Line 33-34	7.652km SCAC conductor
Line 33-38	6.453km SCAC conductor
Line 34-35	25KKVA Transformer
Line 34-36	7.986km SCAC conductor
Line 36-37	10KVA Transformer
Line 38-39	10KKVA Transformer
Line 38-40	11.191km SCAC conductor
Line 40_41	0.019km SCAC conductor
Line 41_42	25KVA Transformer
Line 40_43	0.246km SCAC conductor
Line 40_48	10.545km SCAC conductor
Line 43_44	0.303km SCAC conductor

Line 46_47	25KVA Transformer
Line 43_46	0.188km SCAC conductor
Line 44_45	25KVA Transformer
Line 48_49	0.019km SCAC conductor
Line 49_50	10KVA Transformer
Line 48_51	0.235km SCAC conductor
Line 51_52	10KVA Transformer
Line 53_54	0.352km SCAC conductor
Line 54_55	10KVA Transformer
Line 53_56	4.590km SUL conductor
Line 56_96	0.768km SUL conductor
Line 56_57	0.044km SCAC conductor
Line 57_58	10KVA Transformer
Line 56_59	13.485km SUL conductor
Line 59_60	2.063km SCAC conductor
Line 60_61	10KVA Transformer
Line 59_62	5.489km SUL conductor
Line 62_74	4.940km SUL conductor
Line 62_63	25KVA Transformer
Line 62_64	10.176km SCAC conductor
Line 64_69	9.781km SCAC conductor
Line 64_65	0.301km SCAC conductor
Line 65_66	10KVA Transformer
Line 65_67	0.372km SCAC conductor
Line 67_68	10KVA Transformer
Line 69_70	0.137km SCAC conductor
Line 70_71	10KVA Transformer
Line 69_72	0.308km SCAC conductor
Line 72_73	10KVA Transformer
Line 74_79	1.155km SUL conductor
Line 74_75	0.097km SCAC conductor
Line 75_76	10KVA Transformer
Line 75_77	0.237km SCAC conductor
Line 77_78	10KVA Transformer
Line 79_80	1.566km SCAC conductor
Line 80_81	10KVA Transformer
Line 79_82	8.876km SUL conductor
Line 82_83	0.032km SCAC conductor
Line 83_84	10KVA Transformer
Line 82_85	13.972km SUL conductor
Line 85_86	6.649km SCAC conductor
Line 86_87	10KVA Transformer
Line 85_88	6.523km SUL conductor
Line 88_89	0.287km SCAC conductor
Line 89_90	10KVA Transformer
Line 88_91	1.549km SCAC conductor
Line 91_92	0.749km SCAC conductor
Line 92_93	10KVA Transformer

Line 91_94	5.938km SCAC conductor
Line 94_95	10KVA Transformer
Line 96_97	0.037km SUL conductor
Line 97_98	10KVA Transformer
Line 96_99	7.654km SUL conductor
Line 99_100	5.794km SCAC conductor
Line 100_101	25KVA Transformer
Line 99_102	5.491km SUL conductor
Line 102_103	3.972km SCAC conductor
Line 103_104	10KVA Transformer
Line 102_105	4.827km SUL conductor
Line 105_106	10KVA Transformer
Line 105_107	5.422km SUL conductor
Line 107_108	25KVA Transformer
Line 107_109	8.802km SUL conductor
Line 109_119	4.809km SCAC conductor
Line 109_110	8.002km SCAC conductor
Line 110_111	10KVA Transformer
Line 110_112	0.352km SCAC conductor
Line 112_113	10KVA Transformer
Line 112_114	9.836km SCAC conductor
Line 114_115	0.039km SCAC conductor
Line 115_116	10KVA Transformer
Line 114_117	0.557km SCAC conductor
Line 117_118	10KVA Transformer
Line 119_120	10KVA Transformer
Line 119_121	0.302km SCAC conductor
Line 121_122	25KVA Transformer
Line 119_123	17.124km SCAC conductor
Line 123_124	10KVA Transformer
Line 123_125	0.866km SCAC conductor
Line 125_126	10KVA Transformer