Performance Monitoring of a PMU in a Microgrid Environment based on IEC 61850-90-5

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Abstract*— Reliable protection, communication and control are the key features of a digital protection scheme in a utility substation. Microgrid is an alternative solution of installing long Transmission & Distribution lines could be cost prohibitive. There are number of Intelligent Electronic Devices (IEDs) which could find applications in controlling and monitoring of power network in a Microgrid set up and one such device is Phasor Measurement Unit (PMU). It is a microprocessor based intelligent device which gathers high-resolution data, checks the power quality and records disturbances. However, few issues that remains to be addressed such as, interoperability in a multi-vendor equipment and coordination between individual control systems in an integrated scheme. In this paper, an Operational Network Technology (OPNET) software model of a PMU has been designed and tested for its performance in a Microgrid environment based on IEC 61850-90-5 standard.

***Index Terms* — IEC 61850, Ethernet, Microgrid, OPNET, Phasor Measurement Unit (PMU).**

I. Introduction

Phasor Measurement Unit (PMU) is a microprocessor-based intelligent measuring device which has recently been applied in the transmission and distribution field because of its ability to convey high-resolution data. Fault analysis, power quality analysis, wide area power network monitoring and control of the high voltage (HV) apparatus are some of the other applications of a PMU.

Nowadays, PMU has a wide spread application in other regions, including Asia, Europe and North America. It has the potential to expand further due to its high resolution data analysis capability and also for recording disturbances in the network. Although the PMU was developed for system interface between power facilities for automation of substations, its application in other fields are expanding rapidly. IEC 61850-90-5 standard which lays down the guidelines for PMU, also discusses synchronised power measurement over a wide area network. This concept originated due to a mass blackout in USA in 2003, cyber security requirement in wide area monitoring and requirement to create a time stamping of the substation events. In Microgrids, PMU's application is mainly confined to monitoring and control of grids. Prior to creation of IEC 61850-90-5, industry relied on IEEE 1344 and IEEE C37.118 for improvement in the accuracy of a substation event by time stamping. However, it was not too successful in achieving the same over the wide area network connected substations. In 2011, it was split into two parts with one part focusing on the measurement requirement while the other part discussed the data transfer requirement. Table II below compares IEEE C37.118 versus IEC61850-90-5 protocol. IEC 61850-90-5 has an abstract on communication services supported by this standard.

Table-I: Comparison between IEEE C 37.118 and IEC 61850.

Function	C37.118	IEC 61850-90-5
Streaming Protocol	Yes	Sampled Values
Rate of measurement / Reporting	10-30 samples/ sec	80-256 samples per sec
Natively Routable using IP	Yes	No must used bridged routing
Application focus	Situational awareness	Control
Standard address security	No	Yes
Communication profile fully specified	No	Yes
Measurement specification for synchrophasor	Yes	No
Event driven capability	No	GOOSE
Protocol is semantically driven (i.e., object oriented)	No	Yes
Standard communication language	No	Yes

At present, almost all power systems on Ethernet technology can be interfaced with network devices based on IEC 61850 standards. IEC 61850-90-5 is an exclusive standard for PMU application that guides the end user to define error limits in data transfer, data transmission rate, etc. [2]. Upper-layer management systems have also adapted the IEC 61850 interface. In a Microgrid, there are various upper layer applications for control, monitoring, protection, estimation purpose. Solely due to this reason, we have implemented IEC 61850 standard with the PMU interface.

The time taken for data exchange within the SAS network is given in Table-II which could be categorized as:-

1. Periodic Data
2. Random Data
3. Burst Data stream.

In periodic data transmission, switch status information and analogue data is transmitted at the station level monitoring devices and the quantity of such data varies. In random data stream, the data frames are short in length. These are real time data packet commands such as switching operation command, time synchronization etc. In burst data stream the data messages carry information stacks such as switch position change, node failures, multi fault situation. The requirement of message transmission time for frame sizes between devices and equipment are given as a guide in IEC 61850-9-2 which are summarized in Table-II.

Table - II: Message type and performance requirement [3].

REQUIREMENTS FOR MESSAGE TRANSMISSION TIME

Types of messages	Requirements/ms
The high speed messages (type1)	<3 or <10
The medium speed messages (type2)	<100
The low speed messages (type3)	<500
The raw data samples (type4)	<3 or <10
The file transfer functions (type5)	>=1000

The remainder of this paper comprises of Section II that deals with the background of PMUs. Section III involves the simulation based on OPNET modeller while section IV is focused on a proposed PMU simulation based on OPNET. Finally, the conclusion is in section V.

II. BACKGROUND OF PMUS

PMU is a device which provides accurate time stamping, monitoring, control and synchronization in a power network. It can be used as a fault recording and power quality analysis device in a HV substation or in a distribution network. IEC 61850-90-5 standard guides the use of PMU, which stipulates information requirement, management of smart and Micro grids. In a PMU, data is sampled, analyzed and fault is recorded on a high speed based Ethernet protocol [4].

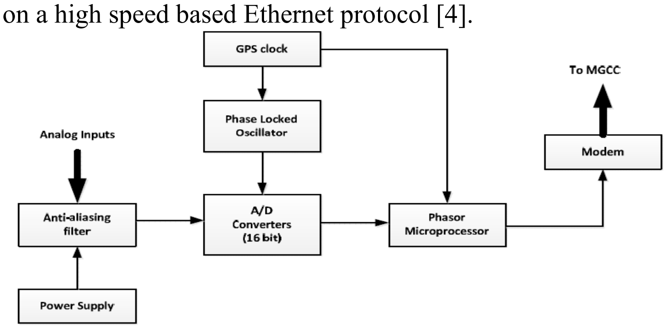

Fig. 1. Process block diagram of a PMU [1].

Fig. 1 exhibits a block diagram with an analog input that comes from the HV primary plant equipment such as Current Transformer (CT) and Voltage Transformer (VT) passing via anti-aliasing filter. The GPS clock is a crystal oscillator which supplies clock pulses while the phase locked oscillator sends the pulse for the clock. Further, in Fig. 1 a network model of the PMU exhibit analog signals from CTs and VTs that are sampled and processed into digital signals. These digital signals are passed on to IEDs. PMUs acquire data, synchronize and communicate with different field devices and communicate to the control room via Phasor Data Concentrator (PDC). PDC is a device which acquires time-synchronized phasor data from multiple PMUs to generate time aligned output data stream. Through the use of multiple PDCs communication and control is achieved in a wide area network controlled substations. Advancement in PDCs not only does data concentrations but also archives data, records disturbances, gives secure access to the user etc. There are logical nodes (LNs) within PMU which use the following symbols MMXU, MQSI. TCTR and TVTR that obtain information from CTs and VTs such as current, voltage and rate of change of frequency respectively. The SCL files of PMU are generated by using .cid, .icd, .scd files [5].

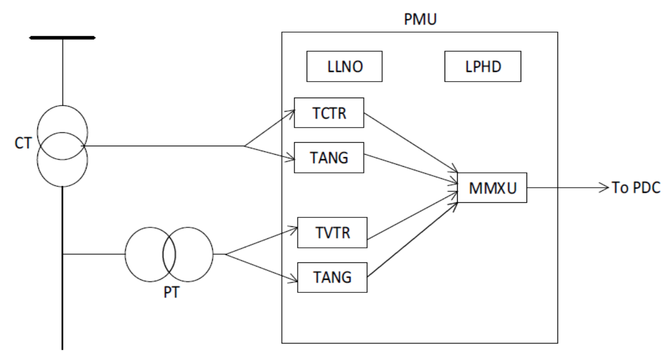

Fig. 2. PMU connectivity in a substation [1].

Fig. 2 shows a single line diagram (SLD) of a simple Microgrid substation having the PMU and PDC network connected to multiple substations in a Microgrid environment. The PMUs are usually kept in substations to collect data before transmitting it to the PDC in real time for alarms, visualization of information controls etc. Local PDCs connects to other substations. These other substations are further connected to a centralized PDC which aggregates data and as shown in Fig. 3.

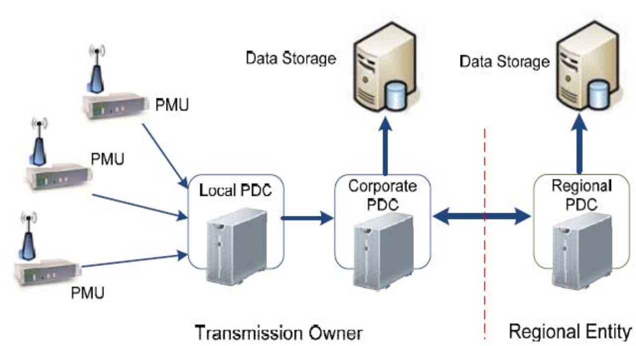

Fig. 3. PMU and PDC set up in wide area network [6].

Messages from field devices i.e. CTs and VTs transmit over TCP/UDP protocol. The real time client server communications are of two types namely Generic Object Oriented Substation Event (GOOSE) and sampled value (SV). GOOSE provide control, trip, start, stop and delay signals while SV collects line parameters in analog form and transforms into digital signal after passing via PMU. Fig.4 shows the protocol stack of the IEC 61850-90-5 in comparison with IEEE C 37.118,1 and OSI 7 layer stack [7].

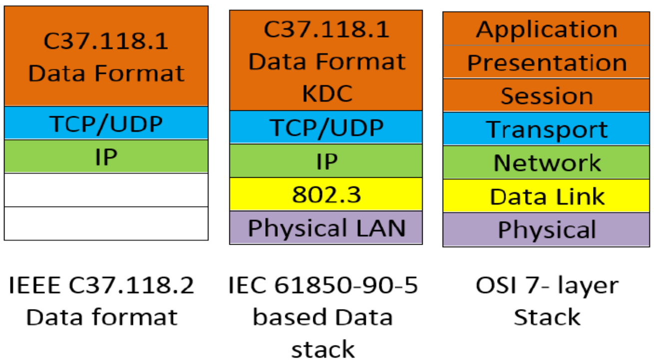

Fig. 4. IEC 61850-90-5 vs. IEEE and OS-7 Layer [1].

Communication delays primarily occur while sampling and signals processing via PMUs, PDCs. This delay at the devices is governed by the IEC 61850-90-5 standard which sets the limit as per Table III.

Table III: Typical delays in substation communications [8].

Cause of delay	Typical range of delay
Sampling window (delay ½ of window)	17 ms to100 ms
Measurement filtering	8 ms to 100 ms
PMU processing	0.005 ms to 30 ms
PDC processing & alignment	2 ms to 2+ s
Serializing output	0.05 ms to 20 ms
Communication system I/O	0.05 ms to 30 ms
Communication distance	3.4 µs/km to 6 µs/km
Communication system buffering and error correction	0.05 ms to 8 s
Application input	0.05 ms to 5 ms

III. Simulation Based on OPNET Modeler

A model of PMU, IED and Circuit Breaker has been proposed in this simulation using Optimized Network Engineering Tool (OPNET) or Riverbed Modeler simulator to predict the mean delay, packets lost, traffic dropped, End to End (ETE) delay encountered etc. in bits/sec within the proposed SAS scheme. These stacks carry raw data in the form of SVs and Generic Object Oriented Substation Events (GOOSE) message packets which delivers real time and mission critical messages to IED's and switches for successful protection operation Formulating devices such as PMUs, Circuit Breakers and IEDs using OPNET editors in C++ programming language is an important feature of this software simulation. The editors are organized in a hierarchical order to perform the modeling tasks as listed below:

1. Parameter editor
2. Process editor
3. Node editor
4. Project editor.

In this case study, IEC 61850-9-2 based communication performance in the process bus architecture has been carried out using an OPNET modeller. The evaluation of ETE delay performance and of PMU, IED and circuit breaker (CB) are based on dynamic performance simulation in a SAS network which provides an indication of its latency in SV frames that travels from field to protection IEDs. This simulation in a laboratory set up helps the user gather vital information of its performance prior to large scale real life implementation and practical applications [9-10].

IV. Proposed PMU Simulation Based on OPNET

In this section, we discuss a proposed PMU simulation based on the OPNET modeller. Fig. 5 shows the SLD of a 132/22-kV HV zone substations in the network.

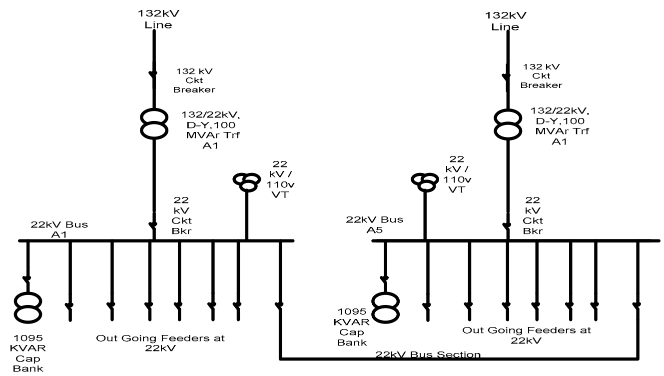

Fig. 5. SLD of a 132/22kV substation.

A typical HV substation consists of the followings incomers and feeders:

- 2 line incomers on the 132/22kV transformer bays
- 14 outgoing 22kV feeders
- 1 bus coupler at 22kV.

PMU application in a Microgrid substation has many advantages such as less error in the frame arrival i.e., +/- 1 µs, reduction in communication delay of frames, which derives samples from CT/VT. It converts analogue SV signals from CTs and VTs (i.e., Currents and Voltages) by processing and sending it over an Ethernet to IED's. SV from each PMU sends raw data message type 4 as shown in Table II to IEDs at a specified sampling rate. Further, the GOOSE packets broadcast in the SAS network linked to IED's via MU's are connected to PMU and PDC. Understanding the ETE delay in message transmission could assist the engineers to achieve protection redundancy in the primary plant equipment located in a Microgrid substation. IEDs provide protection and control while the main task of a PMU in the switchyard located adjacent to CT/VT is to accumulate raw current and voltage samples.

Table-IV provides number of equipment connected in this 132-kV substation for simulation. Application of IEC 61850-90-5 uses multicast data streams and has the ability to support secure tunneling of Ethernet based on GOOSE and SV. Application of this communication standard could reduce the traffic load on the PMU server and delegate data client management into the hands of network protocols. Unicast stream of packets are used at the substation level while multicast is a choice when many substations are inter-connected. However, there could be issues with the firewalls during packet transmission as it passes via various firewalls.

Table-IV: The IED configuration in the 132kV Substation.

Bay Name	PMU	Protection IED	CB IED	Number of Bays	Total
132kV Line incomer	2	2	2	2	8
Transformer	-	2	2	2	6
22kV incomer	2	2	2	2	8
22kV Feeder	-	14	-	14	14
Bus section	1	1	1	1	4
Total					40

B) Proposed OPNET model of PMU, Protection IED and CB

In Fig. 6, two IEDs and MUs and Circuit Breakers are connected to a PMU and PDC on the line incomer side of a transformer. OPNET simulation results in the delay of data transfer has been exhibited in Fig 7 and Fig. 8.

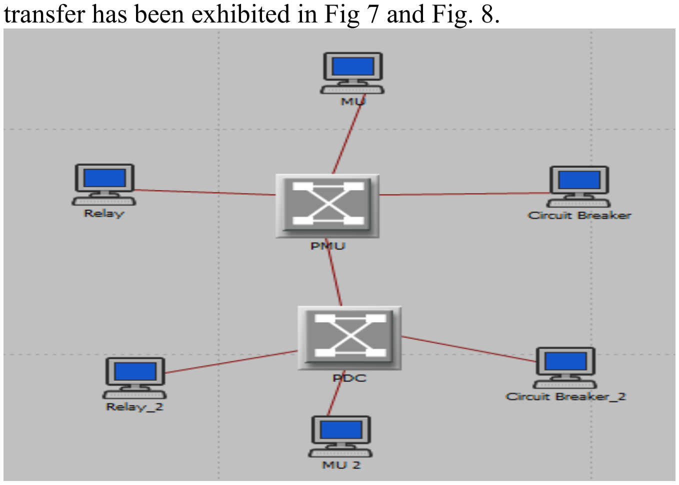

Fig. 6. PMU Model in an OPNET modeler.

In Fig. 6, the overall SAS network is connected in a star topology where the PMU receives SV signals from the primary side of 132-kV CT/VTs as a raw data type 4. PMU processes these raw data into digital packets and transmits it over a fiber optic network from switchyard to IEDs located in the control room. The Local Area Network (LAN) speed used in the simulation is 100-Mb/s for the ETE delay performance analysis as it is widely accepted in the industry to be the optimum performance speed on a digital fiber optic network.

The overall Ethernet delay in the network for the frames reaching the IEDs and CB is approx. 10-20ms which suffices the protection trip and close command speed with PMU's connected and as shown in Fig 7.

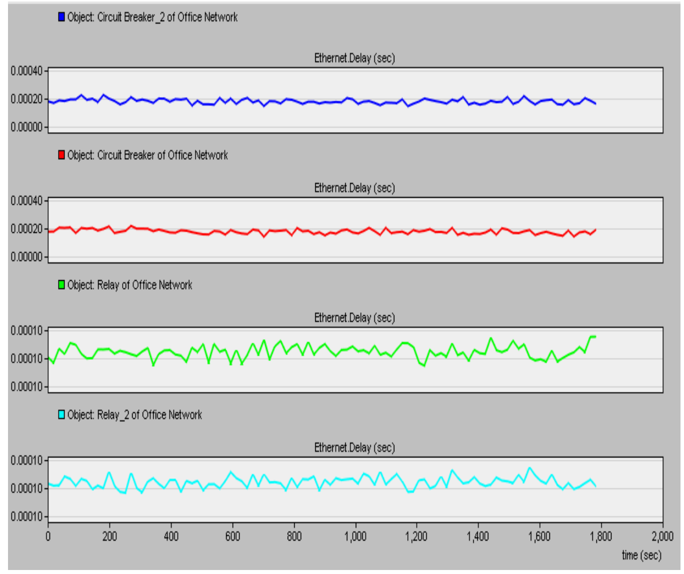

Fig. 7. Overall Ethernet delay in the network.

Fig.8 exhibits the stacked delay at the individual nodes of devices connected to PMU and PDC.

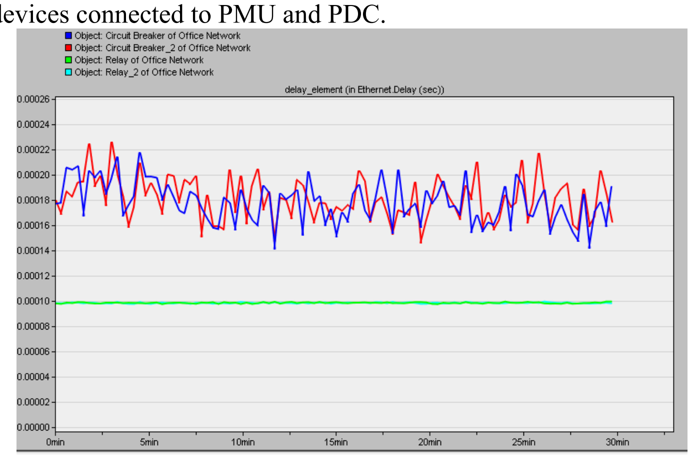

Fig. 8. Ethernet delay in the network.

Fig. 9 shows the average Ethernet delay within the network which is no more than 20ms which is much faster than a conventional substation's trip time and that is about 50-100ms. Introduction of Ethernet has reduced the tripping time drastically to below 20ms which is an improvement.

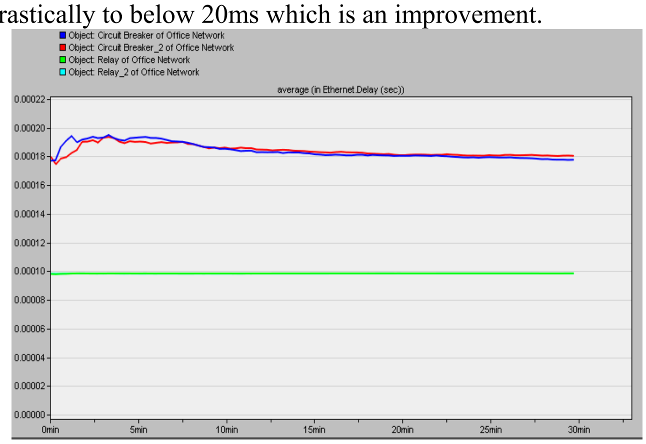

Fig. 9. End to End delay in a Microgrid network.

The overall observation of the simulation study is that the GOOSE messages passing via PMU and PDC from field devices are well within the specified parameters and as stipulated in IEC 61850-90-5 guidelines.

Table-V: Parameters used in OPNET Simulation.

Event Name	Values
Simulated Time (Secs)	30
Discrete Event Simulation Log	4
Elapsed time (s)	45
Average speed (Events/Sec)	3,584,645
Total Events	153,039,609

V. Conclusion

Power system related studies require accuracy in modeling due to its requirement for measurement, control and fidelity which directly impacts reliability of the protection of the assets in the field. A laboratory based PMU simulation is performed and the results are validated for its future application in the substation located in a micro grid environment. The challenges lie in the communication delays of data packet from field devices to various IEDs.

The proposed network architecture of this paper satisfies the application of PMU as per IEC 61850-90-5 standard in a digital substation environment. The results of the simulations are encouraging from a Microgrid environment point of view which were successfully tested and validated. The OPNET models of equipment such as CB, IED and PMU were carried out on C++ platform that could validate the result in a scaled environment. It gave the author information to understand the ETE and overall delay in the network which is very critical from operational point of view when using multi-vendor equipment in a Microgrid substation. Detailed laboratory experimental result show peer to peer communication between PMUs with IEDs and other smart devices in a smart substation for speed, resilience and security. The OPNET simulation software uses C++ codes to model the physical devices within the substation and evaluates the performance of the process bus for latency, ETE delay for SV in a process bus system. Results indicate from practical tests and software simulation that a PMU and PDS performs well for ETE, latency, in an overall micro grid. Finally, the model developed is very useful which could find potential application in micro grid substations leading to the viability of a potentially game changing retrofit in the industry.

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