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Communication Modeling for Differential Protection in IEC 61850 Based Substations

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***Abstract*—Today's power utilities, around the world, own multiple substations which are connected together to form a complex energy network. The functions within and between these substations are being automated according to globally accepted power utility automation standard IEC 61850. This automation results in efficient operation and enhanced protection of power network with the aid of the communication system. Implementing the protection schemes modeled using communication configurations of standardized information exchange will lead to digital power grid. Designing an IEC 61850 based protection scheme to take care of the faults outside the substations is a challenge as the typical LAN (Local Area Network) based GOOSE (Generic Object Oriented Substation Events) and Sampled Value (SV) messages need to be transmitted over a Wide Area Network (WAN). This paper presents communication configuration for line current differential protection schemes applied between two automated substations. It presents the simulation results of communication configuration network between two substations. Its performance is evaluated using a network simulator tool. This work intends to guide the development of a robust protection scheme with IEC 61850 based communication configuration.**

***Index Terms*—Substation Automation; IEC 61850; Differential Current protection; communication configuration; Wide Area Network (WAN)**

I. Introduction

Occurrence of faults, in an electrical power system, happens to be stochastic phenomenon and hampers the overall system reliability. In order to prevent the whole of the power system, from the cascading and detrimental effects of faults, various protection strategies have been proposed. In this pursuit, protection strategies are generally based on overcurrent, overvoltage and differential protection etc. Differential protection is one of the most popular protection scheme utilized in power system protection [1]. That is because it does not require the fault levels beforehand and can operate easily under disturbances such as voltage/current variations [2]. Traditionally, differential protection has been utilized only when the apparatus are close to each other [3]. However with the proliferation of communication systems, in power networks, this trend is changing [4].

The dense loads, such as populated cities, receive the generated power from remotely located generators via the interconnections of these multiple power utility substations [5]. In order to protect the transmission lines between substations, for a reliable operation of utility's power grid, differential protection scheme is utilized.

Some aspects are required to be reinforced for implementation of the differential protection on multi-terminal and long power transmission lines [6]. Firstly the requirement of communication link between the two terminals of the transmission lines [7]. Secondly the latency of the communication links must be very low as the measurements received from both terminals, in differential protection, are compared for any discrepancies [8]. Furthermore the performance of the communication links must be highly reliable and without any interruptions. However, challenges in providing a reliable and deterministic communication for differentially protected equipments have been very well addressed by the use of Information and Communication Technologies (ICT) [9]. At the same time, a standardized and interoperable communication configuration is also essential in order to ensure exchange of information, control commands and real time measurements within an acceptable time frame [10].

International Electro-Technical Commission (IEC) published a standard for substation automation, which provides standardized and interoperable communication framework for substation automation [11]. IEC 61850 based communication is universally accepted for substation automation [12-13], but with the development and publication of new parts in IEC 61850 Ed.2 such as 7-420 [14], 90-1 [15], 90-5 [16] and 90-7 [17], IEC 61850 is being extended as standard for communication networks and systems for power utility automation [18]-[20].

IEC 61850-90-1 deals with different information exchange mechanisms between substations [21]. Whereas a distance line protection scheme between two IEC 61850 based substations has been modeled and designed using appropriate logical nodes, as per IEC 61850-90-1, and was reported in [22]. However the work in [22] did not evaluate the latency performance of communication network. Latency evaluation is vital for assessing the feasibility of the developed system for

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real-life implementations.

This paper is presenting the data structures, needed for standardized measurements, and their use in implementing differential protection schemes over transmission line. The designed communication architecture, which is IEC 61850 based, has been simulated with various communication technologies in a network simulator tool called Riverbed Modeler [23]. For testing the real-time operation of the simulated communication architecture real data packets, as per IEC 61850, are included in the simulation through system in the loop (SITL) feature. Results are presented to analyze the performance of the developed scheme and to discuss the scheme's viability.

There are five sections in this paper. The design aspects of line differential protection scheme are described briefly in section II. Section III describes the data communication essentials, according to IEC 61850-90-1, for implementing line differential protection between two substations. Section IV evaluates the performance of the differential protection scheme while considering different communication network technologies with the help of Riverbed Modeler, i.e. a communication network simulator and analysis tool. While section V gives detail of the SITL platform's operation and the obtained results. Finally, Section VI concludes the paper.

II. Design of Differential Protection Scheme

Amongst the several protection schemes, employed for protection of modern substations and complex power networks, the current differential protection scheme is most widely used. It protects the transmission line between the two substations, namely A and B, as depicted in the Fig. 1 [15]. The current differential relays located at both the substations protects the transmission line as well as the substation transformer for external faults.

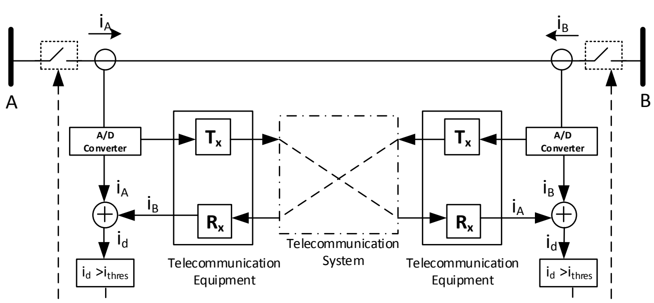

Fig. 1 Current differential protection scheme

The operating current for the current differential relay is obtained as the vector difference of input currents as given by Eq. 1.

$$I_d = | I_A - I_B | \quad (1)$$

The differential relay responds to all the faults arising within the protected zone AB. However due to measurement errors as well as non-identicality of two exactly similar differential relays, the vector difference of the currents is not zero even in the case of normal operation. Therefore, a certain amount of biasing is provided to match both of these currents under normal operating conditions. The relay operates when the operating current is more than the restraining current, i.e. $I_d > I_R$, [4], [6].

A. Design of Line Current Differential Protection

In line current differential protection, the relays are located at different substations and operate separately in terms of sampling the measured values, frequency tracking, filtering and communicating the signals through transmitters and receivers as shown in Fig. 1. The protection logic is executed by comparing the signals from the remote end relay. The communication process forms an integral part of the line current differential protection scheme as the measurements are required to be sent to the other relay. Usually a digital communication is used and channel is multiplexed where channel switching occurs. The signal is received at the other end and if a mismatch is detected, the relay sends a trip signal to the local circuit breaker.

Since the operation of the differential protection scheme relies totally on the comparison of remote and local signals for executing differential protection logic, the communication must be highly reliable, deterministic and fast in order to have efficient and desired protection functionality. Moreover, standardized and interoperable communication is required in order to exchange the information within an acceptable time limit. Thus, the conventional current differential protection relay has been modeled as IEC 61850 based Intelligent Electronic Device (IED) in order to provide interoperable and standardized communication infrastructure. This requires definition of appropriate logical nodes (LNs) which are functions that exchange data as defined in IEC 61850 standard. The current differential protection IED consists of various LNs such as RMXU, PDIF, PTRC and ITPC as shown in Fig. 2. The sampled values (SVs) of current and voltage measurements are collected by the RMXU logical node. The current differential protection logic is executed by the PDIF logical node. PTRC logical node sends the trip signal to the circuit breaker and logical node ITPC is responsible for providing communication interface between the current differential protection IEDs. The descriptions of logical nodes PDIF and RMXU are shown in Table I and Table II respectively. In the succeeding section a detailed description of logical nodes for current differential protection function and intra-substation communication has been elaborated.

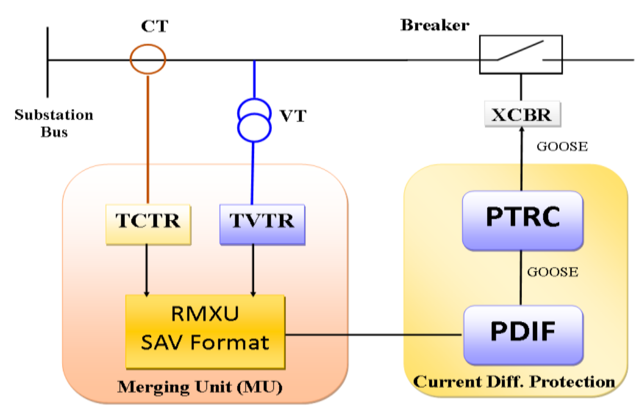

Fig. 2 Local Communication configuration of a substation

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TABLE I
LOGICAL NODE, PDIF [15]

PDIF class			
Attribute Name	**Attr. Type**	**Explanation**	**M/O /C**
LNName		Shall be inherited from Logical-Node Class (IEC 61850-7-2)	
Data			
Common Logical Node Information			
		LN shall inherit all mandatory Data from Common Logical Node class	M
OpCntRs	INC	Resettable operation counter	O
Status Information			
Str	ACD	Start	O
Op	ACT	Operate	M
TmASt	CSD	Active curve characteristic	O
Measured Values			
DifAClc	WYE	Differential Current	O
RstA	WYE	Restraint Current	O
Settings			
LinCapac	ASG	Line Capacitance (for load current)	O
LoSet	ING	Low operate value	O
HiSet	ING	High operate value	O
MinOpTmms	ING	Minimum Operate Time	O
MaxOpTmms	ING	Maximum Operate Time	O
RstMod	ING	Restraint Mode	O
RsDlTmms	ING	Reset Delay Time	O
TmAcrv	CURVE	Operating Curve Type	O

TABLE II
LOGICAL NODE, RMXU [15]

RMXU class			
Data Object Name	**CDC**	**Explanation**	**M/O /C**
LNName		The name shall be composed of the class name, the LN-Prefix and LN-Instance-ID according to IEC 61850-7-2, clause 22.	
Data Objects			
Measured Values			
ALoc	WYE	Current (phasor) of the local current measurement	C
AmpLocPhsA	SAV	Current (Sampled value) of the local current measurement (phase L 1)	C
AmpLocPhsB	SAV	Current (Sampled value) of the local current measurement (phase L 2)	C
AmpLocPhsC	SAV	Current (Sampled value) of the local current measurement (phase L 3)	C
AmpLocRes	SAV	Current (Sampled value) of the local current measurement (residual current)	O
Condition C: Either ALoc or AmpLocPhsA…AmpLocPhsC shall be used.			

III. DATA COMMUNICATION FOR DIFFERENTIAL PROTECTION

This section describes the communication configuration and design aspects of the differential protection scheme. As per the differential protection scheme, to calculate the differential and bias current, it is essential that data must be exchanged between the local and remote end relays. Hence the protective relays must be connected to the local area network, i.e. local substation communication network, as well as Wide Area Network (WAN), i.e. inter-substation communication network. Thus the data communications for the differential protection scheme can be divided into local substation data communication and inter-substation data communications.

A. Local Substation Data Communication

A typical layout of Substation Communication Network (SCN) architecture is shown in Fig. 3. The IEC 61850 based SCN architecture comprises of station, bay and process levels communication as shown in Fig. 3. The station level has operating stations, engineering stations and HMI that are used for monitoring and control of the substation. The information from the field is acquired in the form of voltage and current samples in the MU IED at the process level.

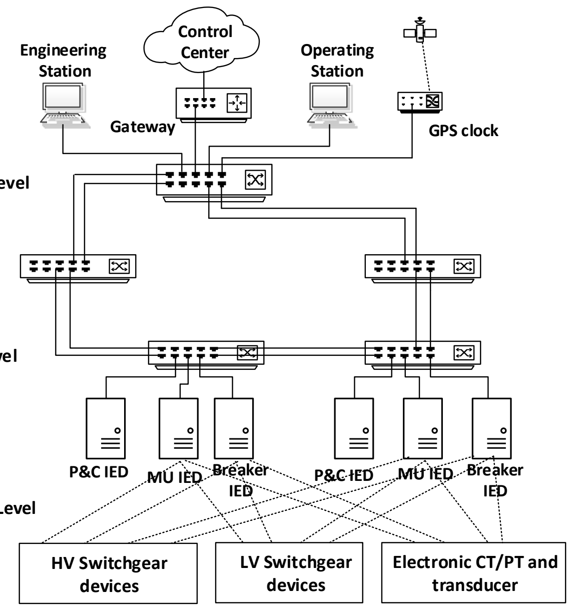

Fig. 3 IEC 61850 based substation communication architecture

The current and voltage samples are transferred through the TCTR and TVTR logical nodes of merging unit to the measurement and metering logical node RMXU. Logical node RMXU calculates the three process values (phasors calculated out of samples) of currents and forward to PDIF logical node located in protection IED. The logical node PDIF also receives the process values from the remote end IED. The PDIF and RMXU nodes are used for providing differential protection function (number 87 according to the IEEE C37.2 standard). When the PDIF logical node detects a fault it issues a operate signal to the PTRC logical node. This, in turn, issues a signal for the trip command, in form of GOOSE message, to the XCBR logical node of the circuit breaker for isolating the fault.

B. Inter-substation Communication

Realizing the fact that for implementing the differential protection at PDIF logical node, the process values of currents from both the local and remote end MU IEDs are required. Thus process value information in form of SVs has to be transferred from the RMXU logical node of remote end substation MU IED to the PDIF logical node of protection IED in local substation. SV messages are required to be transported between distantly located substations through a WAN. However, the typical SV message has only data link layer and does not contain network and transport layers. Thus in order to transmit the SV messages over a WAN for inter-substation communication, IEC 61850-9-1 recommends two communication mechanisms; (1) Tunneling and (2) Proxy gateway approach (using specific telecommunication

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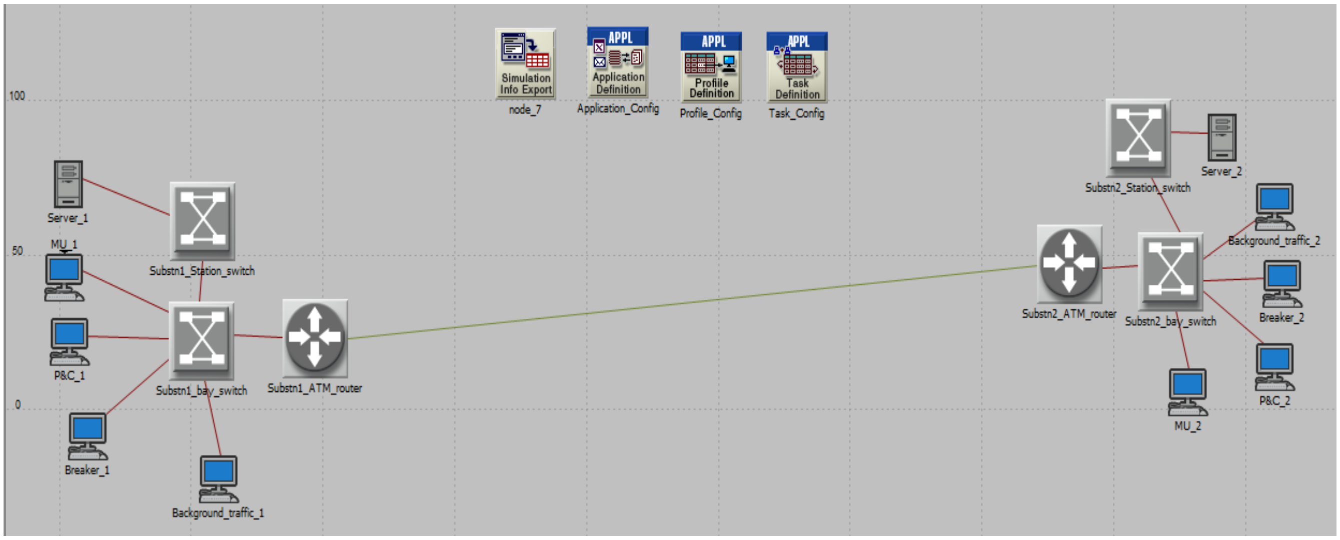

Fig 4. Simulation of WAN between two substations with Riverbed modeler

equipment).

In tunneling technique, a virtual tunnel is established between the two SCNs connected through a WAN. The routers, at the SCNs, wrap (and unwrap) the SV data packets with TCP/IP protocols and transmit to the other end of tunnel. The process of wrapping and unwrapping of the data packet at each end of the WAN introduces an extra time delay but at the same time there is a significant reduction in network routing delay since it establishes a direct virtual connection oriented service. The difference between tunneling and gateway approach is that the former does not require any specific telecommunication equipment. However, instead of using tunnel or gateways, the SVs can also be converted into Routable-SV (R-SVs) by mapping with UDP/IP layers and then routed to other substations via WAN as described in [20].

The performance of this communication network architecture, when various WAN technologies with tunnels are used, is discussed next.

IV. Performance Evaluation

It is important to subject the developed communication configurations to performance test. For this purpose a simple power utility network, comprising of two substations (A and B) utilizing differential protection as depicted in Fig. 1, is considered.

The communication network of each substation consists of station switch, station router, server and different bays containing MU IED, Protection and Control (P&C) IED, Breaker IED and bay switch. For implementing differential protection between the substations A and B, normally the MU IED of substation A sends the SVs to the P&C IED of substation A and P&C IED of substation B. Similarly the MU IED of substation B also sends SV to P&C IED of both the substations. In case of any fault in the line, the PDIF logical node in P&C IED senses it and the PTRC logical node of P&C IED issues a GOOSE trip command to the Breaker IED.

A. Simulation Configuration

To simulate the communication network of test system using Riverbed modeler, different IEDs are modeled with relevant ready-to-use simulation nodes provided by the Riverbed modeler in its object palette library. While this ready-to-use node selection is based on the matching of the type of traffic generated or received by it and corresponding IED. The MU IED is modeled with '*ethernet_station_adv*'. Whereas the P&C IED and Breaker IED are modeled with a hybrid node as developed in [18]. The '*ethernet16_switch_adv*' node, with 16 port interfaces supporting full duplex communication at the rate of 100/1000 Mbps, is selected to model the station and bay switches. Furthermore, modeled network has `100BaseT_adv' node selected as the communication link as it can support 100 Mbps data rate and full duplex fiber optic communication. The server is built with standard '*ethernet_server_adv*' node. Four test scenarios have been run to study performance of the differential protection:

1. WAN using Synchronous Optical Networking (SONET) links
2. WAN using Asynchronous transfer mode (ATM) links
3. WAN over Fiber Optic links
4. Generic Routing Encapsulation (GRE) Tunnel over SONET links

Different profiles, as shown in Fig. 5, are configured for simulation in order to implement differential protection scheme message exchanges. Background traffic is added to represent the traffic of the other bays in the SCN, Since only one bay of the substation is simulated. Profile '*MU_update*' is defined to configure the SV traffic exchanges between the MU IED and P&C IEDs. Similarly '*GOOSE*' and '*background_traffic*' profiles are defined to configure the GOOSE messages and substation background traffic respectively.

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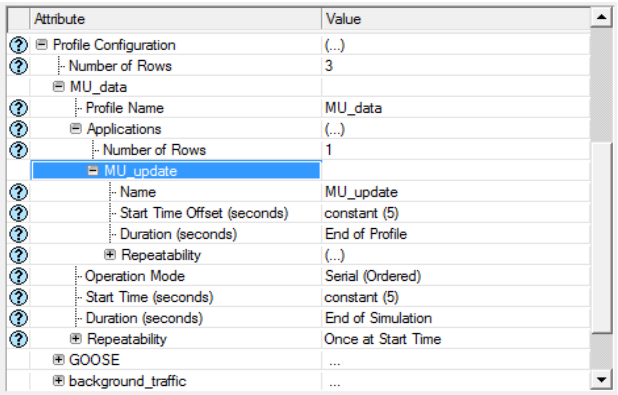
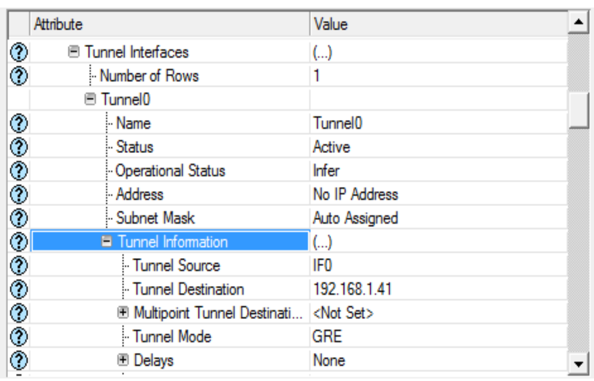
B. Results and Analysis

A tunnel is set up in router node's IP route attributes with the aim of creating a tunnel in the WAN. The parameters utilized in this step are documented in Fig 6. The destination and source points are assigned IP addresses in the network while GRE type is assigned to the type of the tunnel. The simulation has been run for five minutes after the traffic reached a steady state in the network. End-to-end (ETE) delay pertaining to GOOSE messages sent over different network types, such as Fiber optic, ATM, SONET with and without tunnel, are recorded. These values are shown in Fig. 7.



Attribute	Value
Profile Configuration	(...)
Number of Rows	3
MU_data	
Profile Name	MU_data
Applications	(...)
Number of Rows	1
MU_update	
Name	MU_update
Start Time Offset (seconds)	constant (5)
Duration (seconds)	End of Profile
Repeatability	(...)
Operation Mode	Serial (Ordered)
Start Time (seconds)	constant (5)
Duration (seconds)	End of Simulation
Repeatability	Once at Start Time
GOOSE	...
background_traffic	...

Fig. 5 Profile configuration attributes



Attribute	Value
Tunnel Interfaces	(...)
Number of Rows	1
Tunnel0	
Name	Tunnel0
Status	Active
Operational Status	Infer
Address	No IP Address
Subnet Mask	Auto Assigned
Tunnel Information	(...)
Tunnel Source	IF0
Tunnel Destination	192.168.1.41
Multipoint Tunnel Destinati...	<Not Set>
Tunnel Mode	GRE
Delays	None

Fig. 6 Tunnel attributes

In order to create a tunnel in the WAN, a tunnel is set up in the IP router attributes of the router node. The parameters set in the router for setting up a tunnel is shown in Fig. 6. The IP address of the source and destination point of tunnel is set in the network. Fig. 7 shows the comparative ETE delay for GOOSE message over different type of networks, i.e. ATM, SONET, fiber optic and tunnel over SONET. It has been found that the fiber optic link offers a dedicated source to destination connection, hence it offers lowest ETE delay. However, it cannot be used for larger distances. SONET network provides best result but has an inherent problem of time synchronization associated with it. Also, it can be noticed, from Fig. 7, that the delay in ATM network is less than SONET network. While ATM network, has more packets loss than SONET network. Tunnels are configured between two substations by making appropriate settings in gateway routers. After the establishment of tunnel, traffic can easily flow from one node to the other node with least amount of ETE delay. Also, packets loss is very less in case of tunneled networks. However wrapping and unwrapping the packets at the beginning and end of tunnel, respectively, contributes to ETE delay. All the delays of GOOSE messages come out to be below the 4 ms limit as proposed in the IEC 61850 standards. This result can be treated as the justification for using the proposed modeling for communication configuration for differential protection scheme between IEC 61850 automated substations.

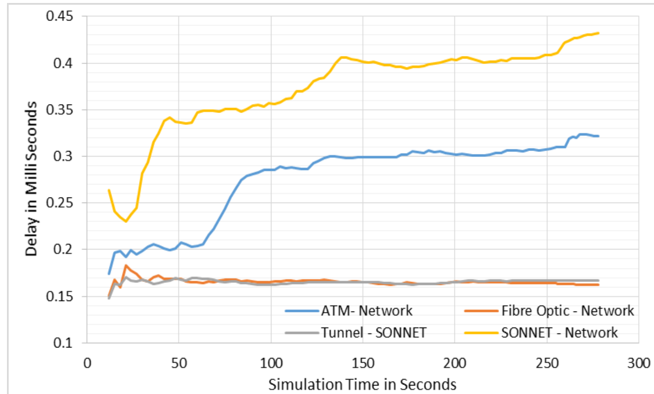


Fig. 7. ETE delay for GOOSE messages

V. SYSTEM-IN-THE-LOOP PLATFORM

A System-In-The-Loop (SITL) functionality facilitates an interface that can enable the information exchange between the simulated network and real network. The synchronization of simulated and real network relies on SITL interface, which serves as a data buffer and translates formats of packets traveling between the simulated and real networks in real-time. In a real-time SITL simulation platform, physical hardware and a simulation can interact as a unified System.

Different IEDs, which are required, are modeled with a PC and using an appropriate software and interfaced, as shown in Fig. 8, to establish a real-time SITL simulation platform.

1) Merging Unit IED

MU IED is modeled by using software called SAV sender [24]. SAV sender generates the required SVs on the network interface card (NIC) of the PC.

2) Breaker IED

Breaker IED is modeled by using software called GOOSE receiver [25]. GOOSE receiver subscribes to the GOOSE sender and receives the GOOSE packets.

3) Protection IED

Protection IED is modeled by running the SAV receiver and GOOSE sender software on another PC. The SAV receiver subscribes to the SV sent from the SAV sender. And the GOOSE sender publishes the GOOSE messages as per the settings.

4) Communication System Simulator

A PC running Riverbed Modeler software is used to simulate the communication network. In the communication system simulator, different types of networks (such as SONET, ATM and Fiber optic) are built and appropriate settings are set to enable information exchanging between the MU_A IED in substation A, P&C_B IED, Breaker_B IED and MU_B IED of substation B. Simulation results provides different communication network related parameters such as latency, packets loss, etc.

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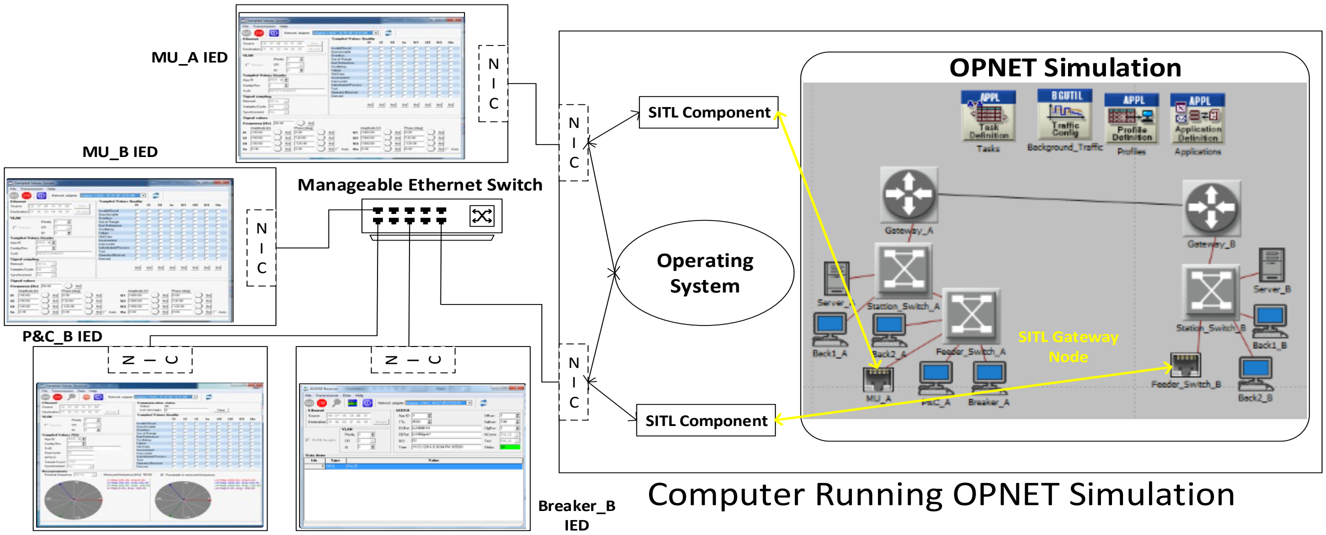

Fig. 8 SITL set up for differential protection between two substations

The connection between the MU_A IED and the communication network simulator (i.e. the PC that has Riverbed modeler installed) is set up using an Ethernet interface. Similarly, the MU_B IED, P&C_B IED and Breaker_B IED are connected to Riverbed modeler simulation through a manageable Ethernet switch. SITL node is used to enable exchange of packets between Riverbed modeler and simulated IEDs. The PC with Riverbed modeler installed has two Network Interface Cards (NICs) and two SITL nodes which are connected to the MU_A IED and manageable Ethernet switch, as shown in Fig. 8. With this interface, the data exchanging between simulated IED and Riverbed modeler can be realized. The SV information from the simulated MU IED is sent to the P&C_A IED of substation A in the simulated network and also to the P&C_B IED of substation B which is outside the simulation. The real SV Ethernet frames generated by the MU_A IED are passed through the simulated network and reaches the P&C_B IED. Similarly, when the P&C_B IED detects a fault and issues trip command, the GOOSE messages are initiated. These GOOSE messages are sent through the GOOSE sender software to the breaker_IED. Table III gives the description of various softwares used to model MU and P&C IEDs on the PC.

The SVs sent from the MU_A IED are sent to both the P&C IEDs of substation A and B. The SV generated by SAV sender can be easily sent to the P&C IED of substation A as they are on same LAN and SV contains only Ethernet headers.

In order to send the SVs to the P&C IED of substation B it has to be routed through WAN which requires addition of transport and network protocols (i.e. TCP/IP) to the SVs. This addition of TCP/IP protocol information to the SVs is achieved by a packet translation function in the SITL node. When the SVs are generated by SAV sender and reach the SITL node the real packets are translated into simulated packets through a translation function. The default "*op_pk_sitl_from_real_all_supported*" translation function is modified to include the TCP/IP layers to the SV packets. Hence, now the simulated SV packets in the Riverbed modeler simulation contains the TCP/IP layers, thus can be routed in the WAN easily. Similarly the real GOOSE messages, generated by P&C_B IED from a PC running GOOSE sender, contain only Ethernet layer are made routable, i.e. TCP/IP layers are added, once they enter the Riverbed modeler simulation through the translation functions in SITL nodes. Thus, the real SV and GOOSE messages are converted to routable SV and GOOSE in Riverbed modeler simulations using SITL translation function.

The same test system and scenarios considered in section IV are used to evaluate the performance of different communication architectures in the SITL platform.

TABLE III
SOFTWARE TOOL USED TO MODEL DIFFERENT IEDS

IED Type	Software Tool Used
MU IED	SAV Sender
P&C IED	SAV Receiver
	GOOSE Sender
Breaker IED	GOOSE Receiver

TABLE IV
ETE DELAY FOR R-SV AND GOOSE MESSAGES

Message	Average ETE delay (ms)		
	ATM	SONET	Fiber Optic
R-SV	8.33	7.9	7.8
GOOSE	6.2	5.6	4.3

The simulation is run for 5 minutes. Traffic in the communication network is considered same as that for simulation in Section IV. Table IV shows the ETE delays for transferring the R-SV messages from MU_A IED to P&C_B IED and GOOSE messages from P&C_B IED to Breaker_IED. From Table IV, it can be concluded that Fiber Optic, being a dedicated link from source to destination, outweighs other networks in terms of ETE. SONET offers less delay than ATM network. However, ETE delays for different types of networks increase in case of SITL simulations.

VI. CONCLUSIONS

To enhance the efficiency and reliability of the existing power grids, information and communications technologies are being introduced in power grids to make them smart grids.

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Efforts are being made to build a robust, deterministic, standardized and interoperable communication. In this regard, IEC 61850 is emerging as one of the most promising solutions as it is based on the interoperability approach.

This paper has presented modeling and simulation of the communication configurations between two substations implementing a line differential protection scheme. With the aim of standardized operation, the modeling is done with suitable logical nodes given in IEC 61850 standards. IEC 61850-90-1 has been used as a guideline in modeling WAN which is pivotal to the realization of the scheme. Protection systems are required to have high resilience and this is evaluated by comparing WANs performance with network types such as ATM and SONET. Also the performance of the tunnel in WAN recommended by IEC 61850-90-1 is evaluated. The Riverbed modeler simulation and real-time STIL simulation results demonstrate that the differential current protection scheme is successfully implemented. Thus, power system protection, based on resilient IEC 61850 communication networks, will ensure that the timing restrictions are met in real-life implementations. This is a solid step towards communication and power field's integration in smart grids of the future.

REFERENCES

[1] I. T. Monseth and P. H. Robinson, Relay systems; theory and application. New York; London: McGraw-Hill Book Co., 1935.

[2] H. Miller, et al., "Modern line current differential protection solutions," 63rd Annual Conference for Protective Relay Engineers, 2010, pp. 1-25.

[3] D. Bejmert, et al., "Differential protection restraining procedures for objects with more than two supply ends," in Universities Power Engineering Conference (UPEC), 2010 45th International, 2010, pp. 1-5.

[4] T. S. Ustun and R. H. Khan, "Multiterminal Hybrid Protection of Microgrids Over Wireless Communications Network," in IEEE Transactions on Smart Grid, vol. 6, no. 5, pp. 2493-2500, Sept. 2015

[5] S. T. Skeie, "Ethernet in substation automation," *IEEE Control Syst. Mag.*, vol. 22, no. 3, pp. 43–51, 2002.

[6] Ustun, T.S.; Ozansoy, C.; Zayegh, A., "Differential protection of microgrids with central protection unit support," TENCON Spring Conference, 2013 IEEE , pp.15-19, 17-19 April 2013.

[7] S. Dambhare, et al., "Current Differential Protection of Transmission Line Using the Moving Window Averaging Technique," *Power Delivery, IEEE Transactions on*, vol. 25, pp. 610-620, 2010.

[8] B. Falahati, Z.Darabi, M.J.Mousavi and Y. Fu, "Stochastic latency assessment in substation automation systems," *In Power and Energy Society General Meeting*, 2012 IEEE

[9] I. Ali, S. M. S. Hussain, A. Tak and T. S. Ustun, "Design and simulation of communication architecture for differential protection in IEC 61850 based substations," 2015 Annual IEEE India Conference (INDICON), New Delhi, 2015.

[10] V. C. Gungor et al., "Smart Grid Technologies: Communication Technologies and Standards," in IEEE Transactions on Industrial Informatics, vol. 7, no. 4, pp. 529-539, Nov. 2011.

[11] IEC 61850 2nd Ed.: 'Communication networks and systems for power utility automation', 2013.

[12] Sidhu, T.S.; Yujie Yin, "Modelling and Simulation for Performance Evaluation of IEC61850-Based Substation Communication Systems," *Power Delivery, IEEE Transactions on*, vol.22, no.3, pp.1482,1489, July 2007.

[13] M.S.Thomas and I. Ali, "Reliable, fast, and deterministic substation communication network architecture and its performance simulation," *Power Delivery, IEEE Transactions on*, vol.25, no.4, pp.2364-2370, Oct. 2010.

[14] Communication networks and systems for power utility automation Part 7-420: Basic communication structure distributed energy resources logical nodes, IEC 61850-7-420, Ed.1.0, 2009.

[15] Communication networks and systems for power utility automation, Part 90-1: Use of IEC 61850 for the communication between substations. IEC 61850-90-1, Ed.1.0, 2010.

[16] Communication networks and systems for power utility automation, Part 90-5: Use of IEC 61850 to transmit synchrophasor information according to IEEE C37.118, IEC Standard, 2012.

[17] Communication networks and systems for power utility automation - Part 90-7: Object models for power converters in distributed energy resources (DER) systems, 2013, IEC 61850-90-7, 1st ed.

[18] I. Ali and S.M. Suhail Hussain, "Communication Design for Energy Management Automation in Microgrid," *IEEE Trans. Smart Grid*, 2016. (Early Access).

[19] T. S. Ustun, C. R. Ozansoy, and A. Zayegh, "Implementing vehicle-to-grid (V2G) technology with IEC 61850-7-420," *IEEE Trans. Smart Grid*, vol. 4, no. 2, pp. 1180–1187, 2013.

[20] I. Ali, M. A. Aftab and S. M. Suhail Hussain, "Performance Comparison of IEC 61850-90-5 and IEEE C37.118.2 based Wide area PMU Communication Networks," *Journal of Modern Power Systems and Clean Energy,* vol. 4, no. 3, pp. 487-495, July *2016.*

[21] J. Holbach et al., "Status on the first IEC61850 based protection and control, multi-vendor project in the United States," *2007 Power Syst. Conf. Adv. Metering, Prot. Control. Commun. Distrib. Resour. PSC 2007*, pp. 254–277, 2007.

[22] Falahati, Bamdad; Darabi, Zahra; Vakilian, Mehdi, "Implementing distance line protection schemes among IEC61850-enabled substations," *T&D Conference and Exposition, 2014 IEEE PES*, 14-17 April 2014.

[23] Riverbed Modeler – (formerly OPNET Modeler), [Online], Available: http://goo.gl/72SgAM

[24] SAV Sender and Receiver (trail version) – INFO TECH, [Online], Available: https://goo.gl/8yLw9A

[25] GOOSE Sender and Receiver (trail version) – INFO TECH, [Online], Available: https://goo.gl/8yLw9A

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