

Performance Analysis of IEC 61850 based Substation

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Abstract—Although power flow of current power utility network, smart grid system exchange digital information and power flow bidirectional interaction between provider and user. Thanks to communication networks, exchange of information between end user and power suppliers can estimate the power consumption more precisely and stable operation of power utility can be possible. To provide these advantages, importance of communication network is increased, and it is required to carefully design the network system. Although a few study and IEC 61850-90-4: Communication Networks and System: Network engineering guideline, which relate to guideline and checklist for network design is suggested, the confirmation of network configuration and guideline presented needs to be considered more carefully. We design and simulate the communication network for IEC 61850 based substation station bus and process bus of Poong-Dong digital substation, which is the first IEC 61850 based substation with multi-vendors' IEDs (Intelligent Electrical Devices). We expect that this study will help to design the communication network for digital power utility.

I. INTRODUCTION

IEC 61850 is the standard which defines the data model, network protocol stack, and service model, e.g., GOOSE (Generic Object Oriented Substation Event) and SMV (Sampled Measured Value) for communication with other power utility devices in smart grid [1]. Through this standard, power utility can offer interoperability and more stable and accurate operation. And also power utility can bidirectionally interact with user through communication network unlike traditional power utility networks, when traditional power system only supplies electric to load and extract usage information from the load. Consumers will be able to trade electricity generated in their DERs (Distributed Energy Resources), e.g., photovoltaic generator or wind farm, and also they will be able to monitor usage or price of electricity in the market. This will make it possible to reduce emission of CO₂ and to encourage saving energy consumption through monitoring.

In the digital substation or other power utilities, which employs the IEC 61850, the network system undertakes importance roll for stable operation to provide advantages described above. If the data frame is lost or delayed by the defection of network system, it may cause a blackout or more critical situations. Therefore the communication network system must be carefully designed by considering various situations and network components. For these needs, IEC 61850-90-4: Communication Networks and System – Network Engineering Guidelines presents various concerns and recommendations

which must be considered when design the network system [2]. There, however, are few attempts to verify whether that configuration is proper under power utility based on IEC 61850. In this paper, we design a communication network and conduct performance analysis of station bus and process bus of Poong-Dong substation, which is first IEC 61850 based substation with multi-vendor IEDs (Intelligent Electrical Devices) with power grid simulator, which is analytical tool for IEC 61850 based power grid network simulator, to confirm whether the guideline offered is proper for real digital power system. Simulator developed is based on NS-2.

II. RELATED WORKS

When carefully design the communication network, computer simulation tool is commonly used as very effective way in the aspect of cost. There, however, is no simulator which completely supports the network components like protocol stack for GOOSE and SMV used in IEC 61850. Simulator for communication network simulation of digital substation is presented in [3]. It presents the structure of digital simulation platform which is constituted Simulation Kernel, Network Analyser, Common Graphics Platform, and simulation process of 3 levels like system modelling, simulation, and analysis. It also stresses that the realistic of simulation model, the accuracy of simulation kernel based on disperse events, and how do we analyze the result of simulation should be considered and solved. Performance comparison between star and bus topology with and without priority queue through the simulation using OPNET is presented in [4]. They implemented MU (Merging Unit) and IEDs (Intelligent Electronic Devices). The traffic of GOOSE and SMV message is mainly analyzed, and the traffic of FTP (File Transfer Protocol) is used as background traffic. Reliable substation communication network (SCN) architecture which supports the resistance about single point of failure, the enhanced reliability, and the deterministic operation is presented in [5]. Although the cost is expensive, SCN is consisted of two independent networks for guaranteeing the reliability of connection when single point of failure is generated. Although these studies are progressed, the study and check about suitability and idea relating to design communication network is required.

III. CONSIDERATIONS ABOUT NETWORK COMPONENTS USED IN SMART GRID

Various network components are presented in IEC 61850 to satisfy requirements. IEC 61850 specifies the protocol stack as shown in Fig. 1 to provide very tight performance for GOOSE and SMV services. These services are used to deliver time and mission critical messages e.g., trip or acquisition messages. IEC 61850 requires to GOOSE services delivered in 3 msec latency, which includes all processing, transmission, queueing, and propagation delay. To support this tight timing requirement, the IEC 61850 defined protocol stack as GOOSE and SMV services mapped directly to ISO/IEC 8802-3 Ethernet with IEEE 802.1 Q priority tagging which reduce the queueing delay generated by passing LLC (Link Layer Control) and ISO transport layer like TCP/IP and UDP. And these services can be delivered faster than other traffic because of priority tagging. These are peer to peer (P2P) service based multicast services. The GOOSE message is used to exchange for interlocking or communication between the IEDs, and SMV message is used to gather periodic digitized sampled measured values. Because this service take vary amount of traffic, it requires to isolate the traffic with others and a link service which supports the bandwidth of almost 1 Gbps.

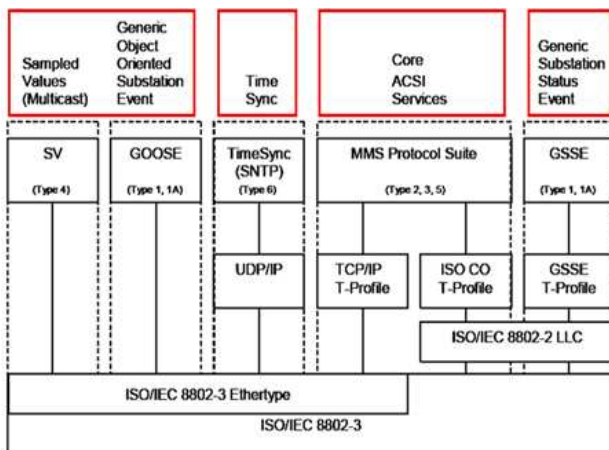


Fig. 1. Protocol stack used in IEC 61850.

MMS (Manufacturing Message Specification) uses client-server model, and is on top of TCP/IP. This service is used to exchange report, reading and writing variable, and control the device. Besides these services, time synchronization service which requires UDP/IP, and FTP service is used.

IEC 61850-90-4: Communication Networks and System – Network Engineering Guidelines presents several checklist and guideline about segmentation, the redundancy of communication network, traffic flow, and topologies. If the traffics are mixed, unexpected delay is added and this delay may affect the performance of network system in particular situation. Therefore we should carefully segment the traffics. It also provides problems about the single point of failure which may cause the lost of important packet like trip message. It suggests RSTP (Rapid Spanning Tree Protocol), PRP (Parallel

Redundancy Protocol), and HSR (Highly-available Seamless Ring) which is used to prevent this critical situation. These protocols makes it possible to recover from failure situation or to support seamless operation by constituting a topology as two independent networks. In the simulation of Poong-dong substation, we seriously consider about these considerations.

IV. PERFORMANCE ANALYSIS OF THE POONG-DONG SUBSTATION

Poong-Dong digital substation is located in Choong-Joo, South Korea, to supply the demand of almost 103 MW. In the Poong-dong digital substation, there are 4 transmission lines, 12 feeders, and 3 main transformers for substation from 154 kV to 22.9 kV. Its station bus is made up by electric equipments for protection and control based on IEC 61850. The single line diagram of Poong-Dong substation is shown in Fig. 2. In this part, we provide implementation of network components like several application, VLAN configuration, and additional NS-2 module for IEC 61850. Then we present the network configuration and numerical results of station bus and process bus.

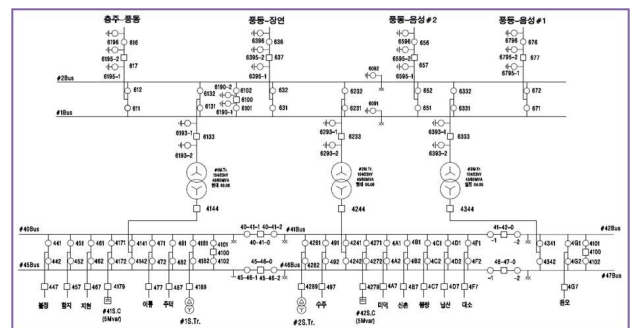


Fig. 2. Single line of Poong-Dong digital substation.

A. Implement of network components for IEC 61850

Network simulator is developed based on NS-2 (Network Simulator-2) [6], which has many protocols. There, however, was a few problems which protocol stack for GOOSE and SMV services is not supported by NS-2, that several applications like SNTP (Simple Network Time Protocol) is not offered, and that simulation time and the size of trace file are large which takes alot of time to analyze them. To tackle these problems, we add module for IEC 61850 in NS-2. GOOSE, SMV, SNTP, and report services which are implemented based on CBR (Constant Bit Rate) application. SMV and GOOSE applications do not have processing delay generated by passing the transport layer and LLC to reduce delay.

SNTP client application usually exchanges 4 times with a server for more accurate time synchronization. To support this, we apply it for IEC 61850, and exchanging times can be adjusted by the end-user. Beside these, application originally supported by NS-2 e.g., FTP, can be used in a simulation as background traffic. To use VLAN (Virtual LAN) configuration, we use multicast function supported by NS-2. The structure of proposed simulator is shown in Fig. 3.

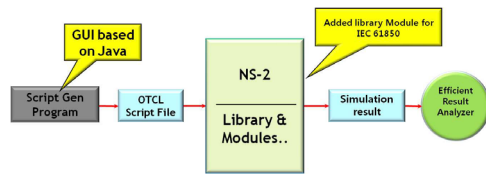


Fig. 3. Structure of proposed simulator.

The problems relating to the size of trace file, and the time of simulation and analysis are solved by only tracing useful information and traffic which is choose by user. This function saves trace types, source, destination, departure time, and arriving time. The events traced are when packet is safely delivered, when packet loss is occurred, and when transfer delay cannot satisfy the requirement presented in IEC 61850. Through this method, we can save upto 20 percent of trace file size compared to original trace file.

As structure of simulator suggested in [3], we develop graphic user interface of simulator to support more convenience network design and result analysis as well as simulation module for IEC 61850 based on NS-2. This simulator will help to make faster and more effective simulation than traditional simulation method using script in original NS-2.

B. Performance analysis of station bus

The topology of station bus in the Poong-Dong digital substation is deployed as hierarchical star topology. We classify and segment the equipments to five segments according to physical location and function of IEDs as shown in Fig. 4. Two segments are allocated to the 170 kV transmission line which have IEDs for 170KV GIS (Gas Insulated Switchgear) bay control and 170 KV bay protection panel. The first segment consists of 6 IEDs for transmission line and 7 GIS bay control IEDs, and another segment consists of 2 IED for transmission line, 3 GIS bay control IEDs, and 5 IEDs for bus protection. VLAN 1 for T/L is tied by IEDs in the first segment. IEDs in the second segment are configured as VLAN 2 for T/L. Each segment is interconnected to each Ethernet switches through link with the bandwidth of 50 Mps as star topology. Another three segments are related to main transformer and distribution line which has 25 KV GIS IED pael, 154 kV main transformer protection, 154 kV and bay control IED panel. They each have 15 IEDs which are interconnected to an Ethernet switch through link with the bandwidth of 50 Mbps. They are configured as VLAN 3 for D/L, VLAN 4 for D/L, and VLAN 5 for D/L. These five switches distributed to each segment are interconnected to main switch which supports connection to HMI (Human Machine Interaction) and to SNTP server with GPS in the station level. 4 main switches is linked with each other to provide redundancy using RSTP. Because SNTP traffic and report messages are converged to main switches, they are interconnected with link which supports the bandwidth of 500 Mbps.

There are traffic flows that consist of the background traffic flow, i.e., report messages and SNTP messages, and the main

TABLE I
MAXIMUM AND AVERAGE DELAY OF EACH VLANs IN STATION BUS

VLAN	Maximum Delay	Average Delay
VLAN1 for T/L	624 usec	620 usec
VLAN2 for T/L	554 usec	528 usec
VLAN3 for D/L	770 usec	720 usec
VLAN4 for D/L	770 usec	720 usec
VLAN5 for D/L	770 usec	720 usec

traffic flow, i.e., GOOSE messages. All IEDs generate report message whose destination is set to HMI in the station level and SNTP message whose destination is set to SNTP server with GPS. Report messages are generated with the interval of 60 sec with the packet size of 123 Bytes. SNTP messages are generated with the interval of 60 sec. with the packet size of 100 Bytes. To increase the accuracy of synchronization, SNTP clients exchanges 4 messages with SNTP server. GOOSE messages are generated with the interval of 0.5 sec. with the packet size of 300 Bytes, and are traced their event. These intervals and packet size are referenced by the study case of station bus in IEC 61850-90-4.

The maximum and average delay for each VLANs are summarized in Table I. Theoretical transfer delay calculated at one hop is 48.02 usec as follows: transmission delay and propagation delay generated at every nodes is calculated as 48 usec and 0.02 usec. In this simulation, final theoretical delay of GOOSE messages is about 96 usec because they are passed to two hops. There, however, is queuing delay which is generated at a switch because GOOSE messages are simultaneously sent from 15 IEDs to the each destination through switch. The maximum delay of 770 usec. in GOOSE messages is resulted from VLAN 3 for T/L, VLAN 4 for T/L, and VLAN 5 for T/L which have the largest number of IEDs in the segments. It is similar with theoretical delay which is 768 usec when 15 GOOSE messages are simultaneously passed through switch which satisfies the timing requirements specified in IEC 61850 part 5.

C. Performance Analysis of Process Bus

The process bus in Poong-Dong substation is not yet implemented. We design the process bus network based on the case study presented in the annex of the IEC 61850-90-4. Topology is constituted as ring topology similar with HSR which supports seamless operation by consisting of two independent communication network. Through ring topology and the recover function of RSTP, we can prevent the single point of failure. The topology is divided into two areas which are the area for transmission line GIS and the area for distribution line to erase delay generated when traffics are uselessly mixed. All of links support the bandwidth of 500 Mbps with the length of 10 m to endure the vary amount of traffic generated by SMV application. The topology of process bus is shown in Fig. 5.

There are five IEDs for bus protection and three segments

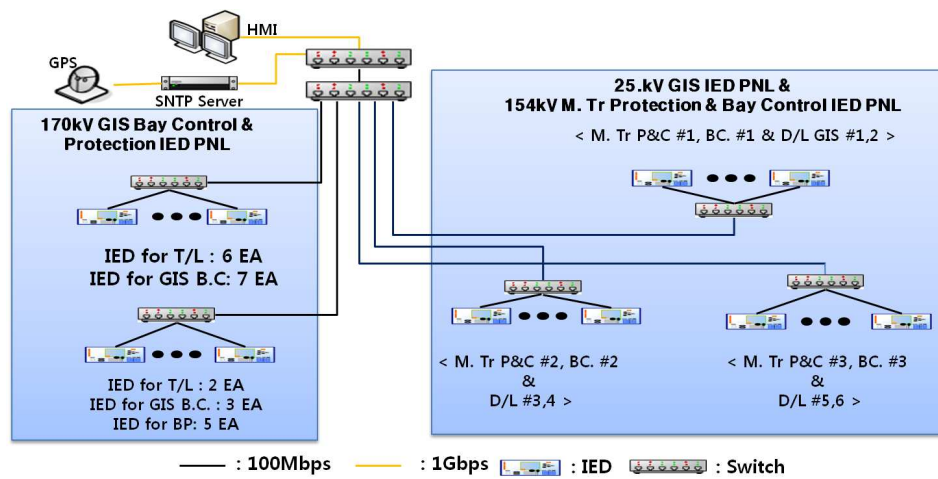


Fig. 4. Structure of the station bus.

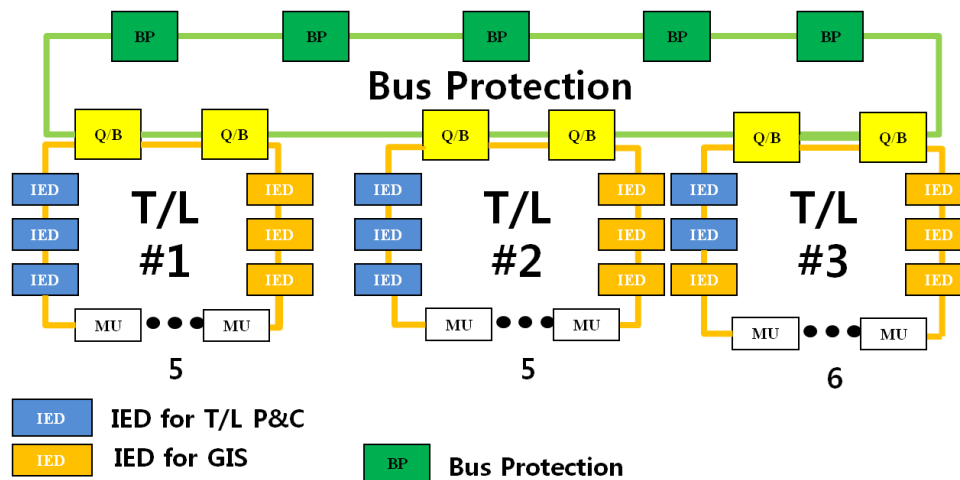


Fig. 5. Structure of the process bus.

which consist of IEDs for protection or control, and MUs for the purpose of current and voltage measurement. And each segment and five IEDs for bus protection are tied into one VLAN which are named as VLAN 1, VLAN 2, and VLAN 3. MUs generate SMV traffic with the size of 180 Bytes with the interval of 0.06 msec. because it samples the CT and PT data with 256 sample/cycle. They send SMV messages to IEDs in their VLANs. SNTP server is connected to main ring. All of nodes exchange synchronization messages at every 60 sec. Simulation result is summarized in Table II. Because transmission delay and propagation delay generated at every nodes is calculated as 2.88 usec and 0.02 usec, theoretical transfer delay generated at one hop is 2.9 usec. The traffic can be jammed into one direction. This is reason that the largest delay is generated from the VLAN 3. Traffics generated from VLAN 3 are passed to clockwise direction in the main ring, and also other traffics generated from VLAN 1 and VLAN 2 are delivered through same direction. All traffics are simultaneously generated. This makes transfer delay to be more and more increased whenever they pass the hops because

TABLE II
MAXIMUM AND AVERAGE DELAY OF DISTRIBUTION LINE AND GIS IN
PROCESS BUS

VLAN	Maximum Delay	Average Delay
VLAN1	57 usec	15.9 usec
VLAN2	73 usec	20.5 usec
VLAN3	97 usec	13.4 usec

of queuing delay.

Distribution line consists of tree segment as shown in Fig. 6. They are completely distributed into three segments which are VLAN 1, VLAN 2, and VLAN 3. In the VLAN 2 and VLAN 3, there are 8 MUs for measurement, 5 IEDs for protection and control of main transformer, and 10 IEDs for GIS. VLAN 1 has 11 IEDs for GIS and 4 IEDs for main stransformer protection and control. Each segment is interconnected with linkwhich has the bandwidth of 500 Mbps and the length of 10m, as ringtopology.

Each segment has a SNTP server and exchanges 4 times

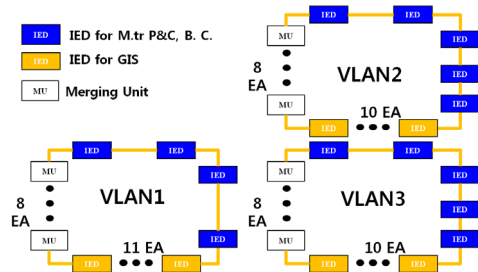


Fig. 6. Topology of process bus for distribution line.

TABLE III

THE RESULT OF SIMULATION FOR DISTRIBUTION LINE

VLAN	Maximum Delay	Average Delay
VLAN 1	47 usec	22.20 usec
VLAN 2	45 usec	22.13 usec
VLAN 3	45 usec	22.13 usec

to synchronize clock. It generates traffic with the interval of 60 sec. with the packet size of 100 Byte. SMV messages are generated with the interval of 0.06 msec. because it samples with 256 samples/cycle, and with the size of 180 Bytes. The destination of SMV messages are set to all IEDs in same VLANs.

The numerical results are summarized in Table III. Simulation result shows that the largest transfer delay is measured in VLAN 1 as the delay of 47 usec. Theoretical delay is 34.8 usec because the number of maximum number of hop is 12. We can conclude that the transfer time of SMV in this topology satisfies the timing requirements specified in IEC 61850 part 5.

V. CONCLUSION

The communication network undertakes an important roll in digital substation based on IEC 61850 because all nodes communicate with others. The standard helps to conduct more stable, faster, and accurate operation in SAS. To prevent desperate situation generated through communication fail, several network components must be carefully considered. We carefully design and simulate the station bus and process bus of the Poong–Dong digital substation. In the simulation, the topology, VLAN, traffic flow, and network traffics are carefully considered. We could conclude that the proposed topology satisfies the timing requirement of IEC 61850 through a thorough analysis of simulation.

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