

Interoperability and Performance Analysis of IEC61850 Based Substation Protection System

Ming-Ta Yang, Jyh-Cherng Gu, Po-Chun Lin, Yen-Lin Huang, Chun-Wei Huang, and Jin-Lung Guan

Abstract—Since IEC61850 substation communication standard represents the trend to develop new generations of Substation Automation System (SAS), many IED manufacturers pursue this technique and apply for KEMA. In order to put on the market to meet customer demand as fast as possible, manufacturers often apply their products only for basic environment standard certification but claim to conform to IEC61850 certification. Since verification institutes generally perform verification tests only on specific IEDs of the manufacturers, the interoperability between all certified IEDs cannot be guaranteed. Therefore the interoperability between IEDs from different manufacturers needs to be tested. Based upon the above reasons, this study applies the definitions of the information models, communication service, GOOSE functionality and Substation Configuration Language (SCL) of the IEC61850 to build the concept of communication protocols, and build the test environment. The procedures of the test of the data collection and exchange of the P2P communication mode and Client / Server communication mode in IEC61850 are outlined as follows. First, test the IED GOOSE messages communication capability from different manufacturers. Second, collect IED data from each IED with SCADA system and use HMI to display the SCADA platform. Finally, problems generally encountered in the test procedure are summarized.

Keywords—GOOSE, IEC61850, IED, SCADA.

I. INTRODUCTION

IEC61850 substation communication standard has been widely applied to Substation Automation Systems (SAS) worldwide [1-5]. The Bradley substation of the Tennessee Valley Authority (TVA) is one such example. This substation integrated different IED (Intelligent Electronic Device) manufacturers including Siemens, GE Multilin, ABB and AREVA, and put them to the interoperability test for IEC61850 communication standard. In the Bradley project, methods to integrate IEDs from different manufacturers by using the

Substation Configuration Language (SCL) defined by IEC61850 are described [6], and methods to accomplish data exchange within substation by using configuration tools and integration tools of different manufacturers under common standard are introduced. As a result, the system architecture of substation protection, measurement, control and communication may be established, and the IEC61850 standard test of GOOSE (Generic Object Oriented Substation Event) communication between IEDs may be performed. Finally, the test tools used in the process are validated, and the problems encountered are summarized to evaluate the circumstances of application of the IEC61850 standard to substation protection system and control system integration.

Logical Nodes and GOOSE messaging of the IEC61850-8-1 [7] substation bus standard were utilized to the design of the protection system and control system for Bradley substation 500 kV and 161 kV transmission lines and breakers, transformer setting protection, data acquisition of the transformer, transformer LTC (Load Tap Changer) control, breaker control, SCADA (Supervisory Control and Data Acquisition) [8] system, Operational Interface Panels (OIP), digital fault recorder interface and miscellaneous station data. There are 33 IEDs implementation in the Bradley project.

In the Bradley substation, all the IEDs that comply with the IEC61850 standard are connected to the Ethernet switches located in the control house via 100 Mbps multi-mode fiber optics. Other station-level and process-level infrastructures, such as the SCADA mainframe, meter and Process Merging Unit (PMU) and HMI (Human-Machine Interface) [9], also act as communication media by performing bidirectional data communication (vertical communication) through the Ethernet switches.

In addition, the configuration infrastructures of the IEC61850 standard P2P (peer to peer) GOOSE messages (horizontal communication) are used to construct the communication network system of data exchange and collection [10-13]. All the regional infrastructures of the substation are connected to Wide Area Network (WAN) and remote control center through backbone Ethernet switches, router and firewall for information management and application program execution.

Although each IED conforms to IEC61850 standard, it is revealed in the Bradley project that there are still communication difficulties among the IEDs because IEDs from different manufacturers configured with different IED Capability Description (ICD) file formats, or simply because the configuration processes are different even for IEDs of the

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same model from the same manufacturer.

The IEC61850 Validator tool which is a software can be used to test the ICD file for errors. An error window will appear in the Validator tool if there is an error in the configuration description of the ICD file. It should be noted that IEC61850 Validator tool can only check for syntax errors but not semantic errors in the ICD file. It can import ICD file and use System Configuration Tool (SCT) to configure system, but under certain circumstances, the IED may not be able to subscribe to GOOSE messages due to different configuration description in the GOOSE messages. In other words, the subscriber still cannot subscribe even though the IED publishes its GOOSE messages. Ethereal, the network protocol analyzing tool, used to analyze this problem and to observe the circumstances and contents of the GOOSE messages published by the IEDs.

Despite the existence of IEC61850 communication standard and the fact that vendors do use configuration tools that conform to the standard to configure IEDs, there are many differences among IEDs. Therefore, various divisions of the manufacturers should be coordinated to solve problems such as IED firmware update or modification.

This study will describe in details the hardware and software requirements when constructing the IEC61850 test platform, analyze the result of the horizontal and vertical communication test, and discuss the problems encountered during the test process. Finally, SCADA HMI is adopted to display the states of the horizontal and vertical communication, and the problems encountered are also discussed.

II. CONSTRUCTING THE ENVIRONMENT OF THE IEC61850 STANDARD TEST PLATFORM

This study constructs a test platform to verify and analyze the interoperability and performance of IEC61850 standard among IEDs. In order to construct the IEC61850 standard test platform, engineers must familiarize with not only the definition and hardware requirements of the IEC61850 communication standard but also the configuration tool, communication analysis software, user manual and the technique resource of the manufacturer of each IED. The knowledge, equipments and procedures for constructing the test environment are as follow:

- 1) Form the concept of IEC61850 communication standard: The first step is to form the IED configuration and test concept. Read definitions of every part of the IEC61850 standard, such as information models, SCL, GOOSE message, information exchange and communication service.
- 2) Hardware:
 - a) IED: The IEC61850 compatible IEDs which are to be adopted in this study are VAMP_257, ABB_REF541, GE_F650, AREVA_P143 and SEL_751A.
 - b) Ethernet Switch: Ethernet Switch as well as knowledge of the communication mode is needed to test the GOOSE functionality. This study uses RuggedCOM RSG2100 as the Ethernet Switch.
 - c) Mainframe computer: The mainframe computer must be capable of running the IED configuration tool and SCADA

software.

- d) Power system simulator: The power system simulator is connected to the test devices to measure the state parameters of the voltage, current and circuit breaker to validate the protection and measurement function of the IEDs.
 - e) Global Positioning System (GPS): Each IED must be synchronized in order to verify the performance of GOOSE functionality and to calculate the transmission speed using the timestamp published and subscribed by GOOSE message. Synchronization devices such as Meinberg SNTP (Simple Network Time Protocol) Time Server and Master Clock should be used.
- 3) IED configuration tools, communication analysis software, user manuals [14–18], and technique support by the vendor: Configuration software and manuals of IED are indispensable to commence interoperability test and to configure functions such as protection, measurement, control and communication. WireShark or Ethereal software may be used to observe transmission status and time delay of GOOSE message.
 - 4) SCADA software: The software for SCADA system deployment is Elipse E3 Studio [19–20]. This software can be used to develop communication driver that follows specific communication protocol, and can support universal databases such as Access, SQL Server and OPC Server. It can also test the interoperability among IEDs and integrate data from different IED manufacturers.
 - 5) Test platform framework: This study analyzes and tests two communication modes of IEC61850 standard. One is the vertical communication (Client / Server information) mode in which IEDs collect power system simulator signals and send data to be collected by Elipse E3 Studio software in mainframe computer through Ethernet Switch. The other is the horizontal communication (GOOSE message) mode in which, in contrast to conventional communication mode, SCADA system is not needed to issue commands to IEDs, thus not only saving wiring cost but also reducing IED response times.
 - 6) Deployment of the hardware test environment framework: Identify the communication port and hardware connection supported by the IEDs, including the connections to power system simulator and Ethernet Switches. Since the communication ports used in this test are all fiber optics ports, fiber optics must be used as communication media. The VAMP_257 and ABB_REF541 connected directly to Ethernet Switch by fiber optics, while the GE_F650, AREVA_P143 and SEL_751A can link to Ethernet Switch through the RJ45 communication port and Fiber Optic Ethernet Converter. Finally, the RJ45 communication port of Ethernet Switch is used to connect the framework to the SCADA mainframe as shown in Fig. 1.

III. COMMUNICATION SETTINGS AND DATA ACQUISITION OF EACH IED

Fig. 2 shows the Elipse E3 Studio software interface driver developed specifically for IEC61850 communication protocol

to add the model and settings of data communication and storage paths of each IED, to link IEDs, and to collect data from each IED. Tag Browser window is used for testing the connection state of each IED, and for mapping selected IED data fields to interface in Elipse E3 Studio software. Fig. 3 shows that the hierarchical object oriented formats of the IED data fields mapped into Elipse E3 Studio software interface are in consistency with the information models defined by IEC61850 standard [21], thus making it much easier for maintenance personnel to manage existing IEDs or to add new IEDs.

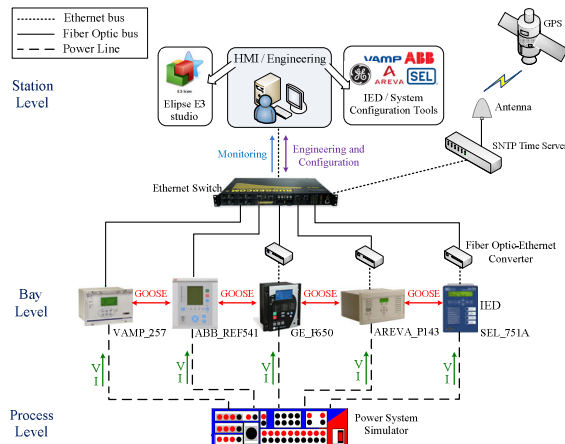


Fig. 1 Hardware test environment framework

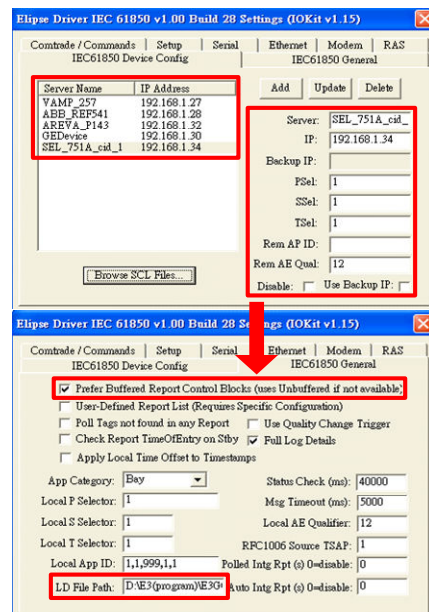


Fig. 2 Elipse E3 Studio – IEC61850 driver communication settings

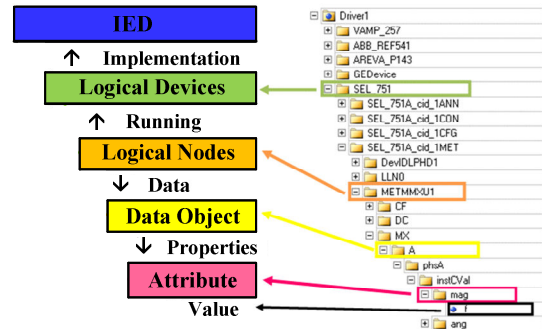


Fig. 3 Correspondences between IED data fields and information models by IEC61850 standard

IV. GOOSE COMMUNICATION AMONG IEDS

A. Configuration Process for Each IED

Each IED must be configured via its own proprietary configuration tool to perform as expected in SAS. Fig. 4 shows the configuration tools used to configure the individual IEDs. IEDs and the configuration software must conform to the format and procedures for data transfer defined in IEC61850-6 standard. The main aim of configuring the IED is to obtain the SCL file types essential for the system configuration [22]. Four standard data formats defined for configuration operations are as follows [23]:

- 1) System Specification Description (SSD): Power equipment specifications and object description file in substation.
- 2) IED Capability Description (ICD): IED configuration description file for function activated items, logic settings, and input/output of analog/digital contacts.
- 3) Substation Configuration Description (SCD): Complete data description file of overall substation.
- 4) Configured IED Description (CID): Description file of mutual communication among IEDs is generated by SCD file.

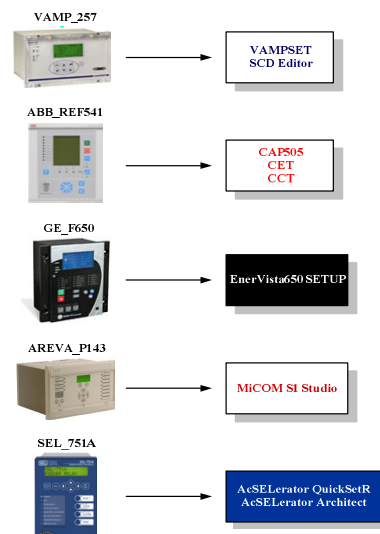


Fig. 4 Proprietary configuration tools used for the configuration of IEDs

Firstly, the one-line diagram of substation is used as foundation design to be sure of the electrical equipment configuration and system architecture in substation. Secondly, input the power equipments and their specifications into SSD file using System Specification Tool. Thirdly, use configuration tool developed by the manufacturer to perform IED function and logic configuration and store as ICD file, according to each IED's role in the system. Fourthly, use SCT to import ICD files into the system to integrate with SCD files, establish function and mutual relatedness of IED and system one-line diagram, and store the configuration result in SCD files. Finally, use IED configuration tool to generate CID file and load the CID file into each IED to complete the configuration process that conforms to IEC61850 standard.

The VAMP_257 Feeder Manager is used as an example for IED configuration process in this study, as shown in Fig. 6 [24]. First, use the proprietary tool, VAMPSET Configurator, to configure ICD file, modify function settings and protection logic of IED. Then the IEC61850 Configurator included in VAMPSET is used to read or create a configuration file to configure settings such as GOOSE communication, Data mapping, BRCB (Buffer Report Control Block) / URCB (Unbuffer Report Control Block), and Publisher / Subscriber. After the configuration is loaded into the IED and output as an ICD or CID file, SCT is used to import the ICD / CID files of other IEDs as shown in Fig. 7.

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graph TD; VAMP257[VAMP_257 IED] -- "Get info from relay & Setting" --> ICD[ICD file]; ICD --> VAMPSET[VAMPSET]; VAMPSET -- "Configure with SCD file" --> VAMP257; VAMPSET --> IEC[IEC 61850 Configurator]; IEC --> CID[CID file]; CID -- "Export*.cid" --> SCT[SCT]; SCT -- "Import other IEDs" --> CID; SCT --> SCD_SCD[SCD file]; SCD_SCD -- "Export SCD file" --> IEC;
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The flowchart illustrates the VAMPSET IED configuration process. It begins with the **VAMP_257 IED** block, which sends information to the **ICD file** (labeled "Get info from relay & Setting"). The **ICD file** then feeds into the **VAMPSET** block. The **VAMPSET** block has a feedback loop to the **VAMP_257 IED** labeled "Configure with SCD file". Inside the **VAMPSET** block is the **IEC 61850 Configurator**, which generates a **CID file**. This **CID file** is then exported (labeled "Export*.cid") to the **SCT** block. The **SCT** block can import other IEDs (labeled "Import other IEDs") into the **CID file**. Finally, the **SCT** block exports an **SCD file** (labeled "Export SCD file"), which is then used by the **IEC 61850 Configurator** to configure the **VAMPSET** block.

The screenshot shows the VAMPduoEditor SCD Editor application. The main window is titled 'Substation: IEC61850 station'. On the left, a project tree shows the hierarchy: 'Add New Item...', 'Add Time Server...', 'Add Subnetwork', 'Connect Inputs...', 'Add Substation', 'Add Voltage Level', 'Add Bay', 'Contents', and 'Go to...'. The right pane displays a file list under the 'AREVA' folder, which is expanded. The files listed are 'AREVA.icd', 'AREVA_V4143.icd', 'PA10..._13C.icd', and 'VAMP_287.icd'. The 'VAMP_287.icd' file is circled in red. The bottom status bar indicates 'IED Capability Description Files (*.icd)' and 'Open as read-only'.

The screenshot shows the 'VAMPTOther - SCD Editor' window. The 'Save As' dialog is open, displaying the file name 'VAMPTOther' and the save location 'SCDeditor Files (*.SCD)'. The file type is set to 'SCDeditor Files (*.SCD)'. The 'Save As' button is highlighted.

The screenshot shows the VAMP 257 Vampnet application window. The 'Connect to Device' menu is open, displaying options like 'Disconnect Device', 'Search and Select Devices', and 'Write AS Settings to Device'. The 'Configure with SCD File' option is highlighted with a red circle. The background shows the main interface with a list of components on the left and a central area displaying 'Sending EXTREF control'.

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Finally, as shown in Fig. 10, Wireshark Network Analyzer is used to observe the transmission circumstance and contents of GOOSE message, to check the consistency between configuration content and setting, and to observe content of GOOSE messages issued by IED in "allData".

There are three stages in IED GOOSE message transmission process: GOOSE message publishing time delay, Digital Input (DI) triggering event time delay, and GOOSE message subscribing time delay [25-26].

In this test, in order to calculate accurately the IED GOOSE message publishing time and subscribing time, GPS Master Clock signal is sent to DI of each IED to serve as a common starting time for GOOSE triggering and also to serve as a common time reference point for calculation of time difference during following communication stage when the timestamp of triggering event is observed [27].

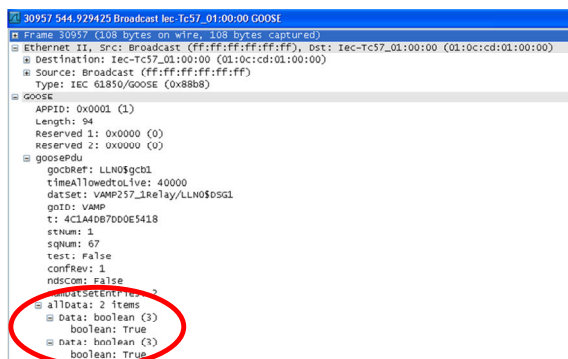


Fig. 10 Wireshark network analyzer

To test interoperability among IEDs, IEC61850 Configurators developed by different vendors are used to configure relationship among IEDs by importing ICD or CID files from other IEDs. The test result shows that not all IEDs support mutual GOOSE message communication, as shown in Fig. 11.

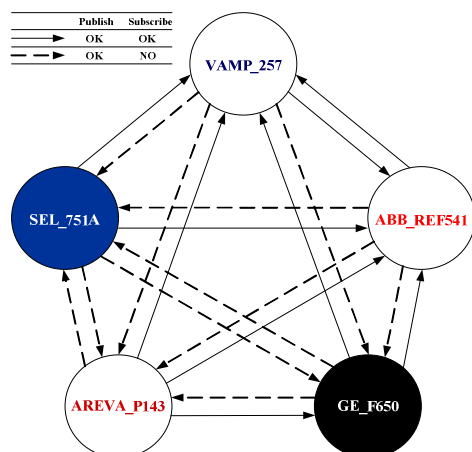


Fig. 11 Result of GOOSE messages interoperability test

When using Wireshark Network Analyzer to analyze IED GOOSE communication, it is found that although there is no

problem in GOOSE message publishing function of each IED, there are some difficulties in GOOSE message subscribing function. The IEDs of VAMP and ABB can subscribe to other IEDs, the IEDs of GE can only subscribe to those of AREVA, and the IEDs of AREVA and SEL cannot subscribe to other IEDs.

The problems encountered in the configuration and test processes for each IED:

- 1) VAMP_257: There is minor difference in the process of setting GOOSE communication between VAMP_257 and other IEDs. If a unique MAC address is assigned to each IED, only GOOSE messages by one IED may be subscribed one at a time. If a same MAC address is assigned to all IEDs and the GOOSE messages is published by multicast, GOOSE messages published by other IEDs can be subscribed all at once, and the individual publishing IED can be identified by its Data-Attributes.
- 2) ABB_REF541: Configuration process of ABB_REF541 can be done simply by loading the Configurator ICD, CID, or SCD file into the GSE Input and then inputting its Target-Path. The test result shows that ABB_REF541 can subscribe GOOSE messages published by other IEDs. In this study, four LEDs are deployed to indicate GOOSE messages subscription status of the IED, as shown in Fig. 12 where a red light indicates a success in GOOSE messages subscription.
- 3) GE_F650: Compared to other IEDs, description for setting the GOOSE Reception of GE_F650 in IEC61850 configuration process is vague. Importing and extracting SCD file of other IED into GOOSE TX Control Blocks and DataSet Elements will show only the source and path of GOOSE data, but not detailed parameters such as MAC address and APPID of the IED, as shown in Fig. 13. Therefore, it is difficult to determine if the GOOSE parameters of ICD or CID file imported from other IEDs are correct. The test result shows that GE_F650 can only subscribe to GOOSE message of AREVA_P143.
- 4) AREVA_P143: Compared to other IEDs, format of the path for the selected parameters should be carefully observed when defining DataSet of GOOSE message publishing, as shown in Fig. 14. The test result shows that AREVA_P143 succeeds in publishing, but fails to subscribe to GOOSE message of other IEDs.
- 5) SEL_751A: Select the FTP communication mode with care when using configuration tool to load SEL_751A configuration file, and use serial port in the front panel of IED to connect to the mainframe computer. The GOOSE communication test result shows that while GOOSE message publishing is OK, there are problems in subscribing to GOOSE message of other IEDs. Only ICD or CID file of IEDs from VAMP and GE can be imported successfully, while error windows appear and programs terminate and shut down when importing files from other IEDs. Test result also shows that SEL_751A can not subscribe GOOSE message published by VAMP and GE IED through IED indicator observation.

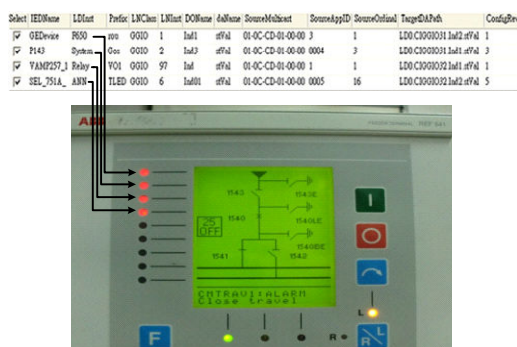


Fig. 12 ABB_REF541 test result – Four LEDs deployed to indicate GOOSE messages subscription status of the IED

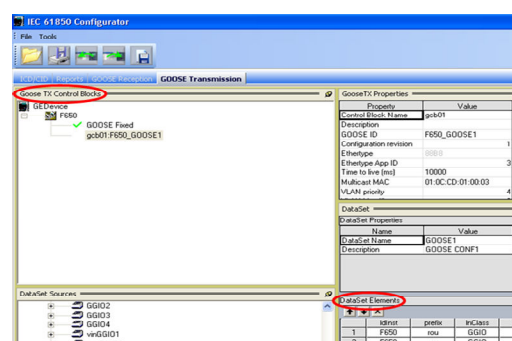


Fig. 13 EnerVista 650 Setup – IEC61850 configurator

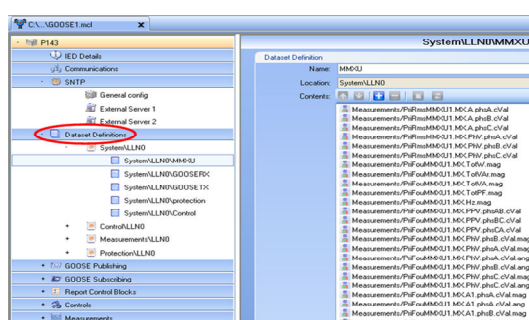


Fig. 14 MiCOM S1 Studio – IEC61850 IED configurator

B. GOOSE Performance Test and Analysis for IEDs

IEC61850 standard requires that the publisher publishes GOOSE messages to Ethernet switch in multicast mode, and that the subscriber subscribes at Ethernet switch with matching GOOSE parameters. Therefore, the times which can be obtained in this study are the time delay of event generated after triggering the subscribe function, the time delay (analyzed by Ethernet software) of first GOOSE message published with SeqNum (Sequence Number) being 0, and the time difference between the two above. The reason why Ethernet software, instead of Wireshark software, is adopted in this study is that the encoding format of time code by Wireshark software is byte array (Fig. 15, left), which does not display information as clearly as Ethernet software (Fig. 15, right) does. Although the functions of the two are largely identical, there are still minor differences. As shown in Fig. 15, the normal format of Ethernet software allows time display to be read and stored more easily.

Since the subscriber only knows the length of time after, but not before, event triggered by IED GOOSE message subscription, there is no way of knowing the time delay between GOOSE message publishing and subscribing.

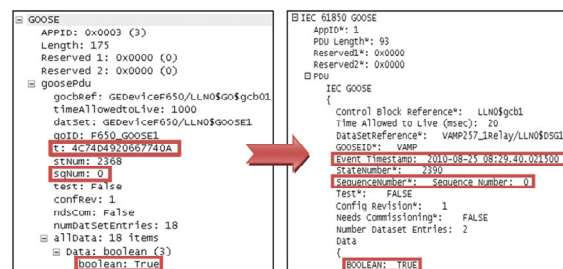


Fig. 15 GOOSE performance test – Wireshark (left) vs. Ethernet analyzer (right)

The test result of the times required for GOOSE message delivery between VAMP_257, ABB_REF541, and GE_F650 are shown in Table I and Table II. These results are obtained by subtracting the publishing time and subscription time after their synchronization errors are removed.

Table I shows the results of ten time delay tests of GOOSE message processing between GE publishing and VAMP subscribing. The average of the time delays is 40.6 ms.

Table II shows the results of ten time delay tests of GOOSE message processing between VAMP publishing and ABB subscribing. The average of the time delays is 32.8 ms.

Test result shows that the time delays vary with both the publishing IED and subscribing IED. Therefore it is not possible to accurately evaluate the performance of GOOSE functionality. There are many uncertain factors in the test process:

- 1) Differences among IED communication media. VAMP_257 uses ordinary fiber optics directly, ABB_REF541 uses exclusive adapter to link to fiber optic, and GE_F650 uses its RJ45 communication port to link to fiber optic via fiber optic Ethernet converter. The information is sent to Ethernet Switch by fiber optics. Each stage of signal transformation may cause additional time delay.
- 2) There are many variables in each stage of GOOSE message transmission process. For example, the time required to generate event record after GPS pulse triggers DI differs with each vendor. In this test, the time GPS pulse was sent is assumed as the time base, and synchronization error is calculated in ms in each record. However, the result that the error with ABB in this test is 0 or -1 ms indicates the inaccurate nature in this respect.
- 3) The volume of data transmission flow in Ethernet switch may cause additional time delay in the process of GOOSE message transmission.

V. SCADA HMI APPLICATION AND RESULT ANALYSIS

After the data of IED are mapped to Elipse E3 Studio software interface, the data can be displayed in SCADA HMI, or they can be set or configured further in functions such as

real-time value, GOOSE message, alarm, event recorder, and trend chart.

Although the data of IED can be mapped to Elipse E3 Studio software interface, there are three possible outcomes when linking the data value of individual IED: successful data linkage, correct display of parameter variation but with data linkage problem, and linkage or function execution failure. Some of the above may cause problems when SCADA HMI is displaying data, as shown in Fig. 16.

The problems that Elipse E3 Studio software encounters when conducting communication test for the IEDs are summarized in Table III. There are clearly some problems, regarding such as Data-Attributes format and parameter definition, which must be discussed among and solved by the manufacturers.

VI. CONCLUSION

Literatures related to configuration of substation under IEC61850 standard are analyzed by this study to determine the software and hardware requirements of test platform, and to construct a communication framework of benchmark systems for horizontal and vertical communication test and analysis. The result may be applied to future construction and configuration of protection system in smart grid.

This test result shows that the IED configuration tools from

different vendors are not fully compatible, and not mutual GOOSE messages communication between any two IEDs can be achieved. There are problems in SCADA HMI application, too. For future application to smart grid, the issues on interoperability and performance of individual IED must be addressed thoroughly. Discussion with and test assistance from experienced manufacturers in IEC61850 standard application will be valuable for efficient test environment establishment and accurate performance verification.

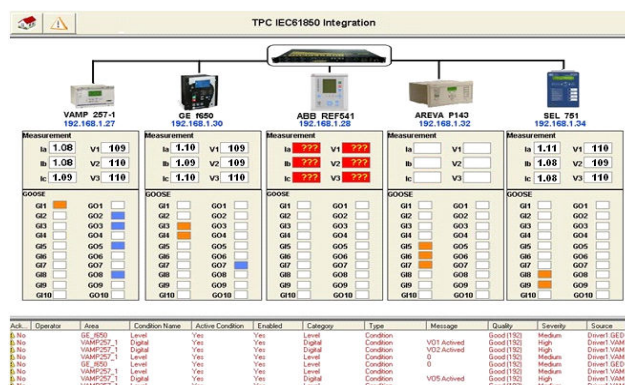


Fig. 16 SCADA HMI application for IED

TABLE I
GOOSE MESSAGE TIME DELAY BETWEEN GE PUBLISHED AND VAMP SUBSCRIBED

Item	GE_F650			VAMP_257		
	Synchronous Error	DI triggering time	GOOSE message publishing time	Synchronous Error	GOOSE message subscription time	Time delay
1	0.023	35.023	35.025	0.001	35.043	0.040
2	0.029	40.029	40.032	0.002	40.044	0.039
3	0.027	45.027	45.029	0.002	45.043	0.039
4	0.027	50.027	50.028	0.001	50.052	0.050
5	0.028	55.028	55.032	0.002	55.052	0.046
6	0.024	00.024	00.025	0.002	00.042	0.039
7	0.025	05.025	05.027	0.002	05.041	0.037
8	0.023	10.023	10.025	0.002	10.043	0.039
9	0.025	15.025	15.027	0.003	15.043	0.038
10	0.022	20.022	20.023	0.002	20.042	0.039

- Time unit: Second
- A "positive" Synchronous Error indicates that the IED internal time is ahead of the GPS Time

TABLE II
GOOSE MESSAGE TIME DELAY BETWEEN VAMP PUBLISHED AND ABB SUBSCRIBED

Item	VAMP_257			ABB_REF541		
	Synchronous Error	DI triggering time	GOOSE message publishing time	Synchronous Error	GOOSE message subscription time	Time delay
1	0.001	35.001	35.011	0	35.023	0.013
2	0.002	40.002	40.021	0	40.049	0.030
3	0.002	45.002	45.021	0	45.056	0.037
4	0.001	50.001	50.020	-0.001	50.030	0.012
5	0.002	55.002	55.020	-0.001	55.046	0.029
6	0.002	00.002	00.020	-0.001	00.071	0.054
7	0.002	05.002	05.019	-0.001	05.037	0.021
8	0.002	10.002	10.011	-0.001	10.078	0.070
9	0.003	15.003	15.021	0	15.045	0.027
10	0.002	20.002	20.020	0	20.053	0.035

- Time unit: Second
- A positive Synchronous Error indicates that the IED internal time is ahead of the GPS Time
- A negative Synchronous Error indicates that the IED internal time lags behind the GPS Time

TABLE III
SUMMARY OF ELIPSE E3 STUDIO SOFTWARE FUNCTION TEST

Manufacture	Measurement/Status	GOOSE	SCADA HMI	Alarm/Event Record
VAMP 257	OK	OK	OK	OK
ABB REF541	OK*	NO	M/S – OK GOOSE - NO	NO
GE_F650	OK	OK	OK	M/S – OK GOOSE-NO
AREVA P143	OK*	OK	M/S – NO GOOSE - OK	NO
SEL 751A	OK	OK	OK	OK

- M/S: Measurement/Status
- OK: successful data linkage
- OK*: correct display of parameter variation in Elipse E3 driver but with data linkage problem
- NO: linkage or function execution failure

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