Preparing to Teach IEC 61850 Digital Substations: A Laboratory Approach

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***Abstract*— The digital revolution is fully influencing operation of power substations. With the suite of IEC 61850 standards, there is now a method to replace copper connections between substation control buildings and yard equipment with digital fiber optic Ethernet networks. This new technology motivates new topics for training. This paper presents the creation of a 61850 digital substation laboratory for training power system students. The training lab consists of three merging units, two SDN switches, three microprocessor protective relays equipped with IEC 61850 support and a GPS clock. A Cleveland State University undergraduate senior design team designed, built, and successfully tested the digital substation as their capstone project.**

The training rack is based on a physical substation model consisting of a transmission line, power transformer, and substation bus. The laboratory successfully demonstrated that the protection and control functions could be securely and reliably performed in a digital substation connecting hardware together through a software-based network. The hardware and software used to create this portable digital substation are explained in detail.

Experience in the development of this laboratory reveals that Electrical Engineers focusing on Power Systems and Protective Relaying will need additional skills in Computer Networks and Digital Communications from the Computer Science and Computer Engineering Departments at their Universities to be prepared for digital substation deployment and support.

***Index Terms*—Power System Education, System Protection, Microprocessor Relays, Protective Relay and Control, IEC 61850, Digital Substation, Sampled Values, GOOSE, Portable Digital Substation Training Laboratory, Process Bus, Station Bus.**

Acronyms

ICD – IED Capability Description
CID – Configuration IED Description
IED – Intelligent Electronic Device
GOOSE – Generic Object Oriented System Event
SV – Sampled Values
SCL – Substation Configuration Language
SCD – Substation Configuration Description
MMS – Manufacturing Message Specification
XML – Extensible Markup Language
PTP – Precision Time Protocol
FTP – File Transfer Protocol
SDN – Software Defined Networking
MAC – Multimedia Access Control

I. Introduction

IEC 61850 is an international standard in the power industry for carrying the communication between IEDs of local and remote power systems. It is a set of multiple protocols used for substation automation, protection, and control with customized communication links. Some of the objectives behind establishing these standards are as follows:

1. Unify the whole substation by combining the different models into a consistent set of protocols.
2. Reducing the copper wire expense by ethernet communication.
3. A fast end-to-end communication network for fault and operation response.
4. Easy substation protection and control modifications over time as new IEDs are added. Changes aside from the power and network connection of the new devices simply involve device configuration changes without extensive wiring modification.

See Figure 1 for an example digital communications architecture for a digital substation.

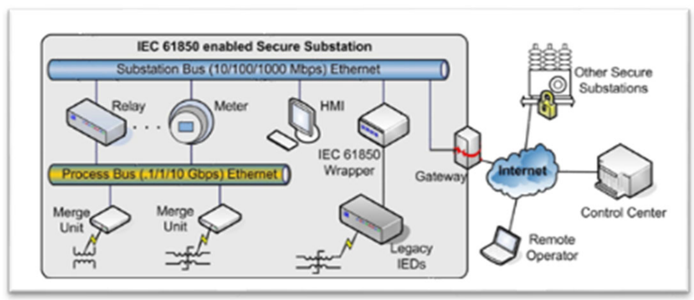


Figure 1 IEC 61850 Substation Architecture Example[1]

II. Background

Software marketplace group under Utility Communications Architecture (UCA) started developing software data objects first for distribution automation, then later for substation automation. This idea was further developed later by the International Electrotechnical Commission (IEC) around 1995, and the IEC 61850 standard was born. Originally, it was called "Communication Networks and Systems in Substation Automation". The first set of object models, called Generic Object Models for the Substation and Feeder Equipment (GOMSFE), was developed and eventually morphed into the IEC 61850 standard.

61850 is structured after the Common Information Model (CIM) under the IEC. CIM is the general information model of utility-specific data and underlines the information structures of most, if not all, IEC utility standards. It was released in 2003 as a standard protocol.

Two major components of the IEC 61850 standard are Sampled Values (SV) and Generic Object Oriented System Events (GOOSE). The SV streams carry analog sampled values from the device performing analog-to-digital conversion over the network to devices that need that information for calculation. Typical analog quantities carried include currents and voltages. GOOSE messages are used to convey binary values, traditionally handled with binary digital inputs and outputs wired into a DC power source. Breaker statuses, trip, and close controls are typical values carried by GOOSE messages. Both SV and GOOSE are layer 2 multicast frames on an Ethernet network. A multicast frame is transmitted by one device out onto the network to be received by multiple devices. This is different from most messages on the network, which tend to be unicast: from one device directly to another device. The layer 2 multicast requires a configured Multimedia Access Control (MAC) address to be used as the destination, signaling to other devices on the network the stream identification. More detail on MAC addresses is available from industry standards and guides[2]. When the device network interface receives a layer 2 multicast message, if the destination address matches a subscription, the network interface will pass that frame along to the processor for handling. If the destination address is not subscribed, the frame is dropped. Modern Software Defined Networks (SDN), allow only desired layer 2 multicast messages to be transmitted to specific configured network ports, which saves end-device network interface processing. The network interface only receives those layer 2 multicasts to which it is subscribed.

Why would a utility want to use the SV and GOOSE technology specified in the 61850 standards for a complete digital substation? Some reasons are shown below[3]:

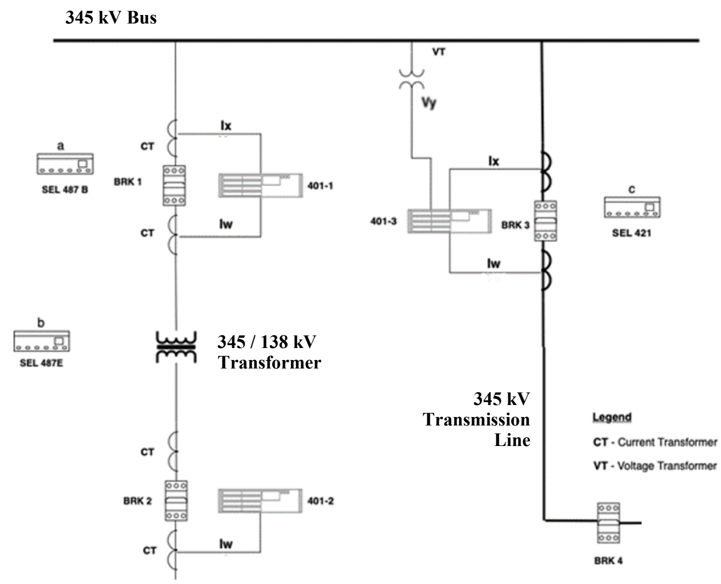
1. Implementation of IEC 61850 not only increases reliability to the system but also reduces the cost of the substation. Investment cost is decreased due to the replacement of copper wires by fiber optic cables.
2. Furthermore, some units used in conventional substation is no longer needed in digital substation since intelligent electronic devices (IEDs) are capable of performing the specific functions of transducer and RTU.
3. Regarding maintenance, a digital substation includes the ability to supervise all the IEDs. Self-monitoring helps reduce maintenance. Instead of having periodic maintenance work, the equipment is repaired only when errors occur in the substation.
4. Less maintenance work results in lower possibility of human errors in the substation. This means higher reliability of operation.
5. A fiber-optic-based communication system is inherently more hardened for electromagnetic events, such as geomagnetic storms or human-induced electromagnetic warfare.
6. Faster recovery after failure is possible since signal paths are logically rather than physically implemented.

Education for this new standard is important for new power engineers to be ready to support installations in industry. Others have undertaken creation of laboratories for hands-on education for students[4], but the laboratory described in this paper undertakes both GOOSE and SV protocols for learning.

III. Model of Demonstration

A. Power System Model

The first task in designing any protection and control system is to understand the power system that is being protected by the equipment. A basic substation model was developed consisting of a 345 kV line terminal, a 345 kV bus, a 345 / 138 kV transformer, two 345 kV breakers, and one 138 kV breaker shown in Figure 2. Typical locations for instrument transformers were identified, along with desired paths for instrument transformer values to protective relays providing typical protection functions. It was decided to not implement any directly redundant relaying, which would typically be found in industry at these voltage levels.



Labels

Breaker	Merging Units	Relays
B1	401-1	487B (a)
B2	401-2	487E (b)
B3	401-3	421-7 (c)

Figure 2 System Topology and Secondary Connections

After designing system topology, the next step is protection design, including needed relationships between instrument transformers, protective relays, and fault interrupting devices (in this case, circuit breakers). In a traditional substation, copper connections of protective relays to instrument transformers and DC status and control systems would be used to establish this relationship. Because this implementation is using 61850, all these relationships are implemented through publisher / subscriber relationships. Each stream or published message has fixed objects that are transmitted on the network The various currents, voltages, breaker status, breaker trip, and breaker close message contents are shown in Figure 3 and Figure 4. 52A represents the breaker status. The -1, -2, and -3 represent the three circuit breaker designations. The TR represents tripping commands. The CL represents closing commands.

Merging Units	401-1	401-2	401-3
Publishing	52A-1	52A-2	52A-3
	IW	IW	IW
	IX		IX - VY
Subscribing			
	TR-1a, TR-1b	TR-2b	TR-3a, TR-3c
	CL-1a, CL-1b	CL-2b	CL-3a, CL-3c

Figure 3 Merging Unit SV & GOOSE Message Content

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Relays	487-B (a)	487-E (b)	421-7 (c)
Publishing	TR-1a	TR-1b	TR-3c
	TR-3a	TR-2b	CL-3c
	CL-1a	CL-1b	
	CL-3a	CL-2b	
Subscribing			
	52A-1	52A-1	52A-3
	52A-3	52A-2	
	[Iw]-1	[Ix]-1	[Ix-Vy]-3
	[Iw]-3	[Iw]-2	

Figure 4 Protective Relay SV & GOOSE Message Content

B. *Network & Communication Model*

Communication between merging units and protective relays is critical for the operation of the protection system in a digital substation. Ethernet networks have many options for topology, limited by network switch port density and device port capabilities. There is also the consideration of communications priority, with SV and GOOSE messages having much more stringent latency requirements compared to, for example, remote access and event file transfer. Because of these differences, the team decided to implement two separate networks. One network, called the process bus, was used to carry SV, GOOSE, and PTP signals, all of which are critical to high-speed protection functions. A second network, called the station bus, was used for device terminal access and device configuration FTP file transfers. Since the network switches selected had sufficient port density, one network switch was implemented per network in a hub-and-spoke/star topology to the IEDs as shown in Figure 5 and Figure 6.

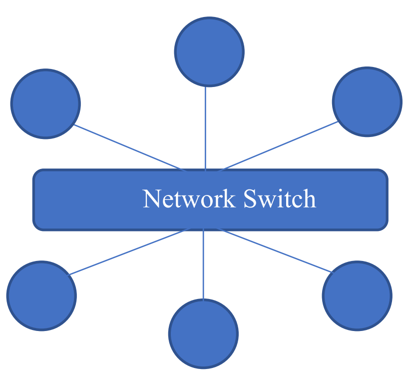

Figure 5 Hub and Spoke / Star Topology

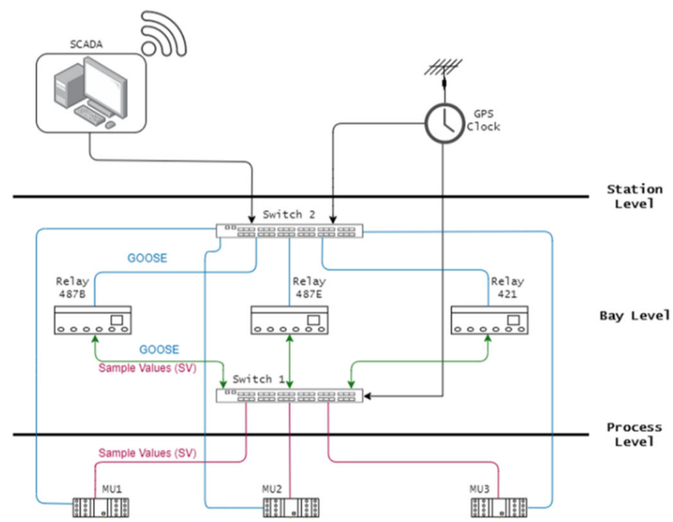

Figure 6 Digital Substation Network Topology

Redundant network switch configuration was considered but ultimately placed in the future activities plan.

SDN switches were selected. SDN offers a more secure approach to network design while maintaining low latency required for the process bus protocols.

Network interfaces were specified as 100BASE-T for ease of use and cost constraints. This also allowed training on how to physically craft copper Ethernet cables from components. If there had been a requirement for electromagnetic interference testing in this laboratory, the team would have selected 100BASE-FX interfaces.

IV. Implementation

Different challenges arose as the project moved from design into reality. Each of these challenges encountered led to learning opportunities. Some examples of these challenges included:

When equipment did not seem to be operating properly, a very warm device was identified. While reviewing the documentation for this device, specific rack spacing requirements were identified for cooling purposes that were not met in the original layout. Modification of the layout accomplished the required cooling, restoring device function.

As configuration of IEC 61850 protocol communications were undertaken, real-time learning about how these protocols actually functioned was required. The team had to learn about layer 2 multicast messages, including source and destination MAC addresses critical to GOOSE and SV operation.

Some issues identifying MAC source addresses led to understanding the best way to use a networking tool called Wireshark.

SDN provides very good security, but it can be a challenge to establish effective and secure flows required to support needed information flows. The FTP protocol was found to not be very compatible with flows, as it uses ephemeral network port designations at the whims of the devices communicating. All ports needed to be opened between two devices to allow FTP communication.

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A. Hardware: Protective Relays, Merging Units, GPS Clock, Network Switches

Protective relay hardware selected for protection of this virtual power system substation consisted of one line protection relay, one transformer protection relay, and one bus protection relay. Three merging units were selected for voltages and currents measurement to SV. These same devices provided process interface for breaker status and protection tripping/closing and control via GOOSE messaging. SV signals were published to the Ethernet network by the merging units for use by the protective relays subscribing to them on the network. Likewise, GOOSE messages were published and subscribed to by these protective relays and merging units.

Time synchronization was accomplished with IEEE 1588 PTP Power Profile, a protocol that uses the Ethernet network to achieve time synchronization between devices. A grandmaster clock was selected, referred to commonly as a GPS clock, which synchronized itself to GPS time and distributed it to the other devices on the network. The synchronization of devices publishing sampled values is critical. For this installation, synchronization of the merging units to a traceable time source is not as critical, since the SV publications are not leaving the local virtual substation. Nonetheless, a GPS antenna was connected to the clock for highly accurate traceable time synchronization.

This hardware, including network switches, was all mounted into a 19” portable rack to allow movement of the equipment between classrooms, office space, and meeting rooms as needed, shown in Figure 7.

Figure 7 Hardware Installation of IEDs in Rack and Test Set

B. Software Tools

Many tools are available for developing configurations for digital substations. There are also different levels of configuration for digital substations. Some are substation-level tools used to develop a substation-level SCD file. This file would contain a complete record of all GOOSE and SV publishers and subscribers, along with other engineering information such as bay associations and substation topology for primary equipment. Work to establish this laboratory focused more on device-level configurations and the associated vendor-provided tools. For IEDs, these tools allowed a direct method of setting up GOOSE and SV published messages and subscribers. For network devices, these tools provided methods to establish the correct flows in the SDN to allow the network messages to be sent through the network between specific devices. Multicast published messages (e.g. GOOSE, SV) were not transmitted to every IED, since the flows regulated the messages to only the required destinations, improving network efficiency. VLAN configuration was not needed with the establishment of proper SDN flows.

Other software tools were needed for troubleshooting. Network tools such as Wireshark are critical when trying to identify and correct problems with device configurations. Further discussion of challenges associated with using these troubleshooting tools will be covered in the section Testing Functionality: Simulation. Additionally, some commissioning tools consisting of specialized software running on hardware straddle the line between software and hardware tools which will also be covered in that section.

C. Configurations

IED configurations consisted of two parts. One was the traditional protection element configuration. The other was the 61850-protocol configuration for GOOSE messages and SV streams. Students were able to leverage existing training for development of the protection elements. The communications protocol configuration was not familiar. The configuration of GOOSE and SV established which messages are published by each device and what values are included in each. The configuration also included subscriptions for what messages were subscribed to from the network and where those messages get mapped into the native logic or analog values of the device. These configurations required multicast destination addresses to be established for each GOOSE message and SV stream publication. Destination addresses selected for each stream are listed in Figure 8. These addresses are used as the destination MAC addresses in each of the layer 2 frames transmitted on the network.

Each device had to subscribe to these published streams. Addresses for each of the GOOSE and SV stream subscriptions are listed in Figure 9.

		MAC Address Multicast Destination (Publish)	
	Device	**GOOSE**	**SV**
	Prefix	01-0C-CD-01-	01-0C-DC-04-
Final Two MAC Address Octets	MU1	10-01	10-01, 10-02
	MU2	11-01	11-01
	MU3	12-01	12-01, 12-02
	Bus	20-01	None
	Transf.	21-01	None
	Line	22-01	None

Figure 8 MAC Addresses Used for Multicast GOOSE and SV Streams

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		MAC Address Multicast Subscriptions	
	Device	GOOSE	SV
	Prefix	01-0C-CD-01-	01-0C-DC-04-
Final Two MAC Address Octets	MU1	20-01,21-01	None
	MU2	21-01	None
	MU3	20-01,22-01	None
	Bus	10-01,12-01	10-01, 12-01
	Transf.	10-01,11-01	10-02, 11-01
	Line	12-01	12-02

Figure 9 GOOSE and SV Subscriptions for Each Device

Finally, the SDN network equipment had to have proper flows established for each of these publications, to ensure they were transmitted as needed to the ports of the switch connected to subscribers. These flows were implemented with ports, multicast source address, and multicast destination addresses. This required determination of the source MAC addresses for the interfaces publishing the multicast messages, being most easily determined using Wireshark after published messages were configured.

V. Testing Functionality: Simulation

Here Simulation is performed in two steps:

Normal operation: Injection of normal secondary current and voltages, pre-fault values, is performed with the help of an available relay test set into the merging units with actual copper wire connections. Merging units convert analog inputs into digital data SV streams, sending them over the process bus network. Data is further routed through SDN switches to desired protective relays. During normal operation, no action is needed. Quiescent GOOSE data travels between IEDs.

Fault operation: Simulation of a three-phase balanced fault on the transmission line is performed where injected fault current is lagging the voltage and the current greatly increases to its short circuit level while the voltage sags during the fault based on the system impedance. Data flows from merging units over the network through SDN switches to the relays. After processing the data, the line distance relay publishes an asserted GOOSE trip command TR-3c. This command again gets transferred back to appropriate merging unit via the network. A built-in simulated breaker mechanism is included in the merging unit. After subscribing/receiving the published asserted GOOSE trip command, merging unit SEL 401-3 trips open simulated breaker 3 and isolates the system from the fault (an output assigned on the merging unit asserts for the trip, stopping the test set fault current injection).

OMICRON StationScout is a monitoring tool for GOOSE messages which includes a human machine interface (HMI). It was used to monitor the state of the simulation including breaker status, breaker trip, and breaker close signals published by all devices in the network. Station Scout simplifies the process of testing the automation, control, and SCADA communication in SAS utilizing IEC 61850. StationScout visualizes and analyzes the communication relationships and depicts the system topology in an intuitive manner.

VI. Areas of Future Development

We successfully implemented IEC 61850 standards for protection of our hypothetical power model. But our model is limited in size and complexity, and hardware is limited to only one manufacturer. Future work is recommended to increase the utilization of the rack as follows:

1. Development of formal laboratory exercises for student learning.
2. Laboratory expansion to demonstrate interoperability between different vendors' equipment.
3. Protection strategy reconfiguration to include the remote end station and even the digital substation architecture.
4. Add redundancy protocols for improved availability of the network grid.
5. A functional HMI will be implemented for good visual view of the state of the substation and to allow operator control. It can also provide monitoring of communication using some reporting features provided by the latest 61850 standards for LGOS Objects. No system integration tool was used during system design at the substation level, so adding this HMI will require use of a true system integration tool to properly configure MMS reporting.

VII. Conclusion

After successfully developing and implementing a fully digital substation laboratory, the need for different course material related to network and communications protocols was realized, which is not typically included in power program course plans. Given the dependence of IEC 61850 protocols on Ethernet networks, this material will be a critical part of power engineer training in the future. Training in the practical functioning of these protocols would also benefit engineers tasked with specifying, designing, implementing, and commissioning equipment that depends upon digital communication for operation. This project was a great learning opportunity for students seeking to learn more about 61850, and it is available now for future classroom use in the training of other future engineers.

VIII. Acknowledgement

The authors thank Schweitzer Engineering Laboratories, Manta Test Systems, Omicron Energy, and FirstEnergy for their donations and sponsorship of the Capstone Senior Design project.

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X. Biographies

Harpreet Kaur earned her B.S.E.E. from Cleveland State University in 2021. Harpreet was a member of the IEC 61850 Senior Design Project. She is currently pursuing her M.S.E.E. and is working at FirstEnergy Corporation as an engineer in the Substation Services Department. (h.kaur33@vikes.csuohio.edu)

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Dr. Allen G. Morinec, P.E. earned his B.E.E., M.S.E.E., and Ph.D. from Cleveland State University in 86, 89, 05. Dr. Morinec is an Adjunct Professor in the Department of Electrical and Computer Engineering at Cleveland State University where he instructs four power systems courses and was a faculty advisor for this Senior Design Project. He is employed at FirstEnergy and works in the areas of transmission and distribution power systems. where he is currently a supervisor in the Transmission and Substation Services Department, Protection & Control section. He is a registered professional engineer in Ohio and his fields of interest include protective relay & control, substation maintenance, FACTS devices, power quality, industrial & commercial power systems, and the National Electrical Code. Dr. Morinec is a Senior Member of the IEEE and was awarded the "IEEE Third Millennium Medal for Outstanding Support and Achievement". He served as an officer at various positions in the IEEE Cleveland Section, assisted in the development of 6 IEEE standards, and authored 20 journal and conference publications.

Aishwarya H. Gandhi earned her B.S.E.E.; M.S.E.E. from Cleveland State University in 2017 and 2019. Aishwarya is an Adjunct Professor at Cleveland State University Department of Electrical and Computer Engineering where she was also an industry advisor for this Senior Design Project. She works in the Transmission Planning and Protection Department at FirstEnergy Corporation as a protection engineer.

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