# DESIGN AND DEVELOPMENT OF IEC61850-ENABLED LABORATORY MODEL TO ENHANCE STUDENTS' UNDERSTANDING OF COMMUNICATION STANDARDS FOR POWER SUBSTATION AUTOMATION

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**ABSTRACT–**Educational technologies have enhanced teaching and learning in Engineering Education, especially in assisting engineering students to integrate theory and practice in a laboratory. The IEC61850 is a new International Electrotechnical Commission (IEC) standard for substation communication networks that is currently being introduced for substation automation projects in South Africa. This necessitates its incorporation into current power engineering curriculums, thereby enabling students to acquire the right graduate attributes required for the implementation and maintenance of this new communication standard. This paper presents the design and development of a laboratory model which is based on the structure of modern power substation automation systems. This model has served as an enabler for power engineering students to be exposed to the basics of networking and data communication over an Ethernet network for protection and control of substations using the new IEC61850 standard. For improved flexibility and availability, the model was transformed into a remote platform by linking it to the university's intranet, thereby making campus-wide access possible at any time of the day. This model supports pre- and post-laboratory work, enabling students to engage more with the course content which has led to a better cognitive understanding of this new communication standard.

**Keywords:** Substation automation; IEC61850; protection; remote platform.

## 1. INTRODUCTION

The advent of intelligent electronic devices (IEDs), and the technological advances made in power system primary equipment requiring the use of electronic boards, has allowed the incorporation of communication interfaces in high voltage apparatus. These developments have led to the use of powerful data highways in power substations, connecting protection, monitoring, control, metering and primary substation equipment (Kasztenny, Whatley, Udren, Burger, Finney, & Adamiak, 2006). This has led to the formation of one integrated system where information can be exchanged over a bus communication system, allowing for more effective operation of the power system (De Mesmaeker, Rietmann, Brand, & Reinhardt, 2005; Wester, Adamiak, & Vico, 2011).

However, until recently, the engineering of substation automation systems has been difficult due to the non-standardization in the field (Sidhu, Kanabar, & Parikh, 2008). Industrial automation requires specifications for the physical connection and protocols for the communication between the power system devices. Even though IEDs from different manufacturers may have the same electrical connection, such as an Ethernet port, they could not communicate effectively due to the different protocols (language), making it difficult to integrate devices from different manufacturers.

Standardized protocols now exist that allow IEDs from different manufacturers to communicate, including the IEC61850 standard, which has gained worldwide acceptance. Most manufacturers now incorporate IEC61850 interfaces into their devices, enabling interoperability between different vendors' products (Adamiak, Baigent, & Mackiewicz, 2009). The standard considerably simplifies the engineering and testing of substation automation systems and is future-proof as the services it provides are independent of the implementation technology (Andersson, Brunner, & Engler, 2003).

The evolution in power system technologies and practices now demands evolution in the graduate attributes of power engineering students (Schulz, 2011; Wajiha, Kotti, & Villanueva, 2013). In the past, protection work dealt primarily with physical wiring and discrete control. Now, most electrical wires in the substation are being replaced with high-speed communication links. Hence, today, protection work also involves dealing with data cables and virtual control and monitoring, requiring skills across disciplinary areas (Schulz, 2011).

These evolving power system technologies require that the power engineering curriculum be adapted to produce properly qualified and skilled technicians and technologists with the right graduate attributes to implement and maintain modern substation automation systems(Grice, Peer, & Morris, 2011). Literature suggests that academic institutions from across the globe are revising and adapting their curricula to meet the evolving industry demands (Wajiha, Kotti, & Villanueva, 2013). In this context, it is important for the protection practitioner, though not an information and communication technology (ICT) specialist, to have a working knowledge of networking and its various components.

## 2. PROBLEM STATEMENT

The IEC61850 standard was introduced into the senior undergraduate Bachelor of Technology (BTech) power engineering qualification at the authors' institution in 2011. The topic is covered in one of the seven required modules for this qualification, termed Electrical Protection IV. With its inception, the author came to realize that students were struggling in grasping the fundamental concepts and application of the standard. This realization was based primarily on the fact that students were not achieving the desired learning outcomes for this standard (see Table 1 for the learning outcomes).

**Table 5: Learning outcomes related to the IEC61850 standard in the module Electrical Protection IV**

| S/No | Learning Outcomes |
|---|---|
| 1 | Describe the current trends in substation automation and protection |
| 2 | Describe the communication architecture of the IEC61850 substation automation system |
| 3 | Identify the components making up the IEC61850 automation system |
| 4 | Contrast partial and full implementation of IEC61850 |
| 5 | Discuss the model of the IED in IEC61850 |
| 6 | Explain GOOSE messaging |
| 7 | Explain the process of integrating and configuring IEDs in an IEC61850 project |
| 8 | Identify the LNs and DAs participating in a given protection/bay control scheme |
| 9 | Apply software tools to the integration and configuration of IEC61850 automation projects |
| 10 | Explain the key benefits of the IEC61850 compared to traditional substation systems |

A possible reason for the low achievement may include the difficulty in understanding the architectural construct adopted by the standard. This includes "abstracting" the definition of data items and services; i.e., the standard creates data items/objects and services that are independent of any underlying protocols (Adamiak, Baigent, & Mackiewicz, 2009). These abstract definitions need to be mapped to real protocols, which proves difficult to understand for power engineering students.

## 3. AIM AND OBJECTIVES OF THE PROJECT

The main aim of the project presented in this paper was to investigate the effectiveness of using educational technologies to enhance students' understanding of communication standards in power substation automation. The specific objectives were to:

- Design and develop an IEC61850-enabled laboratory model based on the structure of modern power substation automation systems;
- Incorporation of remote functionality into the lab design to allow increased access and availability of the lab for experimentation, and addressing the issue of high student-to-resource ratio;
- Develop laboratory exercises on substation automation and communications using the IEC61850 standard; and
- Determine the students' perceptions on the usefulness and effectiveness of the laboratory model in the teaching and learning process.

## 4. RESEARCH DESIGN

The interpretive/qualitative perspective (Cohen, Manion, & Morrison, 2011) was chosen for this study as it allows the authors to adopt an exploratory orientation and arrive at an understanding of the subjective experiences of the students within the educational technology learning situation, and develop useful interpretations, or reality, of student interactions and experiences with the educational technologies. These interpretations provide new and helpful understandings of a context, and point to ways of addressing a problem (Jawitz & Case, 2009). Constructivism (Cohen, Manion, & Morrison, 2011) was also used as a theoretical framework to establish how students build their experiences and understanding when carrying out experiments in the lab. Constructivist learning theory is based on the assumption that learners actively construct knowledge and that knowledge cannot be passively transmitted (Moll, 2002). This approach assisted the authors in assessing how students use the activities to gain understanding of the communication standard. A questionnaire was created by the authors to gather data regarding the students' experiences.

### 4.1. Laboratory Design

It is generally accepted that engineering laboratories are essential for the educational experience (Feisel & Rosa, 2005). The practical work they offer enables students to achieve specific learning outcomes by allowing students to learn from their observations and experiences (Corter, Nickerson, Esche, Chassapis, Im, & Ma, 2007; Gravier, Fayolle, Bayard, Ates, & Lardon, 2008). Exposure to IEC61850-enabled experimental setups and implementation software may assist students in translating the abstract features of the standard into real solutions which they can see in practice. Through experimentation students would be able to organize the complex IEC61850 data items, recognizing the mapping and implementation patterns and drawing inferences for application of the standard to any protection and control automation scheme.

Knowledge of the services provided by the IEC61850 standard shows that the learning outcomes outlined in Table 5 can be achieved by designing a lab model that supports only two of the services, which are: (a) data/object modeling and (b) data communication. These services define how to describe the physical devices in an electrical substation and how to exchange the information between these devices at configuration and at run-time.

The effectiveness of the lab model requires that the design adheres to constructive alignment, where the lab exercises or tasks are aligned to the expected learning outcomes (Corter, Nickerson, Esche, Chassapis, Im, & Ma, 2007; Gravier, Fayolle, Bayard, Ates, & Lardon, 2008).

The lab model should facilitate and shorten the learning curve of the students on the use of the educational technology. Considering the high student numbers, incorporation of remote functionality will allow 'open' access to increase the lab's availability and flexibility for experimentation. Access to the lab from the classroom environment will aid the instructor in introducing the students to the hardware setup and software packages. The lab model should also allow the students to engage collectively with their peers, learning from each other, further developing communication, teamwork and leadership skills that are all essential in an engineering environment.

### 4.2. Data Collection

A questionnaire survey was used along with descriptive statistics to determine student feedback or perceptions on the usefulness and effectiveness of the IEC61850-enabled lab. The target population included all students registered for the Electrical Protection IV module during the first semester of 2015, which equated to 54 students. No sampling technique was required. However, of the 54 students, only 38 were available at the end of the semester to complete the paper-based survey. Participation was voluntary and anonymity was ensured by not requesting any personal student data.

## 5. THE IEC61850-ENABLED LABORATORY

### 5.1. IED Device Modeling in IEC61850

The substation automation system comprises many IEDs communicating over a network. Data items and objects (of the IEDs) that participate in the automation functions need to be identified through modelling. The IEC61850 model begins with a physical device (PD), which is the IED device that connects to the network, as illustrated in **Figure 1**.

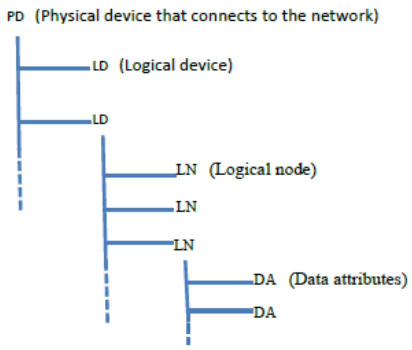


**Figure 1: Object model description of the IED in the IEC61850 (Manditereza)**

Each physical device contains one or several logical devices (LD), each representing a group of functions, for example protection, or control functions. The LD contains one or more logical nodes (LNs), or objects. Each LN breaks down further into data attributes (DA) that define the name, format, range, and representation of possible values related to some power system function, such as status or measurement. LNs are the core elements of the IEC61850 data model. A typical substation automation function is executed by different LNs exchanging information. For example, the following LNs are required to execute a distance protection function: distance protection LN (PDIS), current transformer LN (TCTR), voltage transformer LN (TVTR) and the circuit breaker LN (XCBR), as illustrated in **Figure 2**.

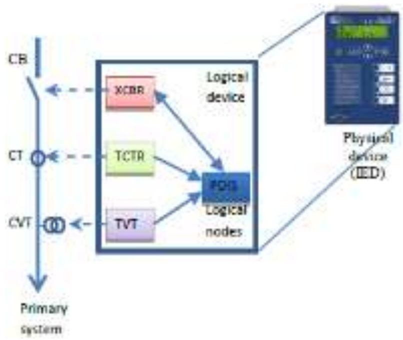


**Figure 2: Example of logical nodes participating in a protection scheme (Manditereza)**

There is a significant amount of configuration that is required in order to put all the objects together and have them work and to enable devices to respond to messages from other manufacturers' devices (Adamiak, Baigent, & Mackiewicz, 2009). Each IED has unique functions and other capabilities, such as available LDs, LNs and DAs. This information needs to be made available to other IEDs in the substation, including those from other manufacturers. This information is provided in the IEC61850 standard by means of the IED Capability Description (.ICD) file. Each IED participating in a substation project must be configured to specify its properties, resulting in the generation of a specific Configured IED Description (.CID) file. This configuration is facilitated by software tools proprietary to each manufacturer, and is illustrated in **Figure 3**. The configuration software tools currently available in the lab model are AcSELerator Architect and AcSELerator Quickset from Schweitzer Engineering Laboratories (SEL).

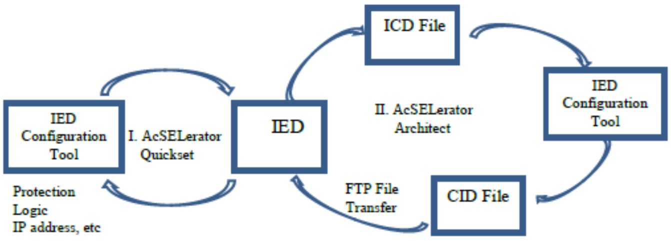


**Figure 3: IED configuration process (Manditereza)**

## 5.2. Laboratory Communication Architecture

The lab communication architecture is based on the IEC61850 architecture, as illustrated in **Figure 4** (De Mesmaeker, Rietmann, Brand, & Reinhardt, 2005). The architecture comprises two buses: the Station Bus (defined in IEC61850-8-1) and the Process Bus (defined in IEC 61850-9-2). However, the developed lab model only supports the Station Bus representing partial implementation of IEC61850. The Process Bus has not been implemented as the currently available IEDs do not have this interface. The lab effectively replaces the conventional hardwired logic necessary for intra-IED coordination with high-speed station bus communications, using GOOSE messaging. GOOSE is an acronym for Generic Object Orientated Substation Events and is an IEC61850 object for high-speed control messaging.

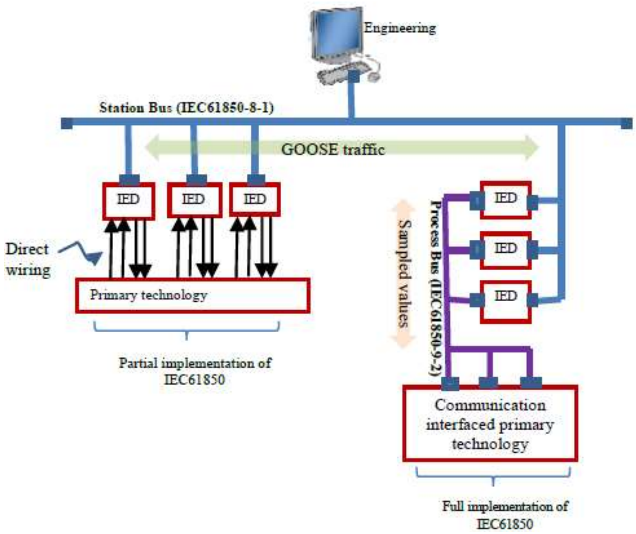


**Figure 4: IEC61850 substation communication architecture (Adapted from De Mesmaeker, Rietmann, Brand, & Reinhardt, 2005)**

## 5.3. Information Exchange with GOOSE

GOOSE messaging supports the exchange of a wide range of common data organized by data sets (Schweitzer Engineering Laboratories, Inc., 2014). Setting up of the IEC61850 communication is limited to stating the IP addresses for each individual device, and specifying what GOOSE messages these IP addresses will receive or transmit, using the IED engineering tools.

Upon detecting an event, an IED uses multi-cast transmission to broadcast GOOSE messages containing status, controls, and measured values onto the network for use by other devices. Only subscriber devices that have registered, through proper configuration, receive the data. The reaction of each receiver will depend on its configuration and functionality, such as tripping of switchgear, starting of disturbance recorder, or providing position indication for interlocking.

## 6. THE DEVELOPED LABORATORY MODEL

The architecture of the lab model developed by the authors is shown in Figure 5. Hard-wired connections are used between instrument transformers and the analog inputs of the IEDs, as well as IED binary outputs and the control inputs. Communication over the Station Bus is used for message exchange between IEDs. The lab Ethernet network includes a star topology centered on an Ethernet switch, comprising four major components: an industrial computing platform (SEL-3354), an automation and control platform (SEL-3530), a range of IEDs from SEL, and automatic relay test sets. The installed Ethernet cards in the devices support the latest industry communication tools including Telnet, FTP, DNP3 protocols and IEC61850.

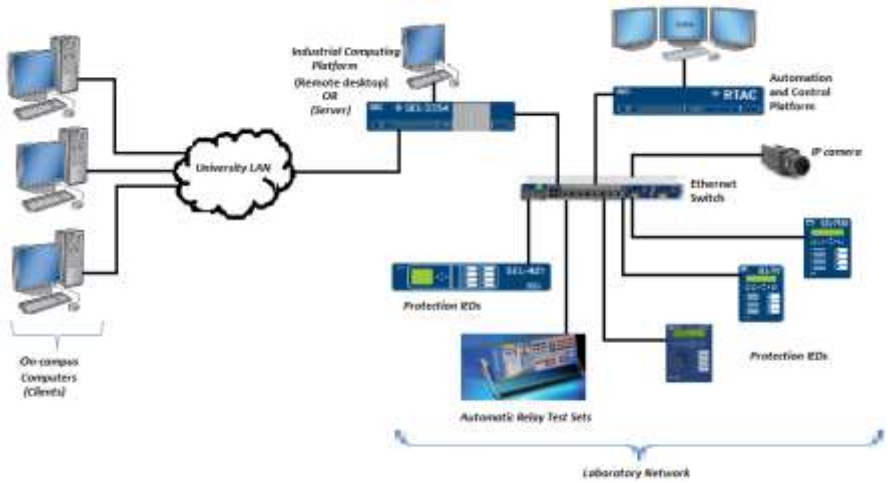


**Figure 5: Architecture of the IEC61850-enabled laboratory (Manditereza)**

The IEDs and test sets are supplied with the appropriate proprietary communication and application software necessary for the integration and configuration of IEC61850 substation automation systems.

### 6.1. The Remote Lab Platform

The Ethernet-based network architecture provided the opportunity to expand the boundaries of the lab model to include any computer on the university's intranet (see **Figure 5**). This was simply achieved by linking the lab model to the already existing university local area network (LAN). The ICT infrastructure of the university allows for wired or wireless connection to the lab model. This development effectively transformed the lab model into a remote lab platform providing all the functionality of the lab, including the IEC61850-based work. A webcam was added to stream live video footage that enables students to observe the IEDs in real-time, making the remote lab platform more realistic.

The remote lab platform is available to students for pre- and post-lab work, and to repeat the lab session where necessary. Students are required to book a timeslot, manually, through the lab instructor. However, the remote lab platform supports only one group of students at a time, as it will not make sense to have multiple accesses where conflicts will arise with the shared experimental setup. Connection is made using the remote desktop application to the host computer in the lab. Students may then access all the software tools necessary to perform the lab tasks, creating a virtual lab environment.

This remote lab platform also addresses the problem of high student-to-resource ratios by making the lab available24 hours a day, thereby enabling access outside the normal scheduled lab sessions. Students have the flexibility to form groups and access the lab at suitable times of their choosing within the assignment delivery period, and may experiment or explore without constraints. Using group work, students have the opportunity to take charge of their learning and collaborate and solve engineering related problems through teamwork. Problem solving and teamwork are essential graduate attributes mandated by the International Engineering Alliance (2013).

The effectiveness of a remote lab platform is, though, still a matter of debate (Ma & Nickerson, 2006). This debate is scattered across different scientific and engineering domains looking at the issue from different perspectives. There is, however, no clear criterion that may be used to evaluate the effectiveness of ALL the learning outcomes of different remote lab platforms. Hence, comparisons, in most cases, are based on different individual learning objectives or outcomes for each type of lab (Ma & Nickerson, 2006; Corter, Nickerson, Esche, Chassapis, Im, & Ma, 2007). However, some studies (Sonnenwald, Whitton, & Maglaughlin, 2003; Nickerson, Corter, Esche, & Chassapis, 2007; Ionescu, Fabregas, Cristescu, Dormido, & De Keyser, 2013) have shown that remote lab platforms are comparable in their effectiveness of delivering specific learning outcomes, as compared to traditional labs. Other evaluations of these remote lab platforms have focused on student perceptions and not necessarily on the learning that has been achieved (Corter, Nickerson, Esche, Chassapis, Im, & Ma, 2007).

It must though be noted that most advanced engineering work in a lab or workplace is mediated by computers and the requisite software. Hence, and especially for an electrical protection practical exercise, the difference between experimenting through software while sitting at a computer on-site in the lab, and sitting at a computer remote from the lab and observing the lab via webcam, may just be the psychological sense of physical presence in the lab, as argued by Ma and Nickerson (2006). The increased availability of open-access lab models enables students to engage more with the course content which leads to better cognitive understanding, as argued by Ionescu, et al (2013).The remote lab model further enables the effective management of large groups of students with varying abilities, ensuring student engagement and participation in the lab work. This is achieved through properly designed lab exercises that are aligned with the core learning outcomes of the lab work (Maiti & Tripathy, 2013).

## 7. IEC61850-BASED LABORATORY EXERCISES

### 7.1. Range of possible lab exercises

Lab exercises have been developed that are aimed at exploring data modelling and data communication using the IEC61850 standard. It is important to note that students must be able to apply the standard in the implementation of substation protection and control schemes. Table 2 provides a list of exercises that can be performed in regard to the IEC61850 standard. An exciting feature of all the identified lab exercises in Table 2 and the relevant software tools is that they have real world relevance, resulting in possible motivation for students to investigate and 'play' with the standard under the lab environment. This experience would be crucial to ensure successful integration into the field of work. The specific lab exercises described in the next section relate to breaker failure, listed 8 in Table 2.

**Table 6: List of possible laboratory exercises**

| S/No | Laboratory Exercises |
|---|---|
| 1 | Integration and configuration of IEC61850 substation automation systems |
| 2 | Activate GOOSE message |
| 3 | Publish GOOSE message |
| 4 | Receive GOOSE message |
| 5 | Implementation of protection schemes (o/c, line differential, distance protection, etc.) |
| 6 | Switchgear interlocking |
| 7 | Synchronization |
| 8 | Inter-tripping/Breaker Failure |
| 9 | Performance testing of IEC61850 |
| 10 | Ethernet topologies |
| 11 | Network analysis |

### 7.2. Communication-based breaker failure scheme

One of the lab exercises is based on the implementation of a communication-based breaker failure scheme for a substation, which is modeled on a single line diagram illustrated in **Figure 6**. Students should be able to integrate and configure the IEDs and verify GOOSE messaging for the automated IEC61850 substation.

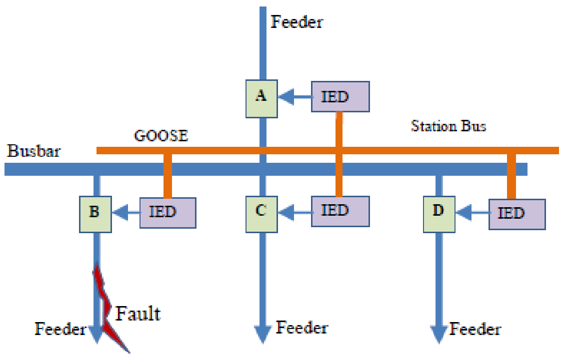


**Figure 6: Substation single line diagram (Manditereza)**

The substation consists of a single busbar and four feeders protected by the IEDs (A through D). A fault is simulated on feeder B, with possible current infeed from all feeders depending on the configuration of the interconnected system. The overcurrent element in IED B will sense the fault and send a signal to trip the local circuit breaker, simultaneously transmitting a GOOSE message to the other IEDs (A, C and D). These three IEDs will immediately initiate the breaker failure timer. If circuit breaker B fails to open and the breaker failure timer expires, IEDs A, C and D will open their respective breakers. In the event of the GOOSE message being lost or not received, IEDs A, C and D will trip according to their overcurrent protection settings, but in extended time. To monitor the progress of the scheme, the participating data attributes and selected logical variables and other bits are used to map the events to target LEDs on the front panel of the IEDs.

Additional lab practice is provided by configuring IEDs A, C and D to send an acknowledgement message to IED B that the “breaker failure initiate” signal was received. IED B acknowledges these three messages and maps the subscribed data item to a target LED on the front panel. However, it should be noted that the IEC61850 GOOSE object does not have an acknowledgement mechanism to confirm to the publishing IED that the message was received. Instead, the GOOSE messages are re-transmitted multiple times by each IED, but with longer intervals for each re-transmission. A virtual wiring diagram for the breaker failure scheme is shown in **Figure 7**. This diagram helps to identify the GOOSE messages as well as the logical variables, timers and outputs that would be required to implement the scheme. The tasks involved in setting up this breaker failure scheme can be split into two lab exercises which are discussed next.

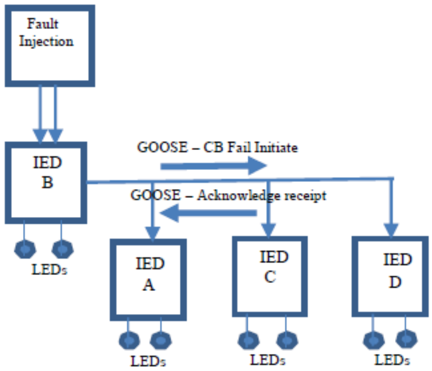


**Figure 7: Virtual wiring diagram for breaker failure scheme (Manditereza)**

### 7.2.1. Exercise 1: Configuration of the IEDs

Tasks for the first exercise are described in Table 3 which must be read in conjunction with **Figure 3**.

**Table 7: Exercise 1 Tasks**

| S/No | Task |
|---|---|
| 1 | Apply the given overcurrent protection settings. |
| 2 | Specify IED IP address of the participating IEDs. |
| 3 | Create the data sets according to the participating LNs. |
| 4 | Configure the GOOSE message published by IED B for breaker failure initiation. |
| 5 | Configure the subscribed GOOSE messages for IEDs A, C and D. Each of the IEDs A, C and D will subscribe to the single GOOSE message published by IED B. |
| 6 | Map relay trip and GOOSE transmitted events to target LEDs on the front panel of IED B. |
| 7 | Map GOOSE receive events for IEDs A, C and D to the target LEDs on the front panel of each IED. |
| 8 | Configure IEDs A, C and D to send acknowledgement messages to IED B that breaker fail initiate signal was received. IED B subscribes to these three messages and maps the subscribed data item to a target LED on the front panel. |
| 9 | Download the CID files into the IEDs. |

The AcSELerator Quickset software is used to configure the IED properties and overcurrent protection functionality. AcSELerator Architect software is then used to configure the IEDs to obtain the .CID files. These .CID files describe the GOOSE messages published and subscribed by each IED. The various events (relay trip, GOOSE broadcast and receive) are mapped to target LEDs on the front panel of the IEDs to ensure a visual representation of the events.

### 7.2.2. Exercise 2: Verification of GOOSE messaging and breaker failure protection scheme

Tasks for the second exercise are given in **Table 8**, and need to be read in conjunction with Figure 6. A current injection set is used to simulate a 3-phase fault into IED B. The various events are monitored on LEDs on the front panel of the IEDs to which the various logical variables and bits are mapped.

**Table 8: Exercise 2 Tasks**

| S/No | Task |
|---|---|
| 1 | Inject 3-phase fault currents (above pick-up current) into IED B |
| 2 | Verify IED B trip |
| 3 | Verify GOOSE message broadcast – IED B |
| 4 | Verify GOOSE message received – IEDs A,C,D |
| 5 | Verify acknowledge GOOSE message send – IEDs A,C,D |
| 6 | Verify acknowledge GOOSE message received – IED B |

## 8. STUDENT EXPERIENCES

The IEC61850-enabled lab model has been used for the Electrical Protection IV course in the BTech programme since 2014. Prior to 2014, the IEC61850 standard was taught exclusively from a theoretical perspective in the classroom with no practical component. The author realized that this approach was not conducive to helping students understand the fundamental concepts and application of the standard. The author therefore implemented the remote lab platform to ensure that students integrate theory and practice in a power engineering curriculum.

The remote lab platform has now been used for two semesters (duration of 12 weeks each) during which improvements were made to the quality and delivery of the exercises and the instruction material. The lab experiments are conducted during scheduled lab sessions, but the students are also able to access the remote lab platform after hours. The remote lab platform is introduced in the classroom to familiarize students with its operation. This enables a live, interactive online practical demonstration of the remote lab model, during which the students are introduced to the application software and the IEDs. The structure of the IEDs is explained and the use of the software is demonstrated in terms of how to apply the relay settings and integrate and configure the IEDs.

At the conclusion of the first semester of 2015, a questionnaire survey was provided to the students to obtain their feedback or perceptions of the IEC61850-enabled lab. The main aim of the survey was to determine if students were benefiting from the remote lab platform and to determine students' opinion on the usability of the lab, in the context of the expected learning outcomes. An international standard (ISO 9241-11:1998) defines usability as the "extend to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use" (Chung & Sahari, 2015, p. 167).

The survey questions were divided into three categories: effectiveness, efficiency and satisfaction. A five-point Lickert-scale was used with answer ranging from "Strongly Disagree" to "Strongly Agree". The survey questions are listed in Table 9 with the corresponding answers of the sample (n = 38) shown in Figure 8.

**Table 9: Post-lab survey questions**

| S/No | **Survey Question** |
|---|---|
| | **Category: Effectiveness** |
| Q1 | The lab helped me to better understand the purpose of the IEC61850 standard |
| Q2 | The lab helped me to better understand IED modelling in IEC61850 |
| Q3 | The lab helped me to better understand GOOSE messaging |
| Q4 | The lab helped me to better understand the use of the configuration tools |
| | **Category: Efficiency** |
| Q5 | The lab provides flexibility (time/location) to efficiently perform and complete the exercises without constraints |
| Q6 | The lab provides the environment to work and learn quicker in small groups |
| | **Category: Satisfaction** |
| Q7 | The lab helped me gain confidence in applying the standard to protection schemes |
| Q8 | The lab motivated me to learn more about the IEC61850 |
| Q9 | I enjoyed the laboratory experience |

As can be seen from Figure 8, more than 80% of the students perceived the remote lab platform to be effective in enhancing understanding of the IEC61850 standard with regard to purpose, device modeling and GOOSE messaging. It also helped students to correctly use the configurations tools to create and implement the IEC61850 project (Q4 in Figure 8). The results further indicate that more than 85% of the students could efficiently and quickly complete the lab exercises which were enhanced by the flexibility afforded by the remote 'open' access platform. More than 80% of the students also indicated that the remote lab platform afforded them the ability to work in small groups (Q6 in Figure 8).

Students expressed satisfaction with the remote lab platform, although an increased number of students returned a "neither agree nor disagree" assessment (Q7 in Figure 8). This suggests that students require more practical hands-on training in boosting their confidence in using the IEC61850 automation systems. However, more than 90% of the students enjoyed the lab exercises, while 75% were motivated enough to learn more about the standard.

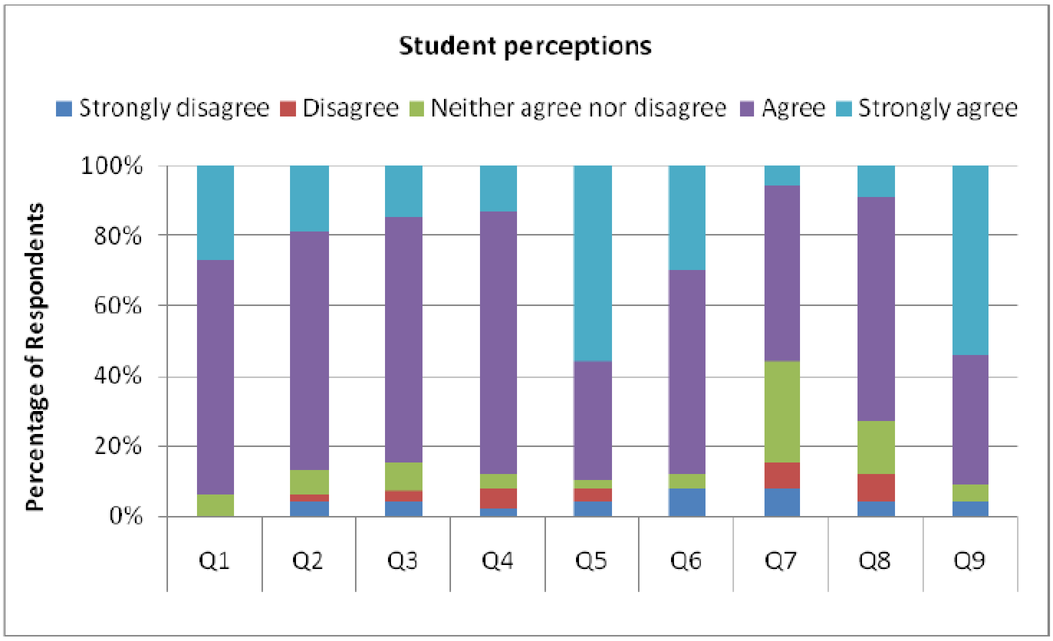


**Figure 8: Results of the survey on student perceptions of the laboratory work**

A few students, with prior exposure to the IEC61850 standard through work experience, gave some additional comments in which they stated that they finally had a clearer understanding of the IEC61850 fundamental concepts and its application. One student noted that "he could now see what was going on". The remote lab platform offered them the opportunity to explore under real life environments something which they cannot do in a real operational power substation.

## 9. CONCLUSION

This paper presented the design and development of a lab model which is based on the structure of modern power substation automation systems. This remote lab platform facilitates teaching and learning of the IEC61850 standard for power substation automation. A wide range of IEC61850-based lab exercises can be implemented on this platform to enhance understanding of the standard. The remote lab platform offers increased availability and 'open' access, allowing students to engage more with the course content which has led to a better cognitive understanding of this new communication standard. Feedback from the students is generally positive and confirms satisfaction with the remote lab platform as an effective and flexible way of learning and experiencing the IEC61850 standard. The remote platform concurrently addresses the issue of high student-to-resource ratios, further allowing the students to work in smaller groups.

The results of student perceptions presented in this paper have shown that educational technologies can positively impact on the learning experience of students, and should be implemented in all fields of study, supported by well-structured sets of learning outcomes and activities necessary to achieve the specified outcomes. Educational technologies motivate students to learn by allowing them to observe and experience the underlying concepts from a real-life perspective, essentially bridging the gap between the concepts and their real-life effects. However, the results of this study are limited in that student perceptions alone do not necessarily give a measure of the learning that has taken place or whether the educational technology has contributed to enhanced achievement of learning outcomes. Further research is needed to establish the trend in actual academic achievement of the students, pre- and post-lab development, to get more reliable evidence of the effectiveness of the educational technologies, the IEC61850-enabled lab in this case, in enhancing teaching and learning. The results of this further study will be presented in a future paper.

**REFERENCES**


Adamiak, M., Baigent, D., & Mackiewicz, R. (2009). *IEC61850 Communication Networks and Systems in Substations: An Overview for Users.* Retrieved October 2014, from GE Digital Energy: http://www.gedigitalenergy.com/multilin/journals/issues/spring09/iec61850.pdf

Andersson, L., Brunner, C., & Engler, F. (2003). Substation Automation based on IEC61850 with new process-close Technologies. *IEEE Bologna Power Tech Conference* (pp. 1-6). IEEE.

Chung, T. K., & Sahari, N. (2015). Utilitarian or Experiential? An Analysis of Usability Questionnaires. *International Journal of Computer Theory and Engineering, Vol. 7, No. 2*, 167-171.

Cohen, L., Manion, L., & Morrison, K. (2011). *Research methods in education.* 7th Ed. London: Routledge.

Corter, J. E., Nickerson, J. V., Esche, S. K., Chassapis, C., Im, S., & Ma, J. (2007). Constructing reality: A study of remote, hands-on and simulated laboratories. *ACM Transactions on Computer-Human Interaction*, 14(2), Article 7.

De Mesmaeker, I., Rietmann, P., Brand, K. P., & Reinhardt, P. (2005). Practical consideration in applying IEC61850 for Protection and Substation Automation Systems. *GCC Power 2005 Conference and Exhibition*, (pp. 1-8). Doha.

Feisel, L. D., & Rosa, A. J. (2005). The Role of the Laboratory in Undergraduate Engineering Education. *Engineering Education*, 121-130.

Gravier, C., Fayolle, J., Bayard, B., Ates, M., & Lardon, J. (2008). *State of the art about remote laboratories paradigms – foundations of ongoing mutations*. Retrieved June 2, 2014, from International Journal of Online Engineering 4(1): http://www.online-journals.org/index.php/i-joe/article/view/480/391

Grice, A., Peer, J. M., & Morris, G. T. (2011). Today's aging workforce — Who will fill their shoes? *64th Annual Conference for Protective Relay Engineers* (pp. 483-491). IEEE.

International Engineering Alliance. (2013). *Graduate Attributes and Professional Competencies.* Retrieved 05 2015, from http://www.ieagreements.org/IEA-Grad-Attr-Prof-Competencies.pdf

Ionescu, C. M., Fabregas, E., Cristescu, S. M., Dormido, S., & De Keyser, R. (2013). A remote laboratory as an innovative educational tool for practicing control engineering concepts. *IEEE Transactions on Education*, 436-442.

Jawitz, J., & Case, J. (2009). Communicating your findings in engineering education: the value of making your theoretical perspective explicit. *European Journal of Engineering Education*, 1-6.

Kasztenny, B., Whatley, J., Udren, E. A., Burger, J., Finney, D., & Adamiak, M. (2006). IEC61850 - A Practical Application Primer for Protection Engineers. *Power Systems: Advanced Metering, Protection, Control, Communication, and Distributed Resources* (pp. 18-50). IEEE.

Ma, J., & Nickerson, J. V. (2006). Hands-on, simulated, and remote laboratories: A comparative literature review. *ACM Computing Surveys*, Article 7.

Maiti, A., & Tripathy, B. (2013). Remote laboratories: Design of experiments and their web implementation. *Educational Technology and Society*, 220-233.

Moll, I. (2002). Clarifying constructivism in a context of curriculum change. *Journal of Education*, 5-32.

Nickerson, J. V., Corter, J. E., Esche, S. K., & Chassapis, C. (2007). A model for evaluating the effectiveness of remote engineering laboratories and simulations in education. *Computers & Education*, 708-725.

Schulz, N. N. (2011). Integrating smart grid technologies into an electrical and computer engineering curriculum. *Innovative Smart Grid Technologies Asia (ISGT)* (pp. 1-4). Perth: IEEE PES.

Schweitzer Engeineering Laboratories, Inc. (2014). SEL-700G Generator and Intertie Protection relay. *Use Instruction Manual*.

Sidhu, T. S., Kanabar, M. G., & Parikh, P. P. (2008). Implementation Issues with IEC61850 Based Substation Automation Systems. *5th National Power Systems Conference (NPSC).* Bombay.

Sonnenwald, D. H., Whitton, M. C., & Maglaughlin, K. L. (2003). Evaluating a scientific collaborator: Results of a controlled experiment. *ACM Transactions on Computer-Human Interaction*, 150-176.

Wajiha, S., Kotti, R., & Villanueva, J. A. (2013). Smart Grid, Industry Trends and Power Engineering Education. *120th ASEE Annual Conference & Exposition* (p. Paper ID#7132). Atlanta: American Society of Engineering Education.

Wester, C., Adamiak, M., & Vico, J. (2011). IEC61850 - Practical Applications in Industrial Facilities. *Industry Applications Society Annual Meeting* (pp. 1-7). Orlando, FL: IEEE.