Functional Testing of Centralized IEC 61850 Based Protection and Control Systems

Alexander Apostolov, Eugenio Carvalheira

OMICRON electronics, USA

alex.apostolov@omicronenergy.com

1. Introduction

In order to perform the testing of a centralized substation protection, automation, and control system (CSPACS) we need to first analyze what are the components of the system and the reasons for the tests. The requirements for commissioning testing are quite different from the requirements for maintenance testing and they depend on the implementation of the centralized protection and control system. This is because the processing of the analog and binary signals from the substation equipment in the yard is performed by different devices that are connected to the central unit using fiber optic cables. These devices we can call process interface unit (PIU). The process interface devices can be with different levels of complexity depending on which process interface functions they are implementing.

Here we use the following naming conventions:

- Merging Unit (MU) converts analog signals (currents and voltages) into time-synchronized streams of sampled values according to IEC 61850-9-2 of IEC 61869
- Switchgear Interface Unit (SIU) provides a binary status and control interface for circuit breakers and switches
- Non-Electric Interface Unit (NEIU) converts analog signals from non-electric sensors into time-synchronized streams of sampled values according to IEC 61850 9-2 or GOOSE messages according to IEC 61850-8-1
- Process Interface Unit (PIU) combines two or more of the functions listed above
- Process Interface IED (PIIED) combines the functionality of a PIU with local protection, control and/or other non-interface functions

The different process interface devices communicate with the central substation device using the required IEC 61850 services. The communications architecture depends on the specifics of the substation and the requirements for performance, reliability, and security. Redundancy protocols such as PRP are used to improve the reliability of the system. All components of the CSPACS are time-synchronized based on IEC 61850-9-3 (a PTP profile).

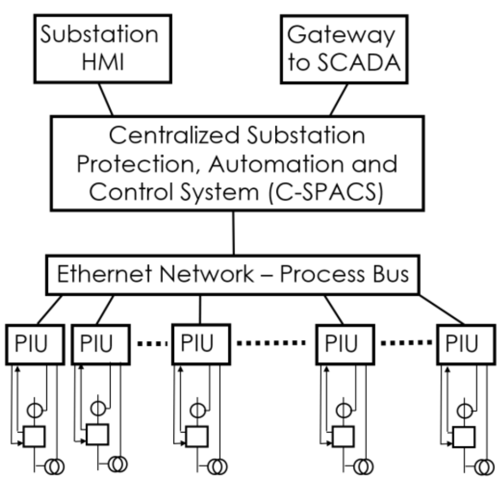

Fig 1 Digital substation with CSPACS

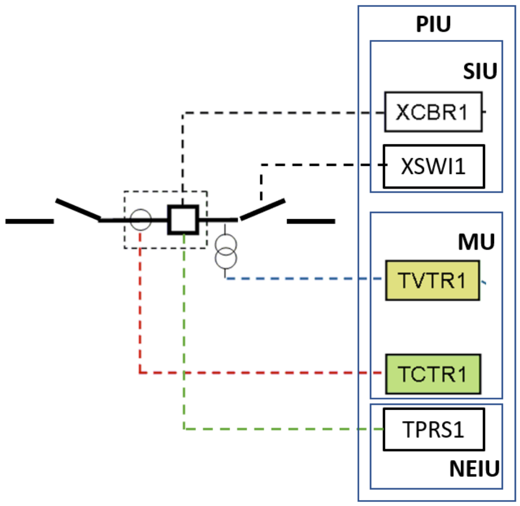

Fig 2   Process Interface Unit (PIU)

The engineering of an IEC 61850 based digital substation with centralized PACS is based on the System Configuration Language (SCL) defined in IEC 61850-6. The introduction of the IED Specification Description (ISD) file and the development of the virtual IED (vIED) concept allows the engineering of a digital substation independent of the actual implementation, including centralized. The engineering of the system needs to take under consideration the integration of the test system which can be used for maintenance testing after the substation is energized. The connectivity of the communication interfaces of the test system to the centralized substation PACS network has to determine where it will be connected and what functionality it will perform.

The engineering process should be based on an object-oriented design approach according to the standardized protection, automation, and control schemes for the different types of bays in a high voltage substation. Figure 6 shows a simplified one-line diagram of a substation and several types of bays, such as a transformer bay or a distribution feeder bay.

Each of the standard bays should be associated with a virtual IED containing logical devices representing the implemented functions, such as:

- Protection
- Automation
- Control
- Measurements
- Monitoring
- Recording

The functional testing of each of these functions must be defined using a standardized test plan that applies to the virtual IED associated with the standardized bay implementation.

Figure 3 Shows a simplified substation one-line diagram with transmission line bays, transformer bays and distribution feeder bays.

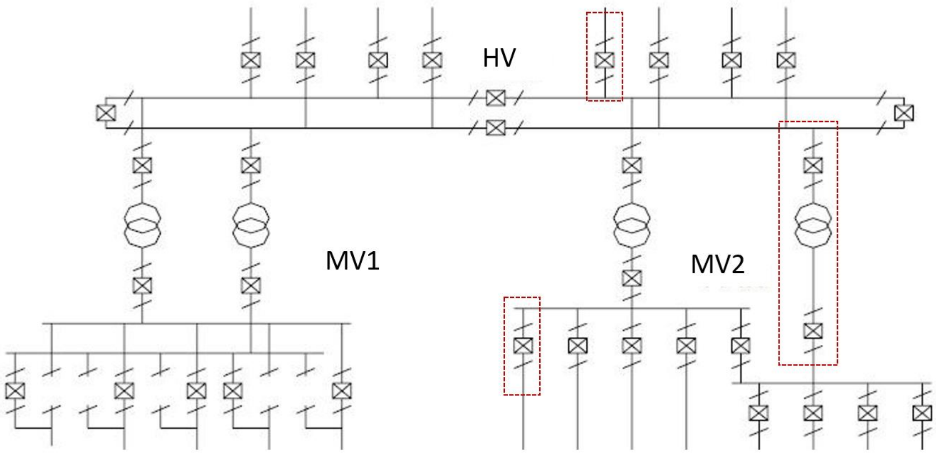

Fig 3 Substation one-line diagram with standard bays

Figure 4 shows an example of a virtual IED for a distribution feeder. It contains four logical devices representing the main function groups:

LD PROT – this is the distribution feeder protection function

LD CTRL – this is the distribution feeder control function

LD MEAS – this is the distribution feeder measurement's function

LD RCRD – this is the distribution feeder protection function

Each of these logical devices may have a single layer or nested hierarchy depending on the complexity of the implemented functionality. In the example the LD PROT contains an overcurrent protection sub-function LD ocp, which then contains a ground and phase overcurrent sub-functions (LD gnd and LD phs). The overcurrent protection function elements (PIOC and PTOC) are contained in these logical devices.

This hierarchical data model is very important for centralized protection and control systems because it allows the testing of individual logical nodes or at any level of the nested logical devices hierarchy.

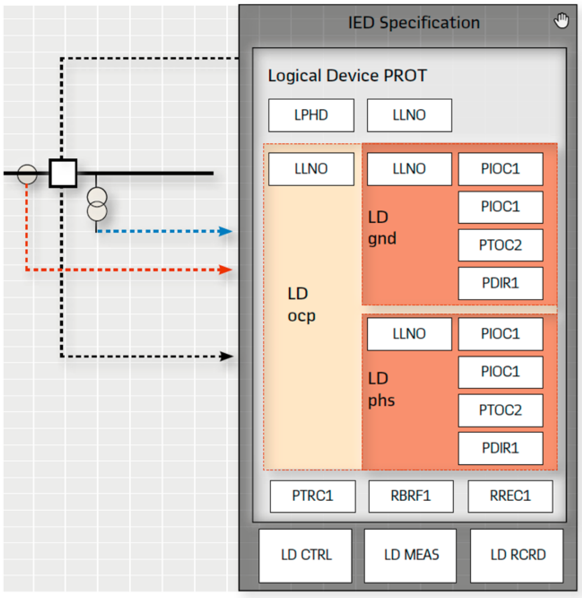

Fig 4 Distribution feeder virtual IED model

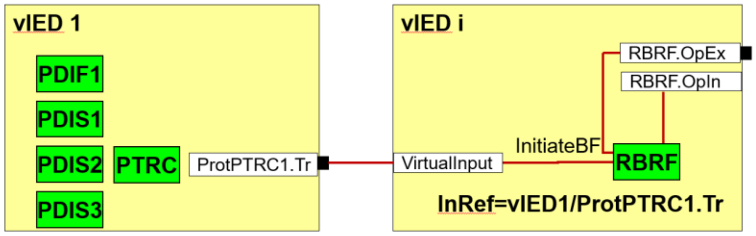

Fig 5 Signal flow definition

Figure 5 shows and example of the signal flow between vIED 1 and vIED I to initiate the breaker failure function from ProtPTRC1.Tr into the virtual input InRef of RBRF of vIED i. This signal flow in this case will be executed over the digital data bus of the substation server, but it also needs to be included in the GOOSE message published over the substation LAN to be visible by the process interface devices and the test system.

The data flow defined in the system configuration language (SCL) file is used by the test system to determine what messages will be simulated and subscribed to in order to perform the testing of the protection and control system or any of its components.

2. Testing of Centralized Protection Systems

The testing of CSPACS depends on the purpose of the test. It has many similarities, but also some differences in comparison with distributed digital substations.

While the testing of the different functions of CSPACS during the design and acceptance testing is not very different from the functional testing of multifunctional IEDs with high-levels of integration in digital substations, the more challenging testing is for commissioning and maintenance.

During commissioning one of the most important goals is to ensure that the interfaces to the process are properly connected. This requires primary injection as shown in Figure 6. The test system then compares the reported by the measuring function elements MMXU of the CSPACS magnitudes and angles of the injected currents and voltages to ensure that all connections are correct.

The functional testing of the different protection functions of the CSPACS should be based on the “White box testing” method. In this case the test system is not only concerned with the operation of the test object under the test conditions, but also views its internal behavior and structure. In the case of a centralized protection system, it means that it will not only monitor the operation of the system at its function boundary, but also monitor the exchange of signals between different components of the system.

The testing strategy allows us to examine the internal structure of the test object and is useful in the case of analysis of its behavior, especially when the test failed.

In using this strategy, the test system derives test data from examination of the test object’s logic without neglecting the requirements in the specification. The goal of this test method is to achieve high test coverage through examination of the operation of different components of a complex function and the exchange of signals or messages between them under the test conditions.

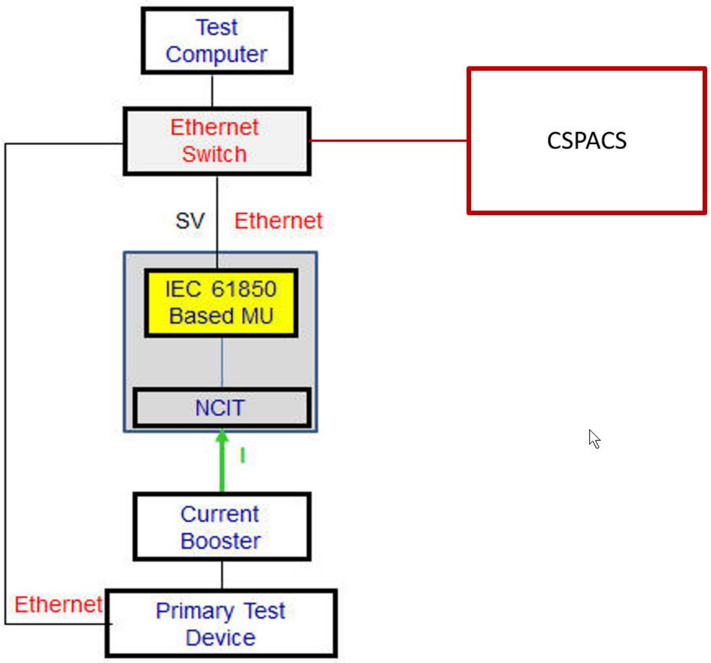

Fig 6 Commissioning testing

This method is especially useful when we are testing distributed functions based on different logical interfaces within a centralized protection and control system. The observation of the behavior of the sub-functions or functional elements is achieved through monitoring of the exchange of messages between the components of the test object Which will not be visible if we are doing the traditional black box testing of the protection and control system.

In the case of protection system, it means that it will not only monitor the operation of the system at its function boundary, but also monitor the exchange of signals between different components of the system visible as data objects or attributes published by the different logical devices of the CSPACS.

The test scenarios however do not have to be different from the ones used under black box testing.

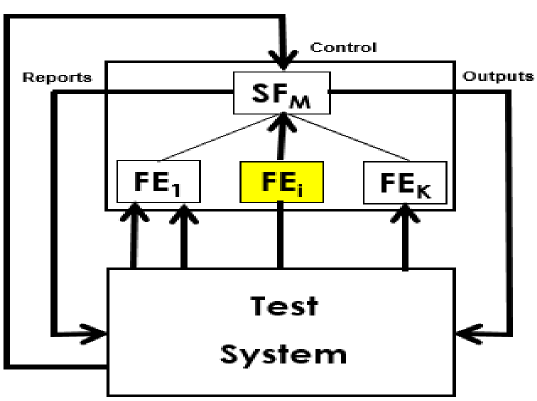

Fig 7 White box testing

In IEC 61850 based systems white box testing is fairly easy to achieve based on the subscription to GOOSE messages whose data sets contain data attributes representing the status of all function elements that are used in the implementation of the tested function (for example SF_M on Figure 7).

The testing strategy allows us to examine the internal structure of the test object and is useful in the case of analysis of its behavior, especially when the test failed.

3. Testing Features in IEC 61850 Edition 2

To support the testing of IEC 61850 system components in energized substations, Edition 1 of the standard already had many different features that could be used for testing. These features included:

- The ability to put logical nodes or logical devices in a test mode
- The possibility to characterize a GOOSE message as a message being sent for test purpose
- The possibility to characterize a service of the control model as being sent for test purpose
- The possibility to flag any value sent from a server in the quality as a value for test purpose

However, Edition 1 was not very specific on how to use these features. Therefore, they were not supported by all vendors since interoperability could not be guaranteed.

This has been improved with Edition 2. Besides more detailed specifications on how to use the existing features, additional features have been added.

3.1 Test mode of a function

A logical node or a logical device can be put in test mode using the data object **Mod** of the LN or of LLN0. The behavior is explained in Figure 8 and Figure 9. A command to operate can be either initiated by a control operation or by a GOOSE message that is interpreted by the subscriber as a command. If the command is initiated with the test flag set to FALSE, it will only be executed if the function (LN or logical device) is "ON". If the device is set to test more, it will not execute the command (Figure 8).

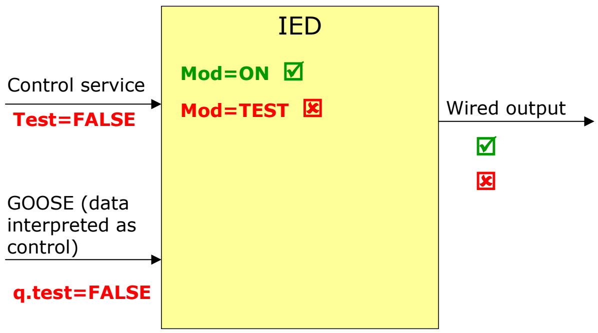

Fig. 8 Command with Test=FALSE

If the command is initiated with the test flag set to TRUE, it will not be executed, if the function is "ON". If the function is "TEST", the command will be executed and a wired output (e.g., a trip signal to a breaker) will be generated. If the function is set to "TEST-BLOCKED", the command will be processed; all the reactions (e.g., sending a command confirmation) will be produced, but no wired output to the process will be activated (Figure 3). The mode "TEST-BLOCKED" is particularly useful while performing tests with a device connected to the process.

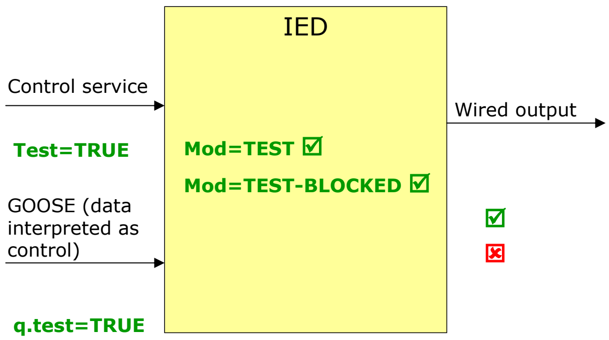

Fig. 9 Command with Test=TRUE

3.2 Simulation of messages

Another feature that has been added to Edition 2 is the possibility to subscribe to GOOSE messages or sampled value messages from simulation or test equipment. The approach is explained in Figure 10. GOOSE or sampled value messages have a flag indicating if the message is the original message or if it is a message produced by a simulation. On the other side, the IED has in the logical node LPHD (the logical node for the physical device or IED) a data object defining if the IED shall receive the original GOOSE or sampled value messages or simulated ones. If the data object Sim is set to TRUE, the IED will receive for all GOOSE messages it is subscribing the ones with the simulation flag set to TRUE. If for a specific GOOSE message, no simulated message exists, it will continue to receive the original message. That feature can only be activated for the whole IED, since the IED shall receive either the simulated message or the original message. Receiving both messages at the same time would create a different load situation and therefore create wrong test results.

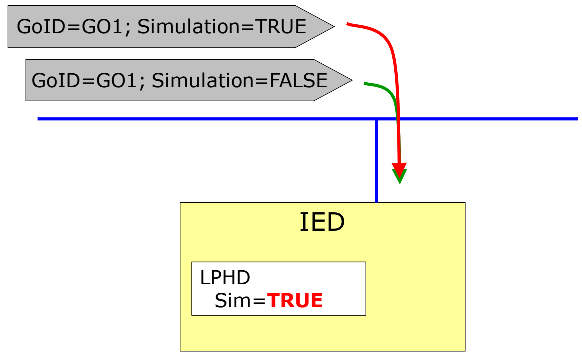

Fig. 10 Simulation of a GOOSE message

3.3 Mirroring control information

A third feature that has been added is the mirroring of control information. This supports the possibility, to test and measure the performance of a control operation while the device is connected to the system.

A control command is applied to a controllable data object. As soon as a command has been received, the device shall activate the data attribute opRcvd. The device shall then process the command. If the command is accepted, the data attribute opOk shall be activated with the same timing (e.g., pulse length) of the wired output. The data attribute tOpOk shall be the time stamp of the wired output and opOk.

These data attributes are produced independently if the wired output is produced or not – the wired output shall not be produced if the function is in mode TEST-BLOCKED. They allow therefore an evaluation of the function including the performance without producing an output.

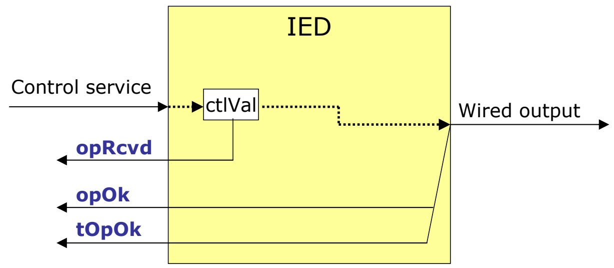

Fig. 11 Mirroring of control information

3.4 Isolating and testing a virtual device in the system

Combining the mechanisms described in the previous sections, it is possible to test a virtual device that is part of the centralized system.

Let's assume we want to test the performance of a protection function that receives sampled values from a merging unit. This is the sequence to perform the test:

1. In the LN LPHD of the CPC, the data object Sim shall be set to TRUE
2. The logical device for the protection function shall be set to the mode "TEST"
3. The logical node XCBR as interface to the circuit breaker in the PIU shall be set to the mode "TEST-BLOCKED".
4. A test device shall send sampled values with the same identification as the ones normally received by the CPC, but with the Simulation flag set to TRUE.
5. The CPC device will now receive the sampled values from the test device and will process them instead of the sampled values coming from the merging unit
6. The protection function will operate and initiate a trip.
7. The XCBR in the PIU will receive and process that trip; however, no output will be generated.
8. The output can be verified through the data attribute XCBR.Pos.opOk and the timing can be measured through the data attribute XCBR.Pos.tOpOk.

3.5 Advanced simulation possibilities

Considering that according to the current definitions of IEC 61850 the control of the subscription to simulated values by the test system in the substation, it may be challenging to isolate individual function elements for testing in a live substation. In this case the TstRef (Figure 12) allows us to directly point to data coming from test equipment that is simulating a specific system condition, without pretending that it is a process interface device or other equipment in the substation.

These are the enhanced simulation possibilities that can be used for functional testing, especially in CSPACS, that have been added in Edition 2 of the standard.

The concept is explained in Figure 12. The possibility to describe references to inputs of a logical node has been added. This is done through multiple instances of data objects **InRef** of the CDC ORG.

That data object has two data attributes providing object references:

- a reference to the object normally used as input
- a reference to a data object used for testing.

By activating the data attribute **tstEna**, the function realized in the LN shall use the data object referred to by the test reference as input instead of the data object used for normal operation.

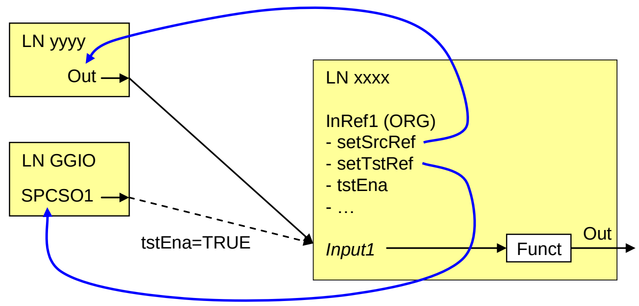

Fig. 12 Use of TstRef for individual LN testing

With that feature, it is possible to test a single function element represented by a logical node, while the rest of the CSPACS is in normal operating mode. Instead of using the data from messages published by the substation PIUs, the LN will use the data from the test system simulator specified by **setTstRef**.

4. Testing Tools Requirements

It is clear from the previous sections that the testing tools need to support the requirements for all the different types of tests described earlier.

There are two types of tools:

- Hardware – the different test devices that generate analog signals or communications messages as required by the application
- Software – the different software tools that are used for:
    - specific types of tests
    - test configuration
    - power system conditions simulation
    - test assessment
    - documentation

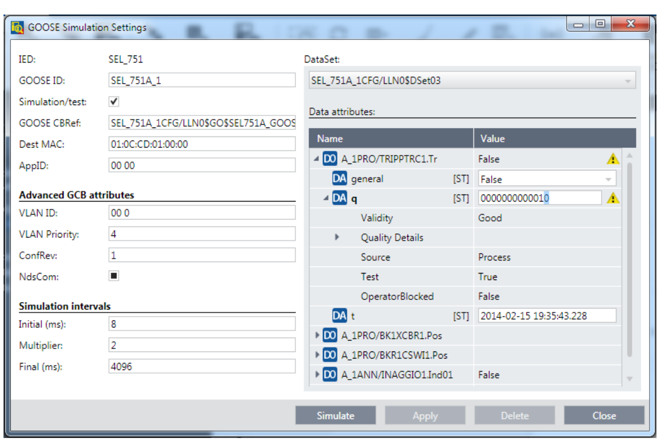

Fig. 13 Virtual isolation test configuration

To support the virtual isolation, the test devices should be configurable to operate in a “normal” operating mode, i.e., by sending messages with all test mode related data objects and attributes set to False. As described earlier, these will be all use cases when there is no need for virtual isolation.

In cases like maintenance testing or commissioning of new bay protection and control schemes in an energized substation, the test equipment should send messages with the simulation bit or test bit set to True, in order to prevent undesired tripping of circuit breakers.

5. Conclusions

The testing of CSPACS depends on the purpose of the test. It has many similarities, but also some differences in comparison with distributed digital substations.

While the testing of the different functions of CSPACS is in many ways similar to the functional testing of multifunctional IEDs with high levels of integration in digital substations, the more challenging testing is for commissioning and maintenance.

During commissioning one of the most important goals is to ensure that the interfaces to the process are properly connected and requires primary injection.

White box testing is a useful testing method and the use of TstRef can be very helpful.

References

[1] IEC 61850-7-2: Amendment 1 – Communication networks and systems for power utility automation – Part 7-2: Basic information and communication structure – Abstract communication service interface (ACSI)

[2] IEC 61850-7-3: Communication networks and systems for power utility automation – Part 7-3: Basic communication structure – Common data classes

[3] IEC 61850-7-4: Communication networks and systems for power utility automation – Part 7-4: Basic communication structure – Compatible logical node classes and data object classes

Biography

Dr. Alexander Apostolov received MS degree in Electrical Engineering, MS in Applied Mathematics and Ph.D. from the Technical University in Sofia, Bulgaria. He has 48 years' experience in power systems protection, automation, control, and communications. He is presently Principal Engineer for OMICRON electronics in Los Angeles, CA. He is IEEE Life Fellow and Member of the IEEE PES Power Systems Relaying and Control (PSRC) Committee and the Power System Communications and Cybersecurity (PSCC) Committee. He is past Chairman of the Relay Communications Subcommittee and serves on many IEEE PES Working groups. He is member of IEC TC57 working groups 10, 17, 18 and 19. He is Convener of CIGRE WG B5.69 "Experience gained and Recommendations for Implementation of Process Bus in Protection, Automation and Control Systems (PACS)" and member of several other CIGRE B5 working groups. He is Distinguished Member of CIGR and IEEE Distinguished Lecturer. He holds four patents and has authored and presented more than 600 technical papers. He is Editor-in-Chief of PAC World and Chairman of the PAC World conference.

Eugenio Carvalheira received his BSc in Electrical Engineering from the UFPE University in Brazil and his MSc in Computational Engineering from the University of Erlangen in Germany. He has 20+ years' experience in Power Systems Protection, Automation and Control (PAC). He spent part of his career as a Project Engineer responsible for the design, implementation, and commissioning of PAC systems at Electrical Substations and Power Plants. He joined OMICRON in 2008 as Training and Application Engineer developing test automation solutions for protection relays, providing technical product application support and responsible for the IEC 61850 training courses at OMICRON. He is currently Engineering Manager for North America based in Houston, TX. He is an active member of IEEE PES serving many PSRC and PSCC working groups.