IEC 61850: Role of Conformance Testing in Successful Integration

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***Abstract*—The IEC 61850 Standard, Communications Networks and Systems in Substations, provides an internationally recognized method of local and wide area data communications for substation and system-wide protective relaying, integration, control, monitoring, metering, and testing. It has built-in capability for high-speed control and data sharing over the communications network, eliminating most dedicated control wiring as well as dedicated communications channels among substations. IEC 61850 facilitates systems built from multiple vendors' IEDs. Many vendors have supported the standard throughout its creation, and they are developing products to handle all the needed functions.**

This paper is the third in a series on the evolution of IEC 61850. It focuses on the purpose and value of conformance testing and certification. IEC 61850 is aimed at making it easy for utilities to install and integrate single-vendor or multivendor control and protection systems in substations and to integrate existing communications. Developers and users recognize the risk of varying interpretations of such a complex standard by designers and programmers in different companies. Conformance testing and certification by independent third parties, carried out with standardized procedures and tools by experts who are not the designers of the equipment under test, can remove much of the risk and can bring these diverse design teams to a common understanding of how exactly to implement the communications functions so that the products work together.

IEC 61850 includes, as part of the standard itself, a section on conformance testing procedures. A conformance testing program has been established by the UCA International Users' Group (UCAIUG). This industry support and technology development committee has broad participation by utilities, vendors, and others. Conformance testing of products is underway, and a selection of certified products is becoming available. It is important for users to understand the value and importance of this testing program, to have a realistic view of the limitations, and to understand what is required to achieve a successful implementation.

The paper focuses on not only what is included in conformance tests, but also what is not included and what end users should expect. Conformance testing and certification is described for system components, including relays and other IEDs, gateway servers, client/server software, integration tools, and certification software. Finally, a description and roadmap is given on how to use the certification process to improve the end-user integration experience. The paper describes additional measures, such as interoperability and functional testing, to fulfill this roadmap to interoperable substation architecture.

I. Industry Vision of Common Communications With IEC 61850

The IEC 61850 Standard, Communications Networks and Systems in Substations [1] and its predecessor UCA for Substation Control arose from the efforts of pioneering utility and vendor relaying and substation control engineers who wanted a single standard solution for communications integration having high-level capabilities not available from protocols in prior use. The most important technical objectives were:

1. Use self-description and object modeling technology to simplify the integration and configuration process for the user.
2. Dramatically increase the functional capabilities, sophistication and complexity of the integration to meet users' ultimate relaying, control, and enterprise data integration needs.
3. Incorporate robust, very high-speed control communications messaging that can operate among relays and other IEDs to eliminate panel wiring and controls.
4. Focus on a utility-oriented object development effort that rests on a standard top-level application layer and map to lower level communications layers that are in widespread use, notably in the IT world.
5. Standardize the protocol, while pushing for adoption by the utility industry worldwide. In this way, users could select products from different vendors and interconnect their communications ports. The products would all exchange the information and control messages as required without creative protocol translation or interfacing by the user. Also, product manufacturers could focus their full efforts on implementing the one protocol, rather than supporting several choices.

On the fourth objective, the most vigorous development of IEC 61850 capable products is based on IEC 61850-8-1, which maps the standard object modeling (message format definition) process to the application layer called Machine Messaging Specification (MMS) and from there to message packets on Ethernet networks.

On the fifth objective, we observe that IEC 61850 is a massive 10-part document comprising mostly detailed statements of what sorts of messages are supported and how they are to be formatted and exchanged among servers and clients in particular communications systems like Ethernet LANs. So the probability that two different implementers read every point in IEC 61850 in the same way is close to zero. It is normal that two separately developed products may work well individually but not interoperate perfectly when they are interfaced together. Therefore, system development must include effective and complete testing and debugging processes to assure that things work right the first time.

For IEC 61850, the industry needs an effective process for validating these interfaces in structured, neutral situations with an effective diagnostic capability and a complete script of features and functions for testing. If this process works, then the user will have a much easier time when he installs these products in a substation and configures them to exchange communications messages to handle the protection and control for that particular substation.

II. Background on Preceding Communications Technology and Practice

In the early 1990s, many utilities were adopting their first generations of microprocessor relays. One of the many drivers for the change was and is the data communications capability. The relays saved operating or event records for faults; oscillographic records; remedial action information including fault type, current, and location; metered values and status indications; self-monitoring health reports; and setting files that could be changed remotely.

The communications ports served serial data, which could be exchanged with a local substation host or with remote users via a modem and telephone circuit. Each relay or IED vendor had a legacy communications protocol or message format. In some cases, the user needed a special client program from that vendor to communicate with that family of products.

For users who installed products from only one vendor, the integration of communications of many relays and IEDs was relatively straightforward, and the access and use of the available information tended to be straightforward. Software interfaces varied in their ease of use, but the user at least only had to become familiar with one.

However, it was impossible to find one vendor with all the products needed for all substations. Accordingly, users had to figure out how to combine products with different protocols. Sometimes, the sharing of communications wound up being strictly physical – the products shared the same communications circuits but had separate communications processes. Users would have to call in to a particular product and start the compatible client software to talk to that product. Those utilities without good data communications expertise relied on third-party integrators. The diversity of communications protocols and styles made effective substation integration difficult. Users asked vendors if they could all adopt a common standard that would make integration easy. Some vendors competed for protocol supremacy while others simply created protocol solutions for the substation where none previously existed. Some opened their protocols by publishing the protocols and allowing others to use them without significant legal restriction or license.

This led to a gradual narrowing of the field of choices and some of the preferred open protocols emerged. Foremost among these are DNP3 and Modbus®. Both of these protocols are still widely used in new installations, and both are still effective solutions where their protocol features are adequate for the level of integration needed. Either of these (or both simultaneously) can be used on a modern Ethernet substation integration LAN. Modbus is widely used in industry with a huge base of suppliers and experience, as well as conformance certification services. For utility users, DNP3 has a particularly effective users' group that tracks application opportunities and challenges experienced in the field, maintains the standard documents, educates and helps users, mediates compatibility issues in differing protocol implementations, and oversees the product conformance certification process carried out by independent test labs. See http://www.dnp.org/ for more information.

In the same time frame, some North American and European substation control visionaries from utilities and manufacturers wanted to initiate development of a single standard for substation communications and control, drawing as much as possible on standard communications layers. Under EPRI sponsorship and funding, a large team of experts from many utilities and manufacturers developed UCA for substation control during the 1990s. With high levels of cooperation among competing relay and IED manufacturers, a number of UCA-compliant, Ethernet communicating relays and IEDs were available commercially by 2000. These included high-speed GOOSE multicast messaging (in a format now called GSSE in today's IEC 61850) for control and continuous state exchange among relays. This protocol could replace wiring and controls with LAN messaging and logic programmed in the relays as was demonstrated in a couple demonstration substations that were built. Meanwhile, starting in 1995, IEC Technical Committee 57 (then called Teleprotection and Substation Control; now called Power System Control and Associated Communications) formed Working Groups 10, 11, and 12 to develop an industry standard communications protocol with objectives similar to those of the EPRI UCA effort. The IEC work carried on independently for about 6 years. Fortunately, the IEC working groups and the EPRI UCA project teams and committees had a high level of shared membership, and the two projects constantly exchanged and compared developments in order to converge on a single solution for the whole world. In 2001, the two projects agreed to merge under the banner and structure of IEC 61850. While each project had defined some elements not included in the other, the overlap was worked out with maximum practical compatibility of existing UCA designs to parts of IEC 61850. TC 57 WG 10 now carries out all new development. All ten parts of the originally envisioned IEC 61850 series have been published. WG 10 continues to develop amendments and updates as refinements are discovered or problems are found. Other TC 57 working groups are developing new families of objects that support expanded application to new areas, such as hydropower or distributed generation. Most recently, TC 57 is initiating work to develop IEC 61850 standards for communications out of substations, among substations, or to control centers and utility enterprise facilities over WAN infrastructure. The IEC 61850 design approach is moving to take over much of the utility information technology world. See more about the current state of IEC 61850 development and use at http://www.ucausersgroup.org/.

References [2] and [3] provide a lengthy technical discussion of the current state of IEC 61850 implementation along with a comprehensive list of references.

III. Implementation Benefits and Challenges of Networked IEDs

A. Networked IEDs Improve System Capabilities

Full integration of intelligent devices in instrumentation and control (I&C) systems requires peer-to-peer, client server, device configuration, and engineering access communications methods. The act of integration realizes significant system benefits over traditional methods of multiple copper terminations instrumenting field contacts regardless of the protocol(s) used or the type of communications media.

The benefits systems constructed of integrated IEDs networked via wireless, copper, or fiber serial or Ethernet connections combined into a LAN include:

1. Reduced number of field terminations, associated wiring, labor, and maintenance due to the reuse of data detected by a single IED digitally communicated to integrated IEDs and other data clients.
2. Reduced quantity of unsupervised process and apparatus functions via use of IEDs that in addition to their primary functions also perform ongoing diagnostics of their own performance and that of the equipment that they are monitoring.
3. Minimized distance of data path that is unsupervised between field source and data client(s), which vastly improves the value of the data by confirming the availability and reliability of the method by which they are being collected and alarming when the data path is broken. Maximizing supervision is done by replacing traditional unmonitorable copper terminations with monitored digital communications at the IED closest to the field data, which in turn detects and alarms communications problems immediately.
4. Reduced quantity of communication connections by use of methods that interleave multiple communication paths onto a single serial or Ethernet connection.
5. Reduced quantity of IEDs due to the fact that newer multifunction IEDs replace multiple individual purpose IEDs and that integration of IED data eliminates several traditional stand-alone systems including those that perform SCADA, metering, sequence-of-events recording, and digital fault recording.
6. Increased process and apparatus monitoring and control capabilities via the exchange and aggregation of data among many IED data sources rather than the traditional implementation of only one IED and, therefore, one data source per function. This ability to freely allocate data sources among IEDs networked via serial or Ethernet networks minimizes the importance of which IED is the data source and leads to more functional, flexible, and data-rich systems.

Any protocol standard that can be used to network IEDs is capable of providing some of the benefits listed above. These protocols include DNP, Modbus, and IEC 60870. However, standards that include suites of protocols to satisfy the aggregate of peer-to-peer, client server, device configuration, and engineering access communications methods will provide the most benefit. The benefits are available whether the protocol suites are proprietary or nonproprietary; however, nonproprietary methods lead to better interoperability among different vendors. Depending on the application specific requirements, it will be necessary to support multiple methods of each type of communications method category simultaneously to match different performance requirements. As an example, command line prompt and file transfer interface to IEDs are two different examples of the engineering access category, each with different requirements.

One major benefit of IEC 61850 is that it is a nonproprietary, international communications standard that includes a suite of protocols to partially satisfy three of the many necessary functions.

1. Peer-to-peer
2. Client server
3. Device configuration

Due to the fact that IEC 61850 specifies an Ethernet network, even though the engineering access function is not specified by the standard, any compatible engineering access communications method can be interleaved on the Ethernet network or done via other communications connections. Also, work is underway to standardize a subset of the engineering access communications methods with a standardized file transfer method that is expected to become part of IEC 61850.

Often, casual observers confuse the value of implementing a complete protocol suite with implementing a specific protocol suite. The implementation benefits of using IEC 61850 are similar to those of other communications standards that support a suite of protocols. The difference, as mentioned previously, is that IEC 61850 is the first such standard that is internationally multivendor and nonproprietary.

B. Design by Committee Maximizes Scope of Use and Increases Size and Complexity of International Standard

The intent of IEC 61850 is to provide a single suite of protocols and services to address much of the data movement necessary within a substation. The existing IEC 61850 documents cover the bulk of the data traffic needs; work continues to add more services. The choice of Ethernet makes it simple to interleave other necessary communications required to cover specific data exchange services not addressed by the standard, addressed but not completely covered in today's IEC 61850 standard, and those needed to support integration of legacy devices with older protocols.

This desire to address a large part of data movement needs makes the effort, and the standard, larger than anything previously done in a nonproprietary method. The technical experts of 22 participating countries have recognized that the increasing competition among electric utilities due to the deregulation of the energy markets asks more and more of systems. The integration of equipment and systems for controlling the electric power process into integrated system solutions is needed to support the utilities' core processes. Equipment and systems have to be interoperable; interfaces, protocols, and data models must be compatible to reach this goal. Because the standard essentially has five protocols within it, the size and complexity of the standard increased proportionally.

The challenges of a development group implementing a standard comprised of a suite of protocols to perform most of the required communications functions in a networked IED I&C system are the same regardless of whether the standard is proprietary or nonproprietary. However, the amount of effort required to implement a nonproprietary international standard, specific to no particular vendor, is much greater. The effort is obviously greater because multiple vendors, or even multiple development groups with a single vendor, are planning to implement the new standard, but more importantly, each implementation is expected to be interoperable with the others. Interoperability is not a new idea to protocols, but simultaneous interoperability for such a great number of useful communications methods is new. Essentially, the effort required to be successful is proportional to the amount of functions addressed by the standard and the number of development groups involved in interpreting the standard and attempting to build interoperable interfaces.

Finally, the flexibility of the standard will pose a challenge to implementation. On one hand, flexibility allows the data and services defined in the standard to support myriads of applications and combinations of applications. This same flexibility permits a virtually infinite number of configurations for each device. Initial implementation and conformance testing will be successful only if a few general implementations are well scoped, appropriately configured, and well tested. From this initial body of conformance, additional data and communications methods will be added to build up the conformant technology in each specific device.

C. Success Will Depend on Common Implementation and Behavior

The obvious benefit to each vendor is to do communications development once and have it be interoperable. The best way to reduce the risk of failure is to work from adequate specifications and to test appropriately. The IEC TC 57 WG that maintains IEC 61850 has created the specifications. The UCAIUG has taken on the role of designing tests to help vendors confirm that their development conforms to the standard. If this conformance testing is adequate, devices from different vendors that pass the conformance test will have a higher likelihood of being interoperable. Deficiencies identified in a vendor product will be made known to them for corrective action. As the process of conformance testing evolves, inadequacies in IEC 61850 or conformance tests are being identified. These problems in testing are addressed by the UCAIUG and then solutions will be added to the test procedures to improve the entire process. When problems are identified in the standard itself or its interpretation, IEC TC 57 WG 10 defines the corrective action through its technical issues resolution (TISSUES) process.

D. Overview of IEC 61850 and GOOSE Messaging

IEC 61850 [1], Communications Networks and Systems in Substations includes a broad range of services and tools for monitoring, control, and protective relaying. From the outset, the standard has been architecturally designed to describe power system application objects that can be transmitted over widely used, evolving and advancing layers of data communications technology. With this approach, years of development work for substation automation and protection object modeling can be mapped to new communications systems as they evolve. Utility users can take advantage of this rapid advancement of IT LAN and WAN technology for the indefinite future, without discarding the old protocol work and starting over again.

Power system objects in IEC 61850 comprise measurement values from relays or IEDs, status of binary points within those IEDs, and control objects that convey action commands to those IEDs. Part 7 of IEC 61850 describes the object modeling approach, the abstract communications services interface (ACSI) to standard communications layers, specific object definitions and descriptions, and logical node and data classification in which these objects are arranged.

A key feature of IEC 61850 IEDs is that they are able to describe themselves (what objects they have available to serve or can receive) to higher-level systems. This feature enables a connection of relays and IEDs to be set up for LAN communications very quickly, compared to the manual process of manually defining and entering a points list as is done with preceding substation control protocols. Part 6 of IEC 61850 also defines a substation configuration language (SCL) to be used in software tools that makes it easy for users of the IEC 61850 relays and IEDs to set up the interunit communications according to the substation connection topology and the functions needed for protection and control.

Parts 8 and 9 of IEC 61850 comprise specific communications services mappings (SCSMs)—how the substation and power-system objects and their organizational structure are to be communicated using standard communications layers that are in widespread and growing use without regard to utility or substation applications. In principle, the power system objects could be mapped and communicated over almost any well-defined, stack oriented communications system.

Part 8 is focused on communications over the substation bus, which is the LAN integrating the relays and control house IEDs. Part 9 focuses on communications services for the process bus, which is a LAN connection to switchyard or power apparatus sources of the raw process information—high-speed streaming of instantaneous voltage and current sampled values, equipment status reports, and access to control circuits of breakers, switches, and other equipment. Fig. 1 shows the Station Bus versus Process Bus levels of the substation communications system as described in IEC 61850.

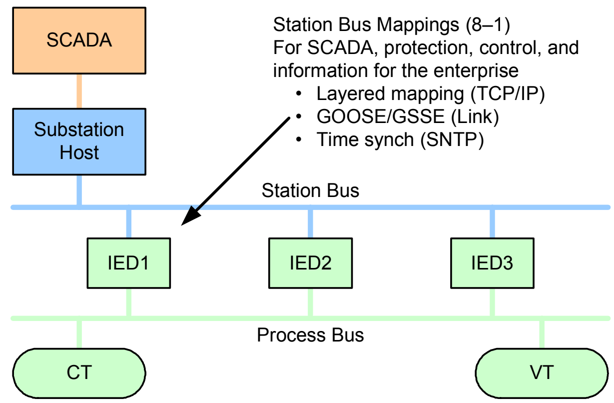


Fig. 1. IEC 61850 Station Bus and Process Bus Levels

For the current discussion, we focus on Part 8. The process bus, Part 9, is in an earlier phase of development by the industry and is an application of future interest to many utilities.

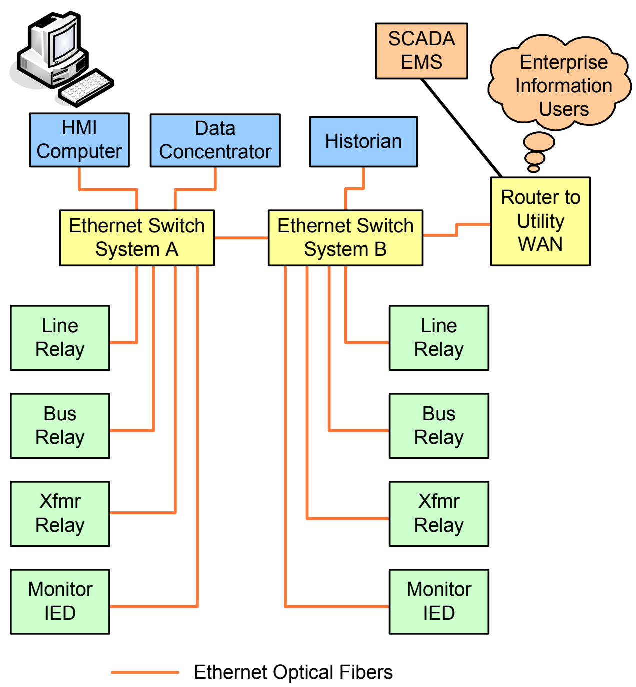


Fig. 2. Typical Substation-Bus LAN Implementation

While Part 8 could include mappings to a variety of LAN environments (including those that have not been invented yet), Part 8-1, which is now in IEC 61850, focuses on mapping substation objects to an Ethernet LAN with TCP/IP or certain other protocol layers. Part 8-1 also focuses on the ISO-standard application layer called Manufacturing Message Specification (MMS) developed for industrial process control.

Fig. 2 shows a typical practical implementation of the Station Bus as conceived in IEC 61850 for a bulk power transmission substation requiring dual redundant LANs with no single point of failure that could disable both of the dual redundant configurations. At the station level, information and control is consolidated for local operators and for a variety of remote enterprise clients such as SCADA, EMS, maintenance, protection and control engineering, operations analysis, planning, asset management, and business management.

Refer to [2] and its comprehensive reference list for more details on IEC 61850 Station Bus and Process Bus protocols.

IV. Steps to Building an Interoperable Network

A. First, Build a Dependable Network

The substation environment is very harsh and installed IEDs in switchgear, within apparatus cabinets in the yard, and on pole-tops endure even harsher environments. Our industry has learned many lessons about reliability and availability that cannot be discarded in the interest of adopting a new communications method. The biggest physical change in moving to an Ethernet substation LAN is the increased number of connections and communications devices between the data server device and the data client device. Take the example of integrating a protective relay to provide currents, voltage, status, and control for remote SCADA. Traditional methods accomplish this with one direct-connect cable between the protective relay and a communications processor with a connection at each end. For a small Ethernet LAN, this single cable is replaced with two cables, an Ethernet switch, and four connections—one each at the relay and communications processor and two on the switch. Therefore, in order for the switch to not become a weak link, it needs to match the performance and reliability of the two end devices. IEEE 1613-2003 [4] is a standard developed specifically for "environmental and testing requirements for communications networking devices in substations" and addresses the following topics:

- Service conditions
- Electrical ratings
- Thermal ratings
- Environmental testing requirements

Therefore, step one is to understand the environmental conditions of the substation and yard, recognize that many Ethernet technologies are developed for commercial applications and choose utility grade devices that will reliable operate in harsh conditions for the life span of the installation.

B. Second, Choose Devices That Are Tested Conformant to IEC 61850

The purpose of the conformance testing, as stated before, is to reduce the risk of failed interoperability between devices when put in service. However, the standard addresses a huge amount of communications scenarios and data models, of which only a subset will be implemented within any specific physical device or client. Therefore, vendors will publish those elements of the standard to which their products have been tested for conformance.

In order to be considered interoperable by the end-user, each device will need to support the appropriate data and services. Vendors intend to use the method outlined by the standard in which they identify the data and services supported within the device and which of these have been proven to conform to the standard. It will then be left to the end-user to select devices with the appropriate combination of data and services. The end-user will expect the devices to be interoperable for each of the data and services that have been conformance tested.

One of the primary activities of the UCAIUG is to support testing. Test centers must comply with the IUG conditions in order to be either recognized or accredited by the UCAIUG for IEC 61850 Device Testing. The minimum requirement for test centers to be recognized is the presence of an ISO 9000-based quality system that covers the procedures for IEC 61850 device testing. The minimum requirement to be accredited is the presence of a certified ISO 9000-based quality system and freedom from commercial or financial pressures that could influence the test results.

Carefully managed in-house and independent third-party accredited/recognized test center reports will show the conformance blocks tested with positive result and the unique identification of the device tested, test center, and test systems used.

Therefore, step two is to understand the data flow requirements, and choose devices and applications for which the required data and services have been tested by accredited/recognized test centers to conform to the standard.

C. Third, Choose Devices That Are Interoperable

Even though devices are expected to be interoperable if they conform to the same standard, industry experience with other standard protocols proves that different development teams may create conformant but noninteroperable devices. We discuss this anomaly in the *Interoperability Testing* section below. One obvious way to improve the chances of interoperability is to choose devices that are all created by the same development group. However, the best method to assure interoperability is to test and observe it. Again, the standard is far too large to test every interoperability permutation. However, specific scenarios can and should be tested prior to product selection. If this information is not available to the end user for their intended application, it will be necessary for the end user to arrange for the proper testing to be done.

Therefore, step three is to understand the required interoperability requirements among IEDs and applications for the final design to function properly and to verify that this interoperability has been demonstrated or arrange for it to be demonstrated. As discussed below, this is best done well before the system is being acceptance tested for commissioning, when schedules are tight.

D. Fourth, Choose Devices That Match Performance Requirements

Local and distributed decisions and actions must perform accurately and fast enough for the intended application, regardless of the vendor or protocol used. Local performance, such as speed of protection or direct action pushbuttons on the IED front panel, must obviously meet the intended use but not affect the distributed network functionality. Accuracy of time synchronization, accuracy of time stamp, and speed of accepting and producing network messages, such as GOOSE, have a direct bearing on distributed network functionality. Therefore, even though the standard does not dictate required accuracy and speed of IEDs, the network designer will need to know these parameters to understand the interaction of networked devices and appreciate how they will perform a distributed function.

Therefore, step four is to understand the accuracy and timing requirements of the local and distributed functions and choose IEDs and applications with acceptable performance.

E. Fifth, Build a Network That Will Function Properly Under All Data Flow Scenarios

Distributed network applications are designed based on the capabilities of the devices chosen. Network connection and cable media, as well as switches, routers, and communications processors, are then chosen to match the necessary data rate. The necessary data rate is determined as that which will accommodate the worst-case data flow loading ever expected on the network. The nature of much of the report by exception reporting methods in IEC 61850 produces the highest data flow load when a problem occurs in the substation and many data values change. Of course, this is the time that the capability of the network to communicate this information becomes most critical. Further, it is possible that network data flow will change in the future due to the addition of new Ethernet traffic caused by either added devices or applications, or the incorrect performance of existing devices.

Therefore, step five is to understand the present and future data flow requirements and design an Ethernet network capable of supporting communications during worst-case network loading.

V. Types of Communications Testing

To have a successful testing program, we need a clear picture of what we are trying to accomplish with each test step, what is possible to accomplish in the end, and what can go awry with product communications performance.

We discuss three major categories of communications protocol testing:

- Conformance testing – does the tested device communicate as the standard specifies?
- Interoperability testing – do two or more devices work together on the LAN as expected when they exchange standard IEC 61850 format messages?
- Performance or stress testing – evaluating device or system performance specifications, often to establish boundaries of their capabilities; results are not specified in the standard.

Fig. 3 illustrates the relationship between these types of testing, product development, and successful projects deploying this technology.

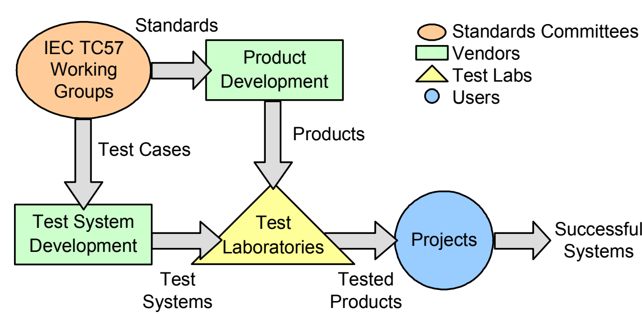


Fig. 3. Relationship Between Standards, Products and Systems [5]

A. Conformance Testing

The objective of conformance testing is to determine if a relay or IED under test (device under test or DUT) conforms to the specifications of the standard. We do this by exchanging messages between a test system and the DUT. The test system sends a carefully selected array of test messages to the DUT and records the responses of the DUT. Messages are selected to exercise all the features of the DUT communication that are to be verified or certified.

The approach for this particular phase of IEC 61850 testing is thoroughly specified in IEC 61850-10, Conformance Testing.

From the DUT perspective, the test system acts like the ensemble of devices on a typical LAN to which the DUT might be connected in field service. If the DUT is a server (such as a relay), then the test system behaves as though it is a networked combination of clients (like a substation data concentrator or historian) and other peer servers (like other relays on the LAN).

In actual test situations, the physical test system can be as simple as a PC with an Ethernet card and physical-layer connection (such as an electrical to optical Ethernet converter) to the relay or an IED Ethernet port, as shown in Fig. 4. For some tests, it may be necessary to connect another test PC or device that generates background LAN traffic, to make sure the DUT is evaluated under realistic service conditions. An HMI may also be connected to the test LAN. Finally, if the DUT requires stimulation of its process I/O points (e.g., voltages, currents, breaker status inputs, and breaker trip and close outputs) to test behavior, then a relay test set or other field device simulator also must be connected, controlled by its own test software, scripted, and interfaced to the communications test process.

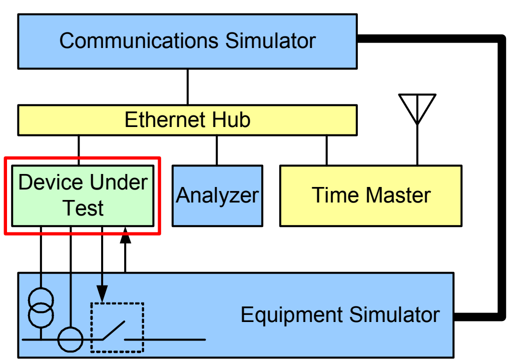


Fig. 4. Conformance Test Setup

The more specialized and complex element of this test setup is the software running on the test PC. The test software includes the following features:

- An implementation of the IEC 61850 services or protocols for which it will be used, plus special testing extensions (such as the ability to send intentionally corrupted messages).
- Scripting capability, by which the test designer can set up an automatic execution of transmission of test stimulation messages and checks for responses.
- Recording function to recognize, record, store, play back, and parse all the responses of the DUT. Note that it must also be able to capture messages from the DUT that were not stimulated or requested, such as GOOSE messages, or client objects requesting data responses if the DUT is a client system.
- For client or peer-to-peer testing, the test system needs to interpret and respond to DUT messages in realistic time frames.
- Analysis to present correct versus unexpected results, making it easy to spot misbehavior or incorrect responses. Through a preceding separate process, this test software has been verified to issue messages that conform to the standard.
- Ability to perform important negative testing by intentionally sending corrupted, nonconformant, or inappropriate messages per the script. These messages verify that the DUT recognizes bad input and behaves benignly or passively when other devices on the LAN misbehave—important to system security.

As a practical matter, IEC 61850 conformance tests to date have been run with scripts written for specially developed IEC 61850 messaging simulator and analyzer tools. Fig. 5 shows the functional interconnection of these tools and the DUT. See [6] for detailed information on examples of such PC-based test tools.

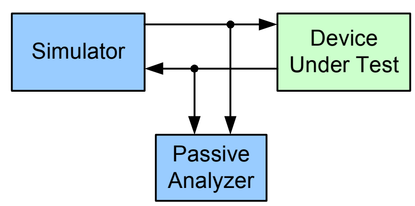


Fig. 5. Conformance Test Tools and Device Under Test

To run a conformance test, the tester first reviews the design information on the DUT. Along with the product itself and its instruction literature, IEC 61850 specifies the format for the following product feature descriptions:

Protocol Implementation Conformance Statement (PICS). Summary of the communication capabilities of the system or device to be tested.

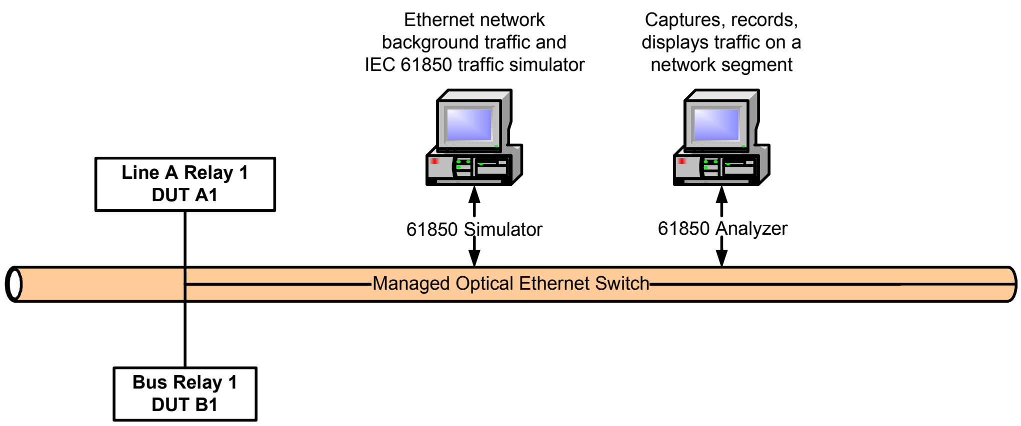
Model Implementation Conformance Statement (MICS). Details the standard data object model elements supported by the system or device.

In addition to the standardized PICS and MICS, there may be a **Protocol Implementation eXtra Information for Testing (PIXIT).** This document contains specific information regarding the communication capabilities of the system or device to be tested that is outside the scope of the IEC 61850 series standards. The PIXIT is obviously not subject to standardization of its format or contents.

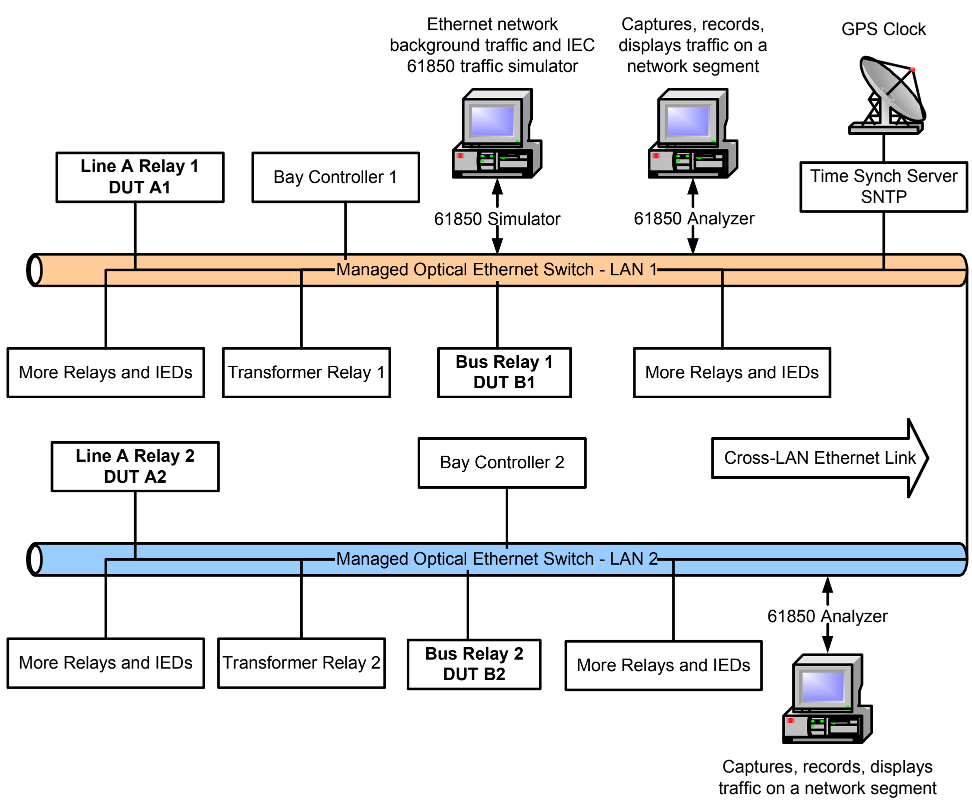
The test scriptwriter and the test sponsor agree on exactly what services in the PICS and objects in the MICS are to be tested or certified, along with custom testing of features described in PIXIT. The tester then creates a test script for these services, including positive tests (correct messaging behavior and response) and negative tests (behavior in the face of faulty messaging is as required in the standard or otherwise acceptable for the system environment). We emphasize here, and again later, that it is not practical to test every variation of every message type that could ever be exchanged for the services and objects under test. The possible combinations rapidly approach infinity. The practical test approach is to script a large sample of behavior that has a very high probability of showing any problems. Highly probable does not mean certain—it is always possible to have an implementation bug such that some obscure untested message configuration is nonconformant, with no sign of trouble in the test process.

B. Interoperability Testing

For interoperability testing, we connect two or more relays and/or IEDs to a LAN and stimulate them to exchange IEC 61850 messages and exercise their interactive behavior. Fig. 6 shows an example of a test interconnection for an elaborate, realistic interoperability test that might precede a substation installation. The stimulation may start with a network IEC 61850 message simulator as shown in Fig. 6(a), or may take the form of application inputs to a full complement of relays or IEDs as in Fig. 6(b). For example, one or more relays are subjected to simulated faults with relay test sets and exchange GOOSE messages for breaker control, or an operator control request is simulated for a client application that passes the action message to a server IED, such as a relay connected to the controlled breaker. Typically, all the interactions among the networked IEDs are to be sample-tested.



(a) Equivalent test in which DUT interacts with simulator for the rest of the LAN devices



(b) Full interconnection of LAN devices simulating field application

Fig. 6. Interoperability Test Setups Simulating Substation Installation

In Fig. 6(b), the bulk of the substation equipment on the LAN is replaced by suitable configuration of the IEC 61850 simulator tool, which can replicate the ensemble behavior of the other devices that generate system services, background traffic, and occasional message stimulation from the substation concentrator/RTU or from other relays not physically connected that publish GOOSE messages. This example test is focused on testing the interoperability of DUT A and DUT B in a realistic environment, without physically connecting the array of substation equipment that would be needed if the simulator were not available to act in their place.

In theory, if the standard is clear in every detail and the IEDs have all been conformance tested for all relevant services, then we expect the IEDs to interoperate flawlessly, and this testing seems superfluous. If all the IEDs are from the same development team at the same manufacturer, the interoperation will likely be fine. However, for a more general interconnection of devices, differing design choices may create challenges, as we explain in *Limits of Testing* below.
If the test combines IEDs from different manufacturers, or even different development locations of a single supplier company, there is a good chance that some standard specification interpretation differences will arise, especially if the industry conformance testing initiative is in its early stages. As the conformance-testing program matures, it adds checks for issues that have been identified in earlier interoperation tests (or field problems, if there wasn't much interoperation testing). Also, the interaction may be corrupted by design variables that have not been specified in IEC 61850, such as certain timing issues. Standard requirements may need to be added for these.

Interoperability testing in the laboratory environment is vastly superior to debugging interactions in the field. The lab testing program focuses on exercising the full range of interactions by a structured sample testing plan. If interoperating problems are found, the specific cause is much easier to identify using the data capture, diagnostic tools, and test repetition capability available in the lab. The designers of the IEDs will have time to make modifications that correct the interaction problem and maintain conformance to IEC 61850. If the problem is traced to an interpretation problem in IEC 61850, the solution may need mediation among the suppliers and also an amendment to IEC 61850 so that all suppliers are informed of the change and can avoid future problems.

Interoperability testing is thus a tool for avoiding a protracted and difficult integration and acceptance testing just before commissioning—when schedules are tight, visibility is high, nerves are raw, and the situation is less ideal for troubleshooting and repair. In this field crunch, competing suppliers may fall back to finger pointing before they focus on working together to fix the problem.

While IEC 61850-10 specifies the approach for conformance testing, there is at this time no standard for interoperation testing, nor is there an industry program like the one we describe in the section "What Testing Is in Place Today for IEC 61850?" that has been set up for conformance testing. Typically, a utility initiating a major IEC 61850 substation project with a new interconnection of IEDs from multiple vendors will commission or request interoperability tests at an independent laboratory or at the in-house laboratory of a large utility.

C. Performance or Stress Testing

Beyond the specified interactions, vendors or potential users may need to explore the limits and capabilities of either individual IEDs or interconnected systems to know how much safety margin exists in a demanding new application.

For example, IEEE C37.115-2003 describes methods for testing IEC 61850 LAN environments in data storm situations [7]. Consider the simulation of a fault that evolves to include multiple zones of protection in a station along with breaker failures or other relaying functional misbehavior. Testing can show that the LAN can handle the high rate of flying messages in this stress situation, with all the IED functions and interactions taking place as necessary.

Performance testing might also evaluate the time needed for a critical control message (such as a GOOSE backup trip command sent across the LAN to several relays) from the initiating event to trip outputs from the subscriber relays.

IEC 61850 contains no separate performance testing section. However, note that for certain critical behavior features, the conformance testing section requires that this performance parameter be tested. For example, an IED supporting the GOOSE or GSSE subscriber service must be tested for time latency from receipt of the GOOSE message to the physical control action output. The same is true for latency in implementing client control object requests. Part 10 describes methodology for checking accuracy of time synchronization using the SNTP service specified in IEC 61850.

VI. What Testing Is in Place Today for IEC 61850?

The community of manufacturers of relays and substation control equipment, both in North America and in Europe, felt the need to migrate to the IEC 61850 communications standard even as the standard was being created. The vast majority either participated in the IEC working groups, developing the sections of the standard, or in the industry consortium of manufacturers and utilities that has overseen the industry standards propagation and support efforts for a common network communications protocol, the UCAIUG, for more information see http://www.ucausersgroup.org/. This collaboration led to a sequence of interesting and unique outcomes.

Manufacturers implemented early versions of IEC 61850 or its predecessor UCA for Substation Control, and integrated their products in public demonstration systems and in substations of early-adaptor utilities. Competing development engineers who had no prior experience of contact with their peers during development found themselves working together to resolve communications problems and get their products to interoperate.

With this experience, they all recognized the need for a formalized, vendor-neutral, consortium-sponsored testing program. Working together on IEC 61850, they commissioned development of Part 10 on conformance testing, which is now a part of the published standard. IEC 61850-10 describes the technical and documentation approach to conduct a conformance test as shown in Fig 7.

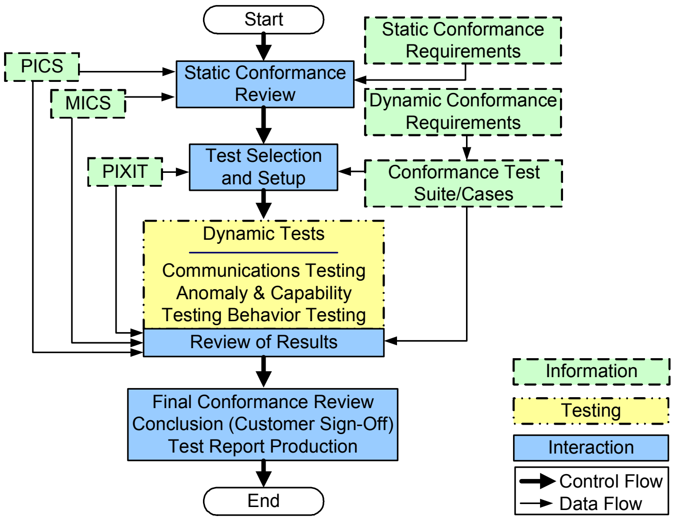


Fig. 7. UCAIUG Conformance Test Process [5]

With a conformance testing standard in place, the consortium then recognized the need for an industry-sponsored management process for the testing program. The consortium also commissioned a Testing Subcommittee within UCAIUG that oversees the conformance testing activities. This includes product certification definitions and approach, certification of test laboratories that are qualified to conduct the tests, and handling the first-tier resolution of problems with the testing process or with interpretation of the IEC 61850 standard protocol definitions. For this first-tier technical support, UCAIUG runs a help desk that developers or users can contact when problems arise that are difficult to resolve.

If the testing or standards problem can't be readily resolved by the UCAIUG help desk or the testing subcommittee, it calls for interpretation or amendment of IEC 61850 sections themselves. This sort of issue is escalated by the UCAIUG Help Desk to the Tier 2 level of support—the technical issues resolution (TISSUES) process of the IEC TC 57 WG 10 that is responsible for development and maintenance of IEC 61850.

A. Contents of IEC 61850-10, Conformance Testing

This part of IEC 61850 specifies standard techniques for conformance testing of product communications implementations, as well as specific measurement techniques to be applied when declaring performance parameters. It defines the methods and abstract test cases for conformance testing of devices. It also defines the metrics to be measured within devices in order to document product claims of compliance and lists requirements in Part 5 of IEC 61850, Communications Requirements for Functions and Device Models.

It is critical to note that the stated objective of Part 10 is to define a means of demonstrating that an IED can interoperate with other IEC 61850 IEDs. In other words, the authors foresee that a complete and effective conformance test can achieve the objectives of an interoperability test. We state here that this is an ideal that the development community is pursuing and has not yet achieved. Implementers must realize that we need deep experience with both kinds of testing before we reach such a maturity level of conformance test effectiveness. We explore this point further in the following section "Limitations of Testing."

VII. Limitations of Testing

From product development through eventual installation, several types of testing against specifications are necessary. These include the following:

1. Type testing to meet functional design specifications
   a. Hardware functionality and reliability
      i. Highly accelerated life tests
      ii. Highly accelerated stress tests
   b. Software functionality and fault tolerance
      i. Features
      ii. Performance
2. System functionality
   a. Performance of combined hardware and firmware including speed, time accuracy, I/O, recording
   b. Conformance to industry standards including UL listing, IEEE C37.94 and numerous others
3. Interface testing
   a. Front-panel display, LEDs
   b. Communications ports and protocols
      i. Conformance to standards—conformance leads to interoperability
         - Proprietary protocols
         - Nonproprietary protocols including:
           – DNP3, IEC 60870, Modbus®, Telnet, FTP
           – IRIG-B, IEEE C37.118
           – IEC 61850
      ii. Integration interoperability
4. Product testing to verify that each assembled product meets customer expectations
   a. Product burn-in (operation of each device destined for customer use through temperature extremes over an established period of time) to establish initial reliability
   b. Out-of-box audit (simulated customer receipt and initial setup and use) to establish customer acceptance
   c. Ongoing reliability testing (much protracted burn-in test of large population of devices that are not destined for customer use) to establish long term reliability
5. Customer acceptance testing to verify product functions as expected
6. Pre-installation testing
   a. Interoperability testing
   b. Integration testing
7. Factory acceptance testing (FAT) of staged integrated system in lab environment

8. Site acceptance testing (SAT) of staged integrated system on site at facility
9. Maintenance testing as needed throughout installed life of system
   a. Diagnostics
   b. Troubleshooting

It can be seen that appropriate due diligence testing of mission critical IEDs for use in our industry encompasses a broad range of expertise and represents a large amount of labor. All of this testing is necessary to create a successful integrated system, however, this paper addresses only a small fraction of this effort. Conformance to industry standards is a large effort, conformance to industry protocols is only one portion of this, and conformance to IEC 61850 represents a subset of the industry protocols requiring testing. However, once accomplished, the conformance testing will not need to be performed again on a tested device unless the device design changes.

Interoperability testing represents another subset of all the required testing. Communications interoperability testing will only be necessary for connections between new devices or for new data flow between previously tested interfaces. This effort will be larger than previous interoperability testing efforts for DNP3 and others simply because the protocol is much more comprehensive. Another contributing factor to the importance and size of the interoperability testing effort is that IEC 61850 is a very new protocol with little established testing to use as a reference.

As can be perceived from comments made previously in this paper, conformance testing of an IEC 61850 implementation tests only a small amount of the characteristics of a device that lead to its successful use. This testing is similar to conformance testing a different protocol.

- It is intended to demonstrate that the physical interface and data flow of the device conform to the rules defined in the standard.
- It does not indicate how fast, accurately, or reliably the IED performs its intended application; the user must determine these measurements.
- It does not indicate how it interacts with other devices other than the test source; interoperability testing provides this information.

Finally, interoperability testing will demonstrate the interaction among IEDs for a given communications architecture and specific network load. Worst-case data flow requirements should be identified and tested. What this does not show is how the network or IEDs will react if the data flow through the network or from an IED reacts unexpectedly.

Conformance testing increases the likelihood that devices will interoperate correctly. Interoperability testing demonstrates that IEDs do, or do not, exchange data appropriately. Negative results can be resolved. The true benefit is that the opportunity for system success increases as new device combinations and data flow scenarios are tested.

The obvious incentive for each vendor is to do communications development once and have it be interoperable. The best way to reduce the risk of failure is to work from adequate specifications and to test appropriately.

VIII. Mediation Plans for When Certified Products Have Interoperating Problems

The UCAIUG and IEC TC 57 WG 10 represent a large pool of "experts" about various parts of the standard and their implementation as represented in Fig. 8. This group of experts, GoE, is the major difference between this effort and other protocols.

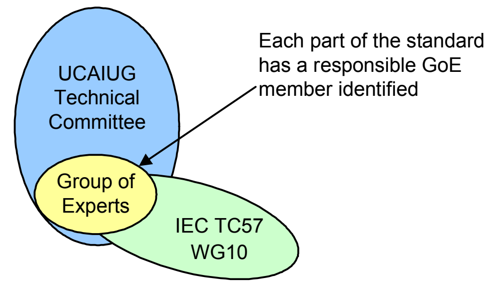


Fig. 8. Group of Experts Created by Overlap of IEC TC 57 WG 10 and UCAIUG Participation [5]

Omissions and ambiguities in the standard have been, and continue to be, resolved by the GoE via the technical issue, or TISSUES, process as pictured in Fig. 9.

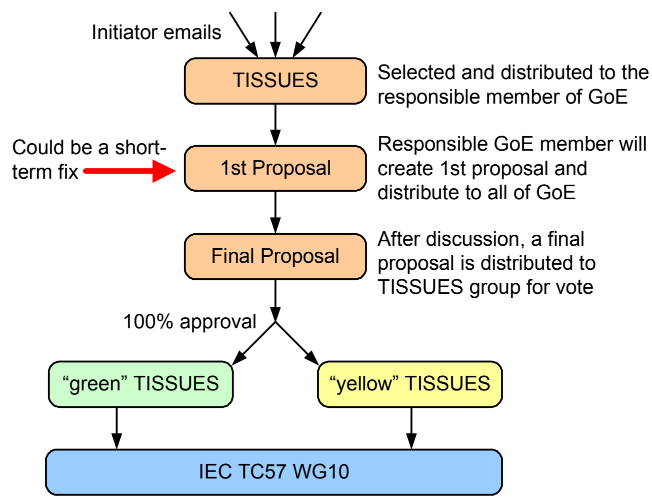


Fig. 9. IEC 61850 TISSUES Process for Providing Feedback Into the Development of IEC 61850 [5]

Interoperability depends both on the device properties and the system design and engineering. Conformance tests shall be performed to verify that the communications behavior of a device as system component is compliant with the interoperability specification of IEC 61850. These tests specify what shall be applied on a device to check that the communications function is correctly performed with a complementary device. Also the pass criteria have to be well defined. However, the most frequently asked question is what happens next if an interoperability test is negative.

Vendors commit to support the standard, work with others in the marketplace to identify and solve errors and omissions to the standard, and create products that are interoperable. Users commit to understand the standard, carefully specify products and systems, create application scenarios with realistic expectations, and work within the standard to request solutions to incompatibility issues. The UCAIUG is now considering the same TISSUES process for resolution of ambiguous product behavior and ambiguous test cases. This will be successful if vendors and users alike commit to this method of resolution of disputes.

IX. Conclusions

IEC 61850 includes, as part of the standard itself, a section on conformance testing procedures. A conformance testing program has been established by the UCAIUG, an industry support and technology development committee with broad participation by utilities, vendors, and others. Conformance testing of products is underway, and a selection of certified products is becoming available. It is important for users to understand the value and importance of this testing program, to have a realistic view of the limitations, and to understand what is required to achieve a successful implementation.

The interactive and iterative nature of the TISSUE process allows subject matter "experts" to resolve disputes or ambiguities neutrally and in the best interest of the marketplace.

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[7] IEEE C37.115-2003, IEEE Standard Test Method for Use in the Evaluation of Message Communications Between Intelligent Electronic Devices in an Integrated Substation Protection, Control, and Data Acquisition System.

XI. Biographies

Eric A. Udren has a 35 year distinguished career in design and application of protective relaying and control systems. He received his BSEE from Michigan State University in 1969, MSEE degree from New Jersey Institute of Technology in 1981, and the Certificate of Post-Graduate Study in Engineering from the University of Cambridge (UK) in 1978. In 1969 he joined the Westinghouse Relay-Instrument Division, where he developed software for the world's first computer-based relaying system. From 1978 to 1986, he supervised relaying and control software development for the EPRI-sponsored first development of a LAN-based integrated protection and control system. In 1990, he transitioned from Westinghouse to the ABB Protection and Automation Division. In 1996, he joined Eaton Electrical (Cutler-Hammer) in Pittsburgh, where he served as Engineering Manager for Electronic Products. In 2004, Mr. Udren joined KEMA T&D Consulting in Raleigh, NC as Senior Principal Consultant. He maintains his office in Pittsburgh. Working with KEMA, Mr. Udren has developed the technical strategy for some of the most progressive utility LAN-based substation protection and control upgrading programs using IEC 61850 and other data communications.

Mr. Udren is a Fellow of IEEE, Member of the IEEE Power System Relaying Committee (PSRC), and Chairman of two PSRC Standards Working Groups. In 2001, he received the PSRC Distinguished Service Award. He serves as Technical Advisor to the US National Committee of the IEC for TC 95, Measuring Relays. He also serves as a US Delegate to IEC TC 57 Working Group 10 responsible for IEC 61850. He has written and presented over 40 technical papers and chapters of books on relaying topics. He holds 8 patents on relaying and power-system communications.

David J. Dolezilek received his BSEE from Montana State University in 1987 and is now the technology director of Schweitzer Engineering Laboratories, Inc. He is an electrical engineer with management and development experience in electric power protection, integration and automation, communications, control systems, SCADA and EMS design, and implementation. He is the author of numerous technical papers and continues to research and write about innovative design and implementation affecting our industry. Dolezilek is a patented inventor and participates in numerous working groups and technical committees. He is a member of the IEEE, the IEEE Reliability Society, CIGRE working groups, and two International Electrotechnical Commission (IEC) Technical Committees tasked with global standardization and security of communications networks and systems in substations.

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