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Practical Experience with IEC 61850 Multivendor Systems and Foreseeable Future Applications – A System Integrator and End-user Perspective

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SUMMARY

Distributed protection, automation and control systems according to IEC 61850 are viewed as a powerful solution for substation automation and such technology is now becoming established worldwide as the foundation for current and future applications. Although most systems today are intra-substation single-vendor systems, the greater benefits of IEC 61850 reside in multi-vendor applications and in its system-wide application.

In the paper the authors, based on experience in Europe and South America, propose to establish and classify the current praxis in the application of IEC 61850 in multivendor systems by describing common physical and logical architectures as well as reporting on multivendor functional and engineering interoperability. The main conclusion is that IEC 61850 as a communications standard is solid and its immediate cost and simplification benefits are effective. Notwithstanding there is still much untapped potential in the industrial application of the standard: achieving communication interoperability within the IEC 61850 system is viable but functional integration and advanced engineering is still below what could be achieved, particularly in multivendor applications.

Regarding communications outside the substation the authors describe the case of the Portuguese transmission network by exploring current paradigm and future trends. Application cases that can bring significant short term benefits are discussed: remote maintenance, tele-protection, direct trip, interlocking schemes and remedial action schemes. The availability of utility-wide high bandwidth communication networks opens the window for such applications but issues pertaining not only to communications design at networking level (security, legacy technology, communication infrastructure, etc.), but also to implementation in current automation products (data models, services and protocol options, etc.) and to the multi-generational character of installed systems, limit the benefits and practicability of this approach which would require the establishment of an adequate transition path.

As utilities turn to IEC 61850 for refurbishing or expanding existing substations as well as introducing new ones, the foundation for system-wide seamless integration is laid out. However, to rip the larger benefits, IEC 61850 must grow in both the engineering practice and in its application scope.

KEYWORDS

IEC 61850, multivendor, substation, substation-to-substation, substation-to-remote center, architectures, interoperability, engineering

1. IEC 61850 MULTIVENDOR SYSTEMS IN THE GENERAL INDUSTRY PRAXIS

Substation automation systems, integrating protection, automation and control (PAC), have been the sole systematic application of IEC 61850 to date. The bulk of such applications target intra-station communication networks to drive distributed automation at bay and station functional levels (the so-called station bus). Applications to the bay-to-process (GOOSE/SMV) interface and to external station interfaces are still to be addressed in the general case.

Single vendor system approaches have been pointed-out (in pre-IEC 61850 systems) to hinder life-cycle benefits. Even though this is expected to be reverted in the long term by applying IEC 61850, many systems today integrate mostly single-vendor technology. In this part of the paper authors present current engineering praxis in IEC 61850 multivendor systems by proposing a classification of installed architectures based on their experience in Europe and South-America.

1.1 Physical Network Architectures

For bay and station levels Ethernet has become, in new systems, the dominant communication infrastructure, supporting both real-time and engineering/maintenance data flows. Three types of network topologies are usually found (tab. 1): star, ring and multiple-ring.

Tab. 1. Common network topology classes for IEC 61850 to date.

Class		D[1]	ST	T	Advantages	Disadvantages
I	Star	-			Cost; Simplicity	Redundancy options; Maintenance impaired
II.a	Single-Ring	+	++	++	Redundancy options	Scalability; Requires single-vendor switches if non-standard RSTP is used
II.b	Single-Ring (embedded switches)	-			Cost (compared to II.a); Redundancy (compared to I)	Multi-vendor integration may be impacted; Maintenance and testing impaired; Network depends on IED availability
III	Multiple-ring		-	+	Scalability	Network is more complex

Star topologies are used in smaller and less critical systems, usually with limited redundancy options. Single-ring topologies with rapid spanning tree (RSTP) variants constitute the most common option with one or more switches per bay. Besides ring-based redundancy, IED connections to two ring switches may be employed (for devices with double network interfaces) or for duplicated devices (mainly gateways or local servers). Ring-based architectures featuring embedded switches in IEDs are also employed mainly for cost reduction. In large substations multiple rings are applied, to ensure network performance and/or functional independence. In such cases functions allocated to one ring may actually be independent of functions in other rings (except for station HMI and gateways), typically at different voltage levels. More complex star/ring architectures or duplicated network infrastructures may be applied, but are less common.

1.2 Logical Architectures

The information flows between devices and the existence and allocation of functions to devices are independent of physical network infrastructure and constitute the logical system architecture. Noting that each system may exhibit a mixed-class architecture, three major classes of logical architectures can be drawn and are presented in tab. 2.

From the defined IEC 61850 client/server (C/S) service set mostly model browsing, controls, polling and event-reporting (buffered and unbuffered) are used for communication between bay devices and station devices or tools (over MMS/TCP/IP) in multivendor systems. GOOSE is invariably applied between functions hosted at bay devices (more frequently applied between devices of same vendor). Other services or service applications are not frequently used. In tab. 3 the most common scenarios of IEC 61850 service application are identified.

[1]D – Distribution substations; ST – Sub-transmission substations; T – Transmission substations

Tab. 2. Classes of logical architectures, use of services and mapping to physical architectures

Class		Services[2]		Topology			Description
		C/S	GSE	I	II	III	
A	RTU/Centralized Automation	+		+	+		Usually applied to existing conventional system upgrades and with independent protection and control. Bay devices operate as data-concentrators, protocol converters and I/O devices.
B	Distributed Automation (No Peer-to-peer)	+	-		+	+	Applied to new systems and system expansions. Inter-bay and intra-bay interfaces are commonly hardwired or use other communication infrastructures, if at all existing. Bay-to-station via IEC 61850 C/S.
C1	Distributed Automation (Inter-bay)	+	+		+	+	Usually applied to new systems. Intra-bay communication hardwired (or other) and inter-bay supported by GOOSE. Bay-to-station via IEC 61850 C/S.
C2	Distributed Automation (Inter/Intra-bay)	+	+		+	+	Usually applied to new systems. All distributed functions heavily supported by IEC 61850 services.

Tab. 3. Common allocation of functions to IEC 61850 services

Function	Use of IEC 61850	Application
Station HMI	C/S Services	HMI and gateway functions may be hosted at the same or different devices, often in duplicated / hot-standby configuration. Data to the HMI is frequently fed from the gateways (usually via non-IEC 61850 IP protocols). Distributed web-based user interfaces have also been applied in some systems (supported by proprietary IP protocols over HTTP).
Station Event Log		
Station Alarms		
Station Gateway		
Clock Synchronization	SNTP	SNTP is used as network-based synchronization and the common method is to have an independent GPS-based SNTP server device (optionally redundant), feeding all other devices in network (including switches). In some systems IRIG-B is used.
Alarm Grouping	GOOSE and C/S Services	GOOSE is applied at bay level and C/S services are used to feed data to the station controller for station-level functional scope.
Control Inhibition		
Interlocking	GOOSE	Constitutes the most common application of GOOSE messaging.
Voltage / Power Transformer Control	GOOSE	Applied at bay-level, particularly in case of parallel operation of power transformers.
Protection, Protection Tripping, Protection Schemes, Measurement and Metering, Disturbance Recording, Fault Location	n/a	These are usually implemented as bay-level device local functions and, when implemented as distributed functions would typically use non-IEC 61850 communication solutions. Some specific applications of tripping or protection schemes may be implemented via GOOSE but such applications are not common.
Zero-Voltage, Maximum-voltage, Breaker Failure, Auto-reclosing	GOOSE	When implemented over IEC 61850 use GOOSE messaging. Mostly applied in distribution substations.
General Automation (bay HMI, auxiliary services, control sequences, shedding, supervision of primary equipment, restoration, etc.)	GOOSE and C/S Services	General automation-related functions may make use of GOOSE messaging as well as C/S depending on where algorithms are implemented (bay or station controllers).

[2] C/S – Client/server services; GSE – GOOSE messaging.

Function	Use of IEC 61850	Application
Operating Modes	GOOSE and C/S Services	Management of station and bay operating modes (auto/manual, local/remote, neutral connection, etc.) and adaptation of function settings is frequently performed via IEC 61850.
Operational Settings	C/S Services	Some settings may be modified via C/S services but non-IEC 61850 IP communication protocols are usually also employed.
Supervision of Automation Devices	GOOSE	Mostly an internal function of each device. When implemented as a distributed function GOOSE messaging is used to track device behavior.
Supervision of Active Communication Equipment	n/a	When applied, management of switches, network clocks and routers (or similar) is performed from station-level devices using the SNMP protocol.
Engineering (configuration, operational settings, records extraction, etc.)	n/a	Non-IEC 61850 IP communication protocols (FTP, proprietary, etc.) are employed as a rule.

1.3 Multivendor System Classes

For any of the drawn logical architecture classes multiple device selection options are possible. Actual systems tend to fall into one of three categories regarding the use of devices from multiple vendors, with increasing level of multivendor integration (tab. 4).

Tab. 4. Multivendor system classes[3]

Class		Characterization
1	Mostly single-vendor	Station controller/gateway/HMI, protection and control at bay level are supplied by a single vendor and some specific bay devices are provided by other vendors (ex: voltage regulation or specific protection functions).
2	Bay and Station	Station controller/gateway/HMI devices are supplied by one vendor, protection and bay control devices are provided mainly by a second vendor.
3	Extensively multi-vendor	Multiple vendor devices for station and bay are employed, even within each bay (ex: control, main 1 and main 2 protection). Two, three or more vendor devices are used with no relative predominance.

1.4 Interoperability Analysis

Interoperability can be defined according to four levels: (i) data communication interoperability, (ii) functional interoperability, (iii) engineering interoperability and (iv) interchangeability. As interoperability is one of the main requirements for adequate multivendor system integration and performance, experience with integration of devices from six different vendors in the last four years is reported.

Data communication interoperability is the capability (of devices and applications) of correctly interchanging data at protocol level.
Regarding data-exchange minor issues have been found but all have been solved by the use of more flexible clients/subscribers and/or by software/firmware changes. Conformance certification and the use of a limited number of protocol stacks between vendors largely contribute to the high level of interoperability found.

Functional interoperability is the capability (of devices and applications) of using the exchanged information for correct execution of PAC functions at application level.
Functional integration in multivendor systems is viable but not straightforward and, although targeted by the standard, actual technology exhibits interoperability issues that often require further analysis and limit the solution design options for a given system. Examples are issues pertaining to: expected

[3] Classification of automation devices only, does not include time servers and switches. Active network equipment is frequently of the same vendor for interoperability (proprietary fast spanning-tree, priority methods, etc.) and maintenance reasons.

data object value behavior; the generation and, particularly the processing of quality attributes; management of timestamps and clocks under abnormal conditions; performance and the availability of optional data objects.

Engineering interoperability is the capability (of tools) of exchanging and using information pertaining to the configuration or configurability of devices and systems for engineering purposes with minimum user intervention.

The proposed engineering model of IEC 61850 based on the interaction of system specification, system configuration and device configuration tools (each potentially from different supplier) streamlines the engineering processes by concentrating the user workload on the object-oriented system tools, but current tool implementations lack in the generation, interpretation and use of SCL files. The lack of broad and interoperable tool support up to now, mainly at the interface between system and device tools, has promoted the use of a device-tool-only approach over the use of a single system configuration tool (fig. 1).

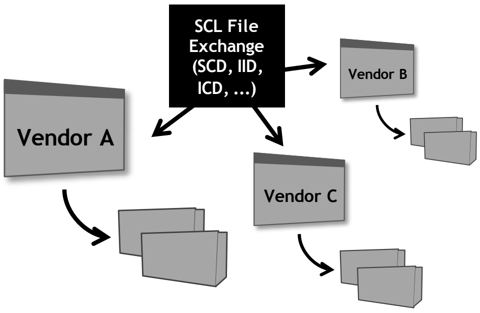

Fig. 1. Typical use of SCL in software tools in a device-tool-only approach.

Interchangeability, being the capability to replace a given device by another of different manufacturer without considerable reengineering effort, is not supported by the standard and is not deemed viable today or in the near future as general practice.

1.5 Engineering

Where engineering is concerned the standard comes to play mostly in the implementation, validation and testing stages, the later stages of the system integration. Automation engineers still focus more on point and document-based approaches instead of object or model-based approaches. Specification, design and documentation of systems according to IEC 61850 is not standard practice today albeit many efforts are currently being employed in this direction. The application of IEC 61850 to the whole engineering process faces some barriers not only in multivendor systems but in the general case, such as: (i) tool implementations frequently lack high levels of interoperability and openness; (ii) tool support for specification and iterative configuration is limited; (iii) configurability of models is limited in many product offerings, (iv) there are no user-targeted (visual) languages defined, only a machine-oriented format and (v) engineering guidelines are only now being established by CIGRE, IEC and other bodies.

2. THE PORTUGUESE TRANSMISSION NETWORK

2.1 Substation Automation Systems Since 2004

Mainly due to the growth in the number of wind farms to be installed after 2004, Portugal had to significantly increment the number of transmission substations (400, 220, 150 and 60 kV) and length of line circuits (400, 220 and 150 kV), as shown in tab. 5.

Tab. 5. Portuguese transmission network assets in service

Type of Asset in Service	End of 2004	End of 2009
Nr. of Substations	56	70
Lines Circuits (in km)	6.489,401	7.546,724[4]

[4] Length of line circuits at 21-12-2009. Final number for 2009 is not yet available.

Given the mentioned forecast, a complete review of the technical specifications for substation automation systems (SAS) was started in 2003, according to internal requirements and the state of the art available at the market. The developed specifications cover a wide range of subjects, from system architecture, level 1 cabinets constructive issues, global system performance, international standard references, functional specifications, up to engineering process certification.

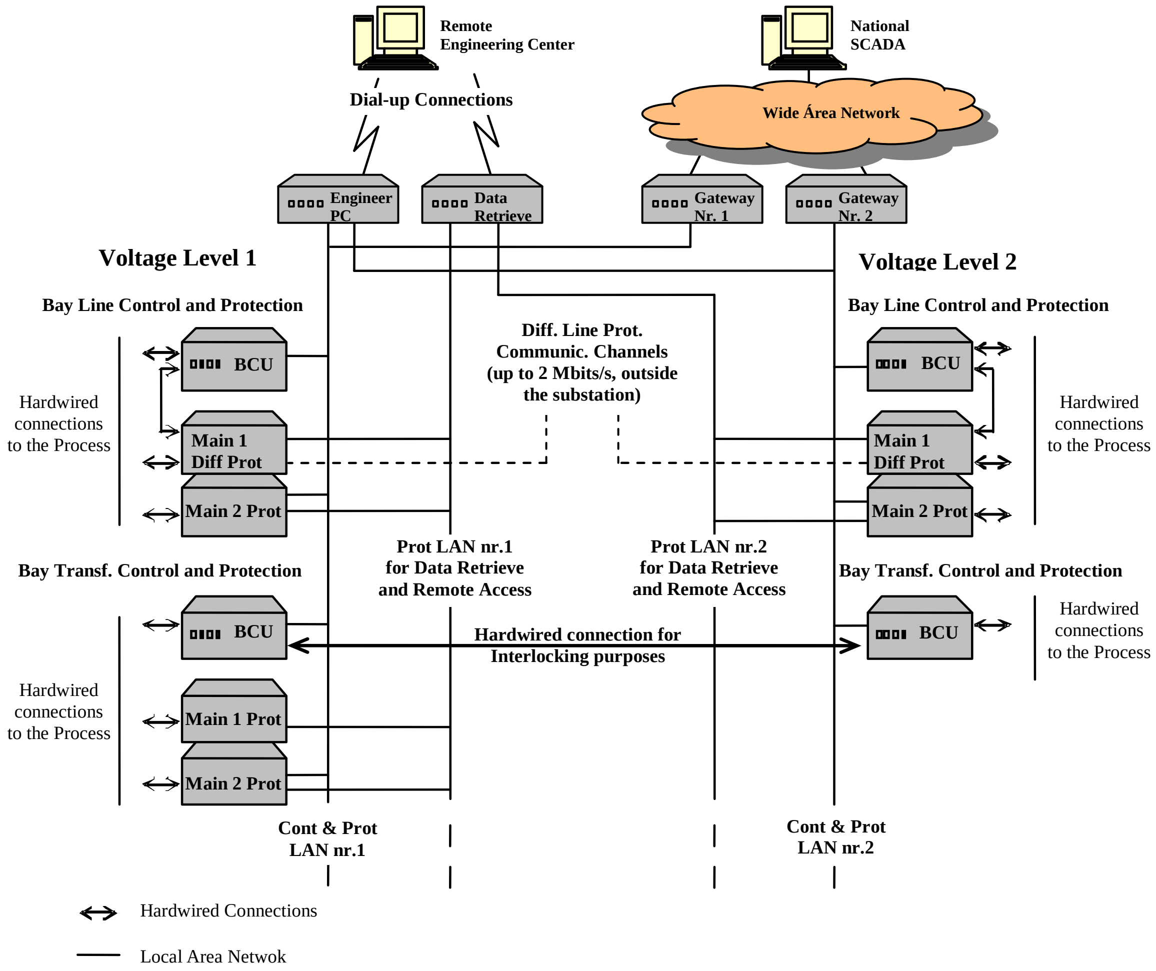

Fig. 2. Current system architecture.

To obtain significant gains in terms of project execution time, all SAS should be supported on numerical bay control and protection units. Bay control units should be interconnected by a local area network (LAN) supporting client/server communications (level 1 to level 2 communication) and data interchange among bay control units. A local HMI and redundant gateways to interchange data between the SAS and the National SCADA were also required. Also the project for line differential protection systems occurred, which should be extended to the major part of the network.

The mentioned specifications were developed without having in mind the new IEC61850 standard. Nevertheless, after the arrival of IEC61850, the main part of the specifications remained up to date. The main exception refers to the system architecture, which can be simplified, taking advantage of an Ethernet based LAN and interoperability between IEDs. As shown in fig. 2, the main 1 differential line protection is still not integrated in the LAN, exchanging information with the control system via hardwired connections. The remote access to protection units, dedicated to maintenance and data collection for fault analysis, is performed via a dedicated network. On control side, for interlocking purposes, the information exchanged between both voltage levels of a transformer is made via hardwired connections. Future trends, with the exception of the substation to substation data exchange, tend to integrate all substation IEDs in a unique local control and protection station bus, which will support all the needed communication network services inside the substation and to the Remote Engineering Centre. However, the connections to the process will remain hardwired.

2.2 Architectures and Applications at System Functional Level

Communication outside substations in the Portuguese transmission network includes the set of services detailed in tab. 6. However none of these are IEC 61850 compliant and some, like Tele-protection, Direct Trip and Remedial Action Schemes, are still implemented with hardwired connections inside substations, whilst line differential schemes will tend to use SDH via E1 or C37.94 interfaces with up to 2 Mbit/s.

Tab. 6. Communication schemes outside substations at Portuguese transmission network

Communication Schemes		Protocol / Link Type	Description
Remote Access	Substation to Remote Engineering Centre	Supported by dial-up connections	Refers to both, control and protection systems. Dedicated to remote maintenance and data retrieval for fault analysis. In service for all recent SAS, since 2004.
Telecontrol	Substation to two SCADA front-ends	IEC 60870-5-101	Refers to real time data exchange between the National SCADA and SAS. In service for all substations.
	Substation to four SCADA front-ends	IEC 60870-5-104	
Interlocking	Substation to substation	Head line voltage observation	The voltage detection at the head transmission line voltage transformers are used for line earthing switch interlock. In service for all substations.
Differential Line Protection		Proprietary Protocols via MUX 64 kbit/s and E1/C37.94 up to 2 Mbit/s	Current differential line protection for multi terminal lines. In service for all recent SAS generations, since 2004.
Remedial Action Schemes		Power line carrier, SDH or PDH	Mainly to prevent against line overloads in special network schemes. Seldom used.
Tele-protection			In use with distance line protection with permissive overreach tele-protection scheme. In service for all substations.
Direct trip			To transfer breaker failure protection trips. In use with a double redundant communication channel. In service for all substations with one and a half breaker topology.

2.2.1 Remote Engineering Centre to Station Interface

The dial-up links to the Remote Engineering Centre do present a lack of performance for most of the modern SAS generations in terms of speed and reliability, constituting a limitation for the remote maintenance itself and for new developments, exploring the potential of IEC 61850 standard. In fact, taking the example of the fault analysis, the market is offering today several tools to automate the process of collecting incident information from several points of the transmission network, making it available in predefined report formats to the persons responsible for their analysis.

Also for maintenance purposes, several features can be explored drawing on IEC 61850, since Logical Nodes (LN) in real IEDs can contain an amount of relevant information about the assets, ranging from switchgear to power lines, including their own substation automation system. As shown in tab. 7, LN are designed to contain settings, measured values and common information of the assets, but also meta-information, which can be retrieved by a centralized application for automatic database generation, statistics, history, reports, alerts or other engineering purposes. The automatic generation of a central database supported by IED data models would avoid duplication of tasks and errors arising from manual data entry as well as provide means to perform time-effective change management.

Such an application would require IED common support for a wider range of optional data and services than what is available today in the market and eventually also additions to the current standard data models. It is also to be noted that IEC 61850 data model extension mechanisms are provided by the standard, but the availability of extra information or model configuration capability of devices are also limited today. These factors limit the actual attainable benefits in such applications.

Regarding the considerations above, near future trends for the Portuguese transmission network include the implementation of a remote engineering centre supported by Ethernet links, which today cover the major part of the Portuguese transmission network.

Tab. 7. Examples of Logical Nodes and their data

Logical Node	Type of Data	Data	Explanation	M[a]/O[b]
XCBR (circuit breaker)	Metered Values	SumSwARs	Sum of switched Amperes	O
	Common LN Information	OpCnt	Operation counter	M
		EEName	External equipment name plate	O
RFLO (fault locator)	Measured Values	FltZ	Fault Impedance	M
		FltDiskm	Fault Distance in km	M
	Settings	Linlenkm	Line length in km	O
		R1	Positive-sequence line resistance	O
		X1	Positive- sequence line reactance	O
		R0	Zero-sequence line resistance	O
		X0	Zero-sequence line resistance	O
		etc.	etc.	---

[a] Mandatory data. [b] Optional data.

2.2.2 Substation to Substation Interface

As can be seen from tab. 6, regular station to station communications are used for Line Differential Protection, Tele-protection, Direct Trip and Interlocking schemes. A seldom usage is identified for Remedial Action Schemes, applied against power lines or power transformers overloads for special network configurations, usually for limited periods of time, which can go from a few months to a couple of years. Several examples of Remedial Action Schemes needs can be found in the recent history of Portuguese transmission network. Interlocking between circuit-end switchgear of power lines, as implemented today, only avoids unwanted close commands to line earthing switches, which do not cover all the possible operator mistakes (for instance a close command of a line isolator switch when the line earthing switch is closed on the other extreme is allowed).

Tele-protection and Direct Trip schemes, as implemented today in the Portuguese transmission network use hardwired connections inside substations, which require physical intervention on site when there are topological changes in power lines, which leads us to say that a more flexible data exchange, compliant with the IEC 61850 standard could be an interesting improvement in this area. The mentioned flexibility refers mainly to the remote configuration and test facilities which would limit or even completely avoid physical intervention on site. Moreover, the Interlocking and Remedial Action Schemes could also take advantage of such a flexible and easily reconfigurable communication infrastructure.

According with [5] two different approaches can be taken for the data transfer as shown in fig. 3: (i) the tunneling mechanism and (ii) proxy gateways. The first approach is more interesting from an engineering perspective as it allows more independent network and logical infrastructures, but requires higher bandwidth.

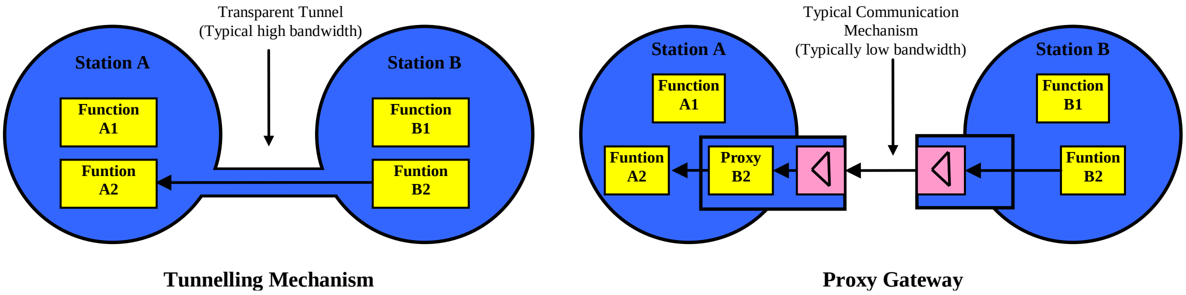

Fig.3. Tunneling and proxy/gateway mechanisms.

Given that information data transfer times are very critical for Tele-protection and Direct trip signals (typically less then 4 ms are required), careful design of the whole intra and extra-station communication infrastructure is essential, not only for maximum delay assurance but also for dependability and security reasons. For example, the adequate design and use of VLANs and priority-forwarding as a way to guarantee network traffic segregation and application-based prioritization would be recommended. The application of such concepts in the Portuguese transmission network, which is widely covered with an Ethernet-based WAN, would be considered interesting. Nevertheless, most of the IEC 61850 compatible IEDs recently installed in the Portuguese transmission network do not support VLAN tagging capabilities and a significant number of substations are still equipped with non IEC 61850 SAS which, among others aspects, may limit the immediate system-wide application for PAC purposes.

3. CONCLUSIONS AND OUTLOOK

Although functional and engineering interoperability may still present room for improvement, IEC 61850 is well established today in the general case of multivendor intra-station systems and the anticipated immediate benefits of its application (simplification of installation, increase in flexibility, cost reduction in cabling and physical infrastructure, reduction of different communication protocols in place, easing of engineering, etc.) have proven to be effective. Multivendor systems of all classes have met customer requirements for functionality and performance which makes the choice of the adequate level of multivendor fall more on to options of anticipated life-cycle cost, product offering and the position of the utility in the value-chain. The expected benefits of IEC 61850 in system maintenance, expansion or evolution are yet to be verified as experience in these cases is limited.

The intra-station application of IEC 61850 is a major step forward for multivendor systems but the full potential of the standard is yet to be attained: (i) installed IEC 61850 system architectures have not deviated much from those of modern systems using pre-IEC 61850 technologies and (ii) automation engineering methods have been made more efficient by the use of the SCL and of new software tools but have not fundamentally changed. Authors expect that architectural revision and improvement in engineering are both fruitful domains for industry investment in the near future.

The application of IEC 61850 outside the substation is highly limited today but growing availability of utility-wide high bandwidth communication networks indisputably brings the topic to the light of day. Taking the Portuguese transmission network as a case study, potential immediate benefits of its application are clear, but when considering technology availability, performance, integration, security, reliability it is also clear that a migration path is required.

Raising the independence of network infrastructure from logical infrastructure and simplifying multi-vendor and multi-application functional and engineering integration are critical, even more in system-wide than in intra-station applications. This is the true power in IEC 61850 and applying it would enable the infrastructure for smart grid operation.

As utilities turn to IEC 61850 for refurbishing or expanding existing substations as well as introducing new ones, the foundation for system-wide seamless integration is laid out.

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