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IEC 61850 Substation Automation Systems-Scope, Overview and Opportunities

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Abstract—*The paper presents an overview of IEC 61850, the standard for 'Communication Networks and Systems for Power Utility Automation' and its major objectives. IEC 61850 Substation Automation System (SAS) functions, interface types, communication types, services, and their performance requirements for various substation automation applications are explored in depth. It investigates the approach, features, scope and benefits of IEC 61850 communication standard which helps not only to develop cost effective and efficient SASs but also provides various opportunities for applications outside the substations. Further, this work examines the huge potential of IEC 61850 standard to impact the design, operation, testing, and performance of Ethernet communication based SAS applications that cannot be achieved with legacy communication protocols.*

1. INTRODUCTION

Substation automation is the effective use of smart equipment, communication and networking technologies in substation applications that has the ability to monitor their own functionality. The introduction of communicable Intelligent Electronic Devices (IEDs) and digital communication in substations has offered a wide range of opportunities for utilities to improve and facilitate the effective substation automation applications. Substation IEDs provide communication capabilities with vendor specific communication protocol and hence were incompatible both at the physical layer interface and the communication protocol layer [1-2].

Thereby, costly and complicated protocol converters were required to bring the substation devices onto a common physical network and allow everyone to speak a common application layer protocol. Earlier, the proprietary protocols for communication in substation were Profibus [3], IEC 60870-5 [4], DNP (Distributed Network Protocol) [5], and Modbus [6]. Thus, due to the proliferation of multi-vendor IEDs and communication technologies in substation, there seems to be an immediate need to adopt a standard approach for meeting the critical communication demands of SAS and also to be future ready to tackle demand growth and changing scenario due to restructuring and deregulation. McDonald discusses the approaches to achieve this in [7]. The major challenges encountered were the successful configuration of the multivendor IEDs (using the proprietary configuration tools), their interoperability and performance tests. An effective communication system played a key role to link substation devices within an electric power substation for the high reliability and real-time operation of a SAS [8]. Modern substation automation system uses IEC 61850, the standard for '"*Communication Networks and Systems in Substation*" for the real time operation of the power system [9]. Standardized data model, communication approach and the configuration language are some inherent features in IEC 61850 standard that offers various benefits over legacy communication protocols such as Modbus, Modbus Plus, DNP3.0, and IEC 60870-5 [10].

This paper discusses the approach, features, scope and benefits of IEC 61850 communication standard which helps not only to develop cost effective and efficient substation automation systems but also provides various opportunities for applications outside the substations in achieving smart grid objectives. The rest of the paper is organised as follows: IEC 61850 communication protocol key components and features are discussed in Section II. The approach and impact of IEC 61850 standards in designing copper-less substation automation system is described in section III of the paper. Section IV discusses the major benefits of IEC 61850 based SAS. Finally, concluding remarks are provided in section V of the paper.

2. IEC 61850 SUBSTATION AUTOMATION SYSTEM

Hardwired interfaces exist between the high voltage primary switchyard equipment such as CT/VT, transformers etc. and the bay level protection and control IEDs in traditional SAS. In IEC 61850 based modern substations, this complex network of copper cables are replaced by Ethernet LAN based serial communication links between primary and secondary level devices.

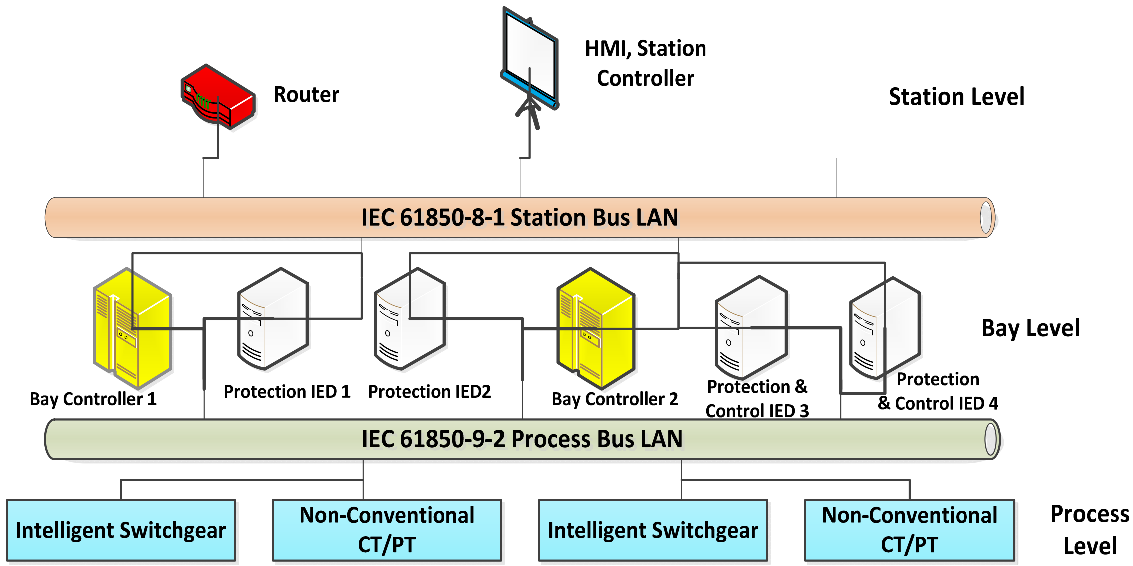

Fig. 1: IEC 61850 Substation Automation System

2.1 Functions and Interfaces of IEC 61850 Substation Automation System

According to the concept of IEC 61850, SAS architecture generally consists of three levels as shown in Fig. 1 [9]:

- **Station level**

It includes Human Machine Interface (HMI) and GateWays (GW) to communicate with remote Network Control Centre (NCC) and integrate IEDs at the bay level to the substation level. Station level functions include event and alarm handling, monitoring, data evaluation, archiving, and status supervision. It also performs different process related functions such as implementation of control commands for the process equipment by analyzing data from bay level IEDs.

- **Bay level**

The protection and control IEDs of different bays of a substation are placed at bay level. The process level equipments are connected to the bay level IEDs through the process bus network for implementing various monitoring, protection, control, and recording functions.

- **Process level**

It includes the switchyard equipments, remote I/O devices, intelligent sensors and actuators etc. The conventional or Non Conventional Instrument Transformers (NCIT) are located at the process level to collect system data and send them to bay level devices to perform automatic control & protection operations which are achieved through circuit breakers and remotely operated switches.

- **Station bus**

It exists at the substation level and is used for communication between IEDs at the bay level and the station level. Several redundancy methodologies are usually employed to select station bus architecture for improving the reliability and performance of various protection and control functions carried out by IEDs at the station level.

- **Process bus**

It is serial communication interface between the process level and bay level equipments. It facilitates the time-critical communication such as Generic Object Oriented Substation Event (GOOSE), Sampled Values (SVs), binary status and control signals between switchyard equipment and bay level IEDs through instrument transformers.

The standard allows the implementation of distributed substation functions such as protection, control, monitoring and metering functions based on the concept of object data modeling approach [9]. These functions are distributed between IEDs located on the same or on different levels of the SAS.

- **Process level functions**

These functions interface the process-level equipment to the bay-level equipment in the substation. The communication involves data acquisition from the switchyard equipments and issuing of control commands; in the form of analog signals, binary status signals or binary control signals.

- **Bay level functions**

These functions are implemented in bay-level IEDs that also perform process-level and substation-level functions.

- **Station level functions**

These functions are responsible for the overall functionality of the substation and are divided into two groups:

Process related station level functions: These functions are basically the substation protections and control functions that utilize the bay level or complete substation data.

Interface related station level functions: This type of interfacing represents the communication of SAS to the substation HMI, to Supervisory Control and Data Acquisition (SCADA) or to a remote engineering station. The standard defines various logical interfaces used for different types of communication in performing these SAS applications. These interfaces are defined in [11].

2.2 Communications System in IEC 61850 SAS

The standard uses ISO/OSI seven layers communication stack consisting of Ethernet (layers 1 and 2), Transmission Control Protocol/ Internet Protocol (TCP)/IP (layers 3 and 4) and Manufacturing Message Specification (MMS) (layers 5-7) for satisfying the different communication needs of IEC 61850 SAS [9]. The standard, based on different logical interfaces, defines the different types of communication services for information exchange between the IEDs and towards local HMI and control centre.

- ***Client-server communication*:**

It is typically used for SCADA applications that involves the data communication from a higher hierarchical control level down to a lower one for local and remote operations of the switchgear and reverse for acquisition of switchgear information such as status or position indications, power system measurands from CT/PTs and other sensors, events, alarms. Client-server communication service model based on MMS over TCP/IP and Ethernet is used for vertical communication between the bay and station level devices. The data transfer is very slow and reliable since the communication is based on seven layers ISO/OSI communication stack model. Thus, client-server communication is not suited for time-critical data.

- ***Publisher/Subscriber communication service model***:

Substation critical protection and control applications require fast data transfers and are based on horizontal communication network between the IEDs at the same hierarchical level. Both GOOSE and SVs communication are based on '*publisher/subscriber*' communication model consisting of fast communication services. These messages are sent as multicast messages over the SCN. GOOSE messages are event driven and are repeated for high transmission reliability while the SVs are time triggered and possess low transmission reliability over the process bus network. Both require real time performance of the communication network and hence to guarantee a timely delivery, advanced Quality of Service (QoS) features like 802.1X are used in addition.

3. APPROACH, FEATURES AND IMPACT OF IEC 61850 COMMUNICATION STANDARD

The standard possess object oriented data models and the set of rules for creating new Logical Nodes (LNs) and Common Data Classes (CDC). It also supports peer-to-peer communication based publisher-subscriber communication mechanisms such as GOOSE) and SVs, and has Substation Configuration Description Language (SCL) for the automatic configuration of systems and devices applied in the whole electrical energy supply chain. With these advanced features, it is possible design cost effective, highly reliable and performing distributed substation protection and automation applications. Also, these features make it possible to extend the scope of the standard beyond the substations [12].

3.1 Object Oriented and Hierarchical Data Modeling Approach

The most promising feature of IEC 61850 standards is its object oriented and hierarchical data model, which contains data models of all possible substation automation functions and devices in substations, and standardizes the names of these functions and data. The CDC elements are defined in part 7.3 [13]. The abstraction of the data objects (LNs) is found in IEC 61850-7-4 [14]. In short, the part 7 achieves the naming of massive data and forming data objects and services.

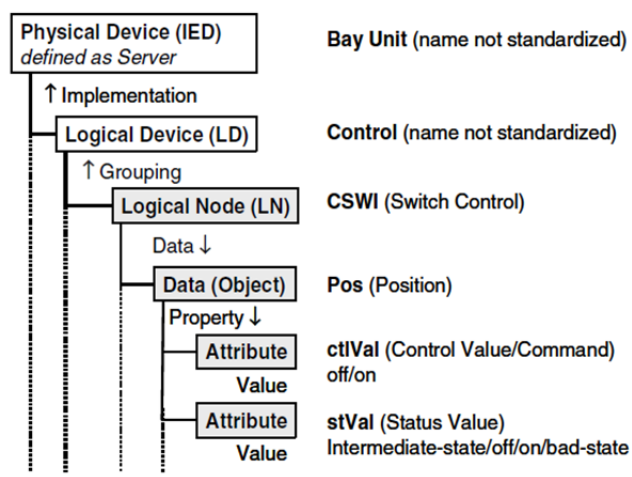

Fig. 2: The object model of IEC 61850

The abstract data and object models of IEC 61850, as shown in Fig. 2, define a standardized method of describing power system devices that enables all IEDs to present data using identical structures that are directly related to their power system function. Each functional element is defined as a logical node which again consists of standardized data and data attributes. Thus, LNs represent either the information content of a function or devices in SAS. This information represents the process, configuration, name plate and diagnostic information. Also, the standard has an object model and the set of rules for creating new logical nodes and common data classes. Thereby it enables to extend the scope of the standard, and include new applications both inside and outside the substation.

3.2 Communication Approach

The communication services and data models are defined in section IEC 61850-7-2 [15] of the standard. IEC 61850 uses OSI-7 layers stack for communication and divide it into three groups as shown in Fig. 3. Here, seven types of messages are mapped to different communication stacks. In client-server communication that involves medium speed messages (type 2), command messages with access control (type 7), low speed messages (type 3), and file transfers (type 5) is used for applications in managing switchgear equipments at process level.

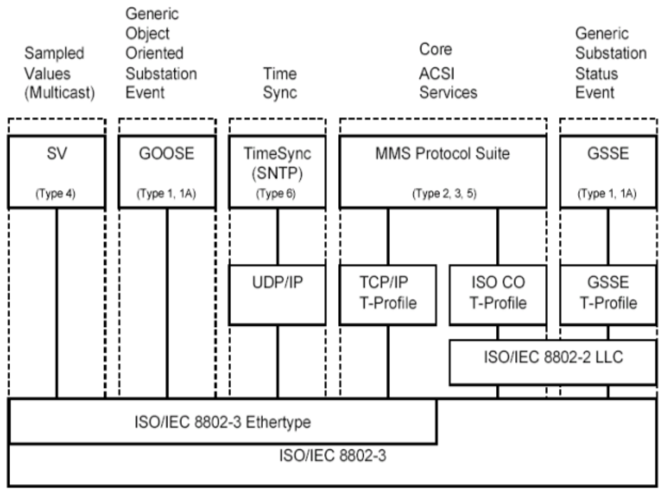

Fig. 3: Overview of IEC 61850 functionality and associated communication profiles [9]

The syntax and encoding of the messages are defined in the SCSM. For example, IEC 61850-8-1 defines the mapping of abstract object models and its services to the application layer of MMS, which has a TCP/IP stack layers on the top of the Ethernet layer. In addition to client/server services by mapping to MMS (connection oriented) stack, the standard provides peer-to-peer services for the transmission of fast, real time information exchange between IEDs, such as GOOSE and SVs. SVs (type 4) messages from Merging Units (MU) and GOOSE messages (type 1, 1A) like interlocking or trip commands are mapped directly to the link layer of the Ethernet thereby eliminating the additional upper layer protocols overheads involved in the transmission [16-18]. This improves the transfer time performance for mission critical messages by reducing the processing time of Ethernet frames, but reduces the reliability in GOOSE and SVs transmission. To increase the transmission reliability of GOOSE messages, the data transmission is repeated. Also for some specific applications like protection tripping, IEEE 802.1Q services of data link and physical layers are used. Time Synchronization messages (type 6) are broadcasted to all substation IEDs in substation based on UDP/IP.

3.3 Substation Engineering Support using Substation Configuration Description Language (SCL)

The standard specifies an XML based SCL, as shown in Fig. 4, which includes the data representation for substation IEDs including all relevant services based on IEC 61850-7-X, their interconnection and the substation automation functions to achieve communication interoperability and reduction of design efforts. These files allocate substation automation functions to the IED that contain logical nodes along with their data and data attributes.

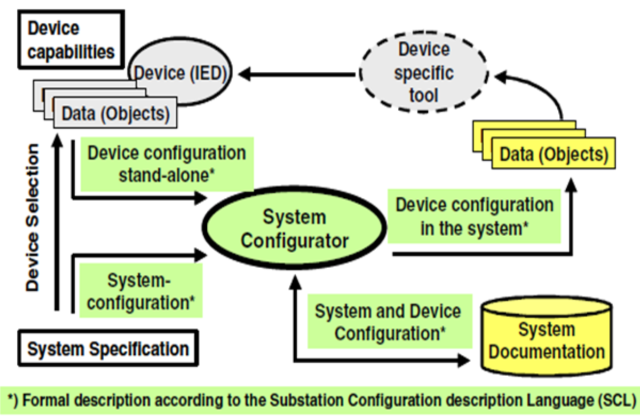

Fig. 4: The use of SCL for system engineering

The standard IEC 61850-6 defines four types of SCL files considering their tasks as follows:

- ***IED Capability Description files (ICD):*** Data exchange from IED configuration tool to the system configuration tool is defined using ICD files.
- ***System Specification Description (SSD):*** SSD files define the data exchange from substation specification tool to the system configuration tool.
- ***Substation Configuration Description (SCD):*** Data exchange from system configuration tool to the IED configuration tool is described using SCD files. The system configuration tool requires ICD and SSD files to generate SCD files.
- ***Configured IED Description (CID):*** It defines the data exchange from IED configuration tool to IEDs.

This feature enhances the communication capabilities of devices and allows IEDs from different manufacturers to exchange data through various SCL files. It further enables automatic configuration of IEDs to share device information among the users and suppliers and allows off-line configuration of 61850 substation applications.

3.4 Switched Ethernet Technology Support and Benefits

Modern managed Ethernet switches offer advanced features which allow SCN to be optimized to deliver consistent, real time performance that are critical for substation protection, control and automation application [19-20]. SCN infrastructure satisfies the real time protection over switched Ethernet with the following key mechanisms:

- ***High speed data rate*:** 100 Mbps/1 Gbps.
- ***IEEE 802.3x*:** Full Duplex operation and collision free environment to ensure deterministic delivery.
- ***IEEE 802.1p*:** it allows prioritizing IEC 61850 SCN message frames with different priority levels and thus providing a delivery guarantee for the high-priority traffic.
- ***IEEE 802.1q Virtual LAN (VLAN)*:** It allows the segregation and grouping of IEDs into Virtual LANs in order to isolate real time IEDs from data collection or less critical IEDs. This feature ensures that real time traffic always makes it through the network even during high periods of congestion.
- ***IGMP (Internet Group Management Protocol) layer 2/3 snooping/multicast filtering*:** It allows for multicast data frames, such as GOOSE/SVs, to be filtered and assigned only to those IEDs which request them to listen.
- ***IEEE 802.1w Rapid Spanning Tree Protocol (RSTP)***: It allows managing redundant paths in a layer 2 network and hence makes it possible to create fault tolerant SAS architecture that will re-conFig. in milliseconds (10-500 ms) depending on the SCN topology and size.
- ***Redundant Substation Communication Network architectures*:** Ethernet allows for a wide variety of network topologies providing different levels of reliability, availability, and performance. Component redundancy and/or communication path redundancy can be chosen to improve reliability at the physical and data link layer of OSI model.
- Availability of **EMI (Electromagnetic Interference)-** hardened, extended temperature range Ethernet switches for operation in the substation environment. Following subsection has discussed the major benefits of IEC 61850 on substation performance.

4. MAJOR BENEFITS OF IEC 61850 COMMUNICATION STANDARD

IEC 61850 defines and offers much more than just a protocol. Several inherent features in IEC 61850 communication standard, as discussed in the previous section, provide various opportunities and benefits over legacy substation communication protocols such as IEC 60870-5 [4], DNP3.0 [5], and Modbus [6]. Some of the benefits offered by IEC 61850 include [21-23]:

- ***Simple and cost effective substation architecture*:** In IEC 61850 based modern substations, costly and complex network of multiple copper cables, both at the station and bay level, are replaced with a few shared Ethernet communication links between process level and bay level equipment. It allows integrating multiple functions in a single IED, and also the replacement of a number of convention instrument transformers at the process level with a few optical/electronic technology based NCITs. It results in very significant improvements in the designing, safety, reliability and performance of substation applications. Further, it allows IEC 61850 SASs to have low installation, commissioning, maintenance, testing and life-cycle costs which bring the long-term economical benefits needed by the utilities to stay competitive in an energy market.
- ***Future proof standard*:** The standard follows progress in main-stream communication technology as it advances due to future developments. With this, it only needs to map the abstract data models are services onto new communication protocols.
- ***Benefits of Switched Ethernet technology*:** Switched Ethernet is used as a mainstream communication technology in IEC 61850 SAS that offers various benefits such as full duplex operation without collision, high data transfer speed among IEDs, supports peer-to-peer communication model like GOOSE and SVs instead of master-slave communication in legacy protocols, permits scalable and redundant architectures etc. Further, the use of IEEE 802.1x network traffic management features such as priority queuing, VLANs, RSTP, IGMP etc., enhances the real time performance of communication based protection and control applications in 61850 substations.
- ***High level engineering support based on SCL*:** The standard supports self-description of device in terms of ICD file that contains data models and its associated functional and communication capabilities. The XML based SCL files contain all information that is relevant to build the SAS and supports the automatic configuration of devices and the system. This feature also makes any future extension of the SAS easier and economical.
- ***Standardized data modeling*:** Data is defined based on an advanced object oriented hierarchical structure, which contains whole data specifications instead of single-oriented model where data is defined by numeric addresses (indexing) as in legacy protocols.
- ***High level communication services*:** IEC 61850 standard supports peer-to-peer communication services like GOOSE and SVs for real time data transfer instead of master-slave model for communication in legacy protocols.

Hence IEC 61850 communication standard allow the substation designer to focus more attention on other important issues like intelligence, reliability, availability, security, and efficiency of the power network.

5. CONCLUSION

This paper has presented the approach and major features of IEC 61850 communication standard, and further investigated their impact on the design and operation of cost effective, reliable and efficient SAS applications. Communication interoperability, object-oriented data modeling, open communication, SCL based engineering support, and GOOSE/SVs based communication services are major features inherited in IEC 61850 standard that provides various benefits and opportunities over legacy communication protocols in designing modern SAS applications.

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