Developing Scalable Smart Grid Infrastructure to Enable Secure Transmission System Control

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Abstract	Substations are key nodes in the power system, where information from the system is retrieved and used for reliable operation and management of the network. In this regard, Substation Automation System (SAS) provides a powerful, fast, and viable way to design and implement substation-based applications in modern transmission grids. As a consequence of employing advanced and fast devices, such as protection and control IEDs, the efficient and high-speed ICT infrastructure has become an important issue. The ICT infrastructure has a key role in the advancement of connectivity and interoperability within system and needs to be evaluated in detail. In this report, the evaluation begins from inside substations and continues over wide areas from substations to control centre.			
Keywords	ICT infrastructures, interoperability, substation automation systems, WAMS			

Contents

Abbreviations

ACSI	Abstract Communication Service Interface
DES	Discrete Event Simulator
EtE	End-to-End
HMI	Human Machine Interface
IEC	International Electrotechnical Commission
IED	Intelligent Electronic Device
IP	Internet Protocol
MPLS	Multi-Protocol Label Switching
OO	Object Oriented
PDC	Phasor Data Concentrator
PMU	Phasor Measurement Unit
SAS	Substation Automation System
SCSM	Specific Communication Service Mapping
WAN	Wide Area Network

1. Introduction

Changes in the wholesale electricity market alongside the difficulties in upgrading the transmission system have increased the complexity of power network operations [1]. This fact has placed heavier demands on developing new technologies to manage power systems reliably. Substations are key nodes in the power system, where information from the system is retrieved and used for reliable operation and management of the network. Substation Automation Systems (SASs) are now being implemented using Intelligent Electronic Devices (IEDs) interconnected through communication network technologies to facilitate substation monitoring, control and protection. Interest in SAS has increased rapidly due to its numerous benefits to utilities. Digital data acquisition affords a level of visibility never considered possible in the electromechanical era of substations. Moreover, SAS provides additional capabilities and information that can be used to further improve the operations, maintenance, and efficiency of substations [2][3].

As a consequence of employing advanced and fast devices, the efficient and high-speed communication infrastructure has become an important issue in the design of substations. In this regard, the state-of-the-art IEC 61850 standard, released by the International Electrotechnical Commission (IEC), has enabled IEDs and devices in a substation to be integrated on a high-speed communication network. Furthermore, IEC 61850 has the objective of enabling interoperability between IEDs within a substation [4]. Interoperability is defined as the ability of two or more IEDs from the same vendor, or different vendors, to exchange information and use it for the correct execution of specified functions [5] .By applying Object Oriented (OO) data and service models, IEC 61850 supports all substation functions and provides more flexibility to the developer and users [6].

2. Substation Automation Systems

SAS can provide a powerful, fast, and viable way to design and implement substation monitoring, protection, and control functions in modern transmission and distribution grids [7]. The deployment of SAS has also fulfilled a market requirement to decrease the total cost. For example, optimization of maintenance costs and, in turn, reducing the life cycle costs of substations, provides highly efficient operation or near-limit operation of substation equipment [8]. Automated substations consist of smart and advanced equipment, such as relays, circuit breakers, transformers, switches, etc. that are integrated and monitored by a graphical interface unit that can be remotely accessed [9]. During the last decades, electromechanical devices in SAS have been replaced by IEDs and they now perform most functions, including protection and control. The basic functions of a SAS can be categorised as described in Table 1. Most SAS have these functions even though they may vary in different projects [8][10].

The architecture of a SAS can be mapped into three levels hierarchically [11]. Station level, provides an overview across the whole station and assures the supervision of all the substation equipment. This level includes Human Machine Interface (HMI) and engineering workstations as well as gateways to connect the substation control centre to WAN. Bay level, includes the protection and control IEDs of different

Table 1 Overview of the functions of a Substation Automation System

Basic Functions	Examples
Monitoring	• Monitoring of switchgear status, status of transformer and tap changer, status of protection and control equipment, etc. • Monitoring of electrical parameters; e.g. frequency, voltage, current, real and reactive power, etc. • Fault record of facility and device disturbance record
Control	• Control of switchgear and transformer tap • Synchronism check and interlocking • Load shedding, voltage regulation, reactive power control, etc.
Protection	• Protection for transmission line, transformer, busbar, feeder, etc. • Overcurrent, distance, differential protection, etc.

bays, such as circuit breakers, transformers, and capacitor banks. Equipment in the bay level and station level are called secondary equipment. Process level, includes switchyard equipment (called primary equipment) such as CTs/PTs, remote I/O, actuators, Merging Units (MU) etc. The main purpose of this level is to acquire data from the electric processes and to make switching operations. The communications of these three levels are carried out through the Process Bus and Station Bus. The Process bus is the communication network which connects the IEDs at the primary equipment level to other IEDs, such as MUs providing sampled measured values of current and voltage via the Local Area Network (LAN). The Station Bus is the Communication network which inter-connects IEDs at the Bay Level, IEDs at the Station Level, and connects the Bay Level to the Station Level [12].

The communication network is now considered the backbone of substation automation. Inappropriate configuration of the communication network may cause failure of substation automation functions and could make the applications at best inefficient and at worse ineffective. The IEC 61850 standard has enabled IEDs and devices in a substation to be integrated on a high-speed peer-to-peer communication network, as well as client/server communication [2][13].

3. IEC 61850 Standard

IEC 61850 is a communication standard released by the Technical Committee (TC) 57 of IEC. The goal of this standard is to provide interoperability between the IEDs from different suppliers or, more precisely, between functions to be performed for power utility automation [12].

3.1 IEC 61850 for Substation Automation Systems

IEC 61850 was originally introduced for the design of SAS. It defines communication between IEDs in substations and related system requirements. As a consequence of employing advanced and fast devices, such as protection and control IEDs, the efficient and high-speed communication infrastructure has become an important issue in substations. The IEC 61850 standard has enabled IEDs and devices in a substation to be integrated on a high-speed peer-to-peer communication network as well as client/server. In this standard, the application is independent from the communication protocol by specifying a set of abstract services and objects. IEC 61850 applies Object Oriented (OO) data and service models to support all substation functions. This provides more flexibility to the developer and users, as well as simplifying engineering tasks [2][12].

The IEC 61850 set of documents is comprised of 10 parts, where each part defines a specific aspect of the standard.

- **IEC 61850-1**: Introduction and overview
- **IEC 61850-2**: Glossary of specific terminology and definitions
- **IEC 61850-3**: General requirements of the communication network with regard to the quality requirements, environmental conditions, and auxiliary services
- **IEC 61850-4**: System and project management with respect to the engineering process, the life cycle of the SAS, and the quality assurance
- **IEC 61850-5**: Communication requirements for functions and device models
- **IEC 61850-6**: Configuration description language for communication in electrical substations related to IEDs
- **IEC 61850-7**: Basic Communication structure:
    - **IEC 61850-7-1**: Principles and models
    - **IEC 61850-7-2**: Abstract Communication Service Interface (ACSI)
    - **IEC 61850-7-3**: Common Data Classes
    - **IEC 61850-7-4**: Compatible logical node classes and data classes
    - **IEC 61850-7-5**: Application guide and usage of information models
- **IEC 61850-8**: Specific Communication Service Mapping (SCSM)
    - **IEC 61850-8-1**: Mappings to MMS and to ISO/IEC 8802-3
- **IEC 61850-9**: Specific Communication Service Mapping (SCSM)
    - **IEC 61850-9-1**: Sampled values over serial unidirectional multi-drop point to point link
    - **IEC 61850-9-2**: Sampled values over ISO/IEC 8802-3
- **IEC 61850-10**: Conformance testing

3.2 IEC 61850 for Synchrophasors over Wide Area

The technical report IEC 61850-90-5 [14], which has been published in 2012, provides a way of sending Phasor Measurement Units (PMUs) data to Phasor Data Concentrators (PDCs) and control centre applications. As the PMUs generate data based on the IEEE C37.118 standard, the data needs to be transmitted in such a way that is also compliant with the concept of IEC 61850. In addition, PMU data are transmitted over wide area where they need a routable profile. Accordingly, the IEEE 61850-90-5 standard has been proposed to provide routable profiles for IEC 61850-8-1 (GOOSE) and IEC 61850-9-2

(SV) services, referred to as R-GOOSE and R-SV, respectively. IEC 61850 is basically a layer 2 protocol and does not provide a Network Layer protocol. As such, this protocol does not inherently provide the routing capability required for wide area applications. The Internet Protocol (IP) is one of the options for communications over wide area. This is the protocol that the IEEE C37.118.2 standard uses for the transmission of data over networks. Although IEEE C37.118.2 allows communication over IP using both the TCP and UDP transport protocols, IEC 61850-90-5 focuses on UDP. The Application Profile (A-Profile) consists of the GOOSE and SV as the Application and Presentation Layers encapsulated in the Session Protocol defined in IEC 61850-90-5. The A-profile in turn is bound to the Transport Profile (T-Profile), which provides a routing tunnel as specified by the Session Layer. In order to conform to IEC 61850-90-5, implementations should at least support IPv4. Additionally, IPv6 can be used in parallel with IPv4 allowing higher wide area routing ability for larger scale information exchange.

The IEEE C37.118.2 standard, which represents the communication aspect of the standard, does not explicitly address the communication services. Instead, it specifies the synchrophasor message format and defines the four message types of Data, Configuration, Header, and Command. Therefore, in order to be compliant with IEC 61850, the functions that are performed by these frame types need to be mapped to the existing services in IEC 61850. The control and configuration services are mapped to the conventional IEC 61850 MMS over TCP/IP, while the data need to use the proposed R-GOOSE or R-SV services. According to the IEC 61850 standard services, fast cyclic communications are typically based on SV, and additional event data can be communicated using GOOSE. Therefore, synchrophasor measurement data should map into the SV service [14].

According to the details that have been laid out in the report, the main focus of IEC 61850-90-5 is to provide a more seamless interoperable system. In this regard, the communications delay may not be as low as the time-critical services of the original three-layer IEC 61850. This is because the fast services of the standard are now mapped into the IP and transmitted over wide area network.

4. Performance Evaluation of ICT Infrastructures

Due to the criticality of some of the smart grid applications, the communications infrastructure performance in such networks needs a thorough analysis to ascertain that the required specifications will be met.

4.1 Substations

In [15], the simulation and modelling of a typical power system substation communications infrastructure have been presented. The purpose of this research is to create IEC 61850-based IED models and setup a simulation framework for substation communication networks. One of the important aspects of communication network performance analysis is the delay characteristics, especially for the smart grid's control and protection functions that have a fast response time requirement. By simulating the substation communications network using Discrete Event Simulators (DESs), the End-to-End (EtE) delay of the specific transmitted information can be investigated in detail. In this research, for the performance analysis of substation communications networks, typical substation communication architecture has been simulated using OMNeT++, an open source DES tool. From the analysis, it can be observed that IEC 61850 based on Ethernet shows acceptable performance for substation communications. Furthermore, preliminary studies were performed to introduce and evaluate the IEC 61850 protocol for PMU applications.

Although IEC 61850 was originally introduced for the automation of substations, the application of IEC 61850 is expanding rapidly. The deployment of IEC 61850 for Wide Area Network (WAN) applications such as PMUs is one of the proposed applications. Basically, PMUs are deployed for WAMS. Although PMUs transmit data from substations to PDC through WAN, investigating their behaviour inside the substation can be an effective step in introducing new protocols for their communications. Hence, in this research, a preliminary analysis on introducing the IEC 61850 protocol for PMU communications at the substation level has been performed.

4.2 Wide Area Networks

WAMS will be vital in the operation of future systems, where the need to instantly detect problems and react swiftly to a wide range of technical issues will become more crucial in order to deliver secure and reliable power. Critical to the operation of such systems is a robust and secure communications infrastructure; with the performance of communications links between PMUs and PDCs having a direct impact on the ability to meet specific monitoring and control requirements. There are several works with regard to the performance evaluation of WAMS communications infrastructure, which determine the characteristics of communication delays and bottlenecks that can occur in WAMS. In [16], an actual WAMS as installed on the transmission system of GB is modelled using both proprietary and open source DES tools, OPNET and OMNeT++. Comparisons were drawn between the modelled approach and measurements from the actual WAMS as well as between the two simulation environments. In addition, different protocols, mechanisms, and topologies were investigated for the GB WAMS future developments. Reference [17], focuses mainly on evaluating the performance of the real-time WAMS communication infrastructure when Multi-Protocol Label Switching (MPLS) capability is added to a conventional IP network. The simulation results are analysed in detail in order to fully determine the different characteristics of communication delays between PMUs and PDC. According to this research, the MPLS/UDP scenario shows better performance, especially in preventing dramatic increase of delay.

5. Conclusion

SAS is widely used in order to improve the reliability of power systems. The success of a SAS relies heavily on the use of an effective communication system as well as standards to link the various monitoring, control, and protection elements within a substation. In this regard, IEC 61850 based on Ethernet shows acceptable performance for substation communications. Furthermore, the ICT infrastructures between substations and control centre play an important role in enabling the concept of smart grid. Therefore, they need to be evaluated in detail due to their critical role in providing satisfactory performance levels in real-time WAMS applications.

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