

Substation Communication Architecture to Realize the Future Smart Grid

Ikbali Ali^{1*} Mini S. Thomas¹ Sunil Gupta²

1. Department of Electrical Engineering, Jamia Millia Islamia, New Delhi, India
 2. Department of Electrical Engineering, Maharaja Surajmal Institute of Technology, New Delhi, India
- * iqali_in@yahoo.com

Abstract

Substation and its communication architecture play an important role in maintaining high reliability, and availability of the power supply. Due to the proliferation of multi-vendor IEDs (Intelligent Electronic Devices) and communication technologies in substation, there seems to be an immediate need to adopt a standard approach for meeting the critical communication demands of Substation Automation System (SAS) and also to be future ready to tackle demand growth and changing scenario due to restructuring and deregulation. This paper presents possible exploitation of the technical features of IEC 61850, the standard for Communication Networks and Systems in Substation, to make the substation communication architecture future ready to accommodate the applications and goals of smart grid.

Keywords: Substation Automation, Interoperability, IEC61850, Smart Grid, Distribution Automation.

1. Introduction

Recent trend in the power industry across the globe is to use advanced state-of-the-art communication techniques and information technologies in electric utility to realize the concept of smart grid. The European Technology Platform defines the Smart Grid as “an electricity network that can intelligently integrate the actions of all users connected to it – generators, consumers and those that do both, in order to efficiently deliver sustainable, economic and secure electricity supply”(Xue-Song *et al.* 2010; Cecati *et al.* 2010). A Smart Grid integrates new innovative technologies and the actions of all the participants throughout the power system for the smart generation, transmission, distribution, and consumption of electrical power. Smart Grid needs an intelligent communication network to enable the real time monitoring of valuable grid assets for improving the automation functionalities and intelligence in the existing power network (Wang *et al.* 2011). Smart Grid is expected to include the following main features for transforming an existing grid (Roncero 2008; Fan & Borlase 2009; Farhangui 2010; Santacana *et al.* 2010; Xue-Song *et al.* 2010).

Smart Grid should provide an opportunity to generate, transmit and distribute the energy optimally, achieved through technological innovations, energy efficient management, healthy market competition and intelligent decisions in management and operation. Smart Grid technologies like Advanced Grid Assets (AGA) and Advanced Asset Management (AAM) reduce losses and improve asset utilization which allows energy to be utilized efficiently with longer life of equipments.

Smart Grid should provide an ability to detect, analyze and rectify the faults. It monitors and controls the system disturbances to avoid or mitigate power outages and power quality problems. It should maintain the power supply capacity through quick fault detection, rectification and thus restoration of services instead of a prolonged large area power outage in conventional power grid. In Smart Grid, power system is self-correcting such as it detects overloading situation in network and reroute the supply to prevent outages. It results in reduced power losses and improved system performance.

Smart Grid empowers the consumer through smart metering that allows two way interaction of energy and information flow between the utility and end consumers. It manages their energy use and thus reduces the energy cost. Advanced Metering Infrastructure (AMI) is a key technology where end consumers participate in grid operations for enhancing the distribution system operations and management. The energy

management system functions help consumers to choose among the various tariff plan options, reduce peak load demand and shift usage to off-peak hours, save money and energy by using more efficient appliances and equipments. It also improves customer satisfaction with increased reliability in grid operations and reduced outages.

Smart Grid should provide an ability to protect the grid from cyber attacks and unauthorized access by deploying new technologies. Data acquisition, handling and processing operations must be secure from any external attack. The system must possess the capability to deal with any corrupt data effectively to avoid any disoperation or damage of equipments.

Smart Grid accommodates distributed generation and storage options. It makes use of various forms of clean energy technologies to reduce the burden on fossil fuels and the emission of green house gases. Smart Grid not only provides a means of distributed green power generation but also helps in load balancing during peak hours through energy storage technologies and applications such as Plug-in Hybrid Electric Vehicles (PHEV).

Smart Grid facilitates integration of power system components and techniques such as process optimization, information flow, infrastructure, market structure and management policies for reliable, economical and secure operation of the power grid. It integrates advanced communication technology and automation infrastructure to the existing power system network for real time monitoring and analyses of data from all parts of the electric grid. Advances in the field of power electronics, grid control, wireless sensor networks, intelligent scheduling technologies and AMI, are inculcated in Smart Grid to provide intelligent decision support.

The primary objectives in Smart Grid are to optimize assets usage, reduce overall losses, improve power quality, enable active customer participation, make energy generation, transmission and distribution eco-friendly and to make detection, isolation and rectification of system disturbances automatic. To achieve these objectives, the Smart Grid utilizes technological enhancements in equipments and methodologies that are cost effective, innovative, and reliable.

Substations are the crucial nodes of a power system hence its increased capabilities and intelligence in its operations will play an important role to realize the concept of Smart Grid. In Smart Grid, the main focus is on smart distribution. It includes advanced technologies such as Distribution Automation (DA), increased interconnection & effective utilization of Distributed Energy Resources (DER) and customer participation in distributed applications by means of innovative methods. To realize these functions in Smart Grid, a substation needs a fully integrated and fully automatic system that performs data acquisition and processing, protection & control functions accurately, and delivers quality power efficiently with minimum environmental impact of green house gases. Demand response, reduction in peak load demand and power losses, improved power quality with less outage hence, overall improvement in distribution system reliability and performance are the main objectives that could be achieved by automating substations using advance networking technology. To implement various functions of the future Smart Grid at the distribution level, a supportive substation architecture is to be designed. This paper is an attempt to figure out the possibilities embedded in IEC 61850 based SAS to support the above discussed Smart Grid features.

The rest of the paper is organized as follows: Section II of the paper provides a brief overview of substation automation for Smart Grid. Section III discusses communication aspects in SAS. IEC 61850 based substation automation is presented in section IV of the paper. The scope of IEC 61850 based SAS in Smart Grid applications are described later in section V of the paper. Finally, concluding remarks are provided in section VI of the paper.

2. Substation Automation for Smart Grid

In Smart Grid, a substation needs to connect a large number of components from distribution side like feeder automation, DER and smart meters etc. at the customer end (Hamidi *et al.* 2010). To overcome the shortcomings of conventional power grid and to increase the automation facilities in distribution system, there is a need to automate substations that should cover all aspects of intelligence in distribution substation

operations. Substation automation functions can add more intelligence to the grid operations and make it more efficient. As a result, modern substation architecture should include following characteristics for Smart Grid functions (Heckel 2009; Fangxing *et al.* 2010; Sooriyabandara & Ekanayake 2010).

To achieve communication interoperability, it must possess seamless communication in power system that provides an open communication interface not only among the IEDs but also for inter-substation communication, and linking substations to control centers. It enables plug and play design of substations to handle different functionality effortlessly at the distribution and feeder level.

High quality of power supply could be achieved by installing de-centralized controllers for corrective or predictive actions, or for normal optimization.

A future Smart Grid supportive substation is required to be resilient to any physical and cyber attacks. It needs a self healing mechanism to automatically identify, isolate, and rectify the abnormal conditions in a power network based on fast, reliable, and accurate data from the monitoring systems at substations. Fault detection, isolation and restoration algorithms are required which maintain the system security by detecting, and clearing or isolating the faults within time constraints, thus restoring the supply for the healthy feeders in a system. It should lessen interruption frequency and duration of outages in system with minimal customer impact. It improves demand and load side management by reducing response time.

A distributed data management system is indispensable in substations to deal with all the environmental, operational and non-operational data. An expert system could be developed to deal with non-operational data for asset management in an optimized way.

A secure substation architecture is also desired to control and manage the data and information flow. Besides this, it will also help in prevention of any unauthorized access of data and devices in substations.

In general, cost reduction, improvement in operational efficiency, and interfacing with other transmission and distribution systems in grid are some of the features which modern substation architecture is expected to possess for transforming an existed power grid into Smart Grid. So they are desired to incorporate various technological features like DA, Demand Response, Demand Side Management, Outage Management System, AMI, Fault Detection and Isolation, Distribution State Estimation and others.

3. Communication within Substation

In SAS, the fast and precise operation of PMUs and IEDs for fault detection and isolation depends on the reliable, scalable and deterministic Substation Communication Network (SCN) architecture. Therefore an effective communication system is required, to share information at various levels of a SAS, which improves the overall reliability, stability and performance of power system for the proper operation and management of power flow in a network (Gungor & Lambert 2006; Qureshi *et al.* 2008). Substation also needs to communicate with control centre and other substations or with generating units and market participants. SCN architecture facilitates sharing of real time information of valuable grid assets and help utilities to observe and measure the current state of the grid thereby enabling grid operators to take intelligent operating decisions and to perform various protection and control functions. The operating decisions must be independent on the control centre and other substations however they must co-ordinate with the control centre to improve the security.

Switched Ethernet technology satisfies the real time performance requirements in substation environments and automation applications (Lee & Lee 2002; Skeie *et al.* 2002; Decotignie 2005). The strategy is to replace a number of multi-core copper cables by light and easy to handle fiber optic cables that provide fast and cost effective operations. Multicasting with switched Ethernet allows messages to be sent simultaneously and hence faster. Priority tagging (IEEE 802.1P) enables time critical messages to be sent on a priority basis. Further, the data throughput is higher with Ethernet switch because it entails no collisions. Virtual LANs(VLANs supported by IEEE 802.1Q standard), Rapid Spanning Tree Protocol (IEEE 802.1W), Simple Network Management Protocol (SNMP) and Electromagnetic Interference (EMI) immunity are some other special features of switched Ethernet technology, which can be harnessed for enhanced performance of SCN architecture(Puzzuoli & Moore 2006). A suitable substation network topology is required at various levels in SAS to satisfy different levels of redundancy and performance issues. The dynamic performance of substation automation architecture in different topologies is analyzed

and simulation results demonstrated that the switched Ethernet satisfies the communication needs of SAS (Sidhu & Yin 2007; Thomas & Ali 2010).

4. IEC 61850 Based Substation Automation for Smart Grid

A number of standard communication protocols are designed for information exchange between process level equipments and devices in SAS. However, data sharing is possible only if devices are protocol compatible. Further to reduce the complexity and the amount of cables in substations and to develop an economical and high performance integrated SAS, interoperability was desired to enable IEDs from different vendors to communicate without gateways. So the utilities understand the need of a standardized communication protocol to link all these IEDs together in SAS.

Modern SAS uses IEC 61850 for the real time operation of the power system. The communication standard IEC 61850, Communication Networks and Systems in Substation, was introduced primarily to permit interoperability between the IEDs for performing a variety of protection, control and automation functions in substations. Thereby no costly and complicated gateways are required for information exchange between devices from different manufacturers as it is required in case of legacy protocols. Thus an open system approach in substation automation system can permit system designer to install cost effective IEDs from different vendors in a competitive environment and also bring other benefits like increased system life, investment protection and easier extension and up gradation of system over time.

Standardized data model, communication approach and the configuration language are some inherent features in IEC 61850 communication standard that offers various benefits over legacy protocols such as Modbus, Modbus Plus, DNP3.0, and IEC 60870-5.

In IEC 61850 based modern substations, copper cables are replaced by communication links between primary and secondary devices. It results in very significant improvements in both cost and performance of electric power system. IEC 61850 based SAS reduces operational and maintenance expenses by integrating multiple functions in a single IED (McDonald 2003). These functions are distributed among IEDs on the same, or on different levels of the SAS. It enables distributed intelligence in a network for developing various new and improved applications. This improves the functionality, design and construction of modern substations (Apostolov 2006; Mackiewicz 2006; Janssen & Apostolov 2008; Mohagheghi *et al.* 2009). 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.

Although various standard protocols exist for communication outside the substations, the features possessed by IEC 61850 may also be utilized to enhance the performance of applications beyond the substation such as in distribution automation applications and for communication with other substations and control centers (Mohagheghi *et al.* 2009).

IEC 61850 based SAS architecture generally consists of three levels as shown in Figure 1(Brunner 2008):

- Station level

It includes Human Machine Interface (HMI) and gateways to communicate with remote control centre and integrate IEDs at the bay level to the substation level. 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 process level equipments are connected to station bus via IEDs at the bay level that implement monitoring, protection, control and recording functions.

- Process level

It includes switchyard equipments, sensors and actuators. The current and potential transformers are located at the process level to collect system data and send them to bay level devices for 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 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.

5. IEC 61850 and Future Smart Grid

The general system characteristics of the SAS are Reliability and Availability (Andersson *et al.* 2006; Hajian-Hoseinabadi 2010; Thomas *et al.* 2011). IEC 61850 possess advanced Abstract Communication Service Interface (ACSI) services and inherent features that allows system designer to optimize the substation architecture according to the customer requirements taking into consideration the performance and constraints of the system (Brand *et al.* 2004). Interoperability, object oriented data model, process bus, switched Ethernet communication technology, Generic Object Oriented Substation Event (GOOSE) and Standardized Configuration Language (SCL) are the unique features in IEC 61850 that can be exploited in realizing the future Smart Grid in the following manner (Brand 2004; Hoga & Wong 2004; Sidhu & Gangadharan 2005).

5.1 Object Oriented Data Model

The most promising feature of IEC 61850 is its object oriented data model, which specifies the data models correspond to various substation automation functions and devices in SAS. Process, configuration, name plate and diagnostic information are included in the data model of IEC 61850. Logical Nodes (LNs) are the basic elements used for information exchange within SAS and provide semantics related to all the data and the switchyard equipments. Each LN constitutes data and each data has data attributes related to it.

The standard IEC 61850 has an object model and the set of rules for creating new LNs and common data classes. It enables to extend the scope of the standard to support Smart Grid functions through development of cost effective new applications such as distribution application, feeder automation and for communication outside the substation (Apostolov *et al.* 2006).

Distribution Automation is the most complex part of the power system that exhibits advance distribution tools and technologies to carry out control, protection and power quality operations in an efficient way. It can bring down operational and capital expenses in power system through reduced power losses and peak load demand. Therefore it is absolutely necessary for IEC 61850 based SAS to support DA functions for achieving the goals of Smart Grid (Smallwood & Wennermark 2010). IEC 61850 standardized, semantic object models can be effectively utilized to model the various components of feeder and DA systems for Smart Grid functions. It is possible to define the LNs for performing various control and automation operations such as power flow control, voltage control and fault clearance at the distribution level for voltage control and fault handling applications in DA (Mohagheghi *et al.* 2009; Mohagheghi *et al.* 2011).

IEC 61850 can also be utilized in different multi-agent systems for monitoring, protection, control, and recording in substations as discussed by Apostolov(2006). Neil Higgins *et al.* (2011) discussed that IEC 61850 lacks the specification of functions and IEC 61499 lacks “standard” communication services. The combined use of both the standards provides a high level of function and communication interoperability. Therefore, it is possible to enhance the flexibility and adaptability of automation systems in Smart Grid by implementing standardized functional models of IEC 61850 using IEC 61499 based distributed control architecture (Vyatkin *et al.* 2010; Higgins *et al.* 2011).

Though, IEC 61850 is used for applications at the substation level. However, some features of IEC 61850 can also be utilized equally well for various applications outside the substation such as in distribution and feeder automation, distributed generation and to communicate with the control centre. It is possible to manage and control variable energy supplies efficiently through IEC 61850 substation automation utilizing Ethernet and router based communication network devices. IEC 61850 enable the seamless integration of various automation technologies in the transmission and distribution systems and support their

functionality. IEC 61850 can be extended to meet the requirements of power industry in various fields like in hydroelectric power plants, wind power generation, distributed energy resources, power quality monitoring etc. For instance, IEC 61850-7-410 is defined for hydroelectric power plants, IEC 61850-7-420 for distributed energy resources, IEC 61850-90-1 for communication between substations and IEC 61850-25-1 for wind power plants (Brunner 2008).

Thus IEC 61850 possess the features, as discussed above, to evolve as a communication standard for various projects contributing towards Smart Grid paradigm. To achieve the objectives of future Smart Grid, it is planned to launch another series of IEC 61850 to include device models for different Smart Grid components like IEC 61850-90-7 for inverter based applications, IEC 61850-90-8 for electric vehicles and IEC 61850-90-8 for battery storage devices (Brunner 2011). Integrating the DERs, energy storage devices and support to other advanced components of Smart Grid in SAS, using a standard data model of IEC 61850, helps in green power generation and improved power quality.

5.2 Process Bus

In IEC 61850 based SAS, Process bus connects process level equipments to conventional or non-conventional instrument transformers for collecting voltage, current signal waveforms and transmits it to the protection and control IEDs connected at the station level. This data along with position and status information about switchgear equipments from Merging Units (MUs), connected at the process level, provide the basis for carrying out various automation functions in SAS. The Sampled Analog Values (SAVs) from the MUs should be time coherent and are communicated to bay level IEDs on a multicast basis to meet the stringent performance requirements of protection functions.

The process bus in IEC 61850 offers various benefits over conventional hardwired analog circuits in implementing automation operations at the process level. Process bus eliminates a number of costly and complicated Remote Terminal Units (RTUs) by a reduced number of multifunctional IEDs to achieve high cost efficiency and reduced maintenance cost in Smart Grid. RTUs in conventional SAS need to be configured manually and has high maintenance cost.

Process bus replaces complex network of heavy copper cables at the process end with simple network of lighter fiber optic cables for connecting switchyard equipments with SAS. It not only brings cost reduction but also improves the performance and flexibility in substations functions to realize Smart Grid operations.

MUs provide an interface between high voltage switchyard equipments and secondary devices in SAS. It improves the physical security at substations by eliminating various safety related issues such as open circuit problem and the current saturation problem in instrument transformers (Andersson *et al.* 2003; Apostolov & Vandiver 2010). Also, MUs replace a number of instrument transformers at the process level by a fewer ones to achieve lower installation, maintenance and transducer costs.

Intelligent switchyard equipments such as non-conventional current and potential with optical outputs in IEC 61850 based SAS can replace the conventional current and potential transformers to achieve high bandwidth, better accuracy and low maintenance costs for handling voluminous data efficiently in Smart Grid.

In IEC 61850, LNs present in different physical devices are connected through logical links to exchange data, which allows free allocation of functions to devices and at different substation levels. Interoperability together with free allocation of functions allows adding new capabilities such as distributed intelligence in IEC 61850 based SAS over the conventional substation automation design. Distributed functionality in conjunction with SAVs and GOOSE features allows the development of innovative automation applications in SAS. Directional comparison bus protection schemes, distributed waveform recording during abnormal conditions in a network, recording of system parameters variations for planning studies in power system, and others are some of the process bus based applications discussed, that can bring significant benefits in terms of high reliability, flexibility and security, for Smart Grid operation (Apostolov 2006; Apostolov *et al.* 2006; Zadeh *et al.* 2011).

Overall, the process bus feature in IEC 61850 allows achieving high cost efficiency, enables enhanced security, deal with different process data efficiently through MUs and also supports the automatic testing and commissioning of equipments for performing Smart Grid functions reliably at the distribution side of

power system.

5.3 GOOSE

In IEC 61850, data models and communication services are mapped over standard communication protocols and hardware such as Transmission Control Protocol (TCP)/Manufacturing Message Specification (MMS) and switched Ethernet, to make this standard a future proof standard. The control and protection system utilizes existing and new data models, client-server communication, GOOSE messaging and SAVs based information exchange from conventional or non-conventional instrument transformers.

Client-server communication is used for applications in managing switchgear equipments at process level. For this, IEC 61850-8-1 defines the mapping of abstract object models and its services to the application layer of MMS. Time critical messages such as SAVs from MUs and GOOSE messages like interlocking and trip commands are mapped directly to the link layer of the Ethernet as shown in Figure 2 (Brand 2004; Sidhu & Gangadharan 2005).

The reliability and overall performance of substation automation functions are improved by the use of high speed peer-to-peer communication commonly known as GOOSE. To ensure that the GOOSE message is received by the subscribed IEDs, GOOSE message can be repeated and multicasted over the LAN. A single GOOSE message contains all the required information about the state of an event and is repeated till the subscribers' received it or the hold time expires. Further VLAN and priority tagging features of advanced Ethernet technology reduce network congestion to improve the performance of GOOSE message based protection schemes.

This feature of IEC 61850 in SAS leads to reduction in hardware cost along with simplifying the complex network of copper cables by replacing it with a LAN network at the station level. With GOOSE, it is possible to achieve fast signaling response over the station LAN, which is suitable for time critical applications in substations such as load shedding, station-wide interlocking, reclosing and protection purposes. It improves the performance of control and protection functions of SAS by satisfying the real time performance requirement of these applications for which the transfer time should not exceed 4ms (Phadke & Thorp 1988; Apostolov & Tholomier 2006; Brunner 2008; Ali & Thomas 2011).

To achieve smart grid goals, several virtual inputs /outputs are available in IEC 61850 based SAS through software configuration. It enables new and improved functionalities to be added in substations in near future, at lower installation, testing and commissioning cost compared to costly and complicated hardwired schemes.

GOOSE enables monitoring of virtual points, for any abnormalities, in the system. If any anomalies found in any device or in communication path, it can be rectified automatically through software configuration. Thus GOOSE in IEC 61850 provides an opportunity to design condition based enhanced testing and protection schemes that support self healing capability of Smart Grid.

GOOSE can be effectively utilized for applications outside the substation to achieve high reliability and performance in Smart Grid operations. For instance, distribution automation and Feeder Automation could effectively employ peer-to-peer communication as standardized communication approach in its control and protection applications. To achieve Smart Grid goals, research is under way on mapping GOOSE and SAVs on a communication stack that supports the routing of these messages (Brunner 2011). Brunner (2008) & Mohagheghi *et al.* (2009) has discussed the design of GOOSE based protection schemes beyond the substation.

5.4 Substation Configuration Description Language (SCL)

In IEC 61850-6, the functional and communication capabilities of devices and the system configuration are described in a standardized way using XML (eXtensible Markup Language) based SCL. Various bay level IEDs, their interconnection and the SA functions in SAS are represented using SCL files to achieve communication interoperability and reduction of design efforts. These files allocate functions to the devices. The devices from different manufacturers exchange data through various SCL files (Brand 2004). This feature enables automatic configuration of devices to share device information among the users.

SCL feature along with the standardized data models in IEC 61850 reduces the reconfiguration cost of

equipments as they share the standard naming conventions. This plug and play design feature in IEC 61850 substation environments support the effortless testing and commissioning of Smart Grid components. Also as the reconfiguration of equipments is not required while adding new devices and applications in a system, it makes any future extensions easier and economical for developing Smart Grid applications.

6. Conclusion

Requirements of the future Smart Grid scenario in Substation Automation System are presented. The potential of technical features available with IEC 61850, to support these requirements and also to streamline grid operations at the distribution level with improved reliability and efficiency, is explored. It has been analyzed that, by adopting IEC 61850 as standardized communication protocol in substation automation system with its advanced features like Interoperability, standardized data model, free configuration, reduced losses, savings in overall life-cycle cost, new and improved functionality, switched Ethernet networking technology, secure and flexible substation design, process bus and GOOSE provide various opportunities for advanced and futuristic Smart Grid applications.

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Ikbal Ali has a Ph.D. in Electrical Engineering and is Senior Assistant Professor in the Department of Electrical Engineering, Jamia Millia Islamia, New Delhi. He is B.Tech. in Electrical Engineering from Aligarh Muslim University and completed the M.Tech. degree from the Indian Institute of Technology, Roorkee, India. His current research interests are SCADA/EMS, IEC 61850-based substation automation systems, substation communication networks architecture, power system communication, and smart grid.

Mini S. Thomas received the Bachelor's degree from the University of Kerala, Kerala, India, and the M.Tech. degree from the Indian Institute of Technology (IIT) Madras, Chennai, India, both with gold medals, and the Ph.D. degree from IIT Delhi, Delhi, India, in 1991, all in electrical engineering. Her employment experiences were at the Regional Engineering College Calicut, Kerala, India; the Delhi College of Engineering, New Delhi, India; and currently as a Professor with the Faculty of Engineering and Technology, Jamia Millia Islamia, New Delhi, India. She has published 60 papers in international/ national journals and conferences. Her current research interests are in SCADA systems, intelligent protection of power systems, and the smart grid. Prof. Thomas received the prestigious Career Award for young teachers, instituted by the Government of India.

Sunil Gupta received the Bachelor's degree in Electrical engineering from Kurukshetra University, Kurukshetra, India, in 2001, and the M.E. degree in Instrumentation & Control from Panjab University, Chandigarh, India, in 2009. He is pursuing Ph.D. from Department of Electrical Engineering, Jamia Millia Islamia, New Delhi, India. Currently, he is working as an Assistant Professor in Electrical and Electronics Engineering Department at Maharaja Surajmal Institute of Technology, New Delhi.

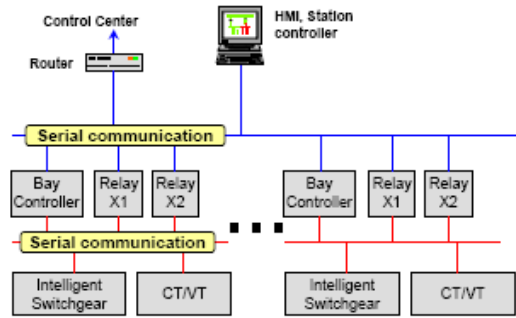


Figure 1. IEC 61850 SAS Architecture

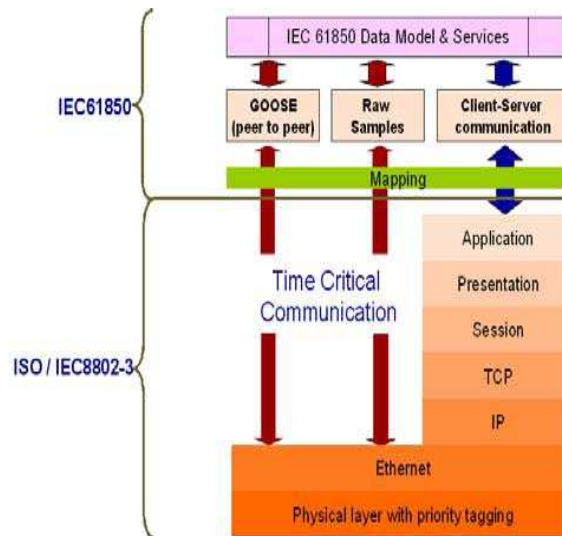


Figure 2. Communication stack of IEC 61850

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