Implementation Issues with IEC 61850 Based Substation Automation Systems

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***Abstract*—International Electro-technical Commission (IEC) has developed a new global standard, IEC 61850 for communication systems in power substations. This standard provides interoperability among the all communication devices within the substation. This paper presents basic features of communication systems proposed by IEC 61850, such as functional hierarchy, OSI-7 layer based communication, and process bus. To obtain complete advantages of the standard, it is important to consider all the major issues related to practical implementation. This paper discusses challenges for implementing new communication architecture, such as process bus and station bus. Further, the overall substation functional issues, and planning issues are also explained. Some possible solutions to several major implementation issues are suggested.**

I. Introduction

The success of a Substation Automation System (SAS) relies on the use of an effective communication system to link the various protection, control, and monitoring elements within a substation. The major challenge faced by substation automation design engineer is to provide interoperability among the protection, control, and monitoring devices from the various manufacturers. Up until recently, all the manufacturers are/were using their own proprietary communication protocols. Huge investment is needed to develop costly and complicated protocol converters [1]. To address these SAS issues, IEC working group TC57 has published IEC 61850 named as “Communication Networks and Systems in Substation” in 2003 [2]. IEC 61850 standard covers not only how to communicate but also what to communicate. IEC 61850 capabilities clearly exceed what former IEC 60870-5-103, DNP3, and most proprietary protocols had to offer [3]. IEC 61850 provides the interoperability by defining the communication protocol, data format and the configuration language. However, there are several unresolved issues which need to be addressed before the implementation of IEC 61850 based SAS.

T. S. Sidhu et al. have evaluated performance of IEC 61850 based substation communication system, and highlighted issues with several communication topologies, in reference [4]. References [5-10] discuss specific issues related to communication network of SAS. In reference [11], B. Kasztenny et al. have investigated functionality issues related to IEC 61850 based SAS.

This paper discusses the challenges for the practical implementation of IEC 61850 based SAS. The issues related to communication system at process level and station level, are analyzed in detail. Further, SAS functional issues and planning related issues are also discussed. This paper also proposes several possible solutions to address some of the implementation issues.

The organization of this paper is as follows. In Section-II, the communication systems proposed in IEC 61850 standard are described. The implementation challenges and solutions related to communication architecture, substation functionality, and planning are presented in Section-III. Section-IV concludes the paper.

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II. Substation Automation Using IEC 61850

A. Features of Communication Systems of IEC 61850

1) Function Hierarchy and Interfaces of IEC 61850: The three levels in the functional hierarchy are shown in Fig.1:

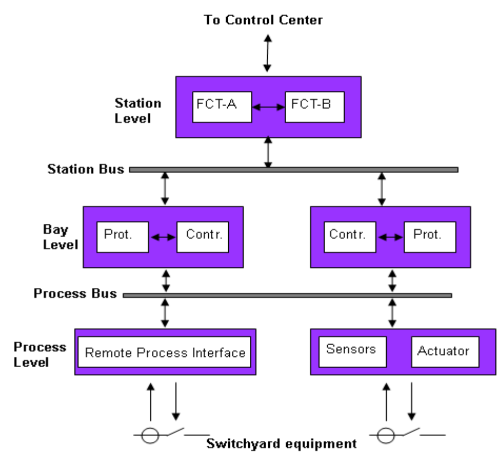

Fig. 1 Interface model of a substation automation system.

Process level: This level includes switchyard equipments such as CTs / PTs, Remote I/O, actuators, etc.

Bay level: Bay level includes protection and control IEDs of different bays.

Station level: The functions requiring data from more than one bay are implemented at this level.

Process bus: This facilitates the time critical communication between protection and control IED to the process (the primary equipment in the substation), such as sampled values, binary status signals or binary control signals.

Station bus: It facilitates communication between station level and bay level. It also allows communication among different bays.

2) OSI-7 Layer Communication System: IEC 61850 uses

OSI-7 layer stack for communication and divide it in three groups as shown in Fig.2. The seven types of messages are mapped into different communication stacks. The raw data samples (type 4) and GOOSE messages (type1) are time critical and are, therefore, directly mapped to low–level Ethernet layer. This gives the advantage of improved performance for real time messages by shortening the Ethernet frame (no upper layer protocol overhead) and reducing the processing time. The medium speed message (type 2), the command message with access control (type 7), the low speed message (type 3) and the file transfer functions (type 5) are mapped to MMS protocol which has a TCP/IP stack above the Ethernet layer. The time synchronization messages (type 6) are broadcasted to all IEDs in substation using UDP/IP.

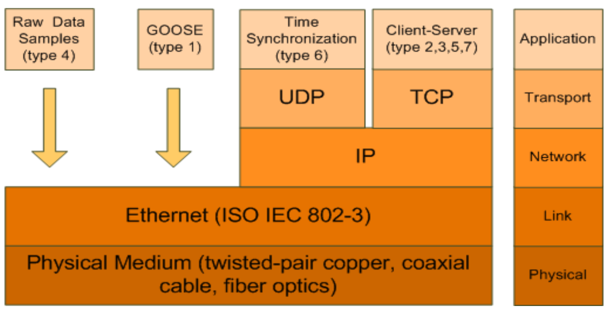

Fig. 2 Message communication OSI -7 layer stack of IEC 61850.

3) Merging Units (MUs) at Process Bus: To reduce the cost of complex and long copper wiring between switchyard and control room, IEC 61850-9 has proposed digital communication at process level, i.e. process bus. Merging unit is a key element of the process bus (IEC 61850-9). As Fig. 3 shows, MU gathers information, such as phase voltages and currents from instrument transformers, and status information from transducers using proprietary links. All these analog values are converted to digital, and merged into a standard data packet format. This data packet is sent to corresponding bay level protection and control IEDs using standardized Ethernet based communication links.

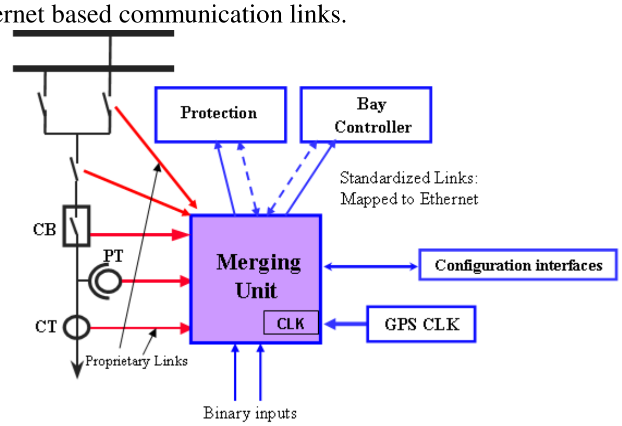

Fig. 3 Process bus concepts.

As figure shows, MU has time synchronization source (GPS clock), using which it provides the time stamp on each data packet. Time synchronization of each packet is required for protection and control IEDs to estimate accurate phasors.

B. Major Benefits of IEC 61850 Based Implementation

1) Interoperability: Different vendors are allowed to provide complete integration of bay functions within one or two IEDs.

2) Free Configuration: Any possible number of substation protection and control functions can be integrated at bay level IED.

3) Simple Architecture: As the plenty of point-to-point copper wires are reduced to just simple communication links. Further, functional hierarchy architecture provides better communication performance for time critical applications.

4) Overall Cost Saving: The high-speed digital communication at process level allows replacing the traditional electrical wiring using virtual wiring, which could save a lot of time and cost for substation automation system.

III. Implementation Issues with IEC 61850

The major implementation issues with IEC 61850 based SAS and possible solutions are discussed as follows.

A. Process Bus Issues

The challenge with process bus implementation is that the utilities do not have practical experience and expertise to work with process bus. Moreover, process bus will be used for time critical messages, such as GOOSE and raw data packets. Therefore, most of the substation protection and control functions will rely on the performance of the process bus. Major issues related to process level communication are discussed as follows.

1) Issues with process bus topologies: One of the key technology ingredients that determine the nature and performance of Ethernet network is the topology of Ethernet Local Area Networks (LANs). In the context of communication network, the term topology refers to the way the work-stations are interconnected with each other [6]. The issues with the common Ethernet topologies, such as Bus, Ring, Star and hybrid topologies are described as follows.

Bus topology: With bus topology, the communication network is simply the transmission medium; there are no switches or hubs/repeaters, as shown in Fig. 4. All stations are attached through appropriate hardware interface known as a tap, directly to the bus.

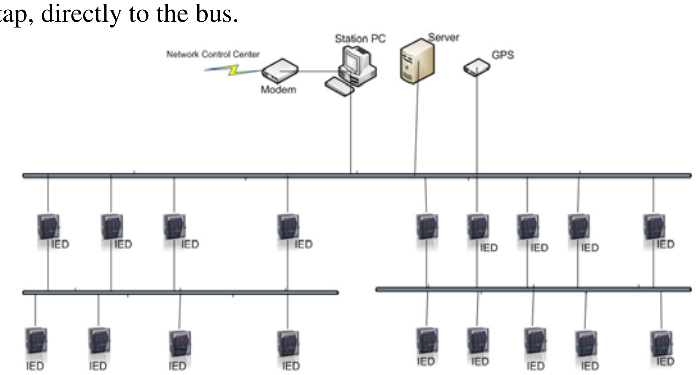

Fig. 4 Bus topology.

Bus topology uses IEEE 802.3 based Carrier Sense Multiple Access with Collision Detection (CSMA/CD) mechanism for successful data communication. However, T. S. Sidhu et al. [4] has demonstrated using dynamic simulations that the time delays for the GOOSE messages and raw data packets are not in compliance with IEC 61850 standard for large SAS. Hence, this topology may not be suitable for large substation process bus.

Ring topology: Fig. 5 shows that the ring topology consists of a set of repeaters or switches joined by point-to-point links in a closed loop.

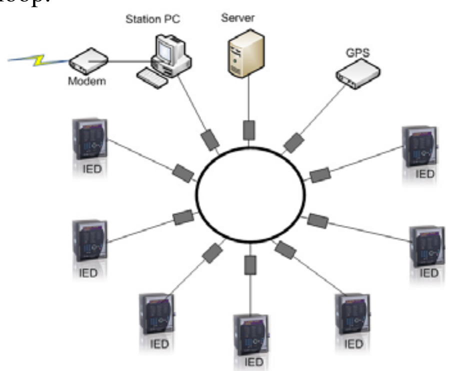

Fig. 5 Ring topology.

The most important benefit of the ring is that it uses point-to-point communication links. Hence, the transmitted signal is regenerated at each node; greater distance can be covered than with baseband bus. Another benefit of the ring is that fault isolation and fault recovery are simpler than for the bus topology. Therefore, the ring topology is considered to be the most reliable topology. However, time delay for message transmission is almost same as bus topology, and hence this topology may not be suitable for time critical messages.

Star topology: In star LAN topology as shown in Fig. 6, each station is connected directly to a common central node, e.g. Ethernet switch. The message transmission time delay for Ethernet switch based star topology has capability to comply with IEC 61850 standard requirements. However, this topology has less reliability because all IEDs are connected to single central Ethernet switch which is highly susceptible to environmental and EMI conditions of the power substation.

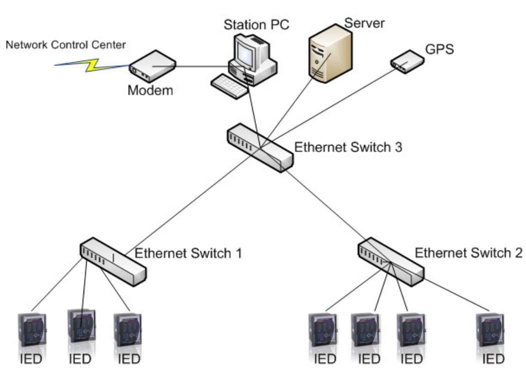

Fig. 6 Star topology.

Cascaded-Star topology: A typical cascading architecture is illustrated in Fig. 7. Each Ethernet switch is connected to the previous switch and/or next switch in the cascade via one of its ports. The maximum number of switches, which can be cascaded, depends on the worst case delay (latency) which can be tolerated by the system [7]. This topology may provide allowable time delays; however, complete reliability is still not achieved with this topology.

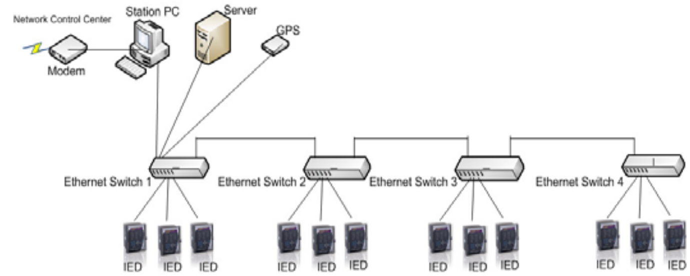

Fig. 7 Cascade-star topology.

Star-Ring topology: As shown in Fig. 8, star-ring topology is very similar to the cascaded-star topology except that the loop is closed from last switch to first switch. This provides some level of redundancy if any of the ring connections should fail. Normally, Ethernet Switches don't support "loops" since messages would circulate indefinitely in a loop and eventually eat up all of the available bandwidth. However, 'managed' switches (i.e. those with a management processor inside) take into consideration the potential for loops and implement an algorithm called the Rapid Spanning Tree Protocol which is defined in the IEEE 802.1w standard. This protocol allows switches to detect loops and internally block messages from circulating in the loop and also allows reconfiguration of the network during communication network fault within sub-second [7]. This topology has potential to provide time delay within allowable range and also offers the better reliability of the process bus. However, this topology is costly and complex as compared to other topologies.

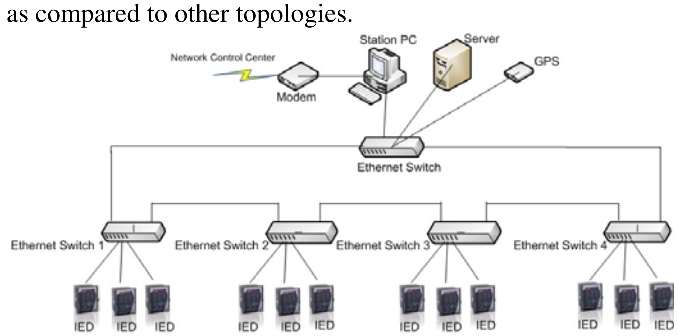

Fig. 8 Star-Ring topology.

2) Communication network performance related issues: The performance of communication network is mainly decided by the end-to-end delay for time critical message transmission. IEC 61850 Part-5 specifies the allowable message transmission delay requirements and approaches that could be used to study the SAS network performance. However, the overall system performance and its extensibility can't be easily solved using this standard although it does classify the message performance class and LAN simulation method. There is no guidance available on how to characterize message delivery performance across the whole substation communication network [4]. For the dynamic performance of a physical SAS network, LAN simulation tools must be used. In IEC 61850-5 I.2, a SAS network' s dynamic performance is studied using COMNET III simulation program without stating how the IEDs are modeled and which worst case scenarios are considered. Moreover, the simulation does not consider process bus and different network topologies. In reference [4], T. S. Sidhu et al. have shown using dynamic simulation that all LAN configurations do not meet IEC 61850-5 message transmission delay requirements. Hence, the communication network should have Ethernet switches and IEDs with the ability to provide priority tagging. However, there are reliability and cost-benefit issues for using expensive and less reliable Ethernet switches at the process level.

3) Time Synchronization issues: IEC 61850-9 proposes digitization of CTs/PTs output at the switchyard (into the MUs) and communicating these sampled values to bay level IEDs through process bus. This stream of sampled values should be synchronized so that the protection function can utilize many such signal streams from independent MUs from various manufacturers. IEC 61850 proposes the implementation of time synchronization on LAN using Simple Network Time Protocol (SNTP). However, SNTP is able to provide accuracy of about 1 ms, which is not sufficient for raw data sampled values. One of the solutions is to use IRIG-B synchronization signal in compliance with IEEE 1588 [12]. Next revision of IEC 61850 standard may include IEEE 1588 based time synchronization in order to achieve accuracy in the range of 1 μs. Nevertheless, IRIG-B needs an external time synchronization source, and accuracy of sampled values depends on availability and quality of time synchronization. Dependency on external time synchronization source must be considered in terms of overall availability of the substation automation system, accuracy of the protection and control functions, and complexity of overall substation [8, 11]. One of the solutions to time synchronization problem is proposed in reference [9], using GOOSE message for sampling the analog values into the MUs by using point-to-point communication links between IEDs and MUs.

4) EMI immunity: Various electromagnetic interferences such as, lightening strikes, switching surges, electrostatic discharges, strokes in SF6 circuit breaker, etc. are commonly encountered in Air Insulated Substation (AIS). Hence, general EMI immunity requirements used for industry are not sufficient for AIS. IEC 61850-3 specifies only outline of EMI immunity requirements. For more details the IEC 61850 refers the requirements and testing procedures given in the parts of the IEC 6100 series (IEC 61000-6-5 and IEC 61000-4-x) [13] or IEEE C37.90.2 [14]. All the SAS devices such as IEDs, MUs, Ethernet switches, and other communication devices must be in compliance with these EMI immunity standards especially at process level.

5) Environmental requirements: Generally, process bus communication equipments will be exposed to atmospheric conditions for the AIS. Hence, it is important for the outdoor mounted communication devices to meet environmental requirements. IEC 61850-3 list out the environmental parameters such as temperature, humidity, barometric pressure, mechanical, seismic, pollution, and corrosion. Further, IEC 61850-3 refers to IEC 60870-2 [15] and IEC 60694 [16] for detailed environmental requirements. At least process level devices such as IEDs, MUs, Ethernet switches, etc. should be in compliance with these standards.

B. Station Bus Issues

1) Communication network issues: Station bus allows communication between station level and bay level, as well as among bay level modules. Station level time critical protection and control applications, such as breaker failure trip, bus differential trip, etc. will use station bus. Hence, performance evaluation of station bus for time critical messages is also needed, as already explained for process bus communication network performance issues in previous sub-section.

2) Co-ordination issues with distributed SAS function: Currently, protection and control functions are not distributed, and in major cases, complete single zone of substation functions is employed from single manufacturer. Hence, there is minimum function co-ordination needed in the legacy design. According to IEC 61850, all IEDs should be connected to common communication network at station level which supports free configuration or flexibility in terms of substation function allocation. This means, single zone of protection can be distributed to separate physical devices e.g. IEDs from different manufacturer. Hence, the major challenge is to co-ordinate all these distributed functions of a single zone of protection in order to execute SAS successfully. Further, this would add as one of challenge for substation automation engineer while allocating and testing all distributed functions.

3) Intra-substation and Remote Control Center communication: Control data exchange between station level substation devices and a remote control centre is beyond the scope of IEC 61850. However, a report IEC 61850-90-1 will discuss the different aspects of the use of IEC 61850 for the communication between substations. And, IEC 61850-90-2 will discuss the communication from substation to the control centers [17].

C. Overall SAS Functional Issues

1) SAS architectural issues: Today, each zone of protection and control system is controlled by a single module, tested, engineered to work optimally as a system, and guaranteed by a single vendor. IEC 61850 based SAS architecture may have distributed functions in several modules for each zone. Moreover, this new architecture would require devices such as IEDs, MUs, Ethernet switch, and source of time synchronization, all coming from several vendors; having each its own hardware modules may face performance problems. The significance of this issue becomes evident when all parties may comply to applicable IEC 61850 standard, and still the system may have problem to complete a task successfully. Building tightly coupled architecture out of several microprocessor-based devices by several vendors brings extra risk and complexity to the SAS architecture [11].

2) Reliability and Redundancy issues: According to IEC 61850-3 reliability requirements, there should be no single point of failure that will cause the substation to be inoperable. Further, standard suggests that a failure of any component should not result in an undetected loss of functions nor multiple and cascading component failures. IEC 61850-3 refers IEC 60870-4 Section-3.1 [18] for the details of the reliability requirements for SAS. However, IEC 61850 does not demand for redundancy even for critical applications, and it is left to substation design engineer.

3) Availability issues: As per IEC 61850-3, the specification for the availability of the SAS is not within the scope of this standard. Hence, it suggests IEC 61870-4 Section-3.3 [18] for the specific availability requirements. However, availability is one of the important functional requirements in order to implement SAS according to IEC 61850 standard. In fact, IEC 61850 proposes few communication devices to be added in to the today's architecture. Generally, these communication devices with integrated electronic circuits may have less availability specifically into the EMI environments such as electric power substation. Therefore, it may be difficult to maintain the current level of availability. And hence, there is need for back-up systems for critical applications. SAS availability improvements will be one of the most challenging issues to the IEC 61850 based substation design engineer.

4) Maintainability issues: IEC 61850-3 suggests IEC 60870-4, Section 3.3 [18] for the maintainability issues. The issues of maintainability of the system will shift towards inner workings of the IEDs. This will put more burdens on manufacturers in order to facilitate the processes for maintainability [11].

5) Data integrity issues: IEC 61850-3 suggests that the SAS communication system shall deliver reliable data in the presence of transmission and procedural errors, varying delivery delays, and equipment failures in the communication facilities. Finally, IEC 61850-3 has referred IEC 60870-4, Section-3.5 [18] for the details of integrity and consistency of the data delivered by the SAS. In Reference-5, E. Demeter et al. have demonstrated that received data from Ethernet network will be distorted, and hence the error correction algorithm has been proposed. However, this solution requires time synchronization which will further add to cost, and will also affect reliability indices.

6) Testing issues: Testing is important during commissioning as well as routine maintenance. IEC 61850-10 discusses the methodology for conformance testing of communication protocol for SAS. However, the major testing issue with integrated IEC 61850 based SAS is to isolate the system to be tested without compromising the operation and performance of complete SAS. This is very challenging especially for the distributed function substation automation system design.

7) Inter-changeability issues: IEC 61850 defines inter-changeability as the ability to replace a device supplied by one manufacturer with a device supplied by another manufacturer, without making changes to the other elements in the system. According to IEC 61850-1, there is also a desire to have IED inter-changeability in SAS from utilities, but Inter-changeability is not in the scope of IEC 61850 standard. However, the issues related to inter-changeability need to be addressed in order to provide complete flexibility and competition for the utility to replace a device supplied by one vendor with another vendor.

8) Data Security issues: An intruder in the substation can easily cause packet swamping, port reservation, etc. which would introduces large time delay or data loss even for high priority GOOSE messages. This may cause damages to many substation devices. Further, data security is even more important while exchanging data with control centre or other substations. Firewalls, encryption (encrypt data at sending end and decrypt data at receiving end with secured key), and authentication (authenticating user by security password or biometrics) can address data security issue to some extend [19]. WT15 of TC57 works on security solutions for the substation protocol [10]. Further, IEC 61850-3 refers IEC 60870-4, Section-3.4 [18] for the details of security requirements.

9) Version upgrade issues: As discussed earlier, IEC 61850 provides free configuration, which would lead to segregation of single zone functions. Hence, single zone operation is dependent on proper hardware and software configuration of various devices installed by different manufacturer. In case of version update of any currently installed hardware or software may not support co-ordination with the existing versions from different manufacturers. This may lead to need for updating the complete zone of functions which includes many devices of various manufacturers.

D. Planning Issues

1) Cost and Complexity issues: A successful IEC 61850 based SAS will have to be cost effective. This shall account not only for the initial engineering, construction and material cost of a solution meeting all other requirements, availability, but also for cost of maintaining extra electronic equipment. It is the cost equation that separates what is technically possible from what is eventually manufactured, and be deployed in the field [11]. Further, the free configuration for SAS function allocation and time synchronization network brings more complexity into the IEC 61850 based SAS design. Hence, the requirement of engineering tools for the future SAS design is recommended from the implementation experience in [20].

2) Allocation of substation functions issues: According to IEC 61850, a single zone functions can be distributed to various physical devices. However, haphazard allocation of distributed functions may cause heavy traffic on communication network which may lead to intolerable high end-to-end delay of time critical messages.

3) System expansion planning issues: IEC 61850 does not suggest any specific architecture and hence, system expansion related issues are not addressed in the standard. However, as power demand increases, power substations need to be expanded. Therefore, issues related to system expansion need to be address during planning itself. Addition of more IEDs and MUs should not create heavy traffic flows into the communication network. Further, existing Ethernet LANs should be scalable.

4) Manpower training issues: Communication network with will be the backbone of the SAS. Hence, substation engineers will have to acquire complete networking training. This is major issue with utilities to train substation engineers and keep updating them with the fast growing communication technology.

IV. Conclusion

IEC 61850 standard has world-wide acceptance from various utilities and manufacturers. Unique communication features of IEC 61850 have been discussed in brief. IEC 61850 standard offers interoperability, free configuration, overall cost saving, and simple architecture. However, in order to realize these benefits, thoughtful SAS design engineering is required which can address the challenges for practical implementation. The major implementation issues from many different aspects have been analyzed in this paper.

For communication network implementation, it has been discussed that Ethernet topology and network performance requirements should be selected according to the size of the substation, time critical requirements, and importance of the substation functions. Moreover, it has been examined that IEC 61850 proposed SNTP protocol has less accuracy (1 ms), and hence need for accurate protocol such as IEEE 1588 has been proposed for time critical applications. SAS functional issues, such as proper architecture, right degree of redundancy, back-up system for high availability, complete testing process, suitable protocols for data integrity and security, etc. have been discussed in details. Finally, the factors need to be addressed during the planning stage, such as cost, SAS expandability, substation function allocation, and man power training, have also been brought out for the power system utilities.

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