# Study of Substation Automation Network Systems [SANS] Design, Simulation and Analysis

[I]Swaminathan.P, [II]Bharathkumar.S
[I,II]Assistant Professor/EEE, Final Year/B.Tech-EEE, Dept. of Electrical Technology,
Karunya University, Coimbatore

**Abstract**
*Substations are nodes in the smart grid infrastructure that help the in transportation of power by connecting the transmission and distribution lines. Hence, the network plays a vital role in the operation of the substation. Networks designed for such applications should be analysed carefully to make sure that the requirements are met properly. We analysed and compared the performance of the SANS under different network topologies. By observing the characteristics of the existing architectures, we came up with new architectures that perform better. We have suggested several modifications to existing solutions that allow significant improvement in the performance of the existing solutions.*

**Keywords**
*Substation, Automation, Smart Grid, IED, IEC 61850*

## I. Introduction

Smart grid is an electricity network that uses digital technologies to handle its communications. This network is used for monitoring line loads, transmission and distribution of power. The network comprises of substations and National Control Center (NCC). The substations are used for transmission and distribution of power. The NCC takes care of monitoring the operations of substations and the line loads in each substation. The older models of this network used telephone lines for communication between NCC and substations [1]. The components inside the substation were hard-wired for communication. However, these methods meant costly wiring, constant human intervention and slower performance. Recently, the smart grid network has moved to modern computer networks to handle the digital communication. Among the smart grid applications, we focus particularly on communications within a substation. These substations have been designed to operate with minimal human intervention and hence they are known as the Substation Automation Network Systems (SANS). Substations in electrical grids are devices which are used for connecting transmission and distribution lines. They are used in transmission and distribution of power. So a typical substation is supposed to receive the electricity and based on the location of the substations, it either needs to step up the voltage or step down the voltage and transmit the power down the line. Correspondingly, the substations have either a step up transformer or step down transformer and lines to distribute the load. So with the involvement of power, a substation needs to have some kind of fault detection, fault tolerance and recovery mechanisms. This combined with the fact that some substations are deployed in rough and inaccessible terrains, Substation Automation Network Systems (SANS) were introduced.

## II. Substation Automation Network Systems [Sans] – Design

The whole idea of substation automation gained popularity with the introduction of IEC 61850 protocol. However, the feasibility of IEC 61850 was showed by [5]. This was the first paper to consider the requirements of the IEC 61850 and explored the protocol's feasibility. Ethernet was explored as a possibility for communications in substation in [6] and it was found to have sufficient performance characteristics to support substation communication. Reference [2] criticized the IEC 61850 protocol of providing no guidance to describe the characteristics of the delivery performance.

### A. IEC 61850

SANS uses Intelligent Electronic Devices (IEDs) to control its functionalities. These IEDs are nothing but a microprocessor based controller that are capable of performing various functions. Various types of IEDs were designed to perform specific tasks. Each of these IEDs used to follow different protocols to communicate based on the type of task they were supposed to perform. This led to a lot of complexities when the IEDs tried to operate together. Costly protocol converters were used to ensure inter operability of IEDs [14]. These protocol converters also introduced delay in the network. To solve all these problems, a common protocol known as the IEC 61850 was introduced. This protocol has been standardized internationally and all the communication inside the substation follows this protocol including the digital communications that happen in the process level of the substation. IEC 61850 used ethernet based technology to be the communication network. This protocol also defines the requirements for various communications and even takes care of substation automation in terms of project management, conformance testing, etc [3]. Thus IEC 61850 reduces the cost of the substation by avoiding protocol converters. It also establishes interoperability with minimum delay.

### B. Role of IEDs

There are many types of IEDs in the substation network. Some of the IEDs include the Merged Unit (MU) IED, Protection IED, Control IED and the Breaker IED. As said before, each type of IED has a specific set of tasks to perform. The MU IED is connected to the current and voltage transformers. The function of the MU IED is to receive the analog current and voltage values from the current and the voltage transformers. It then samples those values and sends the digitized values to the Protection IED. The protection IED monitors these values constantly and sends out a trip message if it detects any anomalies. These trip messages are sent to other protection IEDs and the corresponding breaker IEDs. The protection IEDs associated with the detected fault controls the relays to open the circuit to stop the current flow and hence prevent damage. The breaker IED sends out a Generic Object Oriented Substation Event (GOOSE) message to the entire system informing of the state change that has occurred in the network.

All the three messages discussed here namely, the sample values, the trip message and the GOOSE message are all considered to be high priority and time critical messages. Excessive delays in these messages mean failure to detect fault or failure to open the circuit and so the consequences are severe. Apart from these IEDs, there is a Circuit Breaker Monitor (CBM) that monitors the breaker to see if they have been opened properly. These CBMs and the Protection IED records the event associated with the failure and sends out those records to the substation computer. The MU IED and the Breaker IED belong to the lower level of the substation known as the process level. The protection IED, control IED and the CBM belong to the system level of the substation. In the practical substations, the process level is connected by copper wires and only the system level components of the substation are connected by the Ethernet. Hence the sampled values and the GOOSE message occur in the hard wires network while the trip message alone occurs in the Ethernet.

### C. Substation Model

In the system model, we take into consideration only the components that come under the Ethernet network. The process level of the substation does not come under the Ethernet communication network and hence it is not considered. So we assume that the priority messages like sampled values and GOOSE message are sent and received properly in the network. Among the system level components, we define the substation to be divided into three types of bays. They are the line bays, the bus bays and the transformer bays. Each bus bay and transformer bay unit consists of one CBM, one protection IED and one control IED. Correspondingly, each bay unit consists of one relay and breaker each. Since all the line loads are directly monitored by the line bay, it alone needs to have redundancy to ensure reliability. Hence, neighbouring two line bays share three breakers among them. This model is known as the one and a half breaker model. In case of a fault, the line bay tries to open both the breakers associated with it. Since it has two breakers, it needs two CBM to monitor the breakers and so the line bay unit consists of one protection IED, one control IED and two CBMs. In the substation model considered, we have 16 line bays, 4 bus bays and 2 transformer bays. These bay units occur in the switchyard area of the substation.

A sample bay unit for bus Ethernet is shown in Fig. 1 and a sample bay unit for switched Ethernet is shown in Fig. 2 Along with the switchyard area, the substation consists of the control center. This center, as the name implies controls the operation of the substation and provides configurations to the IEDs. This control center also is responsible for conveying the substation messages to the NCC. Hence the control center acts as the interface between NCC and the substation. The control center consists of the Human Machine Interface (HMI), Digital Fault Recorder (DFR), GPS receiver, a substation server and router. The HMI is nothing but a substation computer that is used to send configuration messages to the IEDs. It acts as the way for human intervention in the substation. The DFR receives the sampled values of the current and voltage from the MU IEDs directly through hardwire and stores them. Whenever there is a fault, the DFR compiles these values into a record and sends the record file to the HMI Through a file transfer.

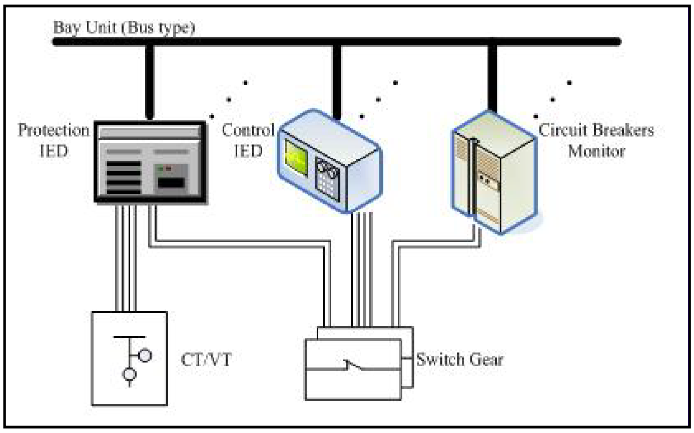

Fig. 1. Bus Bay Unit.

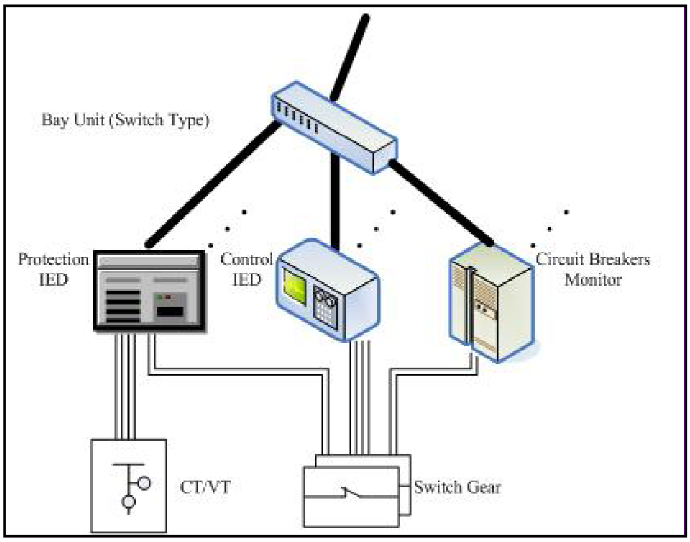

Fig. 2. Switched Bay Unit.

The router is used to connect the substation to the Wide Area Network (WAN). A line diagram of the substation is shown in Fig. 3. The networking view of the substation is shown later in the Figs. 4, 5 and 6. Apart from the trip message, the network also contains file transfer messages, time synchronization messages and configuration messages. A substation network is considered practically feasible only if the delay of the trip message lies under a certain threshold. Hence the primary objective when testing all the developed architectures is to note the delay of the trip message in that network.

### D. Network Topologies in Practical Substation

The components of the switchyard and the control center are built using different topologies in the practical network. The substation might be connected in either bus ethernet or switched ethernet. Among the switched ethernet, the substation can be connected either in Ring topology or the star topology. The bus ethernet in substation employs 10Mbps or 100Mbps ethernet bus.

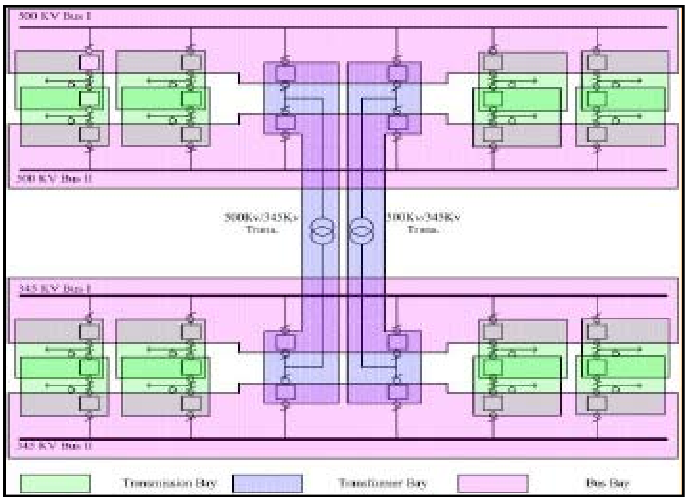

Fig. 3. Substation Line Diagram.

All the bay units and the control devices are connected to the single bus. Since the bus connects all the station level components, it is known as the station bus. All the network messages are exchanged using this bus. The main delays experienced in the bus ethernet are due to collisions. However, since this model employs less number of components, it is significantly reliable [4]. The substation model for the bus ethernet is given in Fig. 4. The ring and the star topology employs switched Ethernet. The way the bay units are connected to one another varies based on the type of topology. The ring topology is given in Fig. 5. This topology defines two paths for each bay to communicate with every other bay. The presence of two separate paths ensures better reliability. However, the number of switches employed in this scheme is more and the path from one protection IED to another lies through many switches. Since queuing and processing at the switches constitute the main cause of delays in switched Ethernet, the delay performance will be a little poor. The star topology example is given in Fig. 6. This topology has less number of switches and has good performance in terms of delay. However, there is just one path between different nodes and so the reliability is less compared to ring topology. This is the most preferred of the three with respect to delay performance. However, practical substations prefer bus ethernet if reliability is the main concern and go for ring topology in cases where the tradeoff in reliability is not a huge issue.

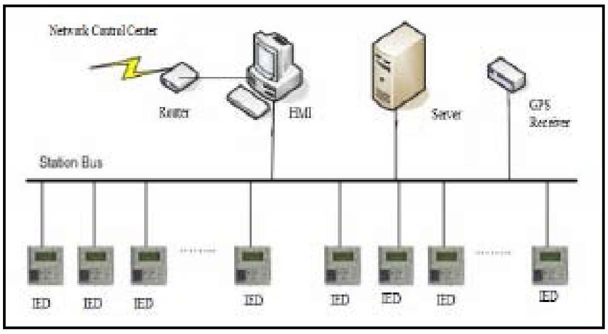

Fig. 4. Bus Ethernet Model.

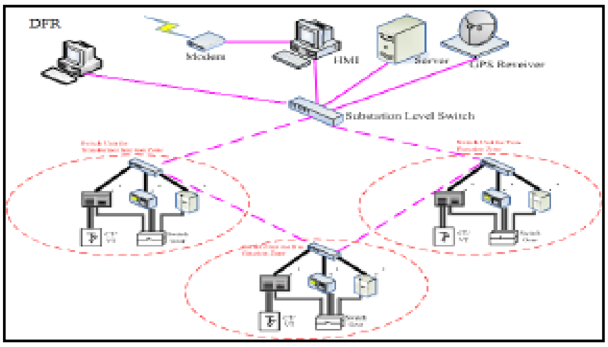

Fig. 5. Switched Ethernet-Ring Topology.

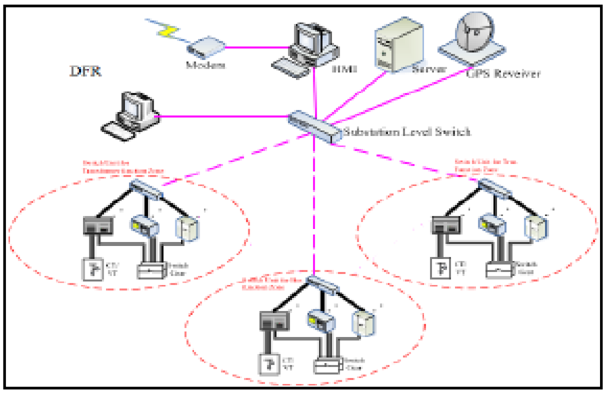

Fig. 6 : Switched Ethernet-Star Topology.

### E. Messages Exchanged

The messages considered in these network consists of the time critical message namely the trip message. This message is generated in the network whenever faults occur. This message is sent from the Protection IED which detects the fault to the corresponding protection IED which shares the breaker with the faulty line bay. If the breakers fail to open, the protection IED tries to open the entire bus associated with the faulty line. This trip message is 16 bytes in size. Once the trip message is sent, the protection IED and the CBMs of the bay unit in question sends error report to the HMI. These error reports are about 300KB in size and are sent using the File Transfer Protocol (FTP). Similarly, the DFR compiles a report of the values and sends a file of size 300KB to the HMI through FTP. Apart from these, the HMI sends a time synchronization message to all the components of the substation every second. This message is of size 16 bytes as well. Except for the trip message, the other messages are considered to be background messages.

## III. Simulation Results

We look at the results of various types of simulations performed. Three kinds of studies were performed in this thesis, namely delay performance, delay aware back off and reliability. So we present these three observations in separate sections.

### A. Delay Performance

For the study of delay performance, we take in to consideration the following scenario. The simulation is performed for 20s. The HMI sends out time synchronization messages to all the devices once every second. One of the protection IEDs of the line bay is made to send a trip message at the 10th second of the simulation time. The protection IED and the corresponding CBMs associated with it sends out files of size 300kb to the HMI after the trip message is sent. The DFR also sends a file of size 300kb to the HMI. The trip message delay is noted for the different topologies under these circumstances. The delay performance of the bus topology, ring topology, star topology, single AP model, multiple AP model and wired/wireless architecture are given in table 1. As we can see, the delay of the star topology and the wired/wireless topology are similar. Also, these delay values are the best performing ones. Also, we can see that the delays of the wireless model are comparable to the ring topology in terms of delay. The bus topology is the worst performing one. Even though the delays of wireless architecture are not equal to star, they provide an architecture which combines the reliability of the bus model and the performance of the ring topology.

Table 1. Trip Message Delays.

| Architecture | Measure Delay (ms) |
|---|---|
| Bus Topology | 1.4 |
| Ring Topology | 0.66 |
| Star Topology | 0.26 |
| Single AP Model | 0.76 |
| Multiple AP Model | 0.4 |
| Wired/Wireless Model | 0.26 |

### B. Delay Aware Back off

For testing the delay aware back off, a discrete model was built in MATLAB. The scenario consists of 10 users out of which 2 users are assigned as priority users. These priority users follow the delay aware back off for α = 1:6. The best effort users follow the normal random exponential back off scheme. In each slot, all the users decide on generating packets using a probability value assigned. Since the priority packets occur rarely in the network, we assign the probability 0.1 for the priority packets. The normal users generate packets at probability 0.7. These packets are queued up by the user and they are sent one after another similar to normal ethernet. This system was run for 100,000 slots and the delay for the real time users and the best effort users are determined. The result of this simulation is shown in Fig. 7.

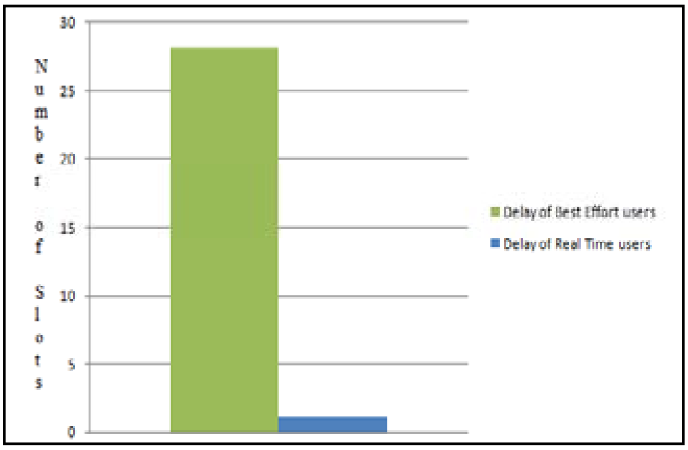

Fig. 7 : Delay Aware Back off Performance.

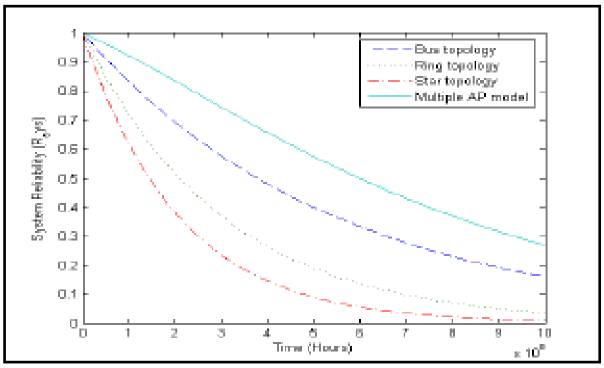

Fig. 8 : System Reliability of Various Models vs. Time.

Table 2. Comparison of Performances for Various Architectures.

| Architecture | Measure Delay (ms) | Reliability (t=1000hrs) |
|---|---|---|
| Bus Topology | 1.4 | 0.9982 |
| Ring Topology | 0.66 | 0.9970 |
| Star Topology | 0.26 | 0.9952 |
| Single AP Model | 0.76 | 0.9982 |
| Multiple AP Model | 0.4 | 0.9993 |
| Wired/Wireless Model | 0.26 | 0.9952 |

### C. Reliability

We analyzed the reliability of different topologies for mission time of 1000 hours. To obtain a more comprehensive result, the reliability values were calculated for various mission times. The simulation was performed in MATLAB. The reliability of the various topologies is noted for each time and are plotted. As the performance of single AP model and the bus topology are same and the performance of the wired/wireless architecture and star topology are same, we plot only one instance for these architectures. The result obtained for the system reliability is shown in Fig. 8. As we can see, the reliability of the wireless architectures are better than the ring and star topology. So the wireless architectures have a better delay-reliability trade off than the traditional architectures. This is shown in the Table. 2.

## IV. Conclusion

In this paper, we looked at the performance of the substation under different topologies. We focused on the delay characteristics of the priority message and the reliability of the substation and proposed new architectures which perform well in both the attributes. We could say that the multiple AP model could very well replace ring or bus topology because it has better performance both in terms of delay and reliability. When we compare the multiple AP model with the star topology, it performs a lot better in terms of reliability but at a slight increase in delay. However, the cost of implementation of the multiple AP model is significantly reduced because of minimal wiring. So it could very well replace star topology.

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## Author's Profile

*Swaminathan.P is Currently working as an Assistant Professor-EEE, Department of Electrical Technology, Karunya University, Coimbatore, Tamilnadu, India. His Reasearch Interest Includes High Voltage Engineering, HVDC and FACTS, Power Electronics and Drives, Renewable Energy Systems.*