Integration Considerations for Large-Scale IEC 61850 Systems

Saroj Chelluri, *NTPC Limited*
Diego Rodas and Ala Harikrishna, *Schweitzer Engineering Laboratories, Inc.*

***Abstract*—During the past few years, IEC 61850 has demonstrated a worldwide acceptance as more and more substation devices are being integrated based on Ethernet technology. This trend represents new challenges for integrators, manufacturers, and end users. In systems with a large number of networked substation devices, including intelligent electronic devices (IEDs), Ethernet switches, servers, front-end processors, gateways, and engineering and operator stations, careful consideration is necessary to effectively manage the traffic on the network and avoid congestion that could lead to long latencies or lost data. On a typical large application with more than 600 integrated devices, a number of parameters require planning and analysis, including:**

- **Effective use and customization of data sets for data concentration within the IEDs**
- **Correct use of information reports**
- **Traffic simulations**
- **Network topology (number of subnetworks, segregation, and subdivision)**
- **Requirements for front-end processors and tag servers**

I. INTRODUCTION

This paper is based on the design and implementation of an IEC 61850 substation automation system (SAS) solution to integrate numerical protective relays for the Indira Gandhi Super Thermal Power Project (IGSTPP) of NTPC Limited in Jhajjar, India.

The IGSTPP is forecasted to generate 1,500 MW of power. Delhi, Haryana, and an additional 40 villages will benefit from around-the-clock power supply. The first 500 MW unit will commence power generation by October 2010, and the other two units are planned to be fully functional by the end of 2010. The SAS consists of around 50,000 data points generated by 600 intelligent electronic devices (IEDs). The IEDs are distributed in thirteen 11 kV and six 3.3 kV single-busbar switchboards. The integration of 415 V low-voltage switchboards is also a part of this SAS.

NTPC Limited chose the IEC 61850 suite of protocols as a tool for the integration of the IEDs in the IGSTPP. The decision was based on engineering, maintenance, and integration advantages.

II. BACKGROUND

A. Brief Project Description

All of the medium- and low-voltage switchgear has numerical relays that communicate using IEC 61850. These relays include protection features, control, measurements, and monitoring. Breaker control is performed by the distributed control system (DCS).

Modern numerical relays, apart from being used for typical protection functions, also capture all feeder data, report events, monitor the equipment, and keep records of energy consumption. Such near real-time data of the complete auxiliary system captured and displayed on a human-machine interface (HMI) help monitor the system from remote locations. The typical key one-line diagram for the IGSTPP is shown in Fig. 1.

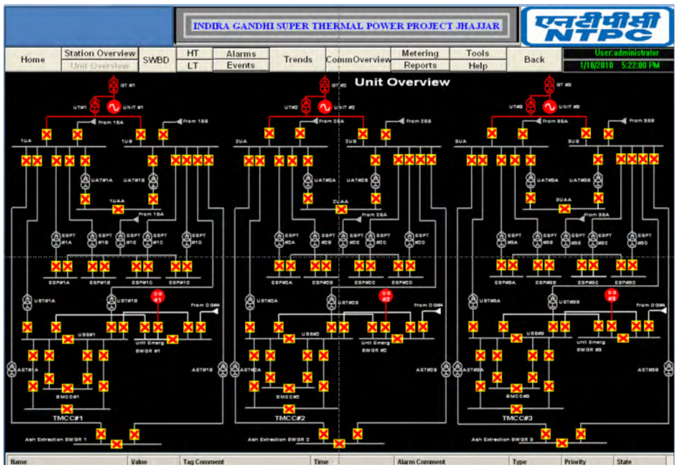


Fig. 1. Typical key one-line diagram with three 500 MW units

Typically, the various feeders are divided into the following types on a modular basis:

- Incoming lines, ties, and bus couplers
- Transformer feeders
- Motor feeders
- Low-voltage feeders

Each feeder type has a standardized configuration with respect to control schematics, data points, signals, and other relay configurations. The typical signal matrix for each module type is shown in Table I. Because the number of IEDs is large (approximately 600), this modular concept helped build the application for the SAS quickly and accurately.

TABLE I
TYPICAL SIGNAL MATRIX FOR FEEDER MODULES

	Signal Name	Front Panel	Alarm	Report/ Trend
Status	Circuit breaker open/close from the control center	✓	✓	
	Circuit breaker in test	✓	✓	
	Circuit breaker in service	✓	✓	
	Circuit breaker on	✓	✓	
	Motor speed switch	✓	✓	
	Trip coil supervision	✓	✓	
	Trip (86)	✓	✓	
	Watchdog alarm	✓	✓	
	Front light-emitting diode (LED) 1 through 8	✓	✓	
	Pushbutton LED 1 through 8	✓	✓	
	IRIG-B status	✓	✓	
Protection	Breaker position	✓	✓	
	Thermal alarm/warning element		✓	
	Thermal trip element		✓	
	Definite-time phase overcurrent 1 (short circuit) and overcurrent 2 (overload alarm)		✓	
	Definite-time neutral overcurrent 1 (earth fault)		✓	
	Definite-time negative-sequence overcurrent 1		✓	
	Speed switch alarm/trip element		✓	
	Load-jam alarm/warning element		✓	
	Load-jam trip element		✓	
	Phase undervoltage element 1		✓	
	Breaker operation count	✓		
Measurement	R-, Y-, and B-phase current	✓		✓
	RY, YB, and BR voltage	✓		✓
	Three-phase real/reactive power	✓		✓
	Three-phase energy	✓		
	Frequency	✓		✓
	Power factor	✓		✓

The data from the IEDs are sent to a data concentrator system and then to the HMI. Data from the concentrators are also sent to the plant DCS through fiber-optic links via Object Linking and Embedding for Process Control (OPC). The network system is monitored with online near real-time status. Any breakage and/or split in the network is immediately alarmed.

B. *Latency Considerations*

Local-area networks (LANs) used to interconnect substation IEDs, servers, concentrators, and gateways are built based on redundant architectures encompassing Ethernet cables and substation-rated managed Ethernet switches. Ethernet uses shared bandwidth-provisioning techniques to merge all of the message packets from multiple conversations onto various network segments. The network devices use variable provisioning and path routing techniques, which increase the likelihood that packets will safely navigate the network. However, these same techniques make the network activity uncertain and nondeterministic, which is generally reflected by drawing the network as a cloud. We push the message into the cloud, and it eventually appears at the destination, but we cannot be certain how it will navigate the network each time. All of these network elements and media introduce latencies that need to be analyzed in order to match the SAS requirements.

For some protection applications, the maximum latency requirement for critical traffic is a few milliseconds [1]. For example, IEC 60834-1 requires that 99.99 percent of commands for intertripping protection schemes be delivered within 10 milliseconds.

1) *Media*

The most common physical media used on substation LANs are Category 5e (CAT 5e) or Category 6 (CAT 6) cables, designed to support 100 to 1 Gbps, and fiber-optic cables (single mode or multimode), with a typical bandwidth of 1 Gbps (10 Gbps is now commercially available).

Table II indicates the latency due to the physical path.

TABLE II
ELAPSED TIME FOR AN IEEE 802.3 FRAME TO TRAVERSE THE PHYSICAL MEDIUM [1]

Medium	Time to Traverse a Link
CAT 5e and CAT 6 cables	0.55 µs per 100 m
Glass fiber optics	0.49 µs per 100 m
Wireless	0.33 µs per 100 m

2) *Ethernet Switch Latency*

Modern substation switches have fast switching capabilities. A 16-port switch operating at 100 Mbps per port needs to support a switching capacity of 1.6 Gbps (100 Mbps • 16 = 1,600 Mbps). Fortunately, modern nonblocking substation switches support higher switching speeds (9.6 to 13.6 Gbps). If the switching bus or switching components can handle the theoretical total throughput of all ports, the switch is considered to be nonblocking.

A common mode of operation for substation managed Ethernet switches is “store and forward.” In this mode, each frame is loaded into the switch memory and inspected before forwarding occurs. This technique ensures that only good packets are transmitted. While other switching technologies, such as “cut through,” impose minimal frame latency, they enable bad frames to propagate into the network, adding traffic. By using the store-and-forward technique, the switch maximizes the use of the network for good data but needs to wait for the complete frame to enter the switch to check the integrity. This introduces a transmission delay. If the Ethernet frame needs to propagate through several hops, this adds to delays during peak activity traffic.

C. Traffic Delays

Normal SAS network architectures typically require all switch ports to send data to one uplink port per client. Sending 1.5 Gbps (15 ports at 100 Mbps each) to a single 100 Mbps port can create a bottleneck. The sharing of this uplink port is possible because of the statistical nature of the network usage and the burst nature of data sources, such as information reports and Generic Object-Oriented Substation Event (GOOSE) messages. If there are not too many data, all is well. But at peak activity, when an event triggers information reports and GOOSE messages from the IEDs, the likelihood of multiple users simultaneously contending for the same network port increases. Switches with priority queues help to reduce the latency of high-priority messages due to traffic delays. Even so, high-priority messages are queued and need to wait for the completion of in-process low-priority message transmission and other queued priority messages. For example, Ethernet switches and traffic introduce delays on the frame propagation through the network. A GOOSE frame propagating through 10 switches of a 100 Mbps LAN with an event trigger burst of 12 GOOSE frames can experience propagation delays of more than 2 milliseconds. Table III compares Ethernet frame propagation time and frame size.

TABLE III
ELAPSED TIME FOR AN IEEE 802.3 FRAME TO
INGRESS OR EGRESS A PORT [1]

Frame Length	Frame Duration at 100 Mbps	Frame Duration at 1 Gbps
64 octets (minimum allowed)	7 µs	0.7 µs
300 octets (compact GOOSE frame)	25 µs	2.5 µs
800 octets (large GOOSE frame)	64 µs	6.4 µs
1,530 octets (maximum)	124 µs	12.4 µs

Within flexible bandwidth-provisioning networks, there is a network saturation point (e.g., 80 percent of bandwidth usage) where this competition for bandwidth noticeably slows message transit through the network.

D. Broadcast Data Storms

Some network designs use unmanaged Ethernet switches to connect several IEDs onto a linear or physically looped network segment. If the mediation control for data transmission fails, none of the devices on the segment can communicate. An IED communications interface can fail in a mode that corrupts the network. The Ethernet phenomenon known as a broadcast data storm occurs if an Ethernet network interface fails and continuously broadcasts messages, corrupting communication with any recipient of the data. Switches and routers prevent a broadcast data storm from influencing communication on other segments of the network, but no data are retrieved from the failed segments [2].

E. Recovery Times

Rapid Spanning Tree protocol (RSTP) provides a way to interconnect managed switches in a ring configuration. This type of configuration is a very attractive solution to achieve double-contingency Ethernet-switching communications architectures. With these arrangements, the system needs a minimum of two separate hardware and/or cabling failures before losing communication to a substation.

Managed industrial Ethernet switches running RSTP send inquiry packets actively seeking information from neighboring switches, providing fast network healing times. RSTP converts a network with endless loops created by a ring topology into a logical tree. An Ethernet switch keeps a list of Media Access Control (MAC) addresses for each device to which it connects. When receiving a message from a port, the switch examines the destination MAC address of the message and forwards it only to the port with a device that matches the address. However, if a network component failure occurs, RSTP needs time for network reconfiguration. Typical RSTP reconfiguration times of the switch MAC tables are approximately 5 milliseconds per switch. Reconvergence of the full end-to-end data path through the LAN cloud can take tens of seconds. Achieve faster recovery times through the use of proprietary improved RSTP-based protocols from switch manufacturers.

While a network reconfiguration does not need to be seamless on the station bus, it needs to be deterministic and fast enough for GOOSE traffic to not be delayed beyond a critical threshold [1]. A good engineering practice is to limit the number of switches per ring.

Other protocols, such as Parallel Redundancy Protocol (PRP) or High-Availability Seamless Ring (HSR), provide specialized redundancy methods but require specific implementations in IEDs and specialized network devices to connect to standard Ethernet networks.

III. BANDWIDTH USAGE SIMULATION

In integrated systems, the amount of data transmitted through the network during an electric fault condition is much larger than the traffic created by the IEDs reporting in normal conditions. During a fault, several IEDs respond to the contingency by protecting the electrical system and clearing the fault. During this period of time, variations of voltages and currents trigger large amounts of data to be reported back to data consumers, such as Manufacturing Message Specification (MMS) clients and GOOSE subscribers. These data, if not properly managed, create bottlenecks in nonfixed bandwidth-provisioning networks that lead to excessive latency and congestion, reducing the effective throughput and transit time of the network.

A simulation system illustrates how much bandwidth a feeder protective relay uses in normal reporting conditions and the relative increase of network bandwidth requirements during event trigger conditions.

A. Test Setup

During testing, a protection IED was configured with necessary protection, control, and communications settings, publishing one GOOSE message and three information reports. The test equipment consisted of the following:

- Hardware
  - One feeder protective relay
  - One test box to inject current and voltage
  - One communications server
  - One managed Ethernet switch
  - Necessary Ethernet CAT 5 cables
- Software
  - IEC 61850 MMS client/OPC server
  - OPC client Ethernet monitoring software

During testing, a packet analyzer was installed within the server, as indicated in Fig. 2. Other setups use managed switches that provide the additional capability of monitoring network traffic on other ports within the switch. This feature is known as switch monitoring or port mirroring. Port mirroring forwards copies of packets on each of the selected port(s) to another selected port. This traffic is viewable by connecting a PC to the port.

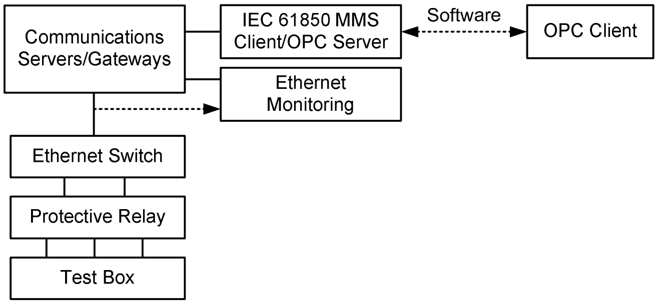
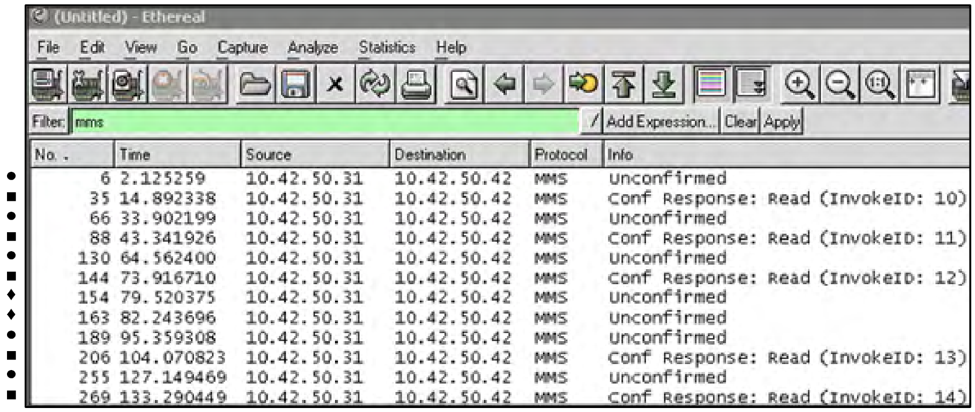


Fig. 2. Test system illustrates network usage

B. IEC 61850 MMS Client Configuration

In IEC 61850 MMS, as in other modern protocols, the amount of data transfer is optimized by the use of report by exception. In this mode of operation, the integral polling period can be increased to several seconds (30 seconds was used during testing to refresh data points). During this testing, the events were configured to trigger on data change; only the data that trigger the report are transmitted. An information report can be triggered by data change, quality change, or periodic rate. The IEC 61850 MMS client was configured to work on the poll information model. With this model, the MMS client updates the OPC client immediately, using variable access data derived from information reports in the order and frequency that they are received. It also polls or issues MMS read requests for OPC items that are not received in an information report at the OPC group update rate.

The relay used in the test system was configured to generate reports based on an integral periodic rate and data change. Fig. 3 shows a capture of Ethernet traffic, filtered to show only MMS frames. Three types of messages are identified: OPC polls or read commands (every 30 seconds), periodic integral reports (every 30 seconds), and reports generated by change of data within the data set (see Section IV).



Filter: mms

```
  No. .  Time        Source        Destination   Protocol  Info
●     6  2.125259    10.42.50.31   10.42.50.42   MMS       Unconfirmed
■    35  14.892338   10.42.50.31   10.42.50.42   MMS       Conf Response: Read (InvokeID: 10)
●    66  33.902199   10.42.50.31   10.42.50.42   MMS       Unconfirmed
■    88  43.341926   10.42.50.31   10.42.50.42   MMS       Conf Response: Read (InvokeID: 11)
●   130  64.562400   10.42.50.31   10.42.50.42   MMS       Unconfirmed
■   144  73.916710   10.42.50.31   10.42.50.42   MMS       Conf Response: Read (InvokeID: 12)
♦   154  79.520375   10.42.50.31   10.42.50.42   MMS       Unconfirmed
♦   163  82.243696   10.42.50.31   10.42.50.42   MMS       Unconfirmed
●   189  95.359308   10.42.50.31   10.42.50.42   MMS       Unconfirmed
■   206  104.070823  10.42.50.31   10.42.50.42   MMS       Conf Response: Read (InvokeID: 13)
●   255  127.149469  10.42.50.31   10.42.50.42   MMS       Unconfirmed
■   269  133.290449  10.42.50.31   10.42.50.42   MMS       Conf Response: Read (InvokeID: 14)
```

● Reports sent periodically every 30 seconds.
■ OPC read commands set for update rate of 30 seconds.
♦ Reports generated by data change.

Fig. 3. Network traffic filter to show MMS frames

If the variation of any analog data within a data set becomes larger than a dead band, a report is generated containing the data that have changed and the reason why the report was issued. In the same way, if any of the discrete points within a data set change status, a report is generated containing the Boolean with its quality and time stamp. Fig. 4 shows the MMS network utilization from one relay during normal traffic with no data change triggered. The traffic is generated from OPC polling and periodic reports.

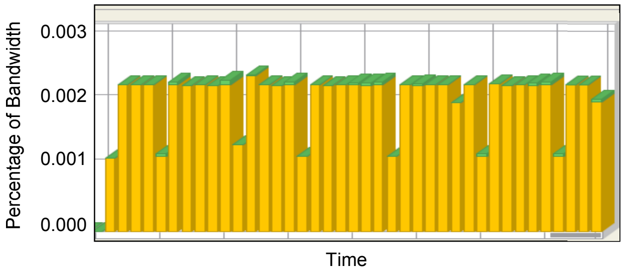


Fig. 4. Percentage of bandwidth used during normal traffic

By changing the currents and voltages using the test box, an electrical fault condition was simulated. The exercise illustrates the relative variation of traffic during these events, as shown in Fig. 5.

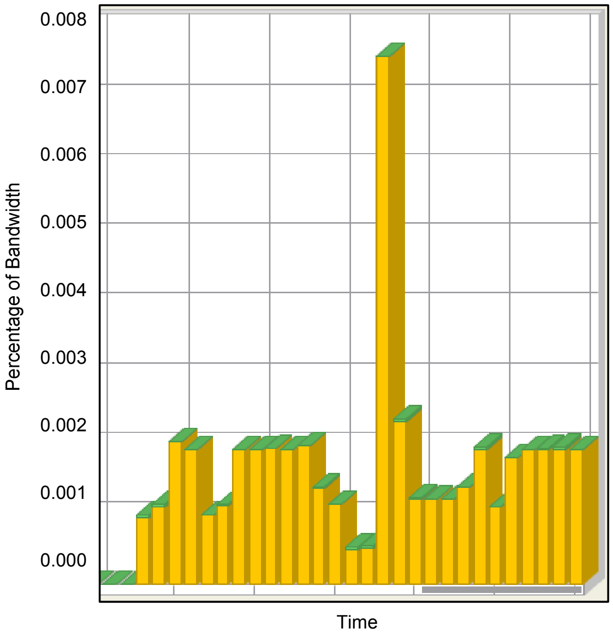


Fig. 5. Peak increase in the percentage of bandwidth used under heavy MMS reporting conditions

When GOOSE is enabled with a time-to-live (TTL) of 1 second, the expected result is an increase of bandwidth use, as shown in Fig. 6. During the test, circuit breaker changes generated an increase in GOOSE publishing.

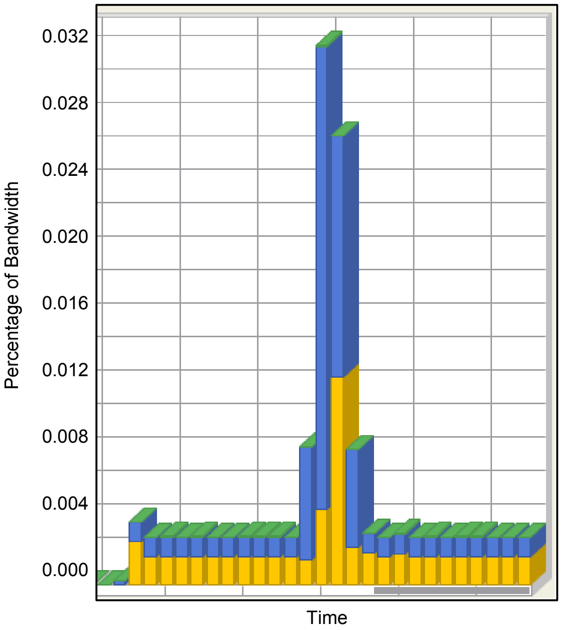


Fig. 6. Increase in the percentage of bandwidth used under heavy MMS reporting conditions with GOOSE messages

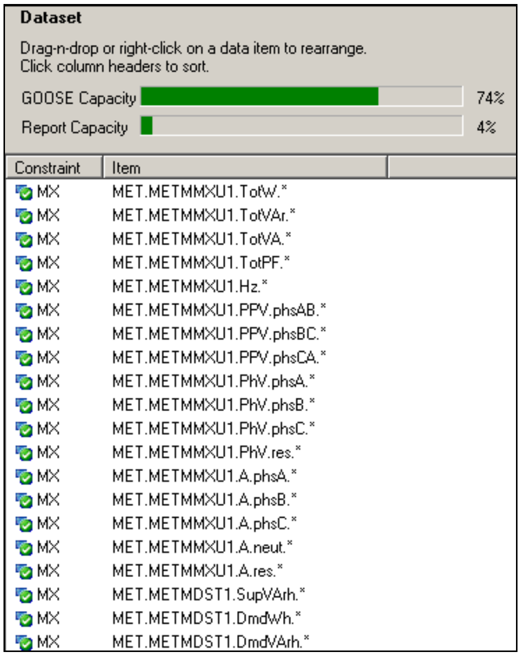
IV. BANDWIDTH MANAGEMENT STRATEGIES

A. Data Sets

Among other techniques to reduce traffic and facilitate the transmission of critical data is the use of information reports. A very effective way to further reduce the bandwidth used for supervisory control and data acquisition (SCADA) data is the customization of the information reports. Some IEDs allow the user to effectively concentrate data using data sets. These data sets can be configured to contain only the information required by each client. Several data sets can be created within the IEDs and linked to information reports in each IEC 61850 MMS client.

In the IGSTPP, there are three data sets: one analog metering data set linked to an unbuffered report and two discrete status data sets linked to buffered reports.

The optimization of the data sets is shown in Fig. 7. Correct dead-band settings from the user, shown in Fig. 8, help to effectively manage the use of the network bandwidth. In this new configuration, internal events, triggered by data change, quality change, or data update, trigger the sending of a data set report rather than multiple individual data element reports.



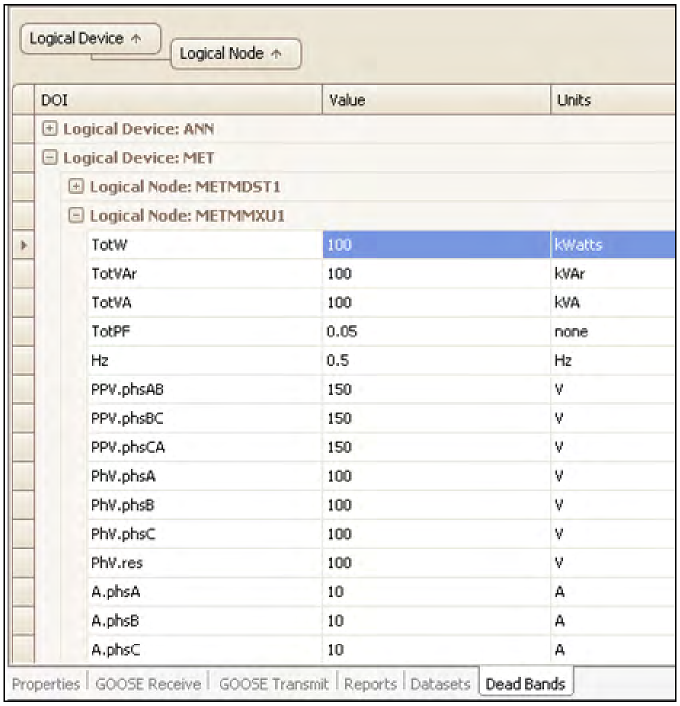
Dataset

Drag-n-drop or right-click on a data item to rearrange.
Click column headers to sort.

GOOSE Capacity 74%
Report Capacity 4%

Constraint	Item
MX	MET.METMMXU1.TotW.*
MX	MET.METMMXU1.TotVAr.*
MX	MET.METMMXU1.TotVA.*
MX	MET.METMMXU1.TotPF.*
MX	MET.METMMXU1.Hz.*
MX	MET.METMMXU1.PPV.phsAB.*
MX	MET.METMMXU1.PPV.phsBC.*
MX	MET.METMMXU1.PPV.phsCA.*
MX	MET.METMMXU1.PhV.phsA.*
MX	MET.METMMXU1.PhV.phsB.*
MX	MET.METMMXU1.PhV.phsC.*
MX	MET.METMMXU1.PhV.res.*
MX	MET.METMMXU1.A.phsA.*
MX	MET.METMMXU1.A.phsB.*
MX	MET.METMMXU1.A.phsC.*
MX	MET.METMMXU1.A.neut.*
MX	MET.METMMXU1.A.res.*
MX	MET.METMDST1.SupVArh.*
MX	MET.METMDST1.DmdWh.*
MX	MET.METMDST1.DmdVArh.*

Fig. 7. Data sets optimize data in information report



DOI	Value	Units
Logical Device: ANN		
Logical Device: MET		
Logical Node: METMDST1		
Logical Node: METMMXU1		
TotW	100	kWatts
TotVAr	100	kVAr
TotVA	100	kVA
TotPF	0.05	none
Hz	0.5	Hz
PPV.phsAB	150	V
PPV.phsBC	150	V
PPV.phsCA	150	V
PhV.phsA	100	V
PhV.phsB	100	V
PhV.phsC	100	V
PhV.res	100	V
A.phsA	10	A
A.phsB	10	A
A.phsC	10	A

Fig. 8. Dead-band settings help to optimize MMS traffic

B. Buffered Reports

Internal events, triggered by data change, quality change, or data update, issue the immediate sending of reports or buffer the events (to a practical limit) for transmission. This prevents the loss of data values due to transport flow control constraints or loss of connection.

C. Unbuffered Reports

Internal events, triggered by data change, quality change, or data update, issue the immediate sending of reports on a "best efforts" basis. The network does not provide any guarantee that the data are delivered. If no association exists or if the transport data flow is not fast enough to support the report, events are lost.

D. Multicast Traffic

GOOSE works with a dynamic repetition of multicast messages communicating on Ethernet Layer 2. When data change, the GOOSE repetition rate is more rapid. If the data within the GOOSE data set stop changing, the repetition rate slows to the configurable maximum time between publications, set to 1 second in this example, which lowers the network load. The consequence of this multicast function that has no destination MAC address, however, is that the Ethernet switches cannot prevent the unrestricted dissemination of these messages. In large installations with a number of devices publishing multicast traffic, this has a serious impact on the network. Some devices do not have multicast filters, so GOOSE messages interrupt normal processes on these devices. Additional measures, like multicast filters or virtual local-area networks (VLANs), are necessary to control and restrict the dissemination of GOOSE messages [3].

E. Proper Configuration of IED Capability Description (ICD) Files

Vendors provide default ICD files with their products. Though these factory default capability files will work immediately without further configuration, it is likely that customization for each specific project will require additional configuration. During the design phase, integrators need to modify the configuration in order to subscribe to other relay GOOSE messages, optimize data sets, change dead bands, or simply remove the default unnecessary GOOSE messages that introduce multicast traffic and are not used by IEDs on the network.

V. OTHER NETWORK CONSIDERATIONS

One very important aspect to consider during the network design phase is the physical arrangement of network elements in order to provide maximum communications reliability, dependability, and efficiency. The correct arrangement of network components provides redundant physical paths for network traffic. Protocols like RSTP help provide efficient logical paths.

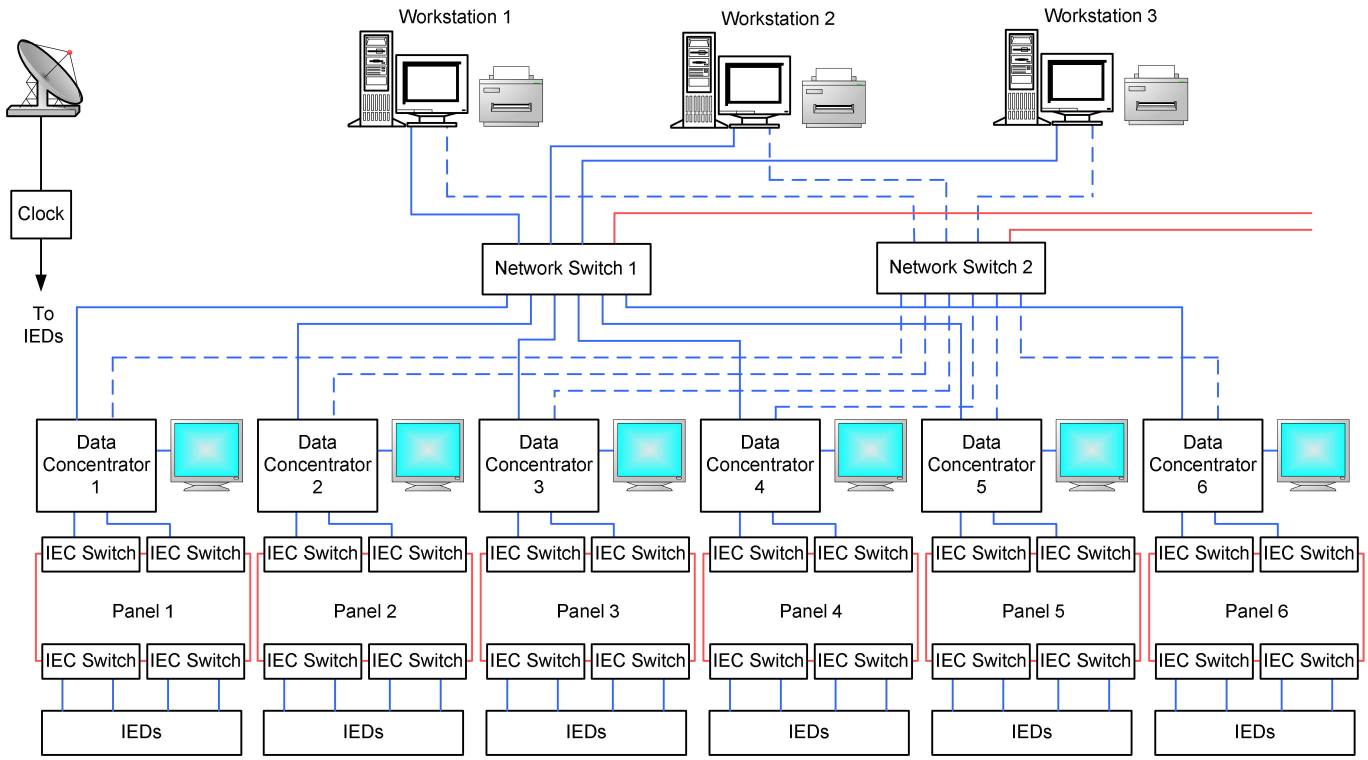


Fig. 9. Ethernet network architecture implemented in the IGSTPP

The network architecture implemented in the IGSTPP is a combination of ring and star topologies. As indicated in Fig. 9, the IEDs are linked to substation-rated managed Ethernet switches connected in a ring topology. Because of the number of IEDs, the network is divided into six Ethernet ring networks, with a data concentrator collecting IEC 61850 reports from approximately 100 relays. The IEC 61850 client software application serves the information through OPC into HMI OPC clients within the data concentrator. Each data concentrator is also connected to an upper redundant star network. This network refreshes the operator workstation HMI data points from tag servers through Transmission Control Protocol/Internet Protocol (TCP/IP) messages and sends information to a remote control center using two Ethernet fiber-optic links. The two networks are physically separated by the data concentrators, adding security to the substation networks.

The project time-synchronization requirement of 1 millisecond for time-stamping was easily achieved using IRIG-B connections to the IEDs. When high-accuracy Ethernet network synchronization is required (e.g., process bus applications), IEEE 1588 is a future alternative for synchronization when the IEEE Power System Relay Committee completes the defining of a profile for use in power systems.

In general, the network topology must be designed to meet the same critical environmental and reliability requirements as the substation protection and control equipment. Determining the communications topology for an SAS can be a significant analytical problem. The following factors should be considered when selecting network topology:

- Availability
- Suitability
- Initial cost
- Lifetime cost
- Diagnostic ease
- Data transfer rates
- Protocol dependencies
- Network segregation

The main factors to consider when selecting the components and designing the system include equipment installation and commissioning costs, performance, security, and vendor independence and reliability. Many technical papers are available to help with the analysis of these topics [4] [5].

Designers can use fault trees to determine the failure rate of a combination of components. Failure rates are useful for estimating maintenance costs but do not adequately indicate whether a device will be available when needed. Reference [4] shows how to calculate estimated unavailability, which is the fraction of time that a device cannot perform. Given the unavailability of the components in a system, fault trees are useful to calculate the unavailability of the system [4].

An example of the fault tree analysis for the architecture used in this project is presented in Fig. 10. The calculations are based on typical reliability factors, as indicated in Table IV.

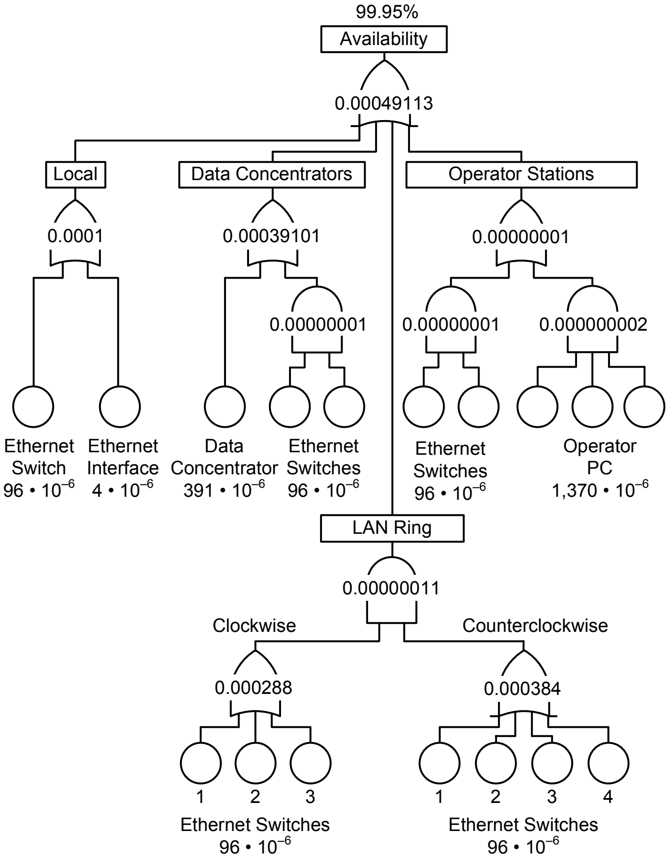


Fig. 10. Fault tree analysis of a typical ring architecture

TABLE IV
APPROXIMATE COMPONENT MEAN TIME BETWEEN FAILURES (MTBF) AND UNAVAILABILITY [6]

Component	MTBF (years)	Unavailability (multiply by 10^{-6})
Substation-grade IED Ethernet interface	1,320	4
Substation-grade fiber-optic transceiver	600	9
Substation-grade communications processor*	335	16
Substation-grade protective relay IED hardware	150	37
Substation-grade Ethernet switch with dual power supply	106	52
Substation-grade Ethernet switch	57	96
Substation-grade computer*	50	110
Substation-grade Ethernet router	40	137
Commercial Ethernet router with dual power supply	35	156
Industrial PC*	14	391
Commercial Ethernet switch	11.5	477
Commercial media converter	11.5	391
Commercial Ethernet router	9.5	577
Commercial PC*	4	1,370

*Used as an information processor.
Note: The most reliable components have the smallest unavailability numbers.

Fig. 11 and Fig. 12 are two examples of typical architectures used on IEC 61850 projects. Depending on the redundancy requirements, the relays connect using one or two ports in failover mode. The number of switches required in the case of dual-port IEDs increases the initial equipment and installation costs, increases the cost and complexity of the relay by forcing it to take on the role of network management, but also increases the availability of the Ethernet system, thereby avoiding single-point network segment failures.

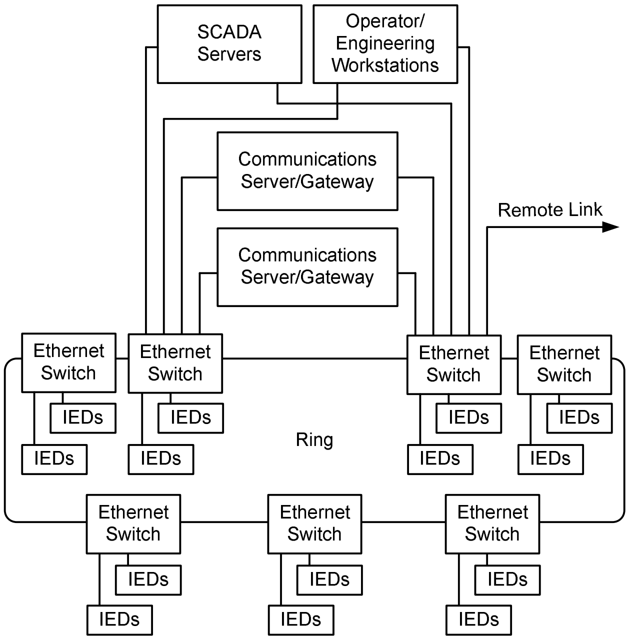


Fig. 11. Typical substation network with ring architecture

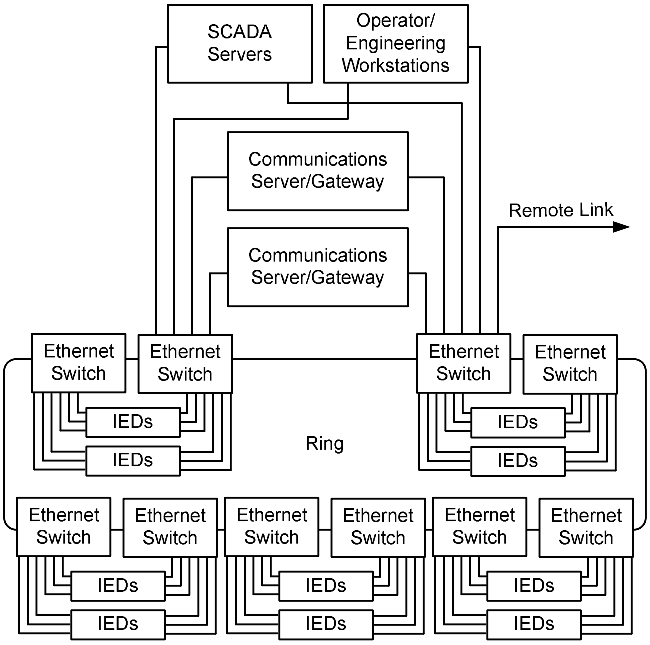


Fig. 12. Typical substation network with ring architecture and dual-port IEDs

VI. RECOMMENDATIONS

The design of IEC 61850 networks requires a clear understanding of the processes and features provided by the standard. Integrators and users must become familiar with the techniques and requirements of Ethernet networks as well as what features and capabilities exist in the IEDs being used.

The best engineering practices must be followed in order to optimize network bandwidth use. This paper presents a few techniques that are available for this purpose, but many additional techniques, like message prioritization, quality of service, network segregation, and VLANs can be analyzed and implemented as needed to satisfy the substation communications requirements.

VII. REFERENCES

[1] *IEC Communication Networks and Systems in Substations*, IEC 61850-90 Standard, 2009.

[2] G. Scheer and D. Dolezilek, “Comparing the Reliability of Ethernet Network Topologies in Substation Control and Monitoring Networks,” proceedings of the 2nd Annual Western Power Delivery Automation Conference, Spokane, WA, April 2000.

[3] J. Rodrigues and C. Hoga, “Next Step in IEC 61850: Large Applications and Process Bus Applications,” proceedings of VII Simpósio de Automação de Sistemas Elétricos, Salvador, Brazil, August 2007.

[4] G. Scheer, “Answering Substation Automation Questions Through Fault Tree Analysis.” Available: http://www.selinc.com.

[5] G. Scheer, “Comparison of Fiber-Optic Star and Ring Topologies for Electric Power Substation Communications,” proceedings of the 1st Annual Western Power Delivery Automation Conference, Spokane, WA, April 1999.

[6] G. Scheer and D. Dolezilek, “Selecting, Designing, and Installing Modern Data Networks in Electrical Substations,” proceedings of the 9th Annual Western Power Delivery Automation Conference, Spokane, WA, April 2007.

VIII. FURTHER READING

V. Skendzic, I. Ender, and G. Zweigle, “IEC 61850-9-2 Process Bus and its Impact on Power System Protection and Control Reliability,” proceedings of the 9th Annual Western Power Delivery Automation Conference, Spokane, WA, April 2007.

S. Coppel, T. Tibbals, and A. Silgardo, “Practical Considerations for Ethernet Networking Within Substations,” proceedings of the 10th Annual Western Power Delivery Automation Conference, Spokane, WA, April 2008.

P. Rietmann and S. Griffin, “Applying IEC 61850 to Substation Automation Systems,” ABB Switzerland Ltd.

B. Kasztenny, J. Whatley, E. Udren, J. Burger, D. Finney, and M. Adamiak, “IEC 61850: A Practical Application Primer for Protection Engineers,” proceedings of the 60th Annual Georgia Tech Protective Relaying Conference, Atlanta, GA, May 2006.

V. Skendzic and R. Moore, “Extending the Substation LAN Beyond Substation Boundaries: Current Capabilities and Potential New Protection Applications of Wide-Area Ethernet,” proceedings of the 8th Annual Western Power Delivery Automation Conference, Spokane, WA, April 2006.

IX. BIOGRAPHIES

Saroj Chelluri received her BS in electrical engineering and an MBA. She is presently working as general manager in the project engineering division of NTPC Limited. Her job involves the design of auxiliary power supply systems in power plants, including concept designs, preparation of technical specifications, tender engineering, detail engineering, testing, and execution. She has about 25 years of experience in auxiliary power supply system design and execution. She has been extensively involved in medium- and low-voltage system automation designs for the last five years.

Diego Rodas received his BS in electronic and control engineering from Politecnica Nacional in 1994. He has broad experience in automation and control systems. Upon graduating, he worked for nearly 16 years in automation systems, from senior field engineering for the oil industry to senior systems design engineering for several industries, including food and pharmaceutical industries. In the last three years, he has been involved in integration and automation projects for numerous substations. Prior to joining Schweitzer Engineering Laboratories, Inc. in 2007, he was involved in the development of automatic machinery for process control and validation of new technology petrochemical data acquisition and telemetry systems.

Ala Harikrishna received his BTECH in electrical and electronic engineering from Jawaharlal Nehru Technological University in 2005. He has experience in process automation and control systems. He worked for nearly five years as a field engineer in automation systems for several industries. After joining Schweitzer Engineering Laboratories, Inc. in 2008, he has been involved in design, testing, and commissioning of substation integration and automation projects, including IEC 61850 applications.

© 2010 by NTPC Limited and
Schweitzer Engineering Laboratories, Inc.
All rights reserved.

20100329 • TP6418-01