

Applying an Ethernet LAN in a Substation

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APPLYING AN ETHERNET LAN IN A SUBSTATION

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ABSTRACT

This paper is a discussion of an NSTAR Electric & Gas Corp. project using current Ethernet technology to build a Local Area Network (LAN) in a single substation application.

NSTAR's Substation 385D is built around a local Ethernet backbone that passes information for Supervisory Control and Data Acquisition (SCADA) and local monitoring and control via a Human-Machine Interface (HMI). The heart of the system revolves around several communications processors.

The system includes the following protection and control devices:

- Communications processors
- Serial-to-Ethernet transceivers
- Ethernet switches
- Intelligent Electronic Devices (IEDs)
- Substation protection and event monitor/viewer

This paper discusses the application of an Ethernet LAN to provide a simplified communications backbone for local and remote control and monitoring. Utility engineers, dispatchers, and operators also use the Ethernet LAN to retrieve and view the real-time operational and fault analysis data. The communications processor is acting as the hub for all the control points and data that are being moved through the system. This paper discusses a practical example of design, application, commissioning, and lessons learned.

INTRODUCTION

NSTAR Electric & Gas Corp. is a utility company that has been serving eastern Massachusetts' customers for more than 100 years, which now number approximately 1.4 million. NSTAR's regulated subsidiaries have approximately 3,200 employees; it was established by the merger of Boston Edison and Commonwealth Energy [1].

NSTAR's new Substation 385D, located in South Boston, is built around an Ethernet LAN backbone. NSTAR chose to use Ethernet technology in this substation because, it was determined that this technology would best meet NSTAR's present and future communications needs. Ethernet supported the substation automation plans while providing substation Ethernet project experience and allowed NSTAR to evaluate this technology for future substation applications. This was the first NSTAR substation utilizing Ethernet communications. This substation is a 115 kV to 13.8 kV distribution class substation, with four 115 kV transmission lines, four transformers, and eight bus sections of two-high enclosed double-aisle sheltered metal-clad switchgear. The general equipment and layout is four 115 kV to 13.8 kV 37/50/62.5 MVA transformers, six 13.8 kV 9.6 MVAR capacitor bank feeders, two future 13.8 kV 9.6 MVAR capacitor bank feeders, and sixty-four 13.8 kV feeders (see Figure 1). This general equipment and layout supplies Boston area customers and supports the new waterfront district.

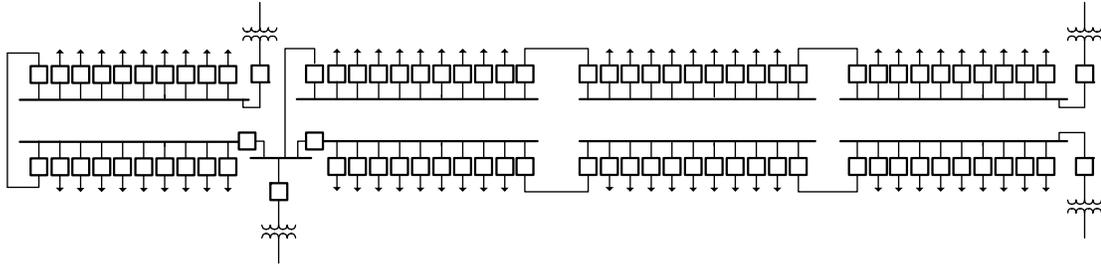


Figure 1 Basic One-Line Diagram of Substation 385D

ETHERNET BACKBONE

Ethernet History

Ethernet is the most popular and widely deployed network technology in the world. In 1973, while working on a way to link the Xerox “Alto” computer to a printer, Bob Metcalfe designed and tested the first Ethernet network. This first Ethernet network defined the physical cabling required of a connected device and defined the standard communications required on the cable. As electronics and networking have grown, the Ethernet standard has developed to include the new technologies, but the basic mechanics of operation of every Ethernet network stems from Mr. Metcalfe’s original design at the Xerox Corporation’s Palo Alto Research Center. The original Ethernet design described communication over a single cable shared by all devices on the network. Once a device is attached to this cable, it has the ability to communicate with any other attached device. This allows the network to expand to accommodate new devices without requiring any modification to those devices already on the network [2].

In the beginning, Ethernet networks were set up in a multidrop network based on Metcalfe’s original “Ether” trunk, where devices “tapped” into the information highway. Ethernet network topologies have since evolved into star networks that include hubs, switches, and routers. A hub is a passive device that passes or buses all the information on the network to every connected device. An Ethernet switch is a step above a hub; it incorporates the same function of a hub where it passes the data to all connected devices but includes the capability to decode parts of those messages and uses this decoded information to direct the traffic to the appropriate internet protocol (IP) address. Switches also have the ability to avoid message collisions by managing the data via store-and-forward methods that act in a deterministic fashion. The process is prescribed in the Ethernet Carrier Sense Multiple Access with Collision Detection (CSMA/CD) protocol. Finally, routers are similar to switches, except they add the function of routing traffic from a LAN to another LAN, thus creating a Wide Area Network (WAN).

Ethernet in Substations

Ethernet networks in substations have become more popular, and as utilities move towards using Ethernet and recognize its advantages in substations, Ethernet use will grow even more. Ethernet technology brings a standard physical connection that a utility can elect to use, which allows them to integrate a substation into a functional system with a combination of the correct physical ports, protocols, storage, and logic.

Many things have to be recognized when applying an Ethernet network to a substation, such as environmental specifications, engineering access, utility standards, and security from hackers. Equipment located in a non-environmentally controlled enclosure or yard cabinet has to be

“substation hardened” or meet certain temperature ranges that most commercial off-the-shelf equipment will not meet.

Ethernet Design at Substation 385D

For this application at Substation 385D, NSTAR used equipment that was all substation hardened, even though both the control and switchgear enclosures have HVAC units. With the concern of security from hackers, NSTAR elected to use a closed-loop LAN. In other words, the Ethernet backbone inside the substation was not accessible from an outside network; it was isolated locally in the substation. Remote engineering access was not allowed, but the information needed and desired by engineering, operations, and management was automatically collected through an additional, but separate, closed-loop Ethernet LAN. The data are pushed to a corporate LAN using Virtual Private Networking (VPN) for internal viewing and analysis. By using an Ethernet backbone in the substation, NSTAR was able to simplify the system complexity of the integration and reduce the amount of wiring that would have previously been installed for a more conventional substation design.

This substation application combined both of the most popular types of Ethernet physical and data link layers. These were twisted-pair metallic (10BASE-T or 100BASE-TX) and fiber optics (10BASE-FL or 100BASE-FX) with standard data transmission speeds of 10 Mbps or 100 Mbps. The fiber-optic cables were for the trunk cable sections, both within an enclosure and between enclosures, which were required to run through the substation yard. The twisted-pair metallic cables were for the short node connections within a cabinet, panel, or rack section. The metallic connection used Unshielded Twisted Pair (UTP) Category 5 enhanced cables. The substation network used a meshed star network topology with several small switches connected to one large Ethernet switch that acts as the central node. All control cables between enclosures were shielded and grounded at one end. Three stages of ac and dc surge protection were applied: main panel, subpanel, and specific feeders. Most equipment manufacturers offer or have an internal surge protection technique located within the specific equipment, and this could be considered a fourth stage of surge protection. This design and construction approach was chosen because of previous experience with other techniques that had random, difficult, and time consuming alarms or error messages. In the past, NSTAR Electric has experienced equipment damage related to radio frequency interference (RFI), induced voltages, electrostatic discharge (ESD), electromagnetic interference (EMI), damaging ground fault current, temperature, vibration, and noise.

Ethernet Devices

The Substation 385D project used a wide variety of Ethernet devices, as shown in Figure 3. The following is a list of devices used and their primary function.

- Ethernet transceivers
 - These transceivers convert serial EIA-232 communications to 10/100BASE-T Ethernet communications. There are two Ethernet transceivers per communications processor. One is for communication to and from the local HMI, and the other is for communication to and from the protocol converter, which connects to the remote SCADA master.
 - These devices plug directly to the rear serial port of the communications processor; the other end is an RJ-45 connection, which goes to an Ethernet switch as shown in Figure 2. These devices were chosen because they are easy to implement and maintain.
 - Each one of these has its own specific IP address and can handle only one TCP/IP session.

- There are a total of 34 Ethernet transceivers at Substation 385D.
- Ethernet switches
 - These Ethernet switches are substation grade and purchased with either 8 or 25 ports. There is one 8-port switch per communications processor and one 25-port switch located in a 115 kV control enclosure.
 - These switches manage data traffic on both the Ethernet copper cables and fiber cables by directing instead of just passing the data. Directing the data substantially reduces the amount of possible data collisions resulting in faster, more dependable communications.
 - There are a total of 17 Ethernet switches at Substation 385D.
- Ethernet communications cards
 - These cards have been installed in each of the communications processors. This design assures that the network traffic processing overhead and network problems and failures do not impact the operation of the communications processor. The communications processors perform the automatic retrieval of the following:
 - Real-time data (periodic analog, periodic digitals, and trending)
 - Fault location reports
 - Sequence-of-events files
 - Transient disturbance records
 - Each card has its own specific IP address and can handle up to three TCP/IP sessions.
 - There are a total of 17 Ethernet communications cards at Substation 385D, one installed in each communications processor.



Figure 2 Ethernet Switches and Serial-to-Ethernet Transceivers

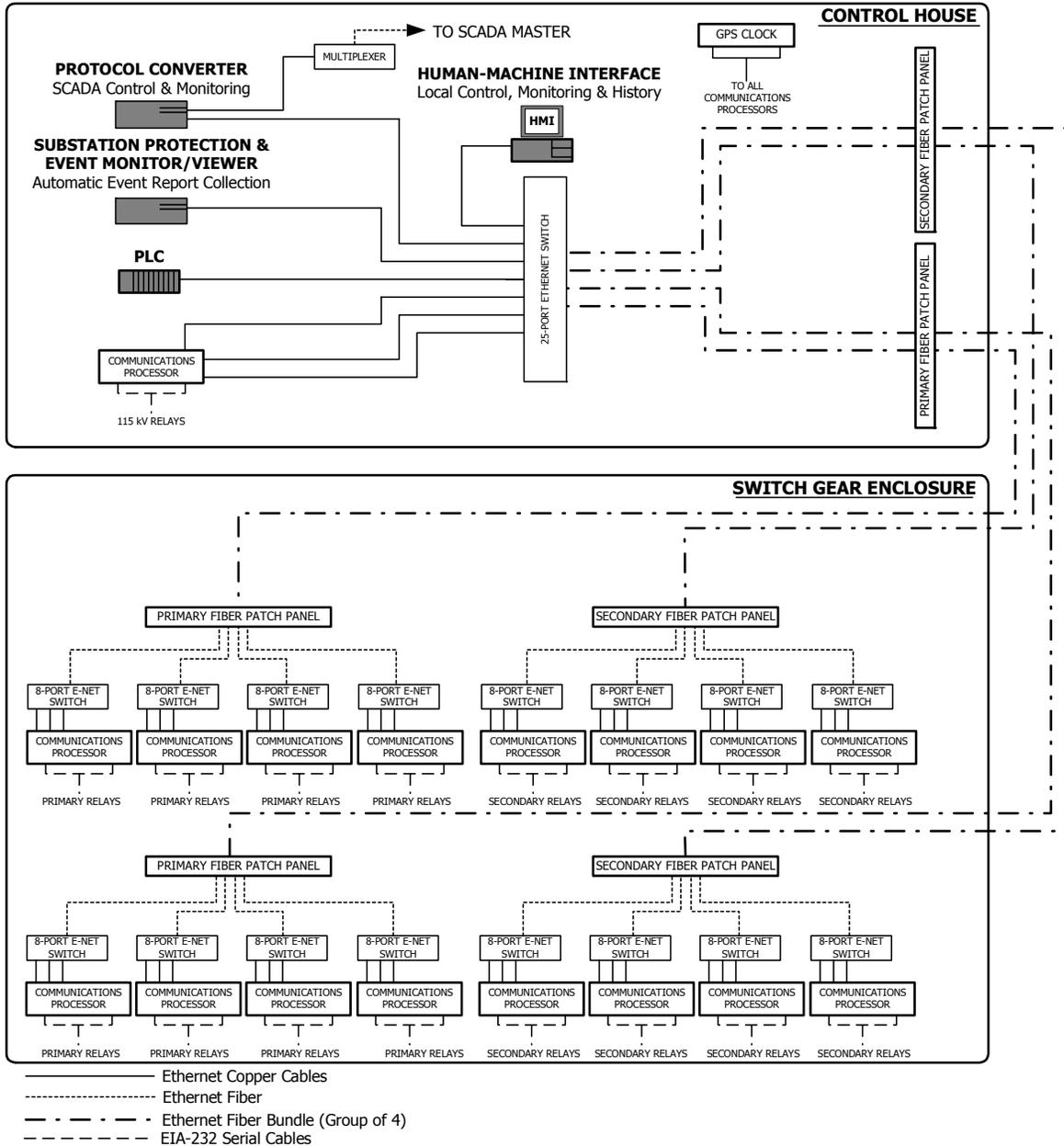


Figure 3 Substation 385D Communications Diagram

COMMUNICATIONS PROCESSOR

At Substation 385D, the communications processor is the heart of the system because it maintains all the data and control features of the system. The functions of the communications processor include the collection of metering values, target data, input/output states, alarm indications, and the control of schemes and breakers.

The application and functions of the communications processor make this design versatile and powerful. Combining the basic functions of the communications processor allowed NSTAR to meet the varied requirements of their application.

- Substation integrator
 - The communications processing and database capabilities of the communications processor are designed to collect and store data from numerous devices, parse it into useful pieces, and distribute just the needed data to other devices or systems. Its networking capabilities allow it to be part of the communications network, SCADA, and HMI interface.
 - The communications processor interfaces with a variety of devices, including the protocol converter, the substation protection and event monitor/viewer, PLC, and the HMI, as shown in Figure 5.
- Time synchronization source
 - The communications processor transmits a demodulated Inter-Range Instrumentation Group Time Code Format B (IRIG-B) signal. This signal is passed down to all connected IEDs. The source for the transmitted IRIG-B signal is from a Global Positioning System (GPS) clock.

Through the use of this technology, NSTAR was able to transmit and receive all the values and control points through one communications connection with the relay or IED. The control commands, metering values, target information, and alarm states were all being passed through the EIA-232 serial communications cable. This eliminated the need for extra transducers and hard-wiring that would otherwise be used in more traditional installations.

The use of the communications processors throughout the Ethernet network simplified the networking of devices and provided a network that was inexpensive and easy to implement and maintain. Also, the communications processor provides a common point to connect several different serial devices that do not support Ethernet connections. The communications processor also allowed NSTAR to parse and store specific data that were needed for SCADA and the HMI, rather than pass all the information that is stored in the IEDs. As shown in Figure 5, the communications processor communicates with the connected IEDs using an interleaved protocol, which multiplexes all binary data (metering and target), ASCII/engineering access (parsing, event reports/fault location, transparent communications), binary sequence-of-events, and IRIG-B time signal.

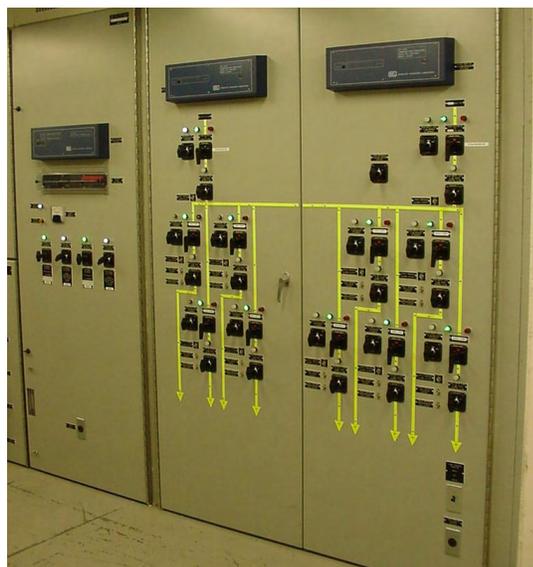


Figure 4 Communications Processors

SCADA

The SCADA master communicates with Substation 385D via a multiplexed fiber network using DNP3 protocol. As shown in Figure 5, the protocol converter takes the data collected by the communications processors and converts them from the vendor's protocol to DNP3. The data are supplied to the protocol converter over the substation's Ethernet network.

- Supervisory control

The remote control of the substation was implemented over the same Ethernet network. For example, the SCADA control command for opening a breaker would be transmitted over the multiplexed fiber network, into the protocol converter, through the substation Ethernet LAN, and to the communications processors. From there, this breaker-open control signal would pass down to a connected relay over the EIA-232 serial connection. Upon receiving the signal, the relay would close the programmed and hardwired relay output contact, allowing current to flow through the associated breaker's trip coil to actuate a scheme that opens the breaker.

- Data acquisition

Typical analog and digital data are transported over the same Ethernet network. For example, consider the digital status of a switch position: a contact from the switch would be hardwired as a relay input, and the binary status of this relay input would pass up to the connected communications processor over the EIA-232 serial connection. The communications processor updates, consolidates, and sorts the digital data. From there, this switch position status goes out of the communications processor, through the substation Ethernet LAN, into the protocol converter, and is then transmitted over the multiplexed fiber network to SCADA as an indication point.

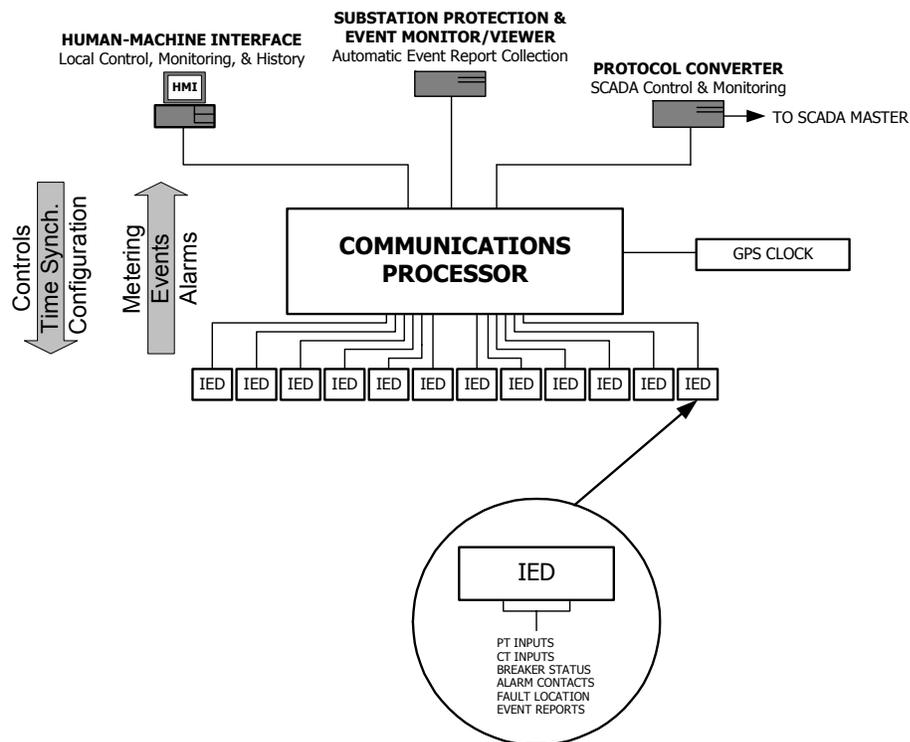


Figure 5 Data Flow Diagram

HUMAN-MACHINE INTERFACE

The HMI resides on an industrial-grade computer that was installed in the 115 kV control enclosure as shown in Figure 7. There is HMI software on the computer that was developed for the Graphical User Interface (GUI). The HMI screens are as follows:

- One-Line Screen
 - Shows a mimic bus of the whole substation (partial mimic also appears on panels of Figure 4)
 - Displays the breaker status (see Figure 6)
 - Displays the metering information for each line, transformer, and feeder
- Annunciator Screen
 - Shows all substation critical and non-critical alarms
- Alarm Screen
 - Provides sorted, time-stamped, and detailed information on each alarm
- Communications Screen
 - Displays the status of all communications channels for serial and Ethernet links inside the local substation perimeter (see Figure 6)
- Breaker Screen
 - Allows control and shows status of breaker (trip and close)
 - Displays the line or feeder metering information
 - Displays and operates switches and schemes
 - Allows control and shows status of reclosing
 - Allows control and shows status of underfrequency, local/remote switches, etc.
- Transformer Screen
 - Displays high-side and low-side breaker status
 - Displays metering information for each transformer
 - Displays tap position, temperatures, and dissolved gas content
 - Allows transformer control (percent voltage reduction and tap changer remote/local)

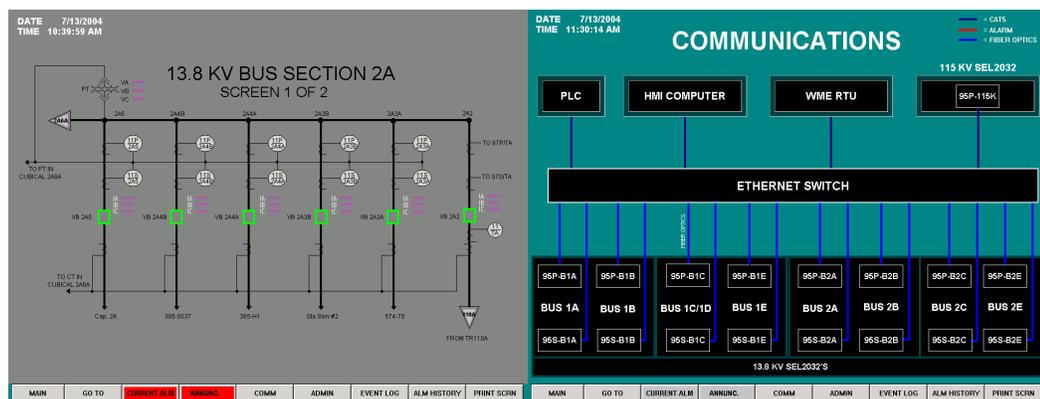


Figure 6 HMI Screen Shots

All of the information that is being populated on the HMI screens is going through the Ethernet LAN. These data come from the IED, to the communications processors, and are then passed on to the HMI. Once the information is at the HMI, it is converted from the vendor's protocol to a standard Dynamic Data Exchange (DDE) tag, which the GUI software can interpret. The controls for the substation go over the same path as shown in Figure 5.

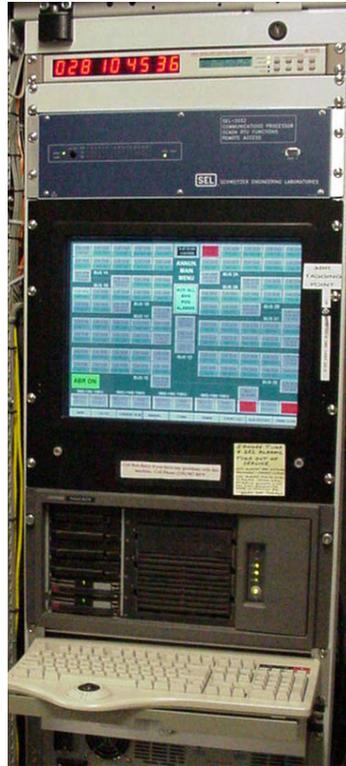


Figure 7 HMI Cabinet

SUBSTATION PROTECTION AND EVENT MONITOR/VIEWER

The substation protection and event monitor/viewer is an industrial-grade computer (solid-state PC104) loaded with automatic data collection and universal analysis software. This software collects the necessary fault and load data from the relays over the Ethernet LAN. As shown in Figure 3, this software accesses each individual communications processor over the Ethernet LAN by using an addressable IP node associated with that communications processor's Ethernet communications card. From the communications processor, this software connects transparently to the IED so that it can perform the following functions while not interrupting the monitoring and control from the local HMI or the SCADA master:

- Collect from the IEDs, 15-minute averages of volts, amps, watts, and vars for each circuit, and detect or report on any overload, inefficiency, and/or imbalance condition
- Periodically poll for the latest fault and disturbance records, detect and report new faults within minutes from occurrence, and provide target and fault distance information in real-time
- Monitor communications errors or health checks
- Detect breaker status and breaker operation counters

The substation information is one-way routed to a stand-alone database on a master station computer that is located in one of NSTAR's central buildings. By mid-2005, NSTAR will have another substation that is one-way routing similar information to this same master station computer. The master station computer's database will push and copy the database information through a firewall to a company network server. This will provide employees with timely and secure access to the substation's database information from any point within the company but will not allow network access within the substations.

Employees on the company network use a database browser for reviewing the reported information. The database provides employees with an array of advanced analysis tools, including, but not limited to, line and circular charts, phasors, harmonics, and sequence components calculations, as shown in Figure 8. The main interface in the database is a real-time monitor showing the latest relay quantities.

Upon initial execution, this system collected over 2,000 records that had previously been held locally in the relays; all of the records were from the functional tests that were done during commissioning of the relays. The records were properly processed and automatically routed to the stand-alone database at the master station.

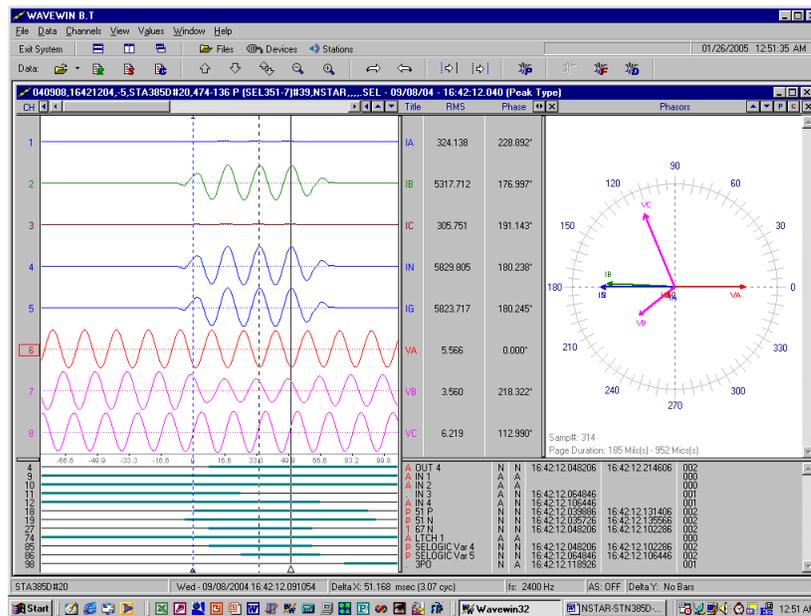


Figure 8 Event Viewer Showing Report for a B-to-G Trip Event

PROTECTION

The basic protection and control schemes that are employed at Substation 385D are based on the theory of having dual protection and control systems. The dual systems are identified as the primary and secondary systems. The relays perform protection, control, and indication gathering functions. Relay control and indication functions are metering, SCADA trip, SCADA close, breaker spring charge, breaker charge status, breaker rack position, SCADA cut-off position, scheme cut-off position, breaker position, reclosing, and trip coil monitoring. Relay protection includes the main scheme, which is dependent on the type of zone, apparatus, or equipment being protected and includes additional schemes like transfer trip and breaker failure. These line protection schemes reside in the relay and are completely independent of the Ethernet network. Basic protection for Substation 385D is as follows:

- 115 kV Line Protection
 - Primary and secondary line current differential
 - Breaker failure direct transfer trip
 - Special Protection System (SPS) transfer trip
- 115 kV to 13.8 kV Transformer Protection
 - Primary and secondary transformer differential
 - Primary and secondary 115 kV and 13.8 kV transformer phase and ground instantaneous and time-overcurrent
 - Bulk underfrequency and breaker failure
- 13.8 kV Bus Protection
 - Primary bus differential and breaker failure
- 13.8 kV Bus Tie Protection
 - Primary and secondary bus differential
 - Breaker failure
- 13.8 kV Feeder Protection
 - Primary and secondary phase and ground instantaneous and time-overcurrent
 - Selective underfrequency and breaker failure
- 13.8 kV Capacitor Bank Feeder Protection
 - Primary and secondary phase and ground instantaneous and time-overcurrent
 - Selective underfrequency and breaker failure
 - Alarm and trip ground overvoltage



Figure 9 Dual Feeder Protection

COMMISSIONING

The complete substation commissioning of Phase 1, along with six scope enhancements, took approximately 45 days. The scope of Phase 1's commissioning was the physical, protection, and operational checks of two lines, two transformers, and four bus sections. Also included in the 45 days were the annunciation and associated remote SCADA and local HMI control and indication functional testing. Of the 45 days, the Ethernet LAN commissioning took three days. The cost of Phase 1's substation, integration, and automation, along with the six scope enhancements, was 20% over the original estimated budget.

The complete substation commissioning of Phase 2 took approximately 15 days. The scope of Phase 2's commissioning was the physical, protection, and operational checks of two lines, two transformers, and four bus sections. Also included in the 15 days were the annunciation and associated remote SCADA and local HMI control and indication functional testing. The complete substation commissioning of Phase 2 took approximately 15 days. Of the 15 days, the Ethernet LAN commissioning took one day. Included in Phase 2 were the installation and commissioning of the substation protection and event monitor/viewer that took one day to install, and its software took ten days to configure. The cost of Phase 2's substation, integration, and automation was 30% of the cost of the original budget.

LESSONS LEARNED

The application of a substation Ethernet network allowed NSTAR's electrical communication, protection, and control departments to take advantage of available technology that has been popular in office networking. This allowed the utility's electrical substation department to work with the company's network and computer information services and leverage their knowledge and solutions to a substation application. Here is a list of lessons learned from NSTAR's installation at Substation 385D:

- The Ethernet LAN installation and commissioning went very well. Because it was NSTAR's first substation installation, the approach for Phase 1 was to install and test the individual pieces of equipment, or fiber, or cable, and then test each Ethernet connection path for a time period of 15 minutes. Also during the Phase 1 testing, each vendor had a representative on site to assist and support the effort. For Phase 2 the approach was modified to install and test each new Ethernet connection path for a time period of five minutes. No issues were encountered. The Ethernet networks were also monitored over several days to verify their overall accuracy and functionality.
- Choose alarms and error messages carefully and try to get input from all areas of the company during the design phase of the project so that the software configuration goes smoothly. The utility or end users need to spend time choosing the type of alarms, errors to message on, the description, and the threshold level. Up front effort on this, combined with previous experience, will be very helpful during commissioning and startup. NSTAR initially chose to configure conventional alarms and error messages. An effort was made to get input during the design phase; however, all of the necessary information was not received. This resulted in changes during commissioning and before acceptance of the substation.

- Keep the project scope clearly defined so that the project will not incur additional costs or delay the in-service date. Identify the needed redundancy or the backup required for network, control, operation, and annunciation. NSTAR had six Phase 1 project scope enhancements, which allowed for an improved and more useful product but delayed the in-service date by fifteen days.
- Define the topology of the network and have a team member who understands data traffic and the time it takes to move data so that this constraint can be clearly expressed to all. Upfront work by the project team on this allowed NSTAR to avoid this possible issue.
- Several components are involved and required to build and successfully communicate to all the different substation devices. On-site spare parts should be considered along with specific documentation. NSTAR does have spare parts and specific system and equipment documentation. User and trouble-shooting training was also provided.
- With the Ethernet LAN, NSTAR was able to do the following:
 - Add eight points to each circuit while reducing wiring requirement. An average of 20 less wires and associated terminations were required per circuit for control and analog or digital indication/alarm.
 - Provide more detailed and specific analog or digital indication/alarm for each circuit.
 - Generate transient fault information.
- This substation Ethernet LAN will aid NSTAR in analyzing power system disturbances, evaluating power system performance, and serving our customers better.

CONCLUSIONS

This was NSTAR's fourth full substation integration and automation project but the first with an Ethernet LAN. As with the other projects, NSTAR gained meaningful and useful experience. This non-conventional type of substation design is continuing at NSTAR and the use of Ethernet will expand. Soon NSTAR will be using Ethernet for substation and service center door entry card access, automatic remote logging, and video surveillance.

Applying an Ethernet LAN in a substation provides a simplified communications backbone, which is cost competitive and easily expanded. Ethernet LANs in substations will become even more popular as IED devices are optioned with direct Ethernet ports, and utility personnel become more comfortable and experienced with Ethernet LANs and the devices they connect to. There are new advancements in the world of Ethernet in substations that are associated with new standardized protocols and new hardware. With the advent of new standardized Ethernet protocols like DNP3 LAN/WAN and IEC 61850, utilities will have the option to choose from many different vendors that will be able to communicate with a common protocol. Some utilities are using Wireless Fidelity (WiFi) and substation-hardened Digital Spread Spectrum Ethernet radios in their substations to expand beyond their substation yards. Because wireless applications increase the security risk, there are many new devices that perform encryption to inhibit hackers. These new innovations will propel Ethernet substation technology into the future.

REFERENCES

- [1] “About NSTAR,” on the NSTAR website at <http://www.nstaronline.com/about/>.
- [2] “How Ethernet Works,” on the How Stuff Works website at <http://computer.howstuffworks.com/ethernet3.htm>.

BIOGRAPHIES

Peter Talacci received his BS and MS in Electrical Engineering from Northeastern University in 1992 and 1997. In 1992 he started work for WJ Griffin Electric and since then he has gained experience with Massachusetts Electric, Doble Engineering, and NSTAR. He presently is an Engineer at NSTAR within the Engineering Department, Protection and Control Group with responsibilities that include transmission, substation, and distribution protection and control.

Swapan Dey is Director of Engineering at NSTAR Electric & Gas Corp., which he joined in 2002. Prior to joining NSTAR, he served as Manager of the Substation and Transmission Engineering Div. of KeySpan (formerly Long Island Lighting Company). During the last 29 years of his professional career, he has been involved with design, engineering, and construction of fossil and nuclear power plants, distribution, transmission, and substations. From January 1993 to December 1994, he served as an electric utility advisor for the EPRI Underground Transmission Task Force. He is a working group member of the Insulated Conductor Committee of IEEE and Electric Power Apparatus Committee of AEIC.

Ronald Moore received his BS in Electrical Engineering Technology from Louisiana Tech University in 2000. In February of 2000 he started working for Entergy in their Substation Operations and Maintenance Division. During his tenure he gained experience in power system protection maintenance, substation design, and installation. Chip joined SEL in August of 2001 as an Associate Automation Engineer in the Systems and Services Division (SSD); in 2002 he was promoted to Automation Engineer. In SSD, Chip worked with engineering drop-in control houses, HMIs, and SCADA systems. In 2003 he became an Integration Application Engineer; his responsibilities now include technical support, application assistance, and training for SEL customers.