CASE STUDY OF A LARGE TRANSMISSION AND DISTRIBUTION SUBSTATION AUTOMATION PROJECT

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ABSTRACT

In this paper, the author describes a case study of a large substation integration design project. The project involves complete integration and automation of distribution and transmission within the substation. The critical design factors that the customer required are discussed, followed by system designs presented to the customer. The author steps through the project with the aid of lessons learned along the way to explain how and why a particular system architecture was chosen. System reliability, redundancy of protection and communications and no single point of failure were essential. The author next presents analysis tools and uses them to quantify attributes of the PECO Energy Company system design. The reader is told how to use these tools to quantify aspects of any system. Review of the progression of this successfully installed system will present the reader with a comprehensive discussion of available technologies, quantification of system attributes, and the implementation of a multivendor system.

The project consisted of a protection and control design for a retrofitted substation, recently renovated for PECO Energy Co., which exploits many of the advanced capabilities of microprocessor relays. For the protection and distribution automation schemes, a completely integrated microprocessor-based design was envisioned, primarily to provide supervisory control and data acquisition (SCADA), distribution automation (DA), and automation of the transmission system through a substation integration system. In addition, this scheme would minimize maintenance cost through the use of self-checking and relay setting verification. The new economical, streamlined design allows for primary and backup redundancy for all single contingency fault conditions, while intuitively replicating existing electromechanical protection philosophies. The microprocessor relays' new digital communications capabilities, incorporated into a substation integration (SI) system, allow exceptionally fast and reliable SCADA control, status and metering for all interrupting devices, lockout relays, and motor operated disconnects (MOD)s.

INTRODUCTION

PECO Energy Co. is an electric utility that serves the metropolitan Philadelphia area. Like many other utilities today, PECO needed a better way, both locally and remotely, to monitor, control, diagnose, and maintain equipment in the substation to reduce operating costs and provide improved customer service. These demands to increase productivity and reduce costs translated into the need to collect and act on decision-making information.

Replace Transmission Substation Data Acquisition and Control Network

A SCADA system had been installed in the early 1980s as a transmission host system. The instrumentation and control (I&C) in the substation was performed by a network of remote terminal units (RTUs). Age and deterioration had combined to adversely affect this substation network, but the transmission host was deemed adequate to remain in service for several more years.

Therefore, PECO had to find a way to upgrade the existing transmission I&C system while maintaining the existing transmission host.

Install Distribution Substation Data Acquisition and Control Network

At the same time, PECO sought to enhance the flexibility of its control system and set out to automate its distribution circuits rated at 34, 13, 4, and 2.4 kV.

During the development phase of this distribution automation system, PECO performed a study to find the most cost effective substation I&C system. They found that significant time and cost were associated with all the direct wiring necessary for the traditional RTU approach. In a typical 13-kV feeder compartment, for example, an average of 26 individual control and metering wires would have to be run from the feeder compartment to the RTU. A significant quantity of analog transducers would have to be installed to sense amp, watt, and VAR values while motor operators would be added to the SB-1 control switches. In addition, the PECO control philosophy called for automatic and manual control, requiring costly motor operators to be added to the existing control points for breaker operation, fast trip, and auto reclose.

PECO had to choose and install an I&C system to interface with the new distribution host.

DEFINE THE PROJECT

The goal was to find the most beneficial and cost effective substation I&C system to work for both the legacy transmission SCADA and the new DA system. In light of the characteristics of the existing hosts, PECO challenged vendors to provide a system with the following attributes.

- No single point of failure should result in loss of data acquisition or control of any piece of substation equipment.
- The speed and throughput of the system should perform such that remote monitoring and control would be maintained at the legacy transmission host and the new distribution host.
- The system should process and confirm a remote breaker control operation within two seconds.
- All metering and status information would have to be sampled, processed, and reported within ten seconds.

IDENTIFY THE CHALLENGE

The challenge was ***choosing*** the most beneficial and cost effective substation I&C system to work for both the legacy transmission SCADA and the new distribution automation system. PECO had experience with RTUs in its transmission SCADA system and programmable logic controllers (PLCs) in some pilot distribution automation projects. Besides being expensive, RTUs and PLCs are, by design, a single point of failure for all the wiring termination and data processing. PECO wanted to start over and evaluate every possible technology but was unfamiliar with many new system integration designs.

In order to determine what type of I&C system to choose in all aspects of protection, integration, automation, and control, the user needs to quantify the benefits that will be derived. As with most utilities, once the functional requirements of a system were met, PECO was concerned with reliability, speed, and cost. Speed can be measured, equipment cost calculated, and engineering effort estimated, but designers are constantly challenged to quantify reliability.

QUANTIFY RELIABILITY AS THE INVERSE OF UNAVAILABILITY

Major motivators of quantifying reliability issues include deriving the best decision-making on how to improve the system, how to manage dependability versus security tradeoffs, as well as how to get the best results for the least money when selecting a design. A quantitative understanding is essential in a competitive utility industry.

Failure Rate

Since reliability is the reciprocal of failure, and failure is a random event, probabilistic measures are most appropriate, and we apply the laws of probability theory.

For example, suppose the reliability of a device is expressed with a mean time between failure (MTBF) of 100 years. The failure rate is 1/100 failures per year. And, if a system has 300 of these devices, then we would expect 300 x (1/100) = 3 or fewer device failures per year.

Unavailability

The failure rate of a component, device, or system is only part of the story. Reliability can be further quantified by comparing unavailability. In calculating unavailability, we are determining the percentage of a duty cycle that a component, device, or system is unable to perform its function. Some devices perform and communicate self-test diagnostics. Detection of failure of devices that do not communicate a self test diagnostic is performed during periodic test and maintenance or when the device misoperates. Though we must rely on statistics to predict unavailability, the root causes are intuitive.

- Unavailability will increase in proportion to the rate of failure.
- Unavailability will increase in proportion to the amount of time it takes to repair or replace a failure.
- Unavailability will increase in proportion to the amount of time that a failure remains undetected.

The unavailability, q, is calculated using mean time to repair (MTTR) and MTBF. The MTTR is the sum of the mean time to detect failure plus the mean time to repair or replace. Therefore, we address the root causes of unavailability with one simple equation.

$$q = \frac{\text{MTTR}}{\text{MTBF}}$$

For example, assuming that the device mentioned above performs and communicates self-test diagnostics constantly, detection of failure is immediate. The failure rate is 1/100 failures per year and MTBF is 100 years. The time to repair or replace the device is the industry average of two days.

q =[(mean time to detect = 0) + (mean time to repair or replace = 2 days)] / (MTBF = 100 years)

q = (2 days)/(100 years) = 0.02 days/year = (0.02 days/year)(1 year/365 days) = 55×10^{-6}

Therefore, the predicted unavailability of this device is 0.02 days per year. Normalizing the ratio by removing the units leaves us with a device unavailability value of 55×10^{-6}. It is essential that the designer use specific product unavailabilities to create a realistic representation of the system or proposed design. Unavailabilities of common I&C system devices were calculated using MTBF values and averages from publicly available sources such as vendor publications and studies performed in the workplace [1]. Rather than inappropriately positively influence the unavailability of microprocessor-based relays and communications processors with high MTBF values from an individual vendor, these values were reduced to reflect an industry average.

Table 1: Approximate Unavailabilities of Devices

Device	Unavailability
Personal computer	2135×10^{-6}
Industrial personal computer	385×10^{-6}
Medium remote terminal unit	480×10^{-6}
Transducer	80×10^{-6}
Programmable logic controller	320×10^{-6}
Substation communications processor	30×10^{-6}
Protective relay hardware	55×10^{-6}
Protective relay multidrop network failure	11×10^{-6}
Network repeater	385×10^{-6}
Network repeater multidrop network failure	70×10^{-6}
Circuit breaker	300×10^{-6}
Leased telephone line	1000×10^{-6}
DC power system	50×10^{-6}
Modem	30×10^{-6}
Simple fiber-optic transceiver	10×10^{-6}
Current transformer (per phase)	10×10^{-6}
Voltage transformer (per phase)	10×10^{-6}

We assume that mean time to detect failure is negligible since microprocessor-based relays, RTUs, and PLCs alert the system immediately if there is a failure in the system. Therefore, the MTTR is just the mean time to repair, which is assumed to be two days or .005 years.

Example: for a PC, unavailability is (MTTR = .005)/(MTBF = 2.56) = .002135.

Further, if the failure of interest can be caused by a PC or a microprocessor-based relay, it can be seen that a relay is (2135)/(55) = 39 times more reliable than a PC.

Reliability is inversely proportional to unavailability. The higher the unavailability value, the less available a device or system will be to perform its function and therefore cause failure.

IDENTIFY A SELECTION PROCESS

Fault Tree Method

"Fault tree analysis," a concept first proposed by H. A. Watson of Bell Telephone Laboratories to analyze the Minuteman Launch Control System, can be used to combine device unavailabilities. This method, used and refined over the ensuing years [2], is attractive because it does not require extensive theoretical work and is a practical tool that any engineer can learn to use. While computer programs are available to assist in developing and analyzing complex fault trees, small fault trees, which are easily analyzed manually, are also useful.

If a system consists of several devices, use a fault tree to combine device unavailabilities to calculate the system reliability. Refer again to our device which has an unavailability of 0.02 days per year. The device might consist of two components, each with an unavailability of 0.01 days per year. Both components must operate properly for the device to be sound. The individual unavailabilities of the two components add up to the total unavailability of 0.02 days per year. Add the component unavailabilities to obtain the device unavailability if either component in a device can cause the device to fail.

Similarly, for a system with two devices which must operate properly for the system to be sound, add the device unavailabilities to obtain the system unavailability since either device could cause the system to fail.

On the other hand, our device with unavailability of 0.02 days per year might consist of two redundant components, each with an unavailability of 0.1414 days per year. Though the individual component unavailability is greater, in this example the components are redundant and either component can give satisfactory performance to the device. Therefore, the product of the individual component unavailabilities is the device unavailability. Multiply the component unavailabilities to obtain the device unavailability, if both components must fail to cause a device failure.

Similarly, for a system with two devices which operate redundantly, multiply the device unavailabilities to obtain the system unavailability since both devices must fail in order for the system to fail.

Fault Tree Construction

A fault tree is tailored to a particular failure of interest and models the part of the system which influences the probability of the failure. The failure of interest is called the top event. A given system may have more than one top event which merits investigation. As an example, consider the traditional RTU centric power and I&C system in Figure 1 which consists of a circuit breaker, a leased line, a modem, three CTs and three VTs, a battery, an RTU, and eight associated transducers. What is the chance that the I&C system will fail to perform its function, i.e., acquire line data such as currents, voltages, kV, and kW, or fail to control the breaker. To answer this, consider the top event "No Line Data or Control." The fault tree in Figure 1 helps analyze this chance.

Use the fault tree to break the top event into lower-level events. The OR gates in Figure 1 express the idea that any of several failures can cause the top event. The circuit breaker could fail OR the leased line could fail, OR the modem could fail, etc. For these simple fault trees, the lower-level events are basic events which are depicted with a circle and referred to as "roots." The roots are failures of devices such as the leased line, modem, instrument transformers, or the dc subsystem.

It is important to identify all causes of the event of a system you are evaluating. This discipline helps find opportunities to improve overall reliability and helps calibrate the contribution of alternatives relative to other common failure causes. Use OR gates to combine multiple events, when any one failure will result in the failure of the event above the gate. Use AND gates to combine multiple events when all devices directly below the gate must fail in order to have a failure above the gate.

Fault Tree Analysis

After entering event data, analysis of the fault tree shown in Figure 1 is straightforward using a single simplifying assumption known as the rare event approximation. It ignores the possibility that two or more rare events can occur simultaneously. For two events, each of which occurs with probability less than 0.1, the rare event approximation produces less than 5% error. When the events in question are failures, the rare event approximation is always conservative; the approximated probability of failure is always greater than the actual probability of failure [3].

Employing the rare event approximation, calculate the unavailability associated with each event expressed with an OR gate as the sum of the unavailability for each input to the OR gate. For example, the unavailability associated with the lower left OR Gate in Figure 1 is the sum of the unavailability of the five inputs to that OR gate. The fault tree of Figure 1 contains only basic events and OR gates. A failure could be caused by the circuit breaker, OR leased line, OR the modem, OR any of six instrument transformers, OR the battery, OR the RTU, OR any of eight associated transducers. Therefore the unavailability associated with the Top Event is simply the sum of all of the basic events or 2160×10^{-6}.

The lower left OR gate identifies a fragment of the fault tree which would be common to all design choices. The lower right OR gate identifies the I&C fragment of the fault tree that is unique to each individual design. The examples use a leased line because PECO planned to use leased lines, as do most installed SCADA systems in the United States.

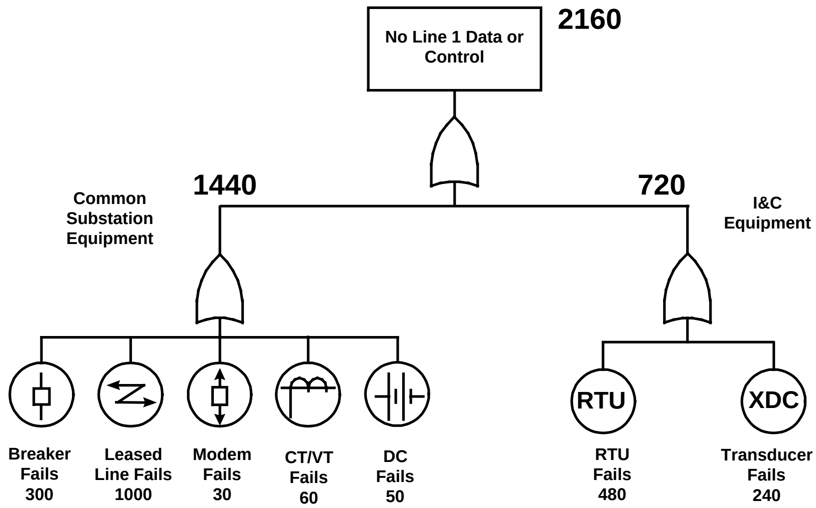

Figure 1: Fault Tree for RTU-Based I&C System

Fault Tree for a Relay and Communications Processor Star I&C System

The fault tree in Figure 2 includes a relay for the line and a communications processor to communicate with the master.

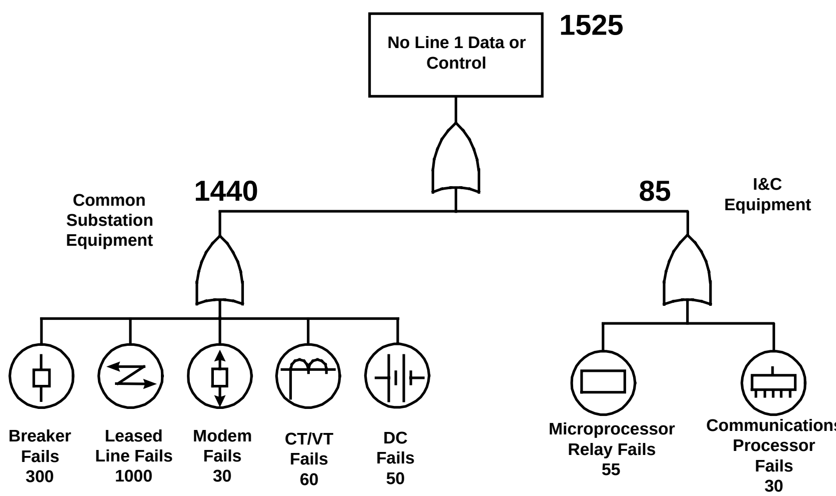

Figure 2: Fault Tree for Relay and Communications Processor Star I&C System

In this design, the communications processor acts as a substation grade client/server with a high MTBF, high availability, and great support for enhancement or expansion. The microprocessor-based relays connected in a star topology [4] collect data and refine it into information. It is also interesting to recognize that, in this design, as information is collected, it can be acted on at the appropriate level and passed no further than necessary. This reduces bandwidth requirements as you pass along only the information that is truly needed by a host.

Observe that for these examples the relay and communications processor star network I&C subsystem is 8.5 times more reliable than the RTU-based subsystem.

EVALUATE THE SPECIFIC APPLICATION

In 1997 PECO began a project to renovate the deteriorating 69 kV-13 kV Westmoreland substation, which presently supplies about one-third of Philadelphia's electrical load. The project scope consisted of a complete turnkey transmission and distribution automation solution from system design through installation and commissioning. The design involved a three-ended 230 kV transmission line to be tapped to supply three 90 MW transformers. Each transformer was to supply three 13 kV distribution buses which include feeders and capacitor banks, as well as tie lines to other stations. The existing four 69 kV subtransmission lines were to be connected in a ring bus arrangement.

The fault tree method tool can be used in mission-critical design applications, regardless of size. The previous simple examples have demonstrated the ease of construction and analysis for a nonredundant substation situation. Since the Westmoreland original requirements suggested 54 breakers and switches, the following example uses this method to compare redundant I&C designs with the top event "No line data or control of any of the 54 breakers and/or switches." The example analyzes only the I&C fragment of the designs, the lower right fragment in the above examples, since the rest of the tree is common to each possible selection.

RTU Centric

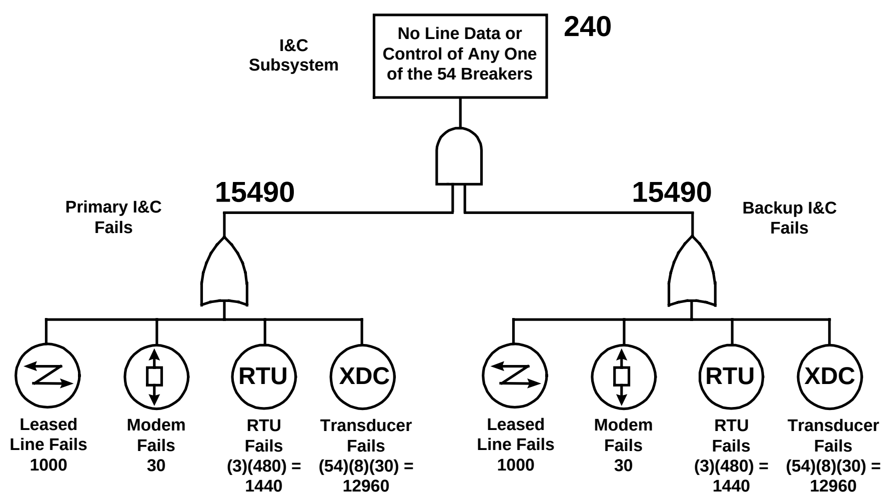

Figure 3: Fault Tree for RTU Centric Westmoreland I&C System

In this RTU centric example, assume the use of a medium-sized RTU. Therefore, use the I/O capabilities and unavailability information for industry average medium-sized RTUs.

Each of the primary and backup I&C subsystems consists of 3 RTUs and 432 transducers. Since both primary AND backup must fail, the unavailability of each subsystem is ANDed together (or multiplied).

PLC Centric

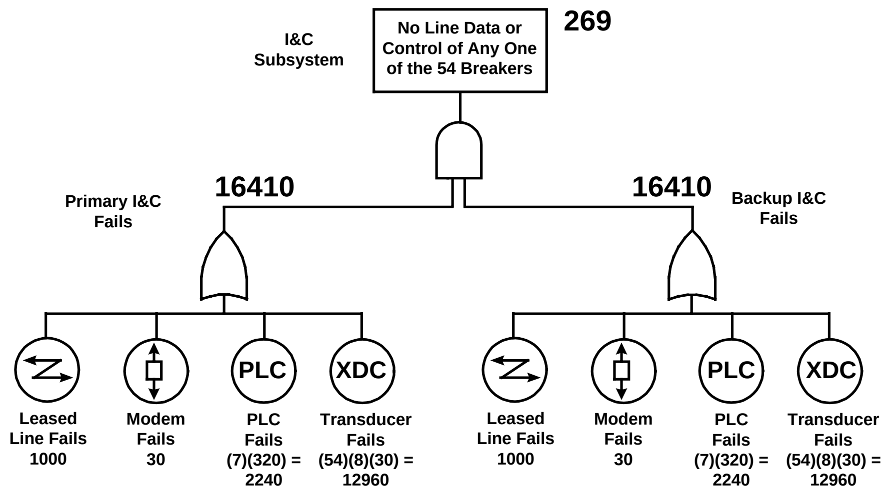

Figure 4: Fault Tree for PLC Centric Westmoreland I&C System

In this PLC example, assume the use of a medium-sized PLC. Therefore, use the I/O capabilities and unavailability information for industry average medium-sized PLCs.

Each of the primary and backup I&C subsystems consists of 7 PLCs, racks, and power supplies, as well as 432 transducers. Since both primary AND backup must fail, the unavailability of each subsystem is ANDed together (or multiplied).

Microprocessor-Based Relays I&C System

PECO recognized that the innovative developments within intelligent electronic devices (IEDs) in the substation created new ways of collecting and reacting to data and then using this data to create information. Simple communication methods between microprocessor-based relays, for example, enable data acquisition and control as well as superior protection systems. The same information created for protection can feed other system needs such as automation, monitoring, and control. By placing microprocessor-based protective relays near the equipment, wiring is reduced and data processing is distributed to be near the source. Control decisions can be made local to the equipment or come from a supervisory system. All data can be communicated via a single robust communication channel rather than the traditional method of a dedicated pair of copper conductors to sense every contact.

Multidrop Relay Network Centric

Direct connect and multidrop are two types of data link connections to protective relays. In a multidrop, Figure 5, several devices can be physically connected in a bus network, and control of the transmit and receive conductors must be negotiated. A multidrop connection requires that only one relay communicate at a time. Software and hardware are used to determine which device has permission to transmit so that data does not collide on the conductor. Since several devices are connected, addressing is necessary within the protocol to identify the source and destination of the data being communicated. This addressing adds overhead in the form of processing time and amount of information that needs to be transmitted thus reducing the amount of data that can be transferred at a given speed. Devices compensate for this by increasing the speed at which they communicate and increasing the amount of communications processing they perform.

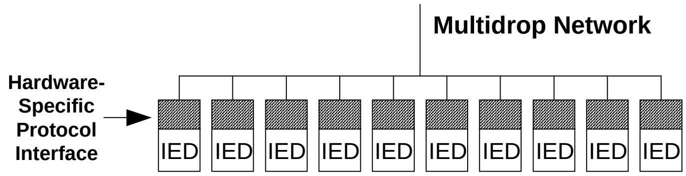

Figure 5: Multidrop Network IED Interface

It is important to keep in mind that if the mediation of control of data transmission should fail, none of the multidropped devices can communicate. This can be caused by relay communications hardware failing to release control, relay communications software failing to process mediation schemes correctly, or corruption of the network [5]. A probable failure rate is that roughly one fifth of the failures of these devices do, in fact, affect the network.

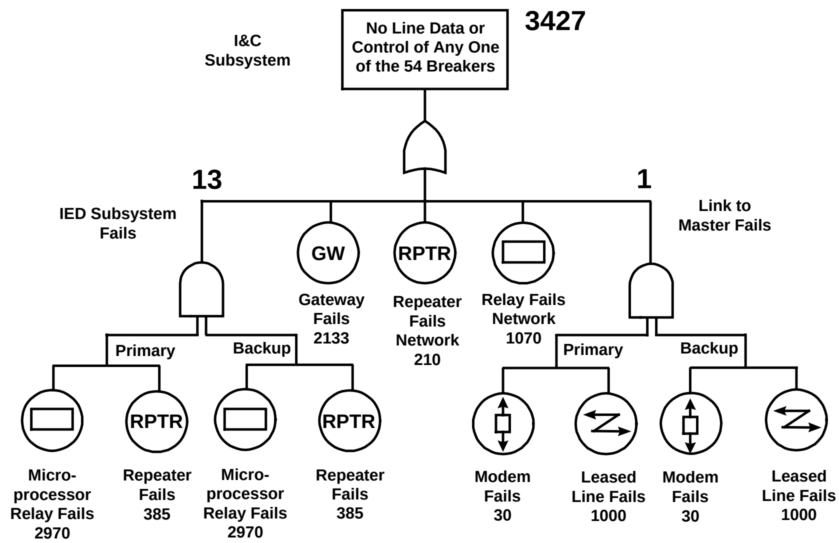

Figure 6: Multidrop Relay Network Centric Westmoreland I&C System

Due to the nature of converting from one protocol language to another, this design includes a protocol gateway. The repeaters are necessary to connect the large quantity of relays onto a bus. This, in turn, changes the way you represent the redundancy of the system. The lower left AND gate represents the redundant IED I&C subsystems. The lower right AND gate represents the redundant host connections. Each relay, each repeater, and the protocol gateway has a failure mode that would cause the top event. The upper OR gate takes these failure modes into account with unavailabilities from the above table. Since the unavailability of the microprocessor-based relays in each of the primary and backup I&C subsystems is 2970 x 10^{-6}, the total for all relays in the system is 5940 x 10^{-6}, and the unavailability of the network, or chance that the bus will be disrupted, due to these components is roughly one fifth of the total or 1070 x 10^{-6}. Three repeaters are needed with an unavailability total of 1155 x 10^{-6}, and the unavailability of the network due to these components is roughly one fifth of this or 210 x 10^{-6}. The gateway is a single point of failure for the entire network with an unavailability of 2133 x 10^{-6}.

Communications Processor Star Relay Network Centric

In a direct connection, there are only two devices connected via a transmit and receive pair of conductors. Use each conductor to transmit from one device and receive by the other device. Since there are only two devices, each of them can constantly control the conductor on which they are transmitting and both can know implicitly to which other device they are connected. Direct connections to many relays allow each of them to communicate simultaneously. Many direct connections originating from one device is called a star network. Figure 7 illustrates the star topology. Many star networks can be connected in a parallel or vertical hierarchy. Any protocol can be used in this configuration. Virtually all microprocessor-based relays have a simple EIA-232 serial port connection to support direct connections. Any of the other communication methods can be used in a direct connection as well.

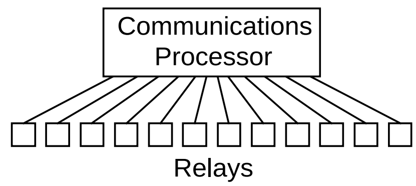

Figure 7: Star Topology

Direct connection designs allow the network to support a wide range of relay capabilities. Simple, slow communicating devices can coexist with more complex fast communicating relays.

Open architecture is a term that refers to networks that are interoperable among vendors. The star network is the only design that is truly open and accommodates multiple protocols, multiple baud rates, and multiple network interfaces.

It is important to keep in mind that if the mediation of control of data transmission of a device in a star configuration should fail, none of the other directly connected relays are affected. Using the relay's redundant counterpart, the system continues to function in the absence of the failed relay.

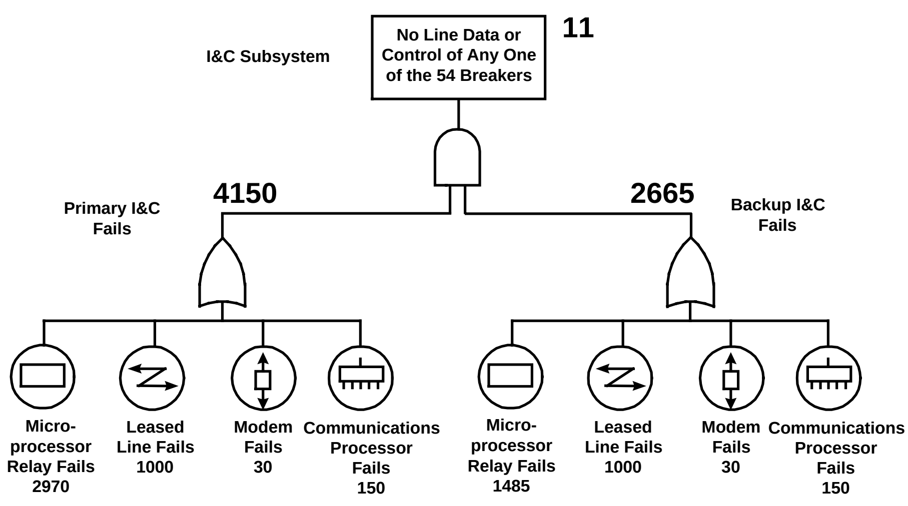

Figure 8: Communications Processor Star Relay Network Centric Westmoreland I&C System

Backup protection for distribution is done with dual application relays; thus, the system is made even simpler with fewer devices. The unavailability of the 54 microprocessor-based relays in the primary I&C subsystems is 2970×10^{-6}. The unavailability of the 27 microprocessor-based relays in the backup I&C subsystems is 1485×10^{-6}. The unavailability of five communications processors totals 150×10^{-6}.

Table 2 summarizes the I&C subsystem unavailability for the four architectures, and for interest, compares both redundant and non-redundant designs.

Table 2: I&C Subsystem Unavailability for 54 Breaker/Switch Design

	Nonredundant Design	**Redundant Design**
RTU Centric	15490×10^{-6}	240×10^{-6}
PLC Centric	16410×10^{-6}	269×10^{-6}
Multidropped Relay Network Centric	7158×10^{-6}	3427×10^{-6}
Communications Processor Star Relay Network Centric	4150×10^{-6}	11×10^{-6}

From Table 2 it can be seen that in addition to the obvious benefit of providing protection, the redundant communications processor centric system design is 22 times more reliable than a redundant RTU design and 25 times more reliable than a redundant PLC design. It can further be seen that the redundant communications processor star relay network centric system design is 312 times more reliable than the redundant multidrop microprocessor relay design.

Why is the communications processor star relay network centric design so much more reliable? This protection subsystem is elegant by its simplicity. The streamlined architecture performs all the necessary functions with a minimal number of components. Thus, the system design is more reliable. The modular nature of the architecture allows for future expansion as well.

The reliability of these substation grade components as well as the use of fiber optics further adds to the reliability of this system design. These components all meet IEEE SWC and radiated EMI tests as well as IEC impulse voltage, vibration, shock, and bump tests -- to name a few. The protection vendor that was eventually chosen employed an innovative arc interruption technology in the relays which eliminates contact wear and auxiliary relays as well as speeds tripping time. Relays are often mounted on doors, in swing panels or directly in equipment that subject them to vibration. Also, during shipment they might be dropped or otherwise abused. Recognizing this long ago, the protection vendor incorporated vibration testing as part of its design. The wide operational temperature range of the protective relays also adds to their reliability. In addition to the ability to use the relays in extremely harsh environmental conditions such as the pole-top, they will suffer degradation, due to temperature, at a much slower rate than products designed to meet lower standards.

An interesting benefit to this analysis was that there existed two direct correlations between reliability and cost. The obvious one is that redundant systems of a particular design are more reliable and more costly than nonredundant systems of the same design. However, when comparing different designs, the most reliable design has fewer devices and components. Fewer components translate into fewer costs. Therefore, for this and many other examples, as you drive reliability up, you drive cost down.

Table 3: I&C Subsystem Hardware Costs for 54 Breaker/Switch Design

	Nonredundant Design	Redundant Design
RTU Centric	$189,700	$379,400
PLC Centric	$210,700	$421,400
Multidropped Relay Network Centric	$60,400	$116,100
Communications Processor Star Relay Network Centric	$12,500	$25,000

Table 3 summarizes the I&C subsystem capital equipment costs for the hardware necessary to perform data acquisition and control for the four different architectures. Both redundant and nonredundant designs are compared. As with the MTBF values, the cost numbers are derived from industry averages. We encourage individuals to use their known costs to create specific comparisons.

Since protection is necessary for each design, the examples assume protection costs to be the same for any of the designs and leave this cost out of these comparisons. The RTU and PLC example costs for integration include all of the RTU, PLC, and transducer hardware. Protection components are a separate investment. The multidrop and communications processor centric relay solutions involve costs for network interfaces, communications equipment, and communications processors. Transducers are not necessary. The distributed nature of the microprocessor-based relay design also reduces wiring, documentation, etc., and all of the associated costs.

RTU Centric

The non-redundant network requires three RTUs ($10,500), multiple I/O panels ($28,000), 324 volt and amp transducers ($97,200), 108 kvar and kW transducers ($54,000) = $189,700. Cost of a redundant system is twice this design cost.

PLC Centric

The nonredundant network requires seven PLCs ($22,750), seven racks ($5,250), seven power supplies ($3,500), multiple I/O panels ($28,000), 324 volt and amp transducers ($97,200), 108 kvar and kW transducers ($54,000) = $210,700. Cost of a redundant system is twice this design cost.

Multidrop Relay Network Centric

The nonredundant network requires 54 relay network protocol interfaces ($54,000), two repeaters ($3,400), one gateway ($3,000) = $60,400. Redundant design involves 54 additional relay network protocol interfaces ($54,000) and one additional repeater ($1,700) = $116,100.

Communications Processor Star Relay Network Centric

The communications processor centric design for this original Westmoreland comparison requires five communications processors ($12,500) for a total = $12,500. The redundant design involves five additional communications processors ($12,500) for a total = $25,000.

Choose the Communications Processor Star Relay Network

One last consideration was that though the microprocessor-based relay and communications processor vendor was well established, in fact PECO engineers had already successfully installed more than 100 of the vendor's relays, they were cautious about trying something new. They were reassured to learn that the vendor had several hundred customers around the globe for each of the devices that PECO was considering in the design. This design was simply a new innovative twist on well-established protective relay technology, simply reusing already available data and control.

After fully evaluating the solutions available, PECO engineers chose the communications processor star relay network centric design. In so doing they were able to upgrade their transmission I&C system, install a distribution I&C system, and completely replace all of their protection systems … all for less cost than a traditional SCADA I&C system. In essence, they felt that they had successfully chosen the most reliable SCADA solution that incidentally offered a premier protection replacement at no additional cost. They enhanced their system requirements to address protection as follows.

- No single point of failure would result in loss of data acquisition, control *or protection* of any piece of substation equipment.

A completely integrated microprocessor-based protective relay design was envisioned which would further minimize maintenance cost through the use of self-checking and relay setting verification. Communications processors would collect and organize the data from the protective relays and some micro PLCs local to the transformers and breakers. Significant benefits of the system would include remote access to the substations from PECO's central office complex, allowing remote configuration and control of relays, and complete SCADA visibility through a substation integration system. In addition to the local displays and control buttons on the relays, an off-the-shelf human machine interface (HMI) software package was to be used to create a customized interface for PECO for local substation control. The interface would need to view settings, change settings, and download relay data. The protection and control network of relays and communications processors was to be designed to provide the SCADA interface so the local computer serves only as an interface to view all of the information and provide access to all of the controls in the substation. Should the PC fail, remote control would be unaffected.

Ultimately, PECO elected to use this topology to implement a major protection and automation upgrade at 87 existing substations.

Although the communications processor star relay network centric design accommodates using in-service IEDs and IEDs from multiple vendors, for the rebuild PECO elected to replace all of the protection components with new products, and they elected to use a single vendor for both primary and backup protection. PECO felt that the product reliability of the protection vendor they chose was so high that they could not increase reliability by choosing separate vendors for primary and backup. However, different products from the vendor were used as primary and backup.

The chosen design offered full redundancy of primary and backup protection as well as communications. The failure of any one of the protection or communication components will not prevent monitoring or control of any one of the 54 breakers and/or switches in the substation.

"This design reflects a substation integration system that has gone well beyond our previous separate systems for protection, data acquisition, and control. The new design uses [*Protection Vendor*] equipment on an unprecedented scale and is the largest single integrated system for protection, control, data acquisition, and monitoring ever undertaken by PECO," says Jack Leonard, PECO Supervising Engineer, System Monitoring, and Control.

Other Communications Processor Star Relay Network Advantages

- IED integration enhances distribution automation, SCADA, and protection by migrating some of the communications functions to an intermediate substation device. Moving protocols into the IEDs adds to their cost and accelerates their obsolescence as technology advances. The resources available within the IEDs are instead better focused on optimizing protection solutions.
- System automation, control, and supervisory data available in protective relays enhance protection and control of individual power system components as well as the entire power system by permitting rapid, well-informed decisions. Adaptive protection and control methods are used as the power system configuration changes dynamically.
- Device diagnostic data enhance distribution automation, SCADA, and protection by maximizing the availability of the protection system.
- Historical data available in protective relays enhance distribution automation, SCADA, and protection through dynamic system trend analysis as well as being the source for remote operator and process forensic analysis. By continually monitoring conditions of devices over time, operators and processes develop a clearer picture of device performance.
- The communications processor can act as a client/server, data concentrator, substation archive, programmable logic platform, gateway, router, dial-out device, communication switch, and time synchronization broadcaster.
- The communications processor can communicate without developing vendor-specific protocol software and can eavesdrop on conversations between two devices in the I&C system.
- Star networks can acquire and transfer substation integration data using much slower direct connections. These direct connections are also more reliable, more robust, and less expensive.
- The communications processor simplifies implementation through auto-configuration. This is similar, though not as comprehensive, as current efforts by the utility communication architecture (UCA) movement to define this function.
- Direct connection designs allow the network to support a wide range of IED capabilities. Simple, slow communicating devices can coexist with more complex fast communicating relays.
- Communications processors enhance the value of the distribution automation, SCADA, and protection I&C system data by making it available to multiple master systems and other users.

- As protocol requirements change in the substation, an individual communications processor can be upgraded instead of each of the IEDs. Protection, monitoring, and control are left undisturbed and in service as a protocol change is made. It is also more economical to make this change in a single device.
- The age of IEDs that are in substations today varies widely. Many of these IEDs are still useful but lack the most recent protocols. Rarely is a substation integration upgrade project undertaken where all existing IEDs are discarded. A communications processor that can communicate with each IED via a unique baud rate and protocol can extend the usefulness of IEDs. Using a communications processor for substation integration also easily accommodates future IEDs.
- Networks are made up of direct and multidrop connections. Point-to-point star networks are much more reliable than multidrop networks. It is important to keep in mind that if the mediation of control of data transmission should fail, none of the multidropped devices can communicate.
- Troubleshooting communications problems is much faster and more efficient through simple LED indication on direct links from a communications processor than attempting to decipher multidrop networks.
- Protocol standardization does **not** mean that every IED must use the same protocol; it means that each protocol must be explicitly defined to support interoperability.

IMPLEMENT A SYSTEM

PECO's new substation uses a completely integrated protection and control design, comprised of over 140 microprocessor-based relays and communications processors – making the substation perhaps the largest completely microprocessor-controlled substation in existence. The design exploits many of the advanced programming and communication capabilities of microprocessor-based relays. All of the relays are integrated into an SI system to provide SCADA visibility and to provide information and control capabilities to a local HMI. The system increases the efficiency of substation maintenance through the use of automated reporting of all pertinent relay-generated fault data and breaker trouble conditions. The economical design allows primary and backup redundant fault clearing for all single contingency fault conditions while intuitively replicating, and to some degree enhancing, existing electromechanical protection philosophies. The relay digital communications capabilities also allow fast and reliable supervisory control and status reporting for all interrupting devices, auxiliary relays, and motor-operated disconnects [6].

The configuration used in this station will be used as a template for each substation converted in the future. To reliably extract and deliver the information from each of the relays to the SCADA systems, a two-tier microprocessor-based communications processor configuration, Figure 9, was adopted [7]. Relay data are received, consolidated, and delivered through communications processor serial ports by means of other serial ports to other devices. PECO's application required two tiers of communications processors to meet the data requirements of SCADA and local control while providing complete redundancy. The lower tiers, connected directly to the relays, extract relay data, perform data manipulations, and send the data from all relays to the upper-tier communications processors. Control is maintained if any upper-tier communications processor is disabled. The as-built design actually includes more than the originally compared

10 communications processors to satisfy additional topology considerations. The ultimate redundancy that the full system provides could not be matched by the other designs.

Control

Redundant primary and backup relays control each breaker, motor-operated disconnect (MOD), circuit switcher, and lockout relay (LOR) through connections to different lower-tier communications processors. This redundant design allows a lower-tier communications processor outage without loss of control. From the upper-tier communications processor, data from the entire substation are organized and sent to various destinations, namely the SCADA and DA masters and the local substation computer that serves as the controller or HMI.

Monitoring

The HMI was designed and configured by an independent system integrator. This system integrator was familiar and local to PECO. As an independent system integrator, they were able to implement a best-of-breed solution that included the products that PECO preferred. The interface provides substation operators with an intuitive graphical interface to the entire integrated substation. This includes all metering measurements and the ability to control and configure all relay devices, breakers, MODs, and auxiliary relays. The PC also contains a software bridge to remote operators via a modem. This allows on-the-road and remote-office access to all control and troubleshooting functions. The PC is an optional operator interface connected to one of the upper-tier communications processors; SCADA connected to the other upper tier allows system operation without dependency on this PC. The independent system integrator provided the communications processor setting configurations and supplied the equipment monitoring interfaces to the SI system. The protection schemes and settings have been generated by the engineering services department of the relay vendor.

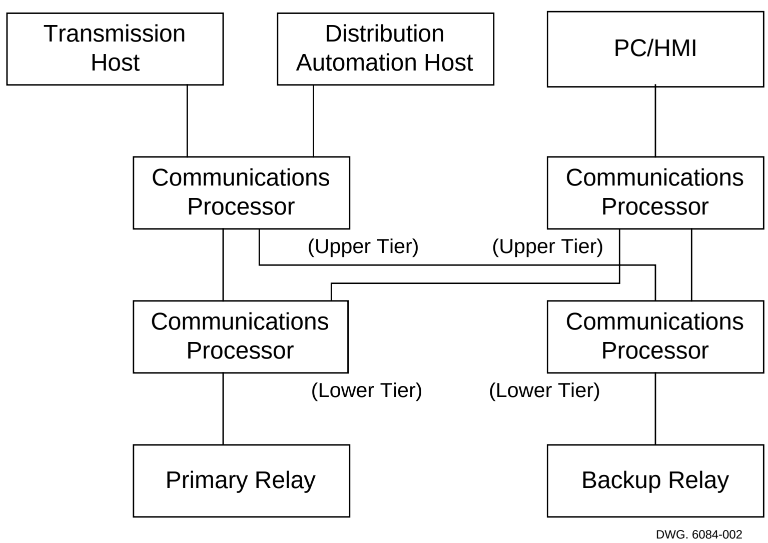

Figure 9: SI System Two-Tier Architecture

Though the protective relays offer a battery monitor, a separate and more elaborate battery monitoring system was easily added to the design. Inexpensive fiber-optic transceivers were also provided by the relay vendor. These were used to provide galvanic isolation between primary and backup systems as well as safer and more reliable direct relay connections.

Maintenance

Data are collected daily and sent to a host computer via modem and dial-up line. This computer acts as an equipment monitoring host and collects and stores this time-stamped data. Process values like temperature, pressure, quantity, and duration of operations, etc., are time-stamped and stored for later evaluation. The customer anticipates evaluating this data with analysis tools to trend deterioration of substation components and predict appropriate maintenance.

Distribution Automation

The customer not only has immediate fault location data to perform better and faster restoration, but also has detailed event reports automatically collected from the system. These event reports can be viewed in a graphic format to analyze system operation. These data can help the customer make intelligent decisions and system recommendations.

Most distribution automation designs rely on a master connection to share data between IEDs. The master collects information from the controllers and other IEDs into one large database and then data from one IED can be sent to another IED by the master. When this master connection is lost, the IEDs become stranded and do not work in a coordinated manner. Often, the master that is used for this is an otherwise occupied SCADA master and this distribution automation function further dilutes it’s ability to perform and could possibly reduce reliability. The reliability of this remote host oriented DA system is drastically reduced by the possibility of failure of the host or failure of a host connection.

The communications processor creates an autonomous coordinated distribution automation, SCADA, and protection system within the substation and out to the pole-top that does not rely on a master connection. The communications processor then collects, processes, and redistributes data between IEDs without relying on a host connection. Pole-top installations can be easily added in the future. The communications processor also provides data acquisition and control to the remote or local hosts but continues with DA functions should the hosts fail. Also, direct links can be established between microprocessor-based relays and recloser controllers based on these relays, as an example, so that protection and automation data can be directly, quickly, and reliably transferred peer-to-peer. Further, the communications processor can support mediation of local or remote control of the entire system.

Equipment Monitoring

Trip coil monitoring is an example of verifying auxiliary equipment. Control Equations in the relays can be used to perform trip coil monitoring as well as other functions in the system, such as capacitor bank supervision and sophisticated reclose and tripping requirements. Personnel safety is enhanced through the fast trip scheme for hot-line maintenance, which provides flashover detection. Simple topology and communication LEDs offer easier and faster communications troubleshooting.

Protection

The microprocessor-based relay and communications processor I&C system also performs the following protection and control [6].

13 kV feeder protection and control
13 kV tie line protection and control
13 kV capacitor bank protection and control
13 kV bus protection and control
13 kV bus tie protection
230/13 kV transformer protection
230 kV circuit switcher remote control
230 kV line protection and control
230 kV bus protection and control

As of this writing, five substations, including Westmoreland, have been successfully integrated on the PECO system. Three more are planned for 1998.

Realize Many Key Advantages to PECO

Distributed Topology

- Number of relays reduced by 75%
- Analog wiring reduced by 30%
- Control wiring reduced by 50%
- Failures detected within seconds vs. at next maintenance interval
- Breaker isolation and system restoration reduced from hours to minutes

Enhanced System Topology

- Automatic fault data
- Remote access to detailed event reports
- View oscillography and digitals for timing details and operation analysis
- Make system improvement recommendations based on data
- Verify auxiliary equipment (trip coil)
- Automated system operation supervision for breaker closing
- Reduced maintenance
- Increased personnel safety
- "Fast Trip" scheme provides instantaneous tripping during hot-line maintenance
- Flashover detection for open switches

Recognize Additional System Benefits

Choose Products from any Vendor

The substation grade, communications processor star relay network centric design does not require the high-speed networks within the substation but can easily connect to them. The solution is nonvendor-specific. Previously installed or newly procured devices from any manufacturer may be connected to the system and eavesdropping can be used to retrieve data via a nonintrusive data link from islanded systems that have no additional communication capabilities.

Leave Protection, Monitoring, and Control Undisturbed While Changing Protocols

One of the most important design features may be the fact that the network protocols are deployed in the upper-tier communications processors. If need arises to add or change a new network protocol or connection, this is easily accomplished in the communications processor. Data acquisition, control, and protection continue uninterrupted within the protection system as network protocol needs change.

Integrate Devices Inside and Outside the Substation

You can easily incorporate devices outside the substation into your design, such as distribution automation controllers out on a pole-top application. This allows coordination between protection, automation, and control products for intelligent sectionalization and restoration. This produces fewer outages, shorter duration of outages, and thus, fewer affected customers. The trial and error method of detecting faults is replaced by fault location.

Enhance Power Quality

Power quality is a broad concept used in comparing the actual power system values to their ideal. Although there are many dedicated power quality measurement devices, relays are an effective measurement and storage device for some power quality data. Harmonics, frequency, voltage sag, voltage swell, and voltage interrupt are examples of power quality data captured by relays.

The relay vendor created a power quality feature called voltage sag swell interrupt (VSSI). An additional set of triggers capture power quality event data such as wave form deformation and/or sagging and/or swelling. The power quality event report is similar to a fault event report, but is of longer duration, to be sure to capture enough information, to effectively analyze a VSSI event.

Most significant power quality problems are identifiable as power system voltage variations: complete interruption of voltage (<0.1 per unit), undervoltage (sag), and overvoltage (swell). A large percentage of these voltage variations are a result of power system faults. Recording and reporting voltage variation in the relay allows low cost correlation and validation of power consumer complaints. Monitoring the power quality allows the relay to react and compensate for power system variation or to alert users.

Benefit from Revenue Class Metering Accuracy

Except for transformers with very few windings, revenue and protection CTs act the same. The difference is that revenue class CTs go into saturation so as to protect the revenue meter to which they are usually attached. Electromechanical relays have such a large burden that, in the past, it was not possible to get revenue class accuracy from the protection CT with electromechanical relays attached. The burden of microprocessor-based relays is so small that we can get revenue class accuracy on a protection CT. In fact, PECO's relay vendor has metering accuracy that equals or exceeds the accuracy of revenue meters between 0.8 and 1.0 power factor. These data can be easily used to verify calibration of revenue devices. The relays obviously also continue to read current values in a fault condition whereas the revenue meters must be protected by a saturating CT.

CONCLUSION

The challenge is often ***choosing*** the most beneficial and cost effective substation design.

Major motivators of quantifying reliability issues include deriving the best solutions on how to improve the system, how to manage dependability versus security tradeoffs, as well as how to get the best results for the least money when selecting a design. A quantitative understanding is essential in a competitive utility industry. As with most utilities, once the functional requirements of a system were met, PECO was ultimately concerned with reliability, speed, and cost. Speed can be measured, equipment cost calculated, and engineering effort estimated but designers are constantly challenged to quantify reliability.

The failure rate of a component, device or system is only part of the story. Reliability can be further quantified by comparing unavailability. In calculating unavailability, we are determining the percentage of a duty cycle that a component, device, or system is unable to perform it's function.

Though we must rely on statistics to predict unavailability, the intuitive root causes are that unavailability will increase proportionally to the rate of failure, unavailability will increase proportionally to the amount of time it takes to repair or replace a failure and unavailability will increase proportionally to the amount of time that a failure remains undetected.

"Fault tree analysis," a concept first proposed by H. A. Watson of Bell Telephone Laboratories, can be used to combine device unavailabilities. This method, used and refined over the ensuing years, is attractive because it does not require extensive theoretical work and is a practical tool that any engineer can learn to use. The author has shown that small fault trees, which are easily analyzed manually, are also very useful. The fault tree method tool can be used in mission-critical design applications, regardless of size.

The communications processor star relay network centric design subsystem is elegant in its simplicity. The streamlined architecture performs all the necessary functions with a minimal number of components. Thus, the system design is more reliable. The modular nature of the architecture allows for future expansion as well.

An interesting benefit to performing this analysis was that two direct correlations between reliability and cost were found. The obvious one is that redundant systems of a particular design are more reliable and more costly than nonredundant systems of the same design. However, when comparing different designs, the most reliable design has fewer devices and components. Fewer components translate into fewer costs. Therefore, for this and many other examples, as you drive reliability up, you drive cost down.

The customer not only has immediate fault location data to perform better and faster restoration, but also detailed event reports automatically collected from the system. These event reports can be viewed in a graphic format to analyze system operations. These data can help the customer make intelligent decisions and system recommendations.

IED integration enhances distribution automation, SCADA, and protection by migrating some of the communications functions to an intermediate substation device. Moving protocols into the

IEDs adds to their cost and accelerates their obsolescence as technology advances. The resources available within the IEDs are instead better focused on optimizing protection solutions.

System automation, control, and supervisory data available in protective relays enhance protection and control of individual power system components as well as the entire power system by permitting rapid, well-informed decisions. Adaptive protection and control methods are used as the power system configuration changes dynamically.

Device diagnostic data enhance distribution automation, SCADA, and protection by maximizing the availability of the protection system.

Star networks can acquire and transfer the distribution automation, SCADA, and protection data using much slower direct connections. These direct connections are also more reliable, more robust, and less expensive.

The star network is the only design that is truly open and accommodates multiple protocols, multiple baud rates, and multiple network interfaces.

Communications processors enhance the value of the distribution automation, SCADA, and protection I&C system data by making it available to multiple master systems and other users.

Substation integration designs that rely on a master connection cannot share data between IEDs when this connection is lost. The IEDs become stranded and do not work in a coordinated manner. The communications processor creates an autonomous coordinated distribution automation, SCADA, and protection system within the substation that does not rely on a master connection and allows mediation of local or remote control of the entire substation.

The age of IEDs that are in substations today varies widely. Many of these IEDs are still useful but lack the most recent protocols. Rarely is a substation integration upgrade project undertaken where all existing IEDs are discarded. A communications processor that can communicate with each IED via a unique baud rate and protocol can extend the usefulness of IEDs. Using a communications processor for substation integration also easily accommodates future IEDs.

Networks are made up of direct and multidrop connections. Point-to-point star networks are much more reliable than multidrop networks. It is important to keep in mind that if the mediation of control of data transmission should fail, none of the multidropped devices can communicate.

The rebuilt Westmoreland substation exploits virtually all of the capabilities of microprocessor-based relays. The new substation contains more than one hundred microprocessor-based relays, integrated into an SI system comprised of 22 communications processors. This is perhaps the largest substation of its kind ever built.

Increased visibility of system trouble and relay alarms is obtained by incorporating relay targets and event reports into the SI system so operators and engineers can diagnose and maintain the system.

The economical design uses relays to control breakers and other devices, and report on the status of each breaker. Metering data on all equipment is derived from the relays, displayed on the local HMI controller, and sent to the remote SCADA operators. These features eliminate substation RTUs, transducers, meters, and control switches.

Transmission breaker failure relaying is enhanced through the use of sophisticated logic that controls the breaker, lockout auxiliaries, and MODs, isolating the failed breaker. This logic enables safe operator control of the breakers, switches, and MODs for quick load restoration.

The microprocessor features allow sophisticated testing techniques to quickly and efficiently test many relay elements in repeatable programmed tests. The results of these tests are stored in software for later reference. Load checking is easily performed from a remote location without additional test equipment. Relay setting verification is achieved during relay configuration through database software, reducing relay setting time by half and increasing accuracy.

BIOGRAPHY

David J. Dolezilek received his BSEE from Montana State University in 1987. In addition to independent control system project consulting, he worked for the State of California, Department of Water Resources, and the Montana Power Company before joining Schweitzer Engineering Laboratories, Inc. in 1996 as a system integration project engineer. In 1997 Dave became the Director of Sales for the United States and Canada and he now serves as the Engineering Manager of Research and Development in SEL's Automation and Communications Engineering group. He continues to research and write technical papers about innovative design and implementation affecting our industry, as well as participate in working groups and technical committees. He is a member of the IEEE and the International Electrotechnical Commission (IEC) Technical Committee 57.

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