ESCO Energy Services Company recently implemented a Supervisory, Control, and Data Acquisition (SCADA) system for the 13.8 kV electric distribution system associated with the campus of a large industrial customer. To get a perspective of the challenges associated with this project, one must first understand the condition of previous system. The electric distribution system is divided into two distinct distribution systems served from two sources by the utility.

The switchgear was installed during the late 1980s and has been well maintained; however, the industrial was interested in replacing installed electromechanical protective relays with the newer solid state relays currently available. Further, there was no initial provision for remote operation of circuit breakers or data acquisition. The remote substations serving the various campus buildings are a hodge-podge of equipment suppliers. The actual design and selection of distribution equipment was a combination of the engineer-architect hired to design the various facilities and the general contractor with the lowest bid to construct the buildings. Although each substation consisted of a breaker on either side of the loop supplying a fused disconnect switch for the building transformer, a variety of manufacturers are represented with protective relaying consisting of the flavor-of-the-day or fire-sale bargains. Loop coordination was achieved by sequencing time over-current settings, starting from the inter-most loop and working out to the bus circuit breaker supplying the loop in accordance with a simplified control philosophy that was used in the 1970s. Coordination had suffered from diminishing time separation of the protective relay settings, failure of the particular consultant to apply the coordination philosophy correctly, not always updating all the relay settings to reflect a change, and a multiplicity of relay types and settings. Consequently, outages required the electrical maintenance department to first determine where the fault occurred, physically break the system apart, and then restore service sequentially until the fault condition was isolated for repair. This often lead to a two or four hour outage, which may have been tolerated 20 years ago, but today, arouses the irritation of facility management.

The system was also supported by two 3750 kW, standby diesel generators. The existing generator controls consisted of several refrigerator sized cubicles filled to the brim with relays, transducers, control devices, timers, and meters. The modes of operation were intended to support running in parallel with the utility power source and standby operation for loss of source power. Unfortunately, the generation would not operate in parallel with the utility and rarely operated with the loss of the utility power source.

Given this system backdrop, system requirements were developed to resolve inherent issues with the current system. The new system design would incorporate capabilities to automate electrical switching within the distribution system, to protect the loop circuits supplying campus loads, and to control and automate the selection of power sources, including generation, for the campus. Other system objectives included:

1. Eliminating a multiplicity of protective relays by selecting one manufacturer and one device that can be used for all the required applications and will be supported by the supplier for at least 10 years.
2. Providing automatic operations and manual operations that are straightforward yet sophisticated enough that the electric maintenance personnel can remember how to use it during unplanned events.
3. Coordinating the system such that a faulted section of the distribution system is isolated without opening the main breaker, both bus loop breakers, or any more remote loop breakers than is absolutely necessary to isolate the fault. Be able to
determine the fault location at a glance using the SCADA system.

4. Obtain serial event recorder information from one location without traveling to each relay location.

5. Provide Human Machine Interface (HMI) software that allows easy access to information from multiple locations within the campus and can be loaded on a tower or laptop computer purchased at Best Buy, and plugged into an Ethernet connection anywhere on the SCADA network.

6. The communications system must run on the campus’ fiber system on a dedicated network, use Ethernet topology that can be maintained by the IT Department.

System Description
The implemented system is presented in the simplified single-line drawing below:

Selection of the protective devices associated with this system was the key to project success. Due to its application flexibility and programming capability, the SEL 451 protective relay was selected as the base device for achieving protection and control for the remote sites and on the corresponding loop supply circuit breakers in the 13.8 KV Switchgear. The SEL 451 is a multifunction solid state relay and metering device that offers the following standard configuration that was ideal for the remote substations:

The SEL 451 also offers the following characteristics that fit the project requirements:

- Configurable Operator Interface with programmable push buttons
- 250 Lines of programmable logic for automation
- DNP and IEC 61850 Communications
- Direct connection with Ethernet interface
- Relay-to-relay serial communications with Mirrored Bits®
- Programmable protective logic
- 10 year warranty

With these features, this device met the three main requirements of remote substation control and protection, power source control and protection, and generation control and protection. Further, supervisory control and data acquisition are accomplished by directly accessing the SEL devices through a Wonderware HMI using DNP protocol. A software program provided free by the relay manufacturer and loaded on the same computer running the HMI software provides direct access to each relay through the Ethernet SCADA network. A detailed discussion of each aspect of the project follows.
Utility Service Switchgear

The 13.8 KV switchgear associated with the incoming utility service is similar to the remote sites, with the exception that each circuit breaker is controlled by a relay. The main breakers have time over-current settings which coordinate with the time over current settings of the loop breakers and an instantaneous setting to detect bus fault conditions. The bus fault condition is used to supervise the auto source transfer of the bus tie breaker. When the generator breakers are closed, additional settings are enabled in the mains for under/over voltage, under/over current, and reverse power.

Logic has been developed and programmed into the relays to open and close the main source breakers and bus tie without operator intervention manually by operator intervention. The logic is a little complicated due to the presence of generation on either side of the bus tie, but the same transmission source for the transformers ensures the generators are in sync when the mains are closed. Mirrored Bits® communications protocol was used to exchange status and control information for the automatic transfer schemes. Again, this capability is available due to all devices being interconnected via Ethernet connection. A brief description of the automatic transfer schemes is described below:

Remote Substations

The objective of the protective relays in the remote substations is to operate the remote loop circuit breakers to isolate a faulted section of line, to protect the service transformer and cabling, and to obtain metering and load information for each substation. For typical installations this is accomplished with three distinct devices. For this application, it was accomplished with this single device. Basic overcurrent protection was provided for both breakers associated with the substation. Additionally, logic was developed and programmed into the device to enable it to evaluate conditions associated with current direction and phasing for each substation feed. With each substation interconnected through a fiber backbone, Permissive Overreach Transfer Trip (POTTT) communications is supported for adjacent substation relays via an Ethernet multicast using the IEC 61850 GSSE (Generic Substation Status Event) standard. Thus the substation conditions are compared and appropriate breakers are tripped to isolate line faults. Each device also acts as a Remote Terminal Unit (RTU), for supplying information and control capability to the fiber-based network.

### Auto Source Transfer:
- Select for automatic bus tie operation for failed utility source
- Failed source is utility breaker closed and loss of potential
- An open utility breaker will not cause an Auto Source Transfer
- Failed source opens first, then tie closes
- Return to normal is by Operator action
- 3 second delay for return of utility potential
- Not blocked if generator breaker is closed
- No action if both sources fail

### Return to Normal:
- Select to close utility breaker and open tie
- Relays (not operator) determine if Utility is available
- Will return to normal only if utility potential is available
- SEL Pushbutton must be in "AUTO"
- Tie and one circuit breaker must be closed
- Not blocked if generator breakers is closed
- Can be latched to return to normal when conditions allow
- Utility Breakers must have SEL in "AUTO"

### Utility 1 Source Transfer:
- Closed Transition to Utility 1 with bus tie closed
- Utility 2 will open after tie closes
- Return to normal by "Return to Normal"
- System must be in "Normal" Condition with Utility 1 and Utility 2 closed, Tie open
- PB4 must be in "Auto"
- Blocked if generator breaker is closed
- Not the same as "Auto Source Transfer"

### Utility 2 Source Transfer:
- Closed Transition to Utility 2 with bus tie closed
- Utility 1 will open after tie closes
- Return to normal by "Return to Normal"
- System must be in "Normal" Condition with Utility 1 and Utility 2 closed, Tie open
- SEL must be in "AUTO"
- Blocked if generator breaker is closed
- Not the same as "Auto Source Transfer"

### Close Tie Breaker:
- Select by pushing SEL Operator Push Button 7
- Closes breaker only if SEL is not in "AUTO"
- Synch check functions is always active
- LED on indicates breaker closed position

### Open Tie Breaker:
- Select by pushing SEL Operator Push Button 7
- Opens breaker regardless of Auto Manual position
- LED on indicates breaker closed position
- Opening tie breaker will not automatically close an open Utility breaker

### Automanual:
- SEL Operator Push Button in AUTO (LED light on)
- AUTO enables Bus Tie Operations
- AUTO disables SEL, Breaker Close push button
- Manual (LED light off) allows SEL push button close
- Manual blocks all remote and automatic operations
- Manual used for Operator close of tie breaker
- Tie breaker opens in either position
Generator Controls

The SEL 451 relay provides the generator protection and control logic for selecting modes of operation. Because the relay does not have the ability to supply an analog output for driving a governor signal, the Woodward 30 series of Generator Controllers was utilized to provide pre-programmed functionality for generator control. The cost and complexity of developing and proving the control logic and outputs required for generator control with the SEL 451 could not be justified. A simple schematic of the generator control scheme is provided below:

The digital Woodward controllers start the engine, parallel the generator to the 13.8 KV Bus, and drive the governor for load control. The digital controller loads the engine up to the Generator rating as determined by operator input for parallel operations. The digital controller provides generator protective functions, alarming, and monitors currents and potentials. The SEL 451 selects the operating mode and controls the utility interface through Mirrored Bits® communication. The SEL 451 also provides generator protection including a differential circuit that wraps the generator, step-up transformer, and circuit breaker. The operating modes for the generation system are as follows:

Standby:
Normal operating mode where a loss of source potential or condition other than a bus fault causes the main breakers to open — both have to open to instigate a standby condition. The loop breakers open to isolate loads from the bus and the tie breaker closes to form a generator bus primarily to have all generation capacity available for load pickup. The first generator breaker closes to the bus and the second is paralleled to the first. The loop breakers are closed sequentially. If the controls anticipate the load of all three loops will exceed the rating of the generators, select substation circuit breakers are opened and left open until sufficient capacity is available or the source returns. When the source returns, the generators parallel to one Utility source and that breaker is closed, then the other utility breaker is closed. The tie breaker is opened and the generators soft unload and the generator breakers open.

Isolate:
Operator selected mode will start both generators and parallel to utility sources. The tie breakers is closed and the load is transferred to the generators. When the power flow across the utility is zero, the utility circuit breakers open. When the operation is cancelled, both generators will unload and open the generator breakers.

Base Load:
Operator selected mode will start both generators and parallel to the utility sources. Both generators will be loaded to the Operator set value up to the rating of the generator. When the operation is cancelled, both generators will unload and open the generator breakers.

Curtailment:
Operator selected mode will start both generators and parallel to the utility sources. Both generators will be loaded to reduce the imported power to the set demand level. The operation is cancelled, both generators will unload and open the generator breakers.

Mapping out how things work before entering the logic into the relays is a very good idea. A written description of generator operations was developed with the control logic flowcharted. The relay programming with settings was then developed in an Excel spreadsheet format before entering them into the relay, because the editing functions of the relay are extremely limited. Logic for individual circuit breaker operations was developed in the relay controlling that breaker rather than concentrated hardwired generator relays. Derived analog variables keep track of generator loading and make predictions regarding breaker closing.

Communications System

The SEL 451 relays were supplied with an SEL 2701 Ethernet processor that will support both Distributed Network Protocol Version 3.0 (DNP3) or IEC 61850 Communications protocol messaging peer devices. The SEL- 2701 appears to have the capability to recognize that GSSE messages are more important than the SCADA DNP interval polling. The 2701 processes incoming GSSE messages and delivers them to the relay through a high speed network card interface so that word bit state changes are processed in milliseconds. Event driven GSSE messages limit the network traffic by utilizing a text ID name of the GSSE sender and a special Ethernet multicast destination address. If nothing has changed, the 2701 sends out a periodic GSSE message to make sure the other devices in the multicast group are listening and waiting for an important GSSE message. Ultimately each device processes only messages containing information it is configured to use, and the whole system is not bogged down with an enormous amount of useless handshaking.

The campus backbone fiber system is a single-mode fiber system consisting of several 24 fiber bundles. Six fibers are
assigned to the SCADA network and those are extended to each remote site by installation of 6 strand, single-mode, direct bury fiber from existing splice points.

**Human Machine Interface (HMI)**

The intent of the HMI is to show at a glance, the current state of all the breakers and if each line section has voltage. The HMI also allows remote control of circuit breakers and reads metering information. Additional information such as currents, voltage values, KW load, alarms, and fault events is available through accessing additional screens. An overview screen of the whole system is the default HMI display. Clicking on an object drills down to the control elements and data displays. Operating breakers requires two distinct operator actions including entering an employee number assigned by the industrial. Current alarms show up at the bottom of any page and are archived in an alarm summary. The operator controls screens mimic the front panel of the relays. Trending is a popular application, so screens were developed to track voltage profile and power usage. The Generator controls have a separate screen. Event and waveform analysis utilize SEL Accelerator software accessing individual relays, one at a time. The HMI package selected was WonderWare with a third party, Imperious Technologies, communications protocol driver for DNP. A Dell tower computer was selected as the platform of choice, because the client uses the same machine in other HMI applications and feels the computer can be changed as the technology changes without sacrificing much of an investment.

The developers and supporters of DNP tout is as a major advance over simple register based communication protocols like Modbus. DNP3 supports a basic polling mechanism similar to collecting data within Modbus, except event data types are collected in a buffer and may be sorted and prioritized. The SEL 451 allows the development of custom DNP maps, so that the amount of exception polling is even further reduced by looking at a smaller subset of all the information available. The concern was to keep routine communications traffic at a minimum for coordination messages. The general consensus during development was DNP is much faster than Modbus.

The HMI screen for a remote substation looks like this:

**Conclusions**

Combining the power of the new programmable multifunction relays with the relative low cost of the several HMI software packages available and the ease of Ethernet communications will accommodate a simple and cost-effective SCADA solution.

Especially in the case of distributed generator applications where the system control logic can be combined with the protective relay interface in one integrated package that can be accessed and programmed remotely.

For those familiar with the SEL 351 and Mirrored Bits® applications, the SEL 451 relay and IEC 61850 communication protocols take the application of that knowledge one step further. With IEC 61850, the engineer can share 64 control variables with eight relays in a few cycles. Ethernet connectivity makes this simple to apply. SEL added a few programming features like being able to annotate logic statements with comments to simplify the programming process. The SEL 451 also offers straightforward logic operators rather than cryptic symbols. Perhaps the greatest long awaited SEL advancement is the ability to manipulate analog variables with math operators. Even though the device lacks even a rudimentary programming editor, at least all the pieces are there to do just about anything you want.

As Operations Manager of ESCO Energy Services Company, Lynn brings over 25 years of working knowledge in design, permitting, construction, and startup of mechanical, electrical, and instrumentation and controls projects as well as experience in the operation and maintenance of facilities.

Lynn is a Professional Engineer, Certified Energy Manager and has a BS in Nuclear Engineering from the University of Tennessee.

As Project Manager for ESCO Energy Services Company, David Charles manages projects and services for industrial, municipal, and utility clients with a focus on power generation facilities, industrial power plant facilities, electrical substations, switchgear selection, protective device settings and coordination, conductor selection and routing, distribution and transmission line design. Further David has experience with SCADA and instrumentation installations, specification and selection of electric power distribution systems and utilization equipment, and load management system specification.

David is a registered professional engineer in the state of Iowa and has a B.S. in Electrical Engineering from the University of Iowa.