Unit Substation Protection & Control Upgrade Using Microprocessor Relays

Case Study

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ZIV p + c

Introduction

This paper describes the application of microprocessor based relays to upgrade existing electromechanical protection and control equipment utilized in 34.5 / 4.16 kV unit substations. A single equipment design was provided that could interface with many of the approximately 800 unit substations in operation within the PECO Energy service territory.

The purpose of the project was to extend unit substation life, improve equipment maintenance cycles, and add remote supervisory control and data acquisition (SCADA).

Unit Substation Design

A unit substation is a complete, self-contained substation designed to supply a single distribution circuit. Each substation consists of a power transformer ranging in size from 1000 to 2500 kVA and a dedicated low side circuit breaker to provide feeder protection and control. At many locations two unit substations are duplexed with a tie breaker installed between the units on the load side of the circuit breakers. The tie breaker is used to automatically transfer load if the high side supply to one of the unit substations is lost. Figure 1 is a one line diagram of a typical two unit substation installation.

The unit substations provide ac station power, but do not include a source of dc control power, thus unit circuit breakers are operated using either a shunt trip or capacitive trip opening design. AC station power is used to close the unit breaker as well as to operate the load transfer tie breaker.

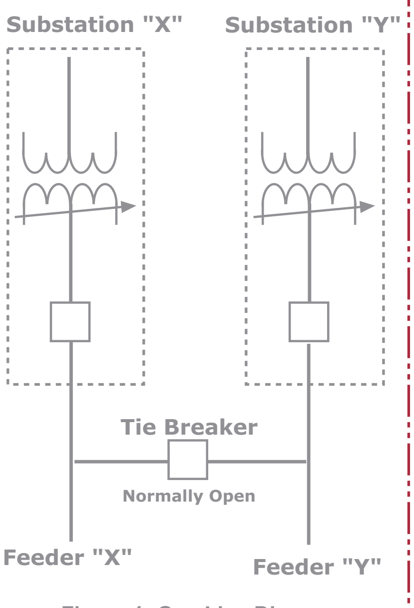

Figure 1: One Line Diagram

Unit transformers are provided with 32 step, 10% load tap changers connected to the low side winding. The tap changers are controlled by voltage regulating relays, many of which are an early electromechanical design.

The high side of the transformer is supplied with power fuses intended to provide primary protection of the transformer and limited back up protection of the feeder circuit. Non-directional overcurrent relays are used for feeder protection; in most installations this consists of two relays monitoring phase currents and one connected in the neutral circuit. Under voltage relays connected to at least two of the phases are used with the load transfer logic. They also isolate the feeder in the event the primary source is lost. A separate relay is employed to auto reclose the unit breaker in the event of a feeder fault. All of these devices are electromechanical relays. Figure 2 shows the location of instrument transformers and protective devices.

Logic for the automatic load transfer scheme is accomplished using a hardwire system comprised of auxiliary control relays, breaker position status contacts, under voltage relays, timers, and control switches. In general, the logic is designed to transfer feeder load to the adjacent unit substation if the supply source is lost. When the source is restored (by sensing voltage) the scheme is designed to return the system to a normal configuration (tie switch open). The system is designed to be bi-directional, that is, either unit transformer must be able to supply power to the adjacent feeder in the event of a source failure. Numerous safeguards are built into the logic to prevent unwanted operations. For instance, manual operation of either of the unit breakers will disable the transfer logic.

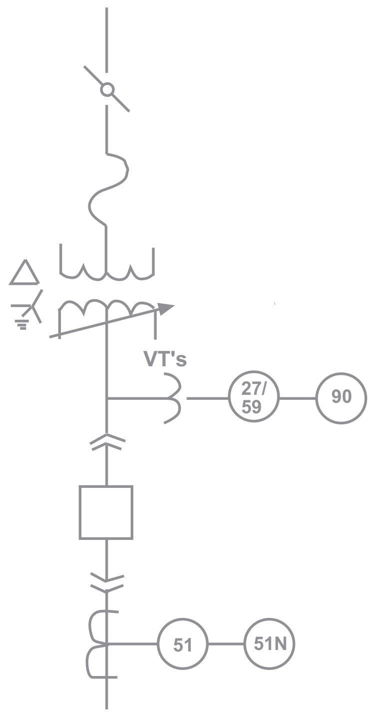

Figure 2: Instrument Transformer Locations

The system is designed to be bi-directional: either unit transformer must be abble to supply power in the event of a source failure

Equipment Limitations

Probably the most significant limitation was the lack of remote SCADA control and monitoring at the unit substation locations. Breaker statuses and phase current readings were obtained during manual substation inspections; however, external changes between inspections could result in operations that compromised preferred equipment utilization. For example, operation of the automatic load transfer scheme at a particular substation would provide the immediate benefit of quickly returning service to customers on a circuit, but could temporarily compromise load distribution. The desired subsequent action may be street switching to balance load, but the action will not occur without knowledge that the condition exists. It is also sometimes necessary to disable the load transfer scheme during high load periods to protect equipment from overloading. Continuous monitoring via SCADA would provide immediate notification to the Distribution System Dispatchers of conditions at the substation; allowing immediate action to improve equipment utilization. SCADA would also minimize the requirement to disable the automatic load transfer scheme, by allowing exact identification of periods of high loads and faster redistribution of load when transfer occurs. The benefits to the load transfer scheme that SCADA would provide include the ability to optimize equipment loading during changing system conditions and improved customer reliability.

A second potential limitation was decreased reliability due to aging electromechanical equipment. Higher maintenance and parts availability were both concerns. For example, the automatic voltage regulators on many units were at end of life and being replaced in kind to improve reliability. Replacement of end of life equipment as part of a project to install SCADA would increase the project reliability benefits and reduce maintenance costs.

A third limitation, that could be solved with microprocessor relays, was the lack of additional protective elements and tools to diagnose system operations. Open phase detection as well as transformer thermal overload and reverse power elements could easily be added. Sequence of events records, fault reports, and oscillography information are now standard offerings in most microprocessor relays.

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Customer Upgrade Requeriments

One of the foremost design criteria that PECO required was that a single equipment design be used for all substation installations. Unit substations are often exchanged between locations as customer load requirements change, thus the protection and control equipment design had to support exchange between different unit substations. PECO also encouraged a design with minimum life-cycle costs.

Protection and control design requirements duplicated functions of the existing equipment with some additional enhancements. PECO supported a design that would allow for complete retirement of all existing equipment. Specifications included:

1. A MMI local operator interface
2. Low side circuit breaker control and indication
3. Tie circuit breaker control and indication
4. Transformer tap changer control and indication including
    - Line drop compensation
    - Selectable voltage control set points
    - Interface with existing tap changer motor operators
5. Distribution feeder protection including
    - Phase time and instantaneous overcurrent protection
    - Ground time and instantaneous overcurrent protection
    - Transformer reverse power protection
    - Open phase detection
    - Over / under voltage protection
    - Automatic reclosing
6. Automatic load transfer control logic
7. Analog metering including
    - watts
    - vars
    - amperes - 3 phases
    - voltage - 3 phases
8. Remote control and data acquisition (SCADA)
    - Communication channel to be multi- drop telephone
    - Protocol DNP 3.0
    - Designed to support future use of radio modem with quiescent communication

The only power source available was ac supplied from the unit substation. New equipment was required to operate for eight hours after loss of ac power.

The supplier was also required to provide all necessary engineering and project management for the entire installation process. This included design of the new equipment, logic to support protection and control requirements, design of the protection and control interface, detailed material lists, documentation and prints, and site assistance with installation and commissioning.

S&C Design

After a review of existing installations S&C decided to offer a design that utilized an external cabinet to house all additional protection and control equipment. This approach provided sufficient flexibility to be used with the variety of unit substations PECO had in service on their system, avoided field modifications to existing relay and control panels, and allowed for "in place" retirement of existing equipment. The cabinet, built for outdoor applications, was securely attached to the outside of the unit substation. An access hole was cut in the side of the unit substation for wiring connections. A single control logic and monitoring design allowed for implementation of a standard wiring harness for all installations. The harness was modified in the field to interface with various manufacturer's equipment. Figures 3 and 4 show pictures representative of this installation method.

Figure 3: Unit Substation With Added External Control Cabinet

A dual microprocessor terminal unit (type 7IRD) manufactured by ZIV Applications & Technology, Madrid, Spain was used for all protection, control, and SDADA communication functions. This device consists of two separately powered microprocessors in a single housing.

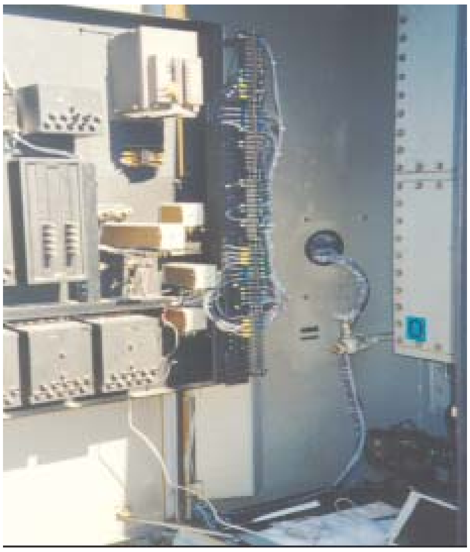

Figure 4: Access Hole and Wiring Harness

One of the microprocessors is specifically designed for distribution feeder protection, the other, the control microprocessor, is used to support a graphical user interface and other logic functions required for the application. The primary functions in this application included remote SCADA, an automatic load transfer scheme, and automatic load tap changer control. An internal communication bus provides a path for control and information data to be exchanged between the two microprocessors.

Figure 5: 7IRD Terminal Unit and Test Switches

Protective Functions

The protection microprocessor provides standard functions required for protection of most distribution feeders. This includes phase and ground overcurrent elements with a variety of user selectable response curves, automatic reclosing, and breaker failure.

The unit also provides phase unbalance detection using an element that measures the ratio of negative to positive sequence current (I2/I1). This element can be used to detect operation of a single high side power fuse then open the low side unit breaker, and thus prevent "single phasing" to connected distribution customers. After installation, operational experience showed that care must be taken when applying this element to feeders that may experience unequal phase loading. Undesirable operations occurred during single phase switching when enough unbalance in both phase magnitude and angle
produced excessive negative sequence current.

A thermal overload algorithm, generally supplied in ZIV's transformer differential relay, was an additional protective function included to enhance transformer protection. This tool, along with SCADA monitoring, will provide PECO with a better indication of transformer thermal capacity during extreme loading conditions. Transformer loading above normal rating is possible after operation of the load transfer scheme. The algorithm is essentially and integral function that uses transformer load current as an input and is based on the following equation:

$$t = T * I_n \frac{I^2 - I_P^2}{I^2 - I_{MAX}^2}$$

Where:

I = The measured current

I_P = The pre-load or previous current. Assume that current has been maintained at this value long enough for the transformer temperature to stabilize.

I_{MAX} = The maximum transformer current that can be carried without overheating, derived from the normal kva rating of the unit.

T = Thermal time constant.

t = Time to trip or alarm.

The user is able to enter in a constant that is intended to simulate transformer thermal mass. By varying the time constant, **T**, overload alarm and trip times can be determined. In this application, the thermal overload scheme is set to alarm 10 minutes after the transformer has reached 150% of continuous full load. This bench mark was determined assuming that a load transfer occurred on a system where both unit transformers were initially loaded at 75% of continuous capacity.

Two other protection algorithms were added to the control microprocessors to improve PECO's protection system. These were reverse power and overcurrent back up.

Protection algorithms are thermal overload algorithm, reverse power and overcurrent back up

Reverse power protection was added to detect situations where unit transformer real power was flowing from the 4.16 to 34.5 kV winding. This situation can sometimes occur during switching operations when one distribution feeder is temporarily looped to another feeder; the system transfers power from one 34.5 kV source to the other with load levels above normal equipment ratings. The reverse power element is designed to open the unit substation breaker, thus eliminating the back-feed condition.

One advantage provided by the original electromechanical relay installation was inherent back up protection for a failed relay. Because these relays are discreet devices, a single failure does not completely disable the protection system, a relay that is measuring current in another phase or the neutral should provide fault response. One disadvantage to most microprocessor relays is dependence on a common processor and power supply for all protection functions. Failure of either of these components will disable all protection. ZIV programmed a definite time overcurrent function in the control microprocessor, which utilizes a separate power supply, and thus provided protection back up. This approach provided a higher degree of reliability and allowed PECO to retire existing electromechanical relays instead of using them as back up protection to the new system.

As mentioned earlier in the paper, a single protection and control package was developed capable of interfacing with a variety of unit substations. The unit breaker trip circuit output had to be capable of operating either a shunt trip or capacitive trip operating mechanism. This problem was solved by adding a multi-contact interpose relay to the trip circuit between the relay trip output contacts and the breaker. The interpose relay was provided with one normally open contact and three in the normally closed position. The single, normally open contact was used to operate capacitive trip breakers. The three normally closed contacts were used for a shunt trip breaker. In this application current from each individual phase current transformer (ct) is connected to a separate current operated trip coil. Under normal circumstances ct secondary current is shunted around the trip coil. In the event that a fault occurs and a protective relay initiates a trip, the shunt contacts open forcing current through the trip coil to operate the breaker.

Figure 6 shows the secondary current circuit for a shunt trip breaker. Note that relay overcurrent elements are provided for all three phases and the neutral.

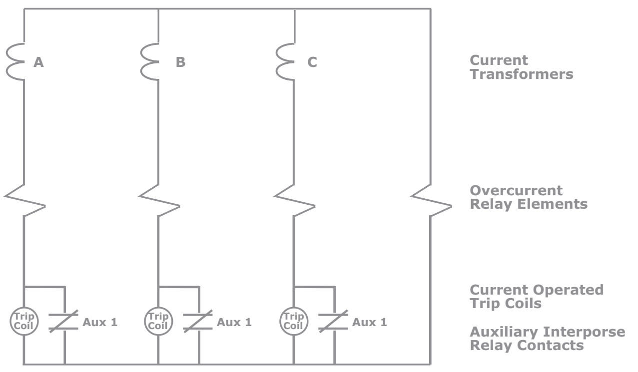

Figure 6: Shunt Trip Breaker Circuit

Control Functions

As stated earlier in the document, a second microprocessor, the control microprocessor, is included in the 7IRD terminal unit to support a graphical user interface and other required logic functions. The protection and control schemes in service at a number of existing installations were studied by S&C and PECO engineers to establish the "best in class" logic to be programmed for the 7IRD terminal unit. In particular, considerable time was spent reviewing variations in the load transfer schemes.

The automatic load transfer scheme and load tap changer control logic will be discussed in some detail.

• Load Transfer Scheme

A simplified logic diagram for the load transfer scheme is shown in Figure 7. The following description will be based on information required for the "X" Unit Transformer (see Figure 1). Logic for the "Y" Unit Transformer is almost identical. In order to sense loss of source voltage on the "X" transformer and transfer load the following status information is required:

- "X" unit breaker position
- "Y" unit breaker position
- Tie breaker position
- "X" transformer voltage level
- "Y" transformer voltage level

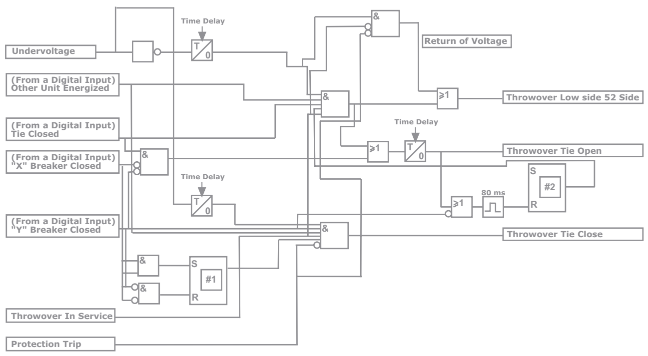

Figure 7: Load Transfer Logic

When the "X" voltage level drops below a preset level the "X" unit breaker opens after a time delay. After an additional time delay a tie breaker close signal is initiated. Several conditions must be satisfied before the tie breaker is allow to close. These are:

- The load transfer function must be in service
- Voltage must be present on the "Y" transformer
- The "Y" unit breaker must be closed
- The "X" unit breaker must not be locked out following a protective relay operation
- Flip-flop #1, which determines the normal state of the unit breakers, must be reset

Flip-flop #1 was added to insure that the "X" and "Y" unit transformers were initially operating in a normal state supplying load to the distribution system before permitting operation of the load transfer function. Flip-flop #1 is set when both unit breakers are open at the same time. This is a condition that could occur if both sources are lost, separate faults occur on both distribution feeders, or both unit transformers are taken out of service at the same time. Other conditions such a fault on the "X" distribution feeder while the "Y" unit substation is out of service would also cause this situation.

When the tie breaker closes transferring additional load to the "Y" transformer, flip-flop #2 is set to register that the tie breaker was closed by the load transfer function. This sets up system logic for future restoration to a normal system once the "X" source becomes available.

When voltage is restored to the "X" unit transformer a timer is started. The "X" unit breaker will close if:

- The load transfer function is in service
- The tie breaker is closed
- Flip-flop #2 is set

After a short delay to insure that load has been transferred back to the "X" unit transformer the tie breaker is opened.

Flip-flop #2, which supervises return to normal, will be reset whenever the tie breaker or "Y" feeder breaker is opened. The "Y" breaker reset signal prevents an unwanted "return to normal" of the transfer function if the "Y" breaker has been opened manually or because of a feeder fault operation.

When the load transfer function is out of service the "X" unit breaker will automatically open upon loss of source voltage and close when voltage is restored. This function can also be disabled if desired.

• Load Tap Changer Control

The voltage regulator logic of the control is designed to operate using one of four pre-determined voltage set points. The set point values are entered from the relay key pad. Set point selection can be made either at the relay or remotely using SCADA control.

The logic generates one of two discreet control signals. One for voltage levels above the set point, the other for levels below. Unlike a conventional control, this allows separate upper and lower voltage margins above and below the set point as well as individual time delays. Figure 8 is a block diagram illustrating this part of the logic.

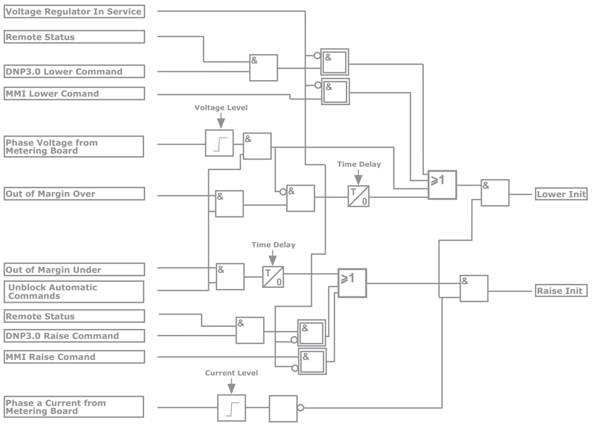

Figure 8: Voltage Control Logic Diagram

When desirable, load drop compensation can be used to bias the sensing voltage signal. The desired voltage *Vd* is modified by adding a factor derived by multiplying the load current *I* by a compensation factor *K*. Then $Vd = V_{set\ point} + KI$.

An over voltage logic function is also provided to operate the load tap changer without intentional time delay. This will allow quick control response in the event that excessive voltage is measured.

Tap changing components are also protected from switching current levels in excess of their design capabilities. An over current logic circuit will block the final output stage in this situation. Similarly logic is used to prevent tap changer operation if the feeder protection logic has initiated the auto reclose function. This will prevent unwanted damage to the switching contacts from feeder fault currents.

Control signals to the tap changer are also blocked if the sensing voltage level is below a preset level. This is intended to prevent tap changer "run-away" operation when the system is de-energized or operating voltage levels are abnormally low. All of these functions are also illustrated in Figure 8.

A control interface had to be designed to produce a customized signal to operate the tap changer motor mechanism. The signal consists of a pulsing control output of which the pulse width and duration between pulses can be regulated. Early field experience taught us that there was a significant difference in the time period required to change taps between the various equipment manufacturers, as well as difference in the design of the motor control circuitry. Longer pulse widths, for example, were necessary for slow moving mechanisms designed without motor seal-in circuitry. Without the ability to lengthen the control pulse these particular mechanisms would not reliably change tap positions.

Communications

The communication infrastructure was designed by S&C to support a multi-drop telephone leased line originating from the SCADA master station. It was also necessary to provide a design that would support future transition to a system using a radio modem with quiescent communication capabilities.

Figure 9 is a block diagram of the communication network used in a single substation. The designed allowed for up to six separate 7IRD terminal units, each acting as a unique remote terminal unit (RTU), to be connected to a single telephone drop point within the substation. A telephone modem and data concentrator were located centrally in the substation. Fiber optic connections were run from the data concentrator to each of the terminal units. The fiber optic design eliminated any concern for ground potential differences within the switchyard or special cable shielding considerations. Fiber runs were generally under two hundred feet although the equipment and fiber characteristics would have permitted lengths in excess of 6000 feet.

The data transfer rate of the present polled mode system is 1200 baud. Equipment capabilities will support rates up to 19.2k baud if the system is modified to operate in an unsolicited response mode in the future.

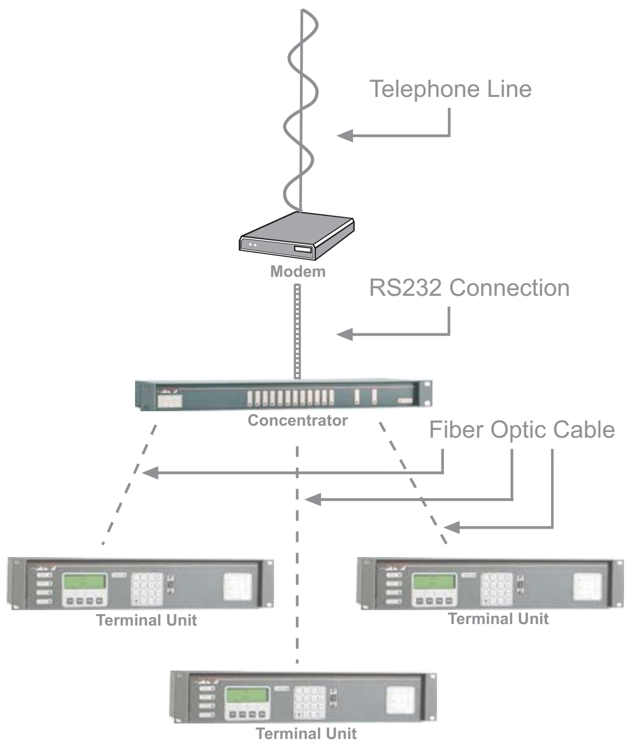

Figure 9: Switchyard Communication Network

Central DC Power Supply

It was necessary to add a dc supply source to power the microprocessor terminal units.

As mentioned earlier, the existing design did not require a dc supply because it used electromechanical relays and circuit breakers that were either capacitive or shunt trip operated. A single, central source for the dc power designed by S&C was the most effective solution. This eliminated the need for duplicate batteries and chargers in each location and also solved space limitation problems present in most of the unit substations. The batteries and charger were installed in the same cabinet that housed the communication equipment (see Figure 10).

Figure 10: Communication and Power Supply Cabinet

The batteries, which operated at 24 V dc, were sized to operate the equipment for eight hours after loss of the ac power input. Two of the unit substations each supplied a source of ac power for the charger. An automatic throwover scheme was provided to transfer power to the secondary source in the event of a primary failure.

“Loss of ac” and “battery trouble” alarms were monitored and transmitted back to the SCADA master station. Individually fused dc supply cables were run to each of the unit substations to supply the terminal units.

The existing design did not require a dc supply becuase it used electromechanical relays

Project Implemention Team

In the initial proposal S&C offered to provide a complete turn key product, supplying all necessary engineering, design, documentation, equipment fabrication, material, and labor required for field installation. This proposal was later modified at PECO's request to enable them to supply part of the material and all field installation labor.

Project management was a joint responsibility shared both by PECO and S&C. It was necessary to establish a close interface between companies to insure that equipment installations and substation outages could be effectively coordinated with other construction work occurring within the PECO system.

S&C also contracted to provide all necessary design engineering and documentation to support the installation, operation and maintenance of the equipment. Final CAD drawings were submitted in Microstation V5.0 format. Many of the substations had been installed before PECO began using a CAD system, thus many of the original prints were scanned as complete blocks. The final prints provided by S&C were a combination of modified scanned original prints and newly drawn prints.

The design engineering process for the completed pilot phase unit substations was a major effort. It required significant drawing review and modification as well as exact design of the logic to be programmed into the microprocessor relays, to insure that the required existing and new control functions were provided. Meetings were held with PECO engineers to insure that there was a clear understanding of existing control logic and to review the design. Site visits were used to confirm equipment information as well as equipment cabinet and cable route locations within the substation switchyards.

S&C provided on site engineering supervision during construction and commissioning. This process provided an opportunity to make minor modifications to the design as differences were discovered between the design and the requirements of the actual installation. It was also an opportune time to provide on site training for PECO technicians and engineers. Formal training in a class room setting was provided at a later date for a larger number of employees.

It was necessary to establish a close interface between companies