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MARK D. DIEHL
ROBERT A. CROGNALE

PECO ENERGY COMPANY
PLYMOUTH MEETING, PA USA

JAMES A. SCHWENK

SCHWEITZER ENGINEERING LABORATORIES, INC.
PULLMAN, WASHINGTON USA

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Mark D. Diehl
PECO Energy Company
Plymouth Meeting, PA USA

Robert A. Crognale
PECO Energy Company
Valley Forge, PA USA

James A. Schwenk
Schweitzer Engineering Labs, Inc.
Pullman, WA USA

INTRODUCTION

PECO Energy Company, provider of electric power to Philadelphia and the surrounding region, recently rebuilt and renovated a major urban substation. The 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 a Substation Integration (SI) system to provide System Control and Data Acquisition (SCADA) visibility and to provide information and control capabilities to a local man-machine interface (MMI). The system will increase 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.

BACKGROUND

Westmoreland Substation, located in urban north Philadelphia, is a critical substation to PECO Energy Company. It serves 16 of PECO's 39 highest revenue customers. However, it is approximately 70 years old and is plagued with numerous maintenance and operational problems. Problems relating to the antiquity of the substation include:

- Imminent failure of aging 69/13 kV transformers.
- 13 kV ungrounded subtransmission system is unable to feed distribution load.
- 13 kV line configuration does not include the other capabilities required for standard distribution load, including line reactors, reclosers, and relays with configurable instantaneous-overcurrent elements.
- Aging underground cables combined with underrated line breakers present an ever-increasing likelihood of total bus outages caused by close-in 13 kV line faults.
- The substation had virtually no remote SCADA visibility for line metering or supervisory control, with the exception of the 69 kV transmission lines.

TOPOLOGY

Prior to rebuilding the Westmoreland Substation, the configuration consisted of three 69 kV ring busses feeding eight transmission lines and four 69/13 kV transformers. Four 13 kV busses supplied a total of 34 feeders. These ungrounded, three-wire lines included many subtransmission lines supplying other 13/4 kV distribution transformers.

The new rebuilt substation consists of a triplex configuration. The tapping of a nearby three-ended 230 kV transmission line provides the 230/13 kV transformer sources for the associated 13 kV bus sections. Each of the three 13 kV bus sections are connected through normally closed breakers in a Y-tie configuration. These three new 13 kV busses will replace the existing 13 kV subtransmission load and provide for new four-wire grounded distribution load. All of the 13 kV feeders are equipped with line-side current-limiting reactors. The new configuration is designed to allow up to two transformer outages or an outage of either of the two 230 kV line sections without service interruptions to the 13 kV loads.

In addition, the existing 69 kV ring busses will be rearranged. One ring bus will remain with five sections. The reconfigured 69 kV lines will no longer supply any Westmoreland load.

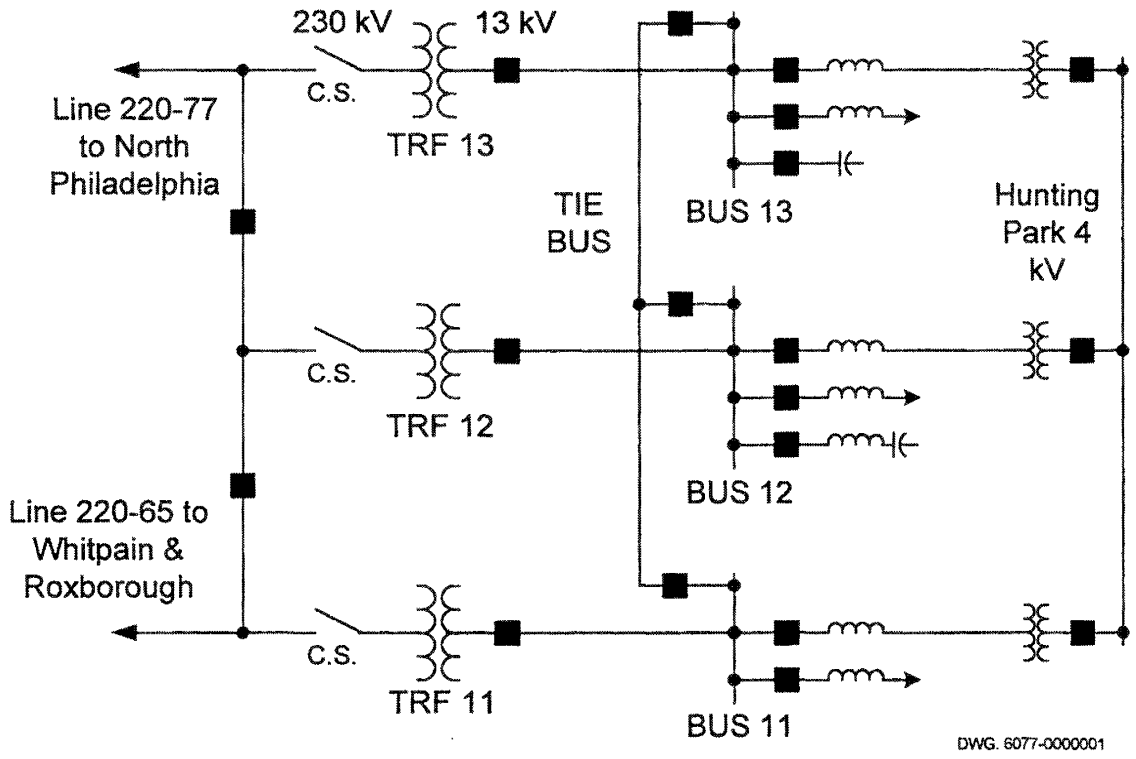

Figure 1: Westmoreland 230/13 kV Single Line

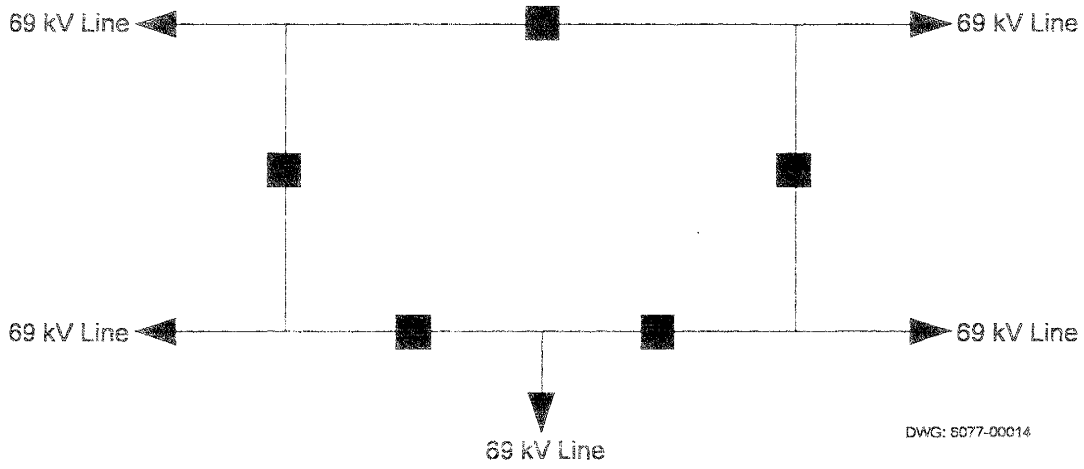

Figure 2: Westmoreland 69 kV Single Line

THE PECO SUBSTATION INTEGRATION (SI) PROJECT

PECO is undertaking an ambitious project to provide SCADA visibility, including feeder metering data, breaker control, and recloser cut-off, at approximately 50 existing distribution substations. While SCADA visibility exists on nearly all of the PECO transmission system, only about one-quarter of SCADA visibility is obtained at the distribution level. The SI Project will increase this percentage to about 80 percent.

The goal of the SI Project is to better serve PECO's customers by providing remote substation data and control to PECO personnel. The existing substation conditions and control ability are available to operators, technicians, or engineers. The SI Project achieves these goals using microprocessor-based relays.

The configuration used in all of these SI conversions remains generally the same for each converted substation. To reliably extract and deliver the information from each of the relays to the SCADA systems, a two-tier microprocessor-based communications processor configuration is adopted [1]. 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 two upper tier communications processors. Control is maintained if either upper tier communications processor is disabled.

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 masters and the local substation computer that serves as the controller, or MMI.

The MMI was designed and configured by a local substation integrator. This 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 substation integrator provided the communications processor setting configurations and supplied the equipment monitoring interfaces to the SI system.

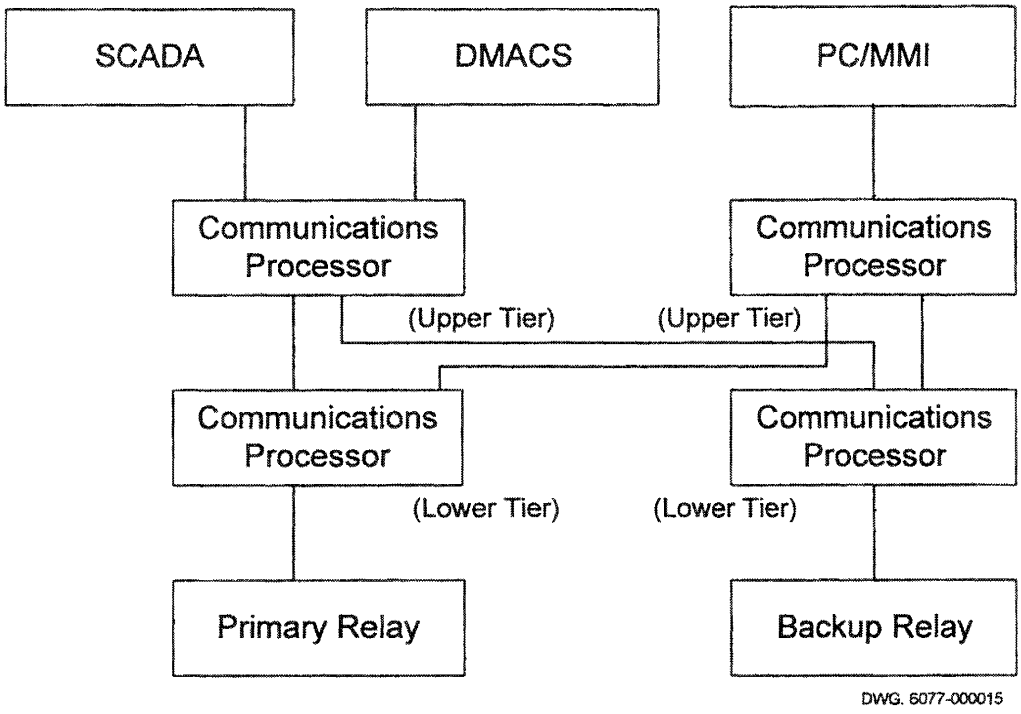

Figure 3: SI System Two-Tier Architecture

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

PROTECTION DESIGN CRITERIA

- Adherence to Existing PECO Protection Philosophies

  The Westmoreland relay system was developed to meet all existing PECO standards, which attempt to maximize the relaying philosophies of speed, sensitivity, security, simplicity, and dependability.

- Redundancy

  Redundancy is one of the major design criteria of the PECO SI system. This aspect of the system design greatly improves the dependability of both relay protection and SCADA

communication. It is common practice to design protective relay schemes so that the failure of a single component will not compromise protection of the protected equipment. Redundancy is also required on the SI communications system. Failure of a single component anywhere within the SI system will, at worst, compromise either local PC control or remote SCADA control, but never both.

- Relay Self-Checking, Alarm Conditions, and Event Reports

  The microprocessor-based relays utilized in PECO's SI system incorporate self-checking mechanisms, as well as programmable alarm/trouble elements. These are monitored by the SI system and reported to SCADA and to the MMI, increasing the reliability and helping facilitate maintenance of the overall system.

- Intuitive Protection Functions

  The protection devices chosen to protect each piece of equipment were selected so operators and technicians can easily identify the primary protection device functionality. This means, for example, that all breaker-oriented functions, including failure detection and auto-reclosing, should be implemented in a clearly designated "breaker" relay, not incorporated inside another relay such as a transmission line relay.

PROTECTION DESIGN

230 kV Transmission Lines

In the past, PECO traditionally used Direction Comparison Blocking (DCB) schemes or Permissive Overreach Transfer Trip (POTT) schemes for transmission line protection. In all recent transmission line protection system installations, POTT schemes are used due to the greater degree of security over DCB schemes [2]. Most often audio tone equipment is used, but PECO now is using fiber optics for communication wherever it is available. In many PECO substations, nodes of a SONET ring allow fiber to pass through the substation and be used by the relay communication system. If the need for communication circuits justifies the expense, PECO installs a SONET node to provide the communication circuits, rather than use leased audio tone circuits. This was done at several substations as part of the Westmoreland project.

Two microprocessor-based distance relays per terminal are used for transmission line protection. Conventional POTT scheme logic is used in the relays. Because Westmoreland is potentially a weak source – especially if one of the two lines is out of service – the relay Weak Infeed logic is enabled to allow the permissive signal from the other end(s) to be echoed back for instantaneous Zone 2 tripping.

SI Control and Data Points

The transmission line protection at Westmoreland does not differ substantially from those at other PECO transmission substations. However, because the relays are used in a substation integration package, the need for transducers, meters, and control switches is avoided. The transmission relays use the following SI features:

- The primary and backup distance relays provide redundant control for the associated 230 kV breaker, using remote logic bits in the relay set by the communications processor system.
- The 52a breaker auxiliaries are brought into the relays to provide the SI system with breaker status information.
- The voltage and current inputs into the distance relays provide the SI system with voltage and current readings for each of the 230 kV lines.

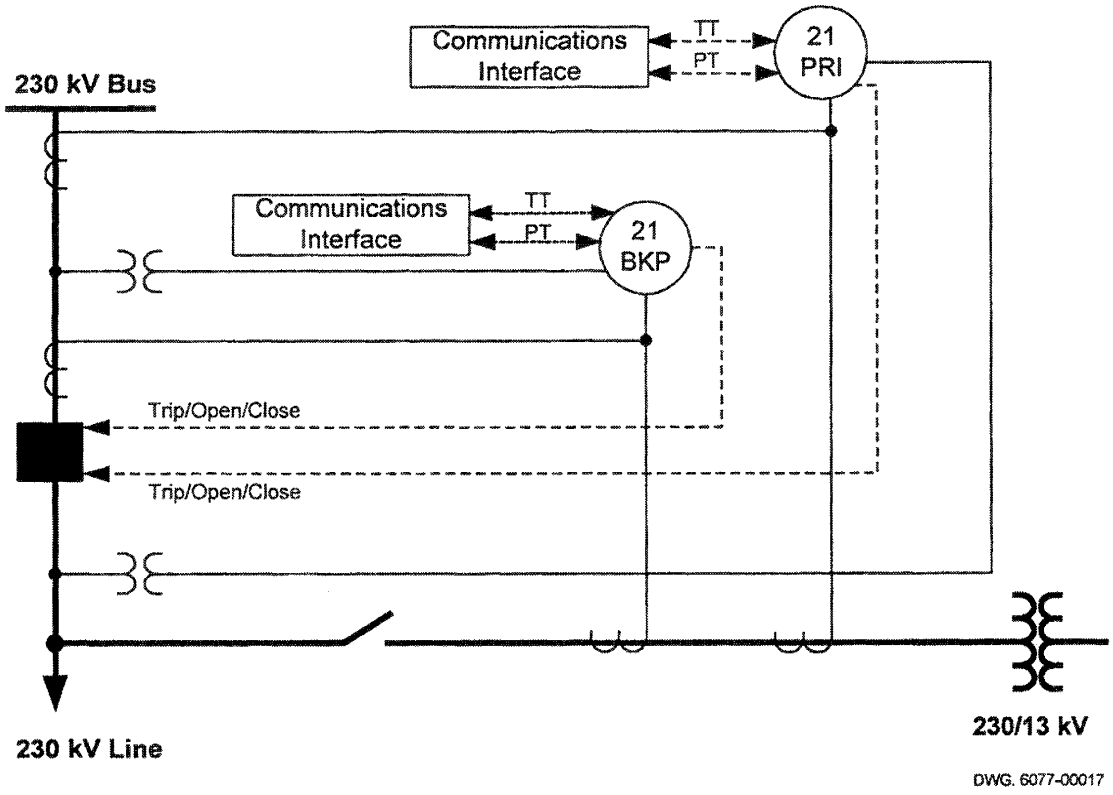

Figure 4: 230 kV Transmission Line Protection and Breaker Control

69 kV Transmission Lines

The 69 kV transmission lines are protected by primary and backup microprocessor-based distance relays (not shown) using POTT logic as in the 230 kV lines. Microprocessor-based breaker failure relays provide breaker failure clearing for each breaker. As in the 230 kV lines, the distance relays provide SI control and status indication for each breaker.

Differential Protection of Busses and Transformers

The 230 kV bus, 13 kV Y-tie bus, and all three transformers are protected with percentage differential relay systems. These use primary and backup relays connected to separate primary and backup current transformers (CTs) (see Figure 5, Figure 6, and Figure 7). The TRIP output of each relay trips for an 87-element fault into an associated primary or backup lockout auxiliary relay (LOR) that opens and locks out each breaker on the bus/transformer. This design is a conceptual simplification and a significant reduction in the number of relays over the previous electromechanical design. Usually consisting of primary differential relays and backup time and instantaneous overcurrent relays, a typical electromechanical scheme using ten relays was reduced to a primary and a backup multifunction microprocessor-based relay.

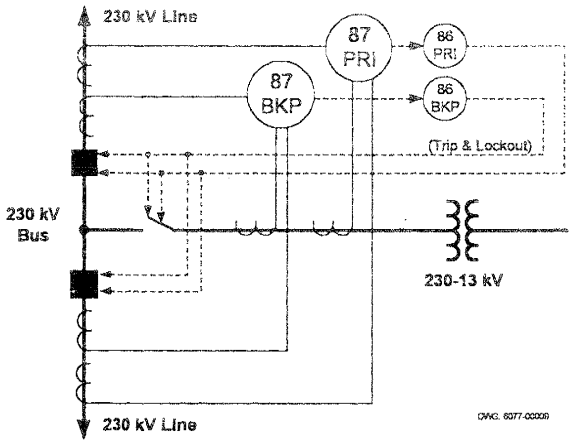

Figure 5: 230 kV Bus Protection

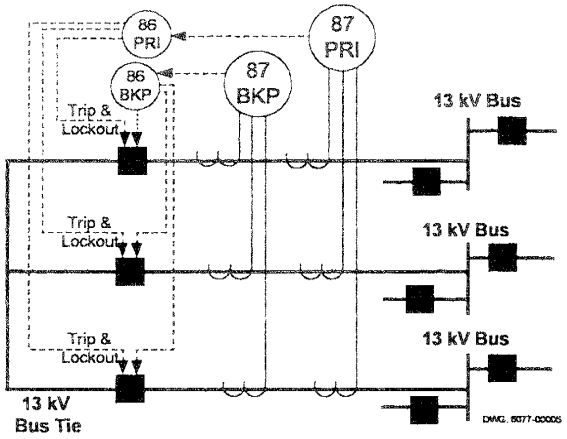

Figure 6: 13 kV Bus Tie Differential Protection

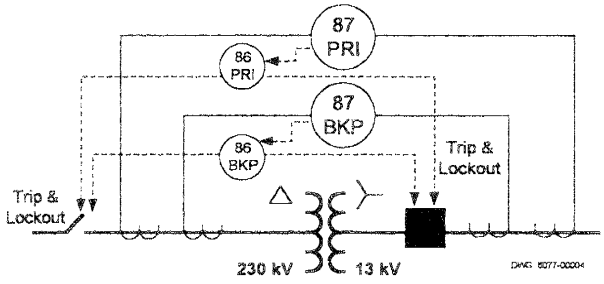

Figure 7: 230/13 kV Transformer Differential Protection

SI Control and Data Points

- The SI system monitors the status of the associated primary/backup LOR through relay inputs energized from the LOR output contacts.
- The 230 kV backup bus relays provide backup open/close control for the MOD associated with the middle transformer high-side circuit switcher.

230 kV Breakers

PECO required a separate relay (i.e., not a transmission line relay) for breaker failure and reclosing. Both of these functions were realized using a single microprocessor-based breaker failure/breaker control relay. The advanced features of this relay allow several protection, control, and operating improvements.

Breaker Failure and MOD Automatic Opening

A breaker failure/breaker control relay incorporates conventional breaker failure logic as well as programmed logic to facilitate the substation operator's local or remote restoration of load after a breaker failure clearing. The relay receives breaker failure initiate inputs from trip outputs of protective relays on either side of the breaker. As a result of a detected breaker failure condition, the relay will trip into an electric-reset LOR that clears all breakers on either side of the breaker and initiates transfer trip where required.

The breaker relay will instigate a breaker failure clearing if the relay flashover logic detects a sudden appearance of current in an opened breaker. This arcing across the breaker is confirmed by the prefault voltage difference across the breaker degrading to a negligible difference during the fault.

If, after upsetting the LOR, the relay determines the fault was successfully cleared and the failed breaker isolated (determined by the absence of current and voltage, and an upset LOR indication), the programmed logic in the relay automatically opens the associated motor-operated disconnect switches (MODs) after a short time delay. Operators can then reset the LOR remotely or with the local MMI controller via an SI remote logic bit command to the same relay. This reset is contingent upon the relay declaring a safe-to-reset condition. This condition requires that all current and voltage measurements are zero and all MODs are successfully opened. All the other breakers involved in the breaker failure clearing can then be closed remotely, thus restoring as much load as possible while still isolating the failed breaker.

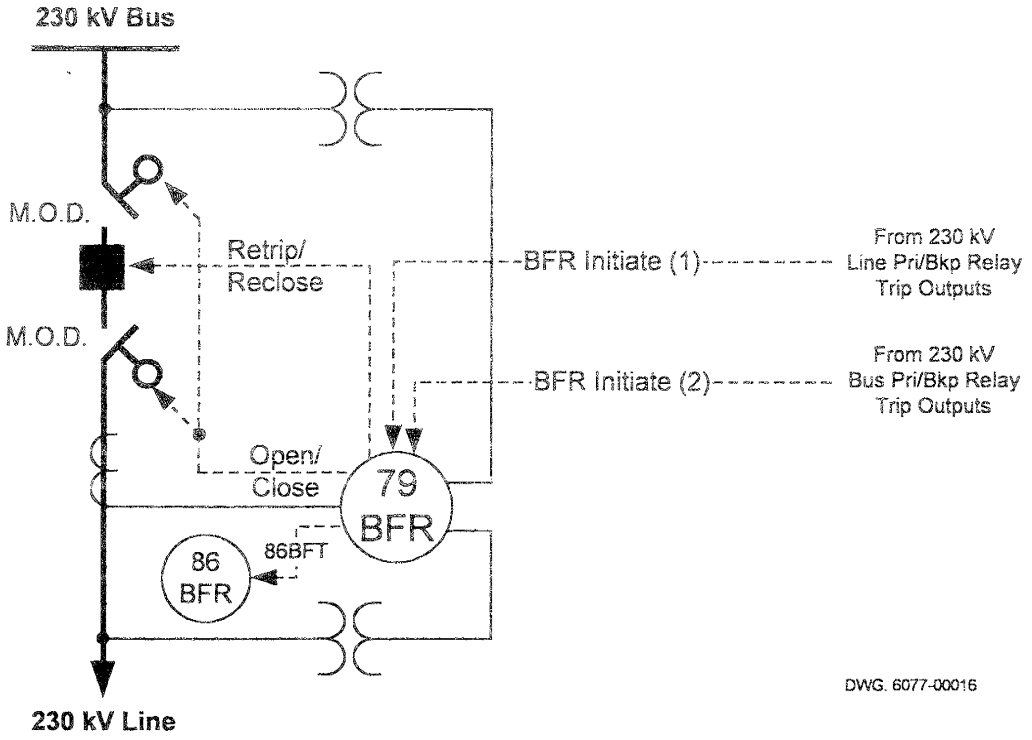

Figure 8: 230 kV Breaker Failure/Reclosing and Breaker Control

Automatic Reclosing

The programmable features of the breaker relay allow the relay to perform a single shot automatic reclose for faults indicated by the line relay trip output. One of the two 230 kV breaker relays is a follower recloser (line voltage must be first restored by the remote line recloser before initiating reclose); the other is a leader (only a live bus voltage is required). The relay cancels reclosing as a result of any of the breaker failure or trouble conditions in the relay or upon a fault indication from the breaker failure input of the bus relay.

An advanced programming feature in the breaker relay allows all elements to use aliases. Thus in programming the reclosing settings, meaningful labels are assigned to programming elements. These labels facilitate troubleshooting after a potentially complex breaker opening/reclosing sequence because the aliases are used in the sequential event recorder (SER) and clearly indicate the "mode" the recloser is in, e.g., "79RSD" (reset), "79LO" (lockout), or "79RI" (open interval timing):

T3pu = 60.00

1 second open interval time

T4pu = 1800.00

30 second reset interval

L4BS (set 79RI) = LINE_TRIP * 79RSD

Initiate reclose sequence upon a LINE_TRIP, alias for input IN102, which is a line fault breaker failure/reclose initiate input. 79RSD is alias for D3Q, set to the output of the T4 reset timer indicating the end of the reset interval. L4BQ (alias 79RI) thus is set only on a line trip with the recloser in "reset."

L4BR (reset 79RI) = INITBF_BUS+BKR_TRBL+ BLK_RECL+Y27D3+CCMD+ MCLOSE+CTD*52AA

*79RI is reset when breaker failure is initiated by the bus relays (INITBF_BUS), when the internal generic breaker trouble element (BKR_TRBL) is asserted, when the reclose cancel input is asserted (BLK_RECL), when the bus PT input indicates a dead bus (Y27D3), on a close command (MCLOSE), or if the breaker has reclosed (CTD*52AA).*

L4CS (set 79DTL) = (INITBS_BUS+BKR_TRBL+ BLK_RECL+Y27D3+!52AA*!L4BQ) * !79RSD

Drive reclose to "lockout" on bus fault initiate from bus relays, when the internal generic breaker trouble element within the relay is asserted, when the reclose cancel input is asserted, when the bus PT input indicates a dead bus, or when the breaker is opened without initiating reclose (!52AA!L4BQ) (a manual open) if the recloser is not in "Reset" mode (!79RSD).*

L4CR = 79OI1 + 79RSD

Cancel lockout mode if recloser is timing to reclose or is in "Reset" mode.

T3A (79OI1) = L4BQ*Y59L3*X59L3*!TRIPA* !52AA

Commence open interval timing when L4BQ (79RI) is turned on and the PT inputs indicate live bus and (if a follower) voltage elements indicate a live line and the fault has been removed and the breaker is open.

T4A (79RS) = 52AA*Y59L3*!(INITBF_BUS+ BKR_TRBL+BLK_RECL)

Commence reset timing if breaker is closed and bus is live (Y59L3) and there is no breaker failure input from bus relays (INITBF_BUS), a breaker trouble indication (BKR_TRBL), or a block reclose input (BLK_RECL).

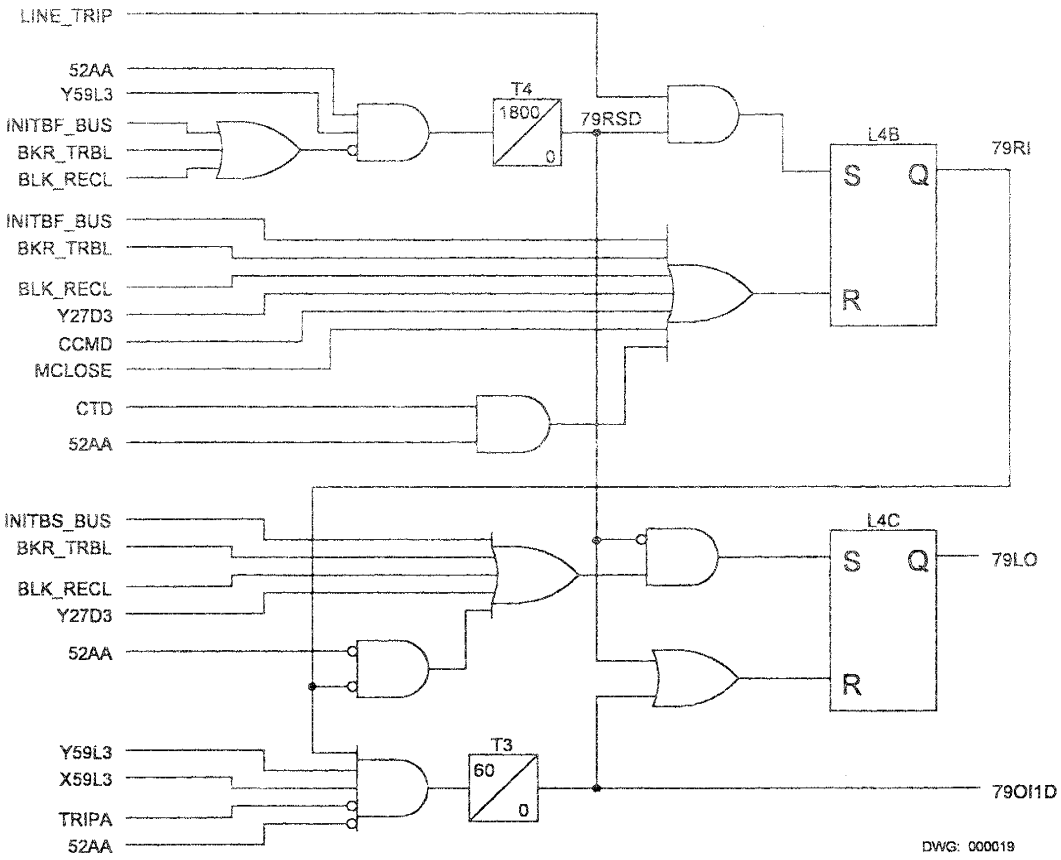

Figure 9: Reclosing Logic

SI Control and Data Points

- Outputs from the LOR wired into programmable inputs on the relay report the status of the LOR auxiliary relay.
- Remote logic bits from the attached communications processor initiated by operator control are used for resetting the upset breaker failure LOR, contingent upon a safe-to-reset condition:

M4 = !(M86T+50MD+MODST) * LOR_UPSET

Variable M4 is set if the following conditions are true: the breaker failure tripping element M86T is not set, the MOD current element 50MD is not set indicating no current through the MOD, the MOD status element indicates an opened MOD, and the status input LOR_UPSET indicates the LOR is upset.

86RS = M4D

Safe-to-reset condition 86RS is set 5 seconds after M4 is set.

OUT208 = 86RS * C_86RESET

86RS is Safe-to-reset element; C_86RESET is alias for a remote logic bit, set from the communications processor by the operator's SI command to reset the LOR. Output OUT208 electrically resets the LOR.

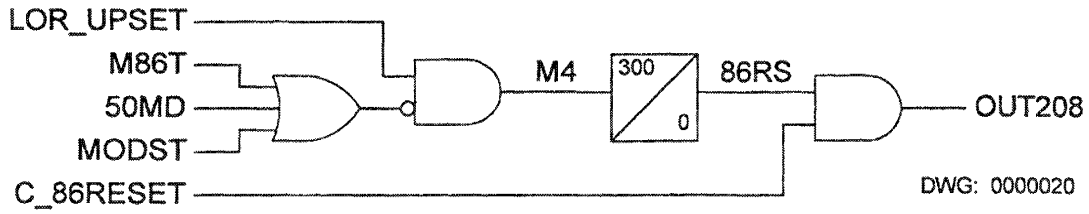

Figure 10: Reset LOR Logic

- Status indications from the four 230 kV MODs are brought into inputs of each of the two breaker relays to provide primary and backup MOD open/close indication.

- The breaker relay for the two 230 kV breakers provides primary and backup control of the four MODs. Open/close operations are qualified by either an open breaker or an upset LOR, so that the MOD never interrupts or closes into a live line or bus:

  D7Q (MODOP_OK) = !50MD * X27D3 * Y27D3 * (!52AA + LOR_UPSET)

  No MOD current and no line voltage or bus voltage, and either an open breaker or an upset LOR will set variable D7Q.

  OUT203 = ... + C_OPEN707*MODOP_OK

  MODOP_OK is alias for D7Q, which qualifies C_OPEN707, which is alias for remote logic bit command to open MOD 707.

  OUT204 = C_CLOS707*(!52AA+ LOR_UPSET)

  C_CLOS707 is alias for the remote logic bit command to close MOD 707. It is qualified by either an open breaker or an upset LOR to allow MOD closing.

- The breaker relay monitors the trip circuit through an input on the relay. If this input disagrees with the breaker status input, the relay registers a Trip Circuit Monitor alarm. This alarm is combined with other breaker trouble conditions:

  - Breaker failure to trip
  - Breaker failure to open under load
  - Breaker failure to close
  - Open breaker flashover
  - Phase imbalance

  These breaker trouble conditions were not monitored prior to PECO's SI project. Monitoring these conditions gives PECO indication of breaker trouble within 5 seconds. PECO immediately dispatches maintenance crews to investigate and correct the problem.

230 kV Circuit Switchers

Circuit Switcher Failure and Overstressed Scheme

The circuit switcher breaker relays function similarly to the 230 kV breaker relays for breaker failure and MOD opening, except that the circuit switcher relay only reads voltage on the line side of the switcher and only has one MOD to open.

The circuit switcher limitation of 20 kA interrupting duty, however, requires a breaker failure mode wherein the breaker relay must initiate a trip to the high-side equipment if transformer fault current through the switcher exceeds the 20 kA rating (called an "Illegal Zone" fault at PECO). Thus the element 50LD, normally used to detect load current, is set to 85% of 20 kA and set to trip directly into two of the outputs of the breaker relay. One of these outputs is a normally closed output, and is wired in series with the trip coil of the switcher so that when it opens it prevents any relay from tripping the switcher. The other contact is wired into an input of the primary relay (21 or 87) associated with the high-side line (or bus), and is programmed to "direct trip" (i.e., in the case of the line relays, trip the 230 kV breaker and initiate transfer trip to the remote end to clear the line).

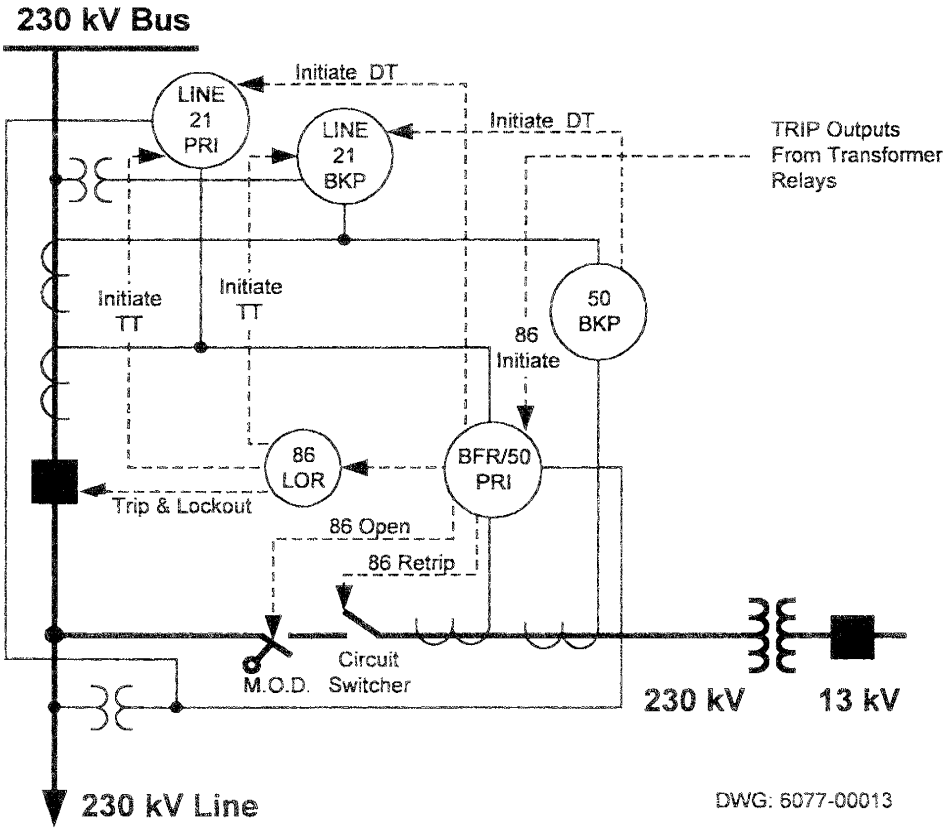

Figure 11: Circuit Switcher Breaker Failure

This overstressed scheme is a direct tripping protection function, as opposed to a conventional breaker failure scheme, so primary and backup redundancy is required. No other relay, including the line relays or the transformer relays, can be set to detect a 20 kA fault in the transformer leg.

The partial differential connection of the line relays does not allow measuring the current in the circuit switcher. The transformer relay setting range is not high enough with the provided CT ratios. Because of these factors, a backup microprocessor-based overcurrent relay is added to backup the line (or bus) direct trip function.

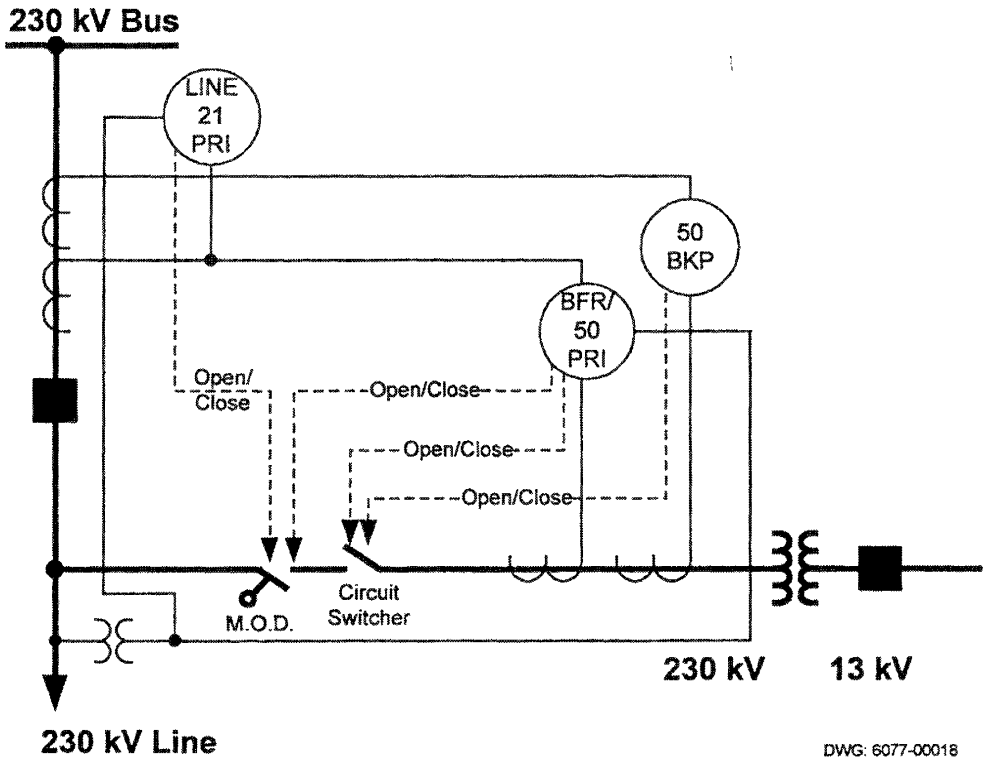

Figure 12: Circuit Switcher and MOD Control

SI Control and Data Points

- Outputs from the LOR wired into programmable inputs on the relay report the status of the LOR auxiliary relay.
- Remote logic bits from the attached communications processor are used for resetting the upset breaker failure LOR contingent upon a safe-to-reset condition. The relay logic is similar to that described above for the 230 kV breaker relays.
- Status indication from the MOD energizes inputs of the breaker relay or the primary associated distance relay (21) or bus differential (87) relay to provide MOD primary and backup open/close indication.
- The breaker relay for the 230 kV circuit switcher provides primary control of the MOD. The associated line primary distance (21) relay or bus differential (87) relay provides backup control.
- The breaker relay provides primary status and open/close control for the circuit switcher. The separate overcurrent relay provides the similar backup functionality.
- The breaker relay provides a circuit switcher failure status point similar to the breaker-trouble point described above for 230 kV breakers.

13 kV Transformer Low Side Breakers

Breaker Failure

A breaker failure/breaker control relay is used as a breaker failure relay for the 13 kV transformer main breakers. The relay receives two separate breaker failure initiate inputs from the associated transformer primary and backup relays and from the primary and backup bus relays. If the transformer relay input initiates a breaker failure and the breaker failure logic is satisfied, the relay will upset the bus backup lockout auxiliary relay that trips and locks out all of the bus breakers. Similarly, if the bus relay input initiates a breaker failure, the failed breaker logic will upset the transformer backup lockout auxiliary that trips and locks out the transformer high-side circuit switcher as well as the low-side breaker.

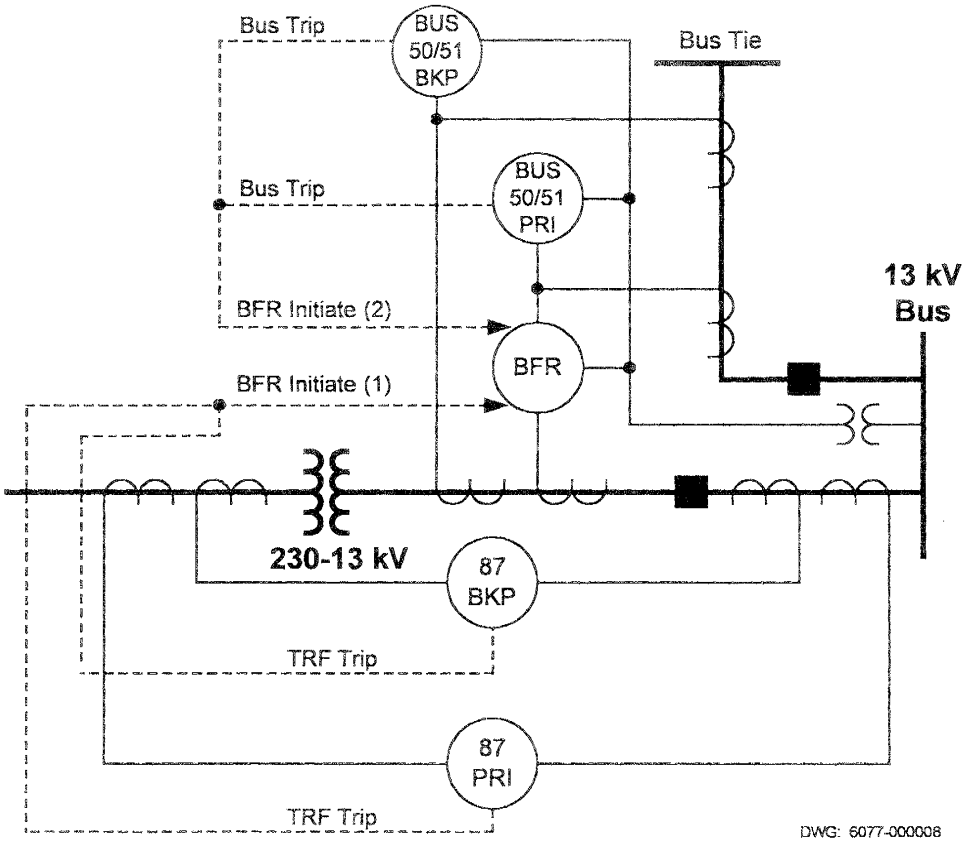

Figure 13: Transformer Low-Side Breaker Failure

SI Control and Data Points

- The transformer low-side breaker relay provides ampere, voltage, and watt/var readings to the SI system. This necessitated a relay with voltage inputs as well as current inputs.

13 kV Bus Tie Breakers

Breaker Failure

A microprocessor-based breaker failure relay is used to provide breaker failure protection for the normally closed 13 kV bus tie breakers. The relay receives two separate breaker failure initiate inputs from the associated bus primary and backup relays and from the primary and backup bus tie relays. If the bus relay input initiates a breaker failure and the breaker failure logic is satisfied, the relay will upset the bus tie backup lockout auxiliary relay that trips and locks out all of the bus tie breakers. Similarly, if the bus tie relay input initiates a breaker failure, the failed breaker logic will upset the bus backup lockout auxiliary that trips and locks out all the bus breakers.

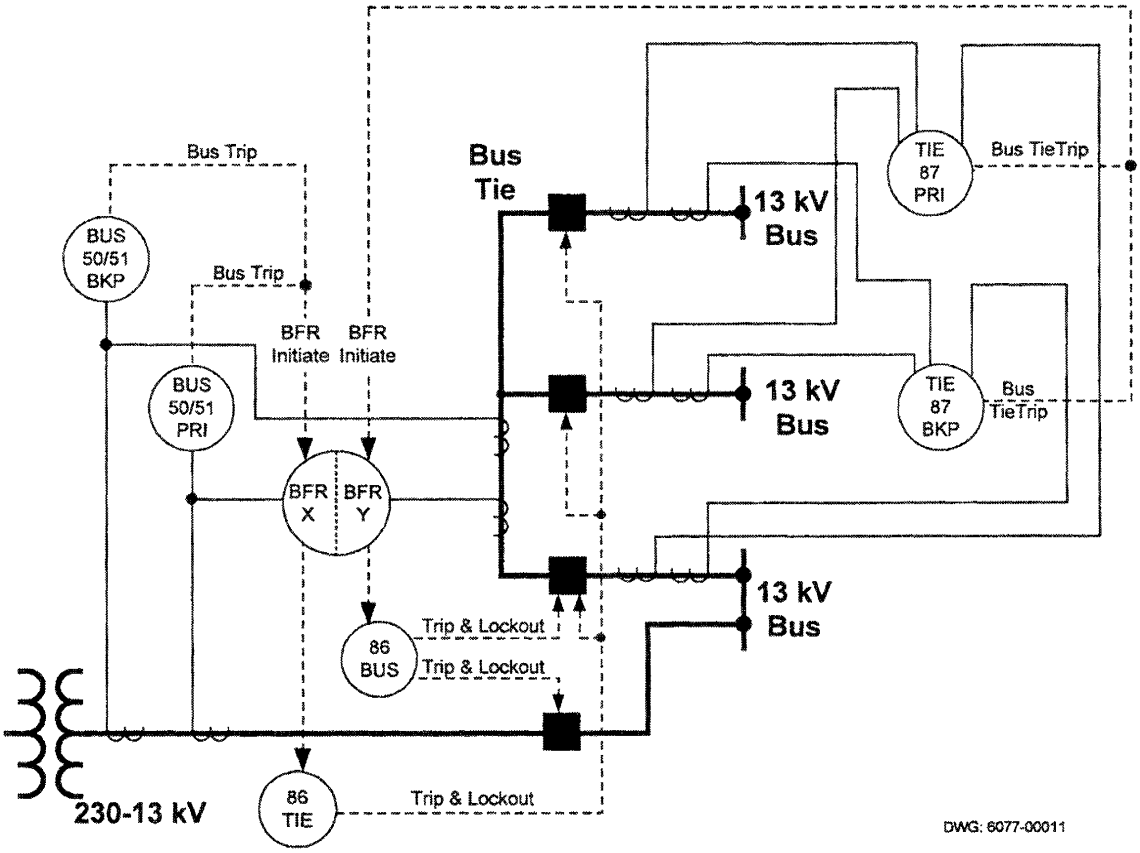

Figure 14: 13 kV Bus Tie Breaker Failure

13 kV Busses

Bus Fault Protection

Redundant microprocessor-based overcurrent relays connected in partial differential CT connections to the two bus sources provide protection for the 13 kV busses. The scheme utilizes a Fast Bus Trip logic similar to the scheme used previously at PECO [3], wherein high-set instantaneous elements from all the feeder relays trip into inputs in the bus relays, qualifying

whether the bus relay definite-time high-set overcurrent elements can trip the bus after a 2.5 cycle coordination time delay:

50P2P, 50G2P = 8.75 A

Phase and ground definite time pickups set to 115% of feeder faults past the line reactors.

67P2D, 67G2D = 2.5 Cycles

Phase and ground definite time delay set to coordinate with feeder torque control input. This coordination time allows the feeder relay time to detect the fault, close output, and assert an input on the breaker relay.

SV2 = .. + (67P2T + 67G2T) * !IN2

Variable SV2 is indication of a bus fault condition. It asserts by either phase or ground definite time overcurrent output assertion, qualified by the absence of the feeder relay torque control input IN2, which if asserted would indicate a feeder fault.

OUT6 = SV2

Element SV2 asserts the output OUT6 to upset the bus LOR, which trips and locks out all breakers associated with bus.

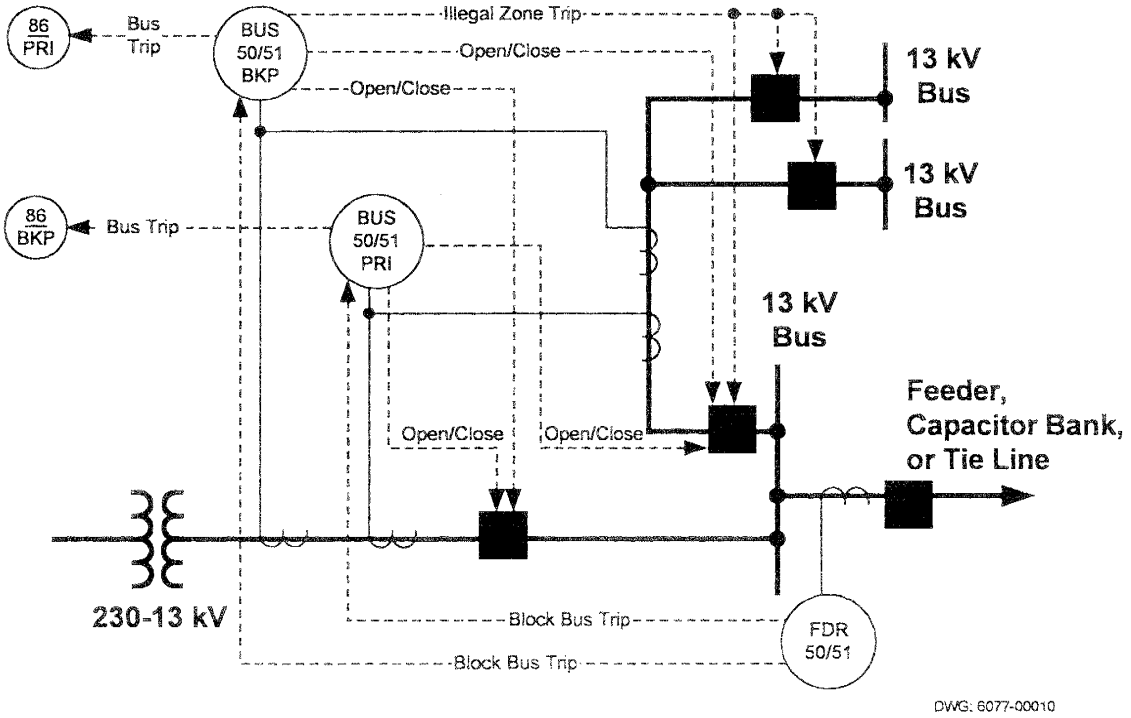

Figure 15: 13 kV Bus Protection and Breaker Control

This scheme was used instead of a full bus differential scheme that would have necessitated installing bus CTs on every feeder. According to the Westmoreland switchgear vendor, the estimated material cost saving resulting from this CT reduction is about $100,000.

Feeder Breaker Failure

Time-overcurrent elements set above the slowest feeder settings trip the bus through lockout auxiliaries, as in PECO's conventional partial differential bus schemes. This provides backup protection for feeder line faults that result in a failed breaker. An improvement to this scheme is provided by the load-encroachment logic in the bus protection relays. This logic enables the phase elements to be set much closer to the feeder phase elements, providing faster backup protection.

The bus relays provide feeder close-in fault breaker failure protection. A feeder breaker failure trip occurs when the bus relay definite-time overcurrent elements remain asserted for the duration of the feeder breaker failure timer, set at 20 cycles:

SV1 = 50P2 + 50G2

Phase and ground definite time element pickups (the same as described above) assert element SV1 indicating the presence of either a bus fault or a close-in feeder fault.

SV1PU = 20.00 Cycles

Feeder breaker failure time delay element SV1 picks up 20 cycles after the fault condition.

SV2 = .. + SV1T

Variable SV2 is indication of bus fault condition. In addition to other fault conditions, it asserts by the output of the feeder breaker failure timer element to trip the bus LOR through output OUT6, as described above.

This logic guarantees a bus tripping always will occur, although with a time delay, regardless of the status of the feeder torque control input, which is ignored in this part of the logic. The bus relay Fast Bus Trip logic necessitates this time-delayed trip as a safeguard against a permanently asserted torque control input that otherwise would have permanently blocked the relay bus trip elements. Because a permanently asserted torque control input would cause all bus trips to be time delayed 20 cycles, a timer in the relay is set to timeout upon a needlessly long torque control input. This timer instigates a trouble alarm, indicating either a short circuit across the torque control input or a failed-while-asserted output contact in a feeder relay.

The feeder relays will drop out their torque-control outputs to allow a faster bus trip through the bus relays Fast Bus Trip logic if the feeder relay detects a breaker failure. Their breaker failure time delay for close-in faults is 12 cycles.

Overstressed Feeder Breaker Clearing ("Illegal Zone")

13 kV busses on PECO's system are normally operated with tie breakers to other busses closed. The most typical bus configuration is a duplex – two parallel transformers supplying associated

busses. With two or more transformers energized into solidly-connected busses, faults in the close-in region between the line reactor and line breaker typically are above the symmetrical rating of the breaker. Consequently, the bus backup relay system uses instantaneous overcurrent elements to trip the bus indiscriminately for close-in feeder faults.

These close-in faults occur most frequently as a result of cable failures of aging underground feeder cables. This area between the feeder breaker and line reactor is nicknamed the Illegal Zone at PECO. Illegal Zone clearings have resulted in approximately seven bus faults per year out of approximately two hundred 13 kV busses.

The Westmoreland design deals with this problem as follows:

- Replacing the underground cables from the line reactor to the breaker
- Upgrading the breakers to 30 kA interrupt duty
- Using the programmable features of both the bus relays and the feeder relays

Even though the feeder breakers are rated for 30 kA symmetrical fault current, with all three transformers energized into the three busses, the total fault current still may exceed 30 kA for Illegal Zone faults. So, the bus relays are wired to trip each of the three bus tie breakers directly. Overcurrent instantaneous elements in the bus relays pick up on fault current values corresponding to 30 kA. These elements trip all three bus tie breakers to reduce the fault current into the feeder breaker so that the feeder relay selectively trips its breaker. All three tie breakers are tripped simultaneously to avoid the need for a breaker failure scheme.

The bus overcurrent elements are qualified by closed breaker indications from all six bus main breakers. The 52a inputs from all of these breakers are brought into programmable inputs on each of the bus relays. Consequently, the Illegal Zone clearing is only enabled when the three busses are loaded from all three transformers:

SV3 = IN1 * IN3 * IN4 * IN5

Variable SV3 is set by the positive assertion of transformer low-side breaker status input IN1 and all three bus tie/transformer low-side breaker status inputs IN3, IN4, and IN5, indicating a fully loaded bus.

50P1, 50G1 = 43.00 A.

Phase and ground instantaneous element pickups are set according to the feeder breaker interrupt rating.

SV4 = (50P1 + 50G1) * SV3

Variable SV4 is set when the instantaneous overcurrent elements indicate a fault near or above the feeder breaker rating with a fully loaded bus.

OUT1 = SV4 + OUT1*IN5

Variable SV4 asserts the output OUT1 to trip one of the bus tie breakers. The output will seal in until IN5 indicates the tie breaker has opened.

OUT2, OUT3 Similar to OUT1.

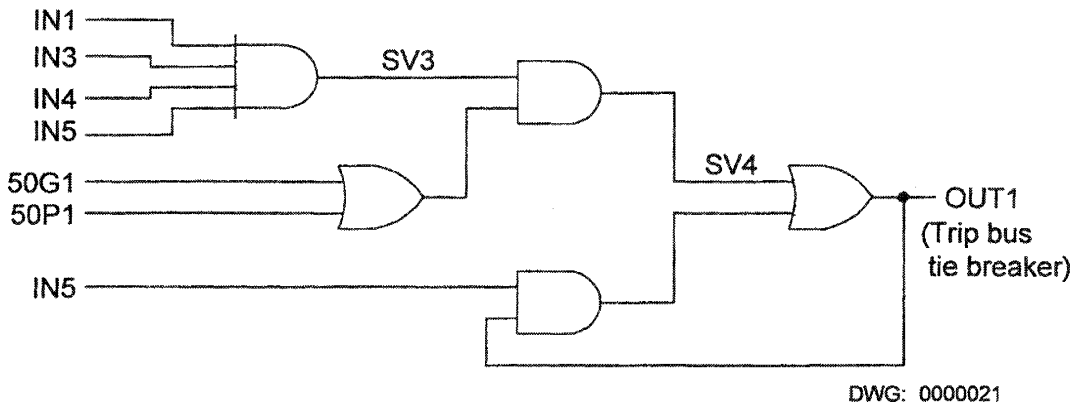

Figure 16: Overstressed Feeder Breaker Clearing Logic

The feeder relays qualify the instantaneous trip of the associated breaker either by the dropout of an overcurrent element set according to the breaker interrupt rating (for the primary feeder relay) or by a timing out of a definite-time timer (for the backup feeder relay).

SI Control and Data Points

- The transformer low-side breaker as well as the bus tie breaker associated with the 13 kV bus provide 52a status inputs to both primary and backup bus relays.
- Each relay also provides open/close control of the same breakers through either breaker bits or remote logic bits set by the communications processors.
- The bus relays monitor the trip circuit of the transformer low-side breaker and provide a bus main Trip Circuit Monitor alarm to the SI system.
- The bus relays monitor the trip circuit of the bus tiebreaker and provide a bus tie breaker Trip Circuit Monitor alarm to the SI system.

13 kV Feeders

One microprocessor-based overcurrent relay per feeder provides primary protection for each of the 13 kV distribution circuits and subtransmission lines. One-half of a microprocessor-based dual universal overcurrent relay provides backup protection. Time-overcurrent and definite-time instantaneous elements provide conventional distribution circuit protection. In addition, high-set instantaneous elements provide torque-control for the bus partial differential relays, allowing for selective clearing of faults in the close-in region, as described above. This is an improvement over PECO's previous bus scheme, which often tripped the bus indiscriminately for close-in faults. PECO estimates that one unnecessary bus trip in ten years can be avoided.

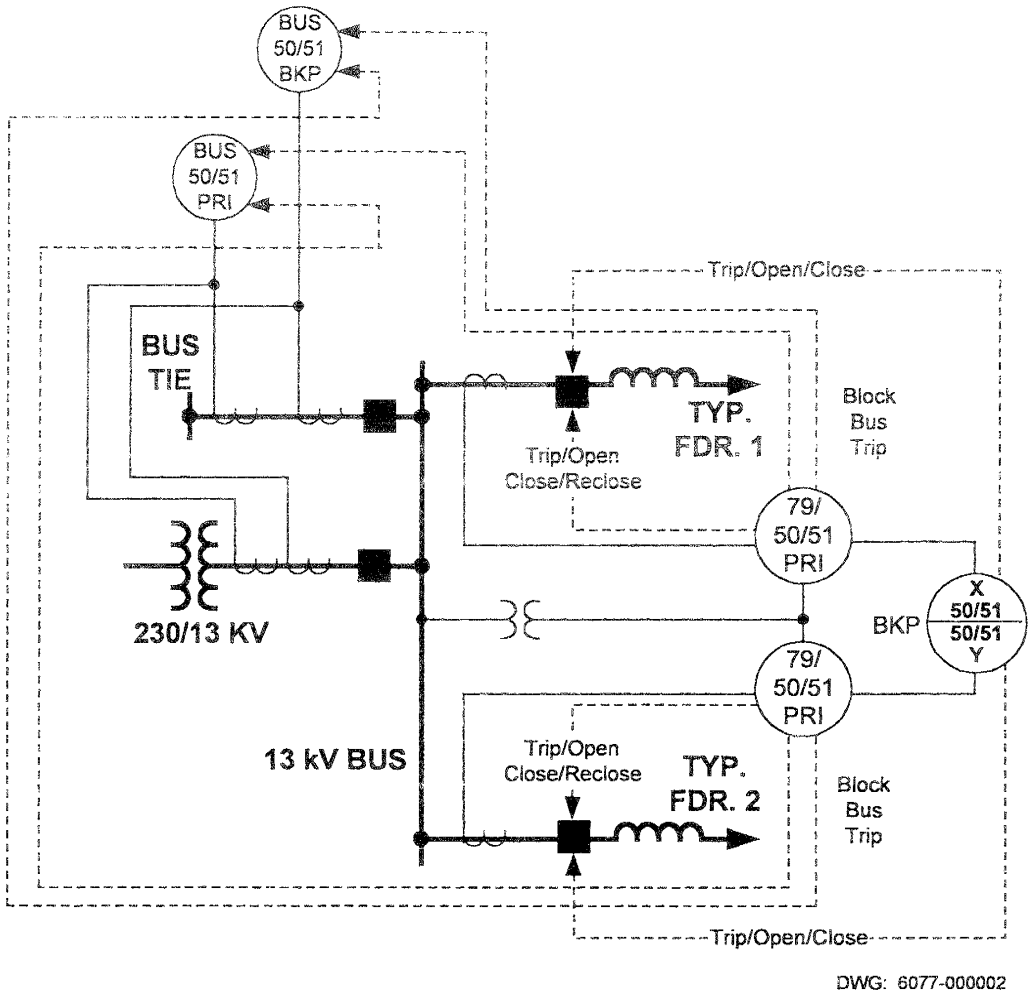

Figure 17: Feeder Protection and Breaker Control

The relays use remote logic bit logic, controlled by the connected communications processors, to implement special setting configurations: reclose on/off, fast trip (hot line maintenance safety settings) on/off. When these remote logic bits are set, a corresponding latching bit is set in order to maintain the configuration after a relay power loss. This latching bit is then used in the relay logic to control the appropriate elements.

Fast trip settings are controlled by latching bit LT2:

SET2	=	/RB2	*Sets latching bit LT2 ON when Remote logic bit RB2 is turned on.*
RST2	=	\RB2	*Sets latching bit LT2 OFF when Remote logic bit RB2 is turned off.*
67P3TC	=	!LT2	*Phase fast trip element 67P3 is OFF when LT2 is ON & vice-versa.*
67G3TC	=	!LT2	*Ground fast trip element 67G3 is OFF when LT2 is ON & vice-versa.*
51PTC	=	LT2	*Phase time element is only on when LT2 is on.*
51GTC	=	LT2	*Ground time element is only on when LT2 is on.*

Auto-Reclose cutoff is controlled by latching bit LT1:

SET1	=	/RB1	*Sets latching bit LT1 ON when Remote logic bit RB1 is turned on.*
RST1	=	\RB1	*Sets latching bit LT1 OFF when Remote logic bit RB1 is turned off.*
79RIS	=	.. *LT1	*Initiate reclose only when LT1 is on.*
79DTL	=	.. + !LT1	*Drive to lockout when LT1 is off.*

These settings allow the special configurations to be switched on and off remotely, without requiring alternate setting groups. Upon receipt of the control message, the microprocessor-based relay remote logic bits are set within 0.5 cycles, with the resulting changed condition reported back to the SI controller in less than 3 seconds after the controller sent the message. This compares favorably to setting group changes that take up to 10 seconds to take effect and be reported back to the SI controller. The use of remote logic bits also saves the relay tester the time that otherwise would have been required to test all the settings in each group.

SI Control and Data Points

- The primary and backup feeder relays provide open/close control of the circuit breaker.
- The primary and backup feeder relays receive breaker 52a status inputs.
- The primary feeder relay provides watts, vars, and current metering data.
- The primary feeder relay provides a breaker trouble status point that combines the following:
    - Trip failure timer for both relay-initiated and externally-initiated breaker openings
    - Close failure timer
    - Trip circuit monitor alarm
      (indicates the trip circuit has an open circuit while the breaker is closed or vice-versa)
    - Battery monitor alarm
      (indicates the battery dc voltage to the relay is above or below set thresholds
    - Opened breaker flashover condition alarm

All of these alarms are maintenance-enhancing improvements over other PECO substations.

13 kV Hunting Park Tie Lines

A microprocessor-based transformer differential relay (primary) and a microprocessor-based overcurrent relay (backup) provide protection for the three 13 kV feeds to Hunting Park Substation. The Hunting Park 13/4 kV transformers also are included in the relay primary zone of protection. As with the other 13 kV feeders, the multifunction overcurrent relay provides bus torque-control. The relay also trips the Hunting Park 4 kV breaker on a breaker failure of the 13 kV feeder breaker as a result of a Westmoreland bus trip.

SI Control and Data Points

- The primary and backup tie line relays provide the same control and status points as those listed above for 13 kV feeders.
- The primary and backup tie line relays provide open/close control of the Hunting Park 4 kV breaker.
- The backup tie line relay receives and reports breaker 52a status inputs from the Hunting Park 4 kV breaker.

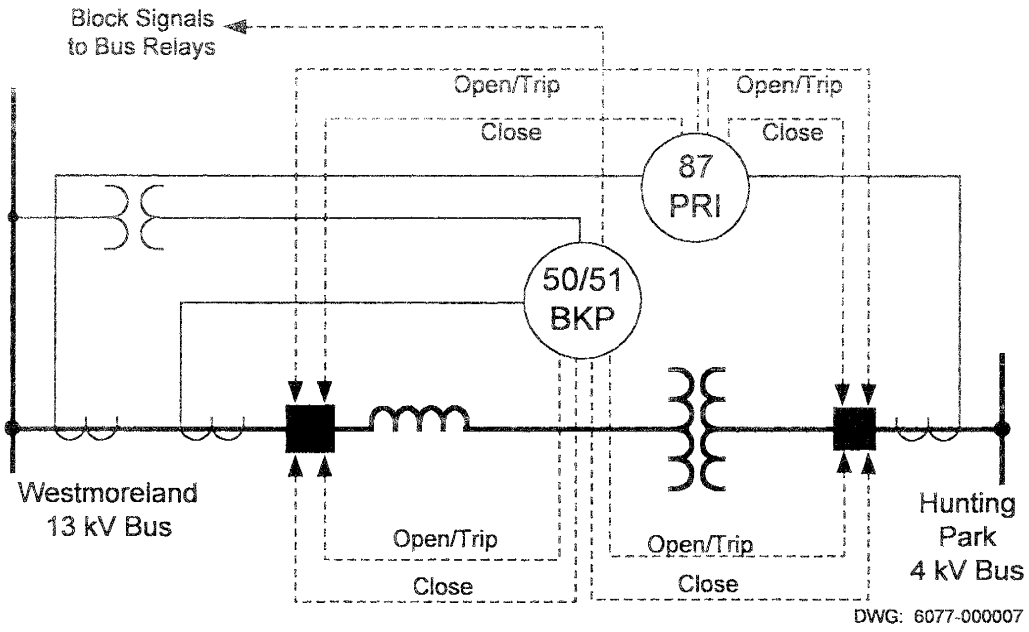

Figure 18: Hunting Park Tie Lines

13 kV Capacitor Banks

The ungrounded capacitor configuration includes two banks of capacitors in parallel, connected to the 13 kV feed through vacuum switches. The switchgear compartment that supplies the banks is protected with a circuit breaker. Two multifunction overcurrent relays provide primary and backup time- and instantaneous-overcurrent protection for the feed and the capacitor banks. Both relays provide torque-control outputs to both the primary and backup bus relays.

One of the two neutral CTs is connected to the residual current input (IN) of one of the relays to provide neutral overcurrent protection. This CT input supplies capacitor bank neutral current to 50N and 51N elements that trip the local vacuum switch when the fault current indicates failure of both banks. Other 50N/51N elements, set more sensitively, alarm to the SI system when there is a failure of one bank.

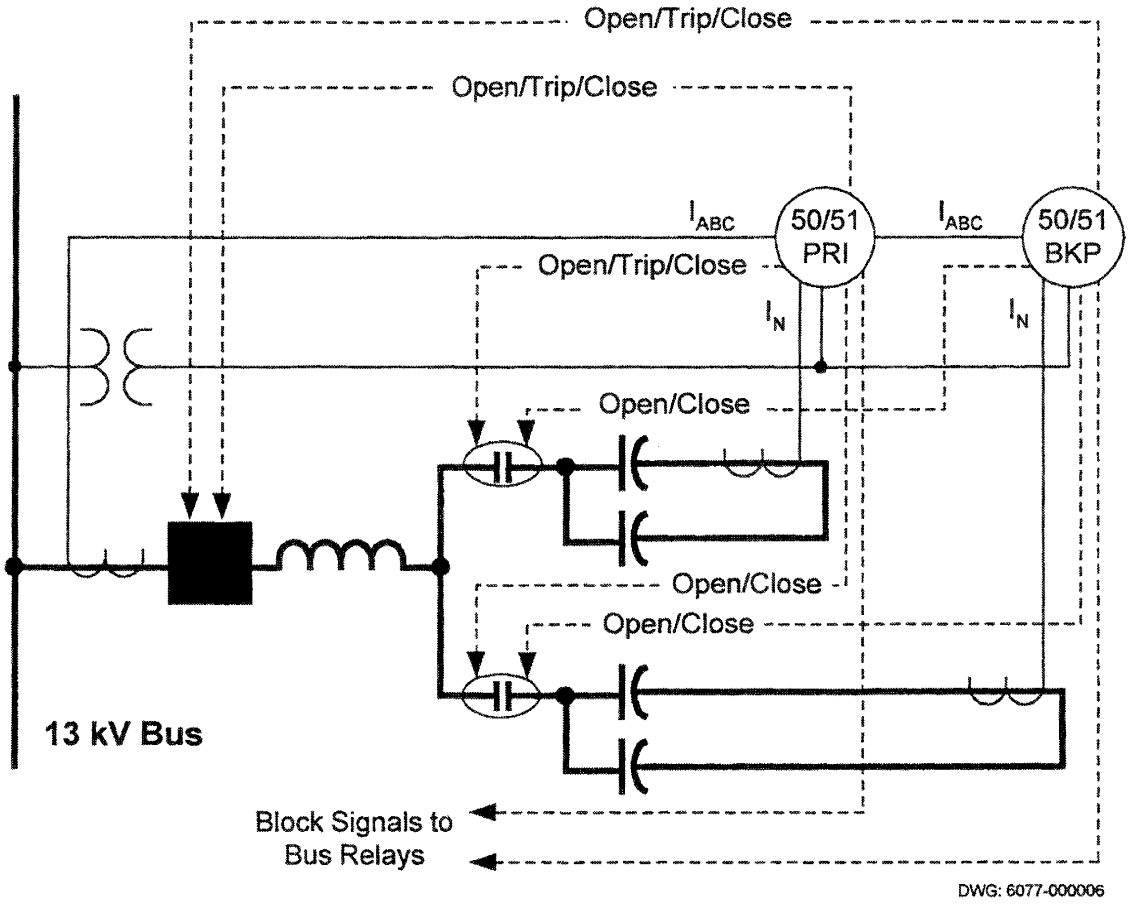

Figure 19: Capacitor Bank Protection/ Control

Both primary and backup relays provide control of the vacuum switches and source breaker. Breaker openings and closings are qualified by both vacuum switches being opened to minimize arcing damage to the breaker. If either switch is closed upon a command to open/close the circuit breaker, the relays will open the closed switch to deenergize the capacitor banks. Breaker closing is also blocked for five minutes after a fault:

SV1 = 51PT + 51GT + 67P1T

Phase and ground time overcurrent elements or the close-in fault instantaneous element assert to set variable SV1.

SV1DO = 18000.00 Cycles

Fault indicator SV1T remains set for 5 minutes after the fault condition SV1 drops out.

OUT1 = TRIP * !SV1 * !(IN3 + IN4) + SV1 * !50P3

Output OUT1 closes into the breaker trip circuit. A Trip command from the operator to open the breaker, with no fault condition present, is qualified by the absence of either vacuum switch status input IN3 or IN4. A fault condition will also trip the breaker if the breaker overstress element 50P3 is not picked up.

OUT2 = CLOSE * !SV1T * !(IN3 + IN4)

Output OUT2 closes into the breaker close circuit. A Close command from the operator will close the breaker 5 minutes after fault indicator SV1 has dropped out (!SV1T) and both vacuum switches are opened as indicated by IN3 and IN4.

OUT7 = (TRIP + CLOSE) * IN3 + /RB5 + LB3 + 51NT + OUT7 * IN3

Output OUT7 closes into the trip circuit of one of the vacuum switches. A Trip or Close command to control the breaker will assert OUT7 to open the switch if IN3 indicates the switch is closed when the command is given. The switch also is opened by remote logic bit command RB5, front-panel command LB3, or by the neutral overcurrent element 51NT. The output is sealed in while IN3 indicates the switch is closed.

OUT8 = /RB6 + LB4 + OUT8 * !(IN3 + SV7T)

Output OUT8 closes into the trip circuit of one of the vacuum switches. A remote logic bit (RB6) or front-panel (LB4) command will close the vacuum switch. The output is sealed in until either IN3 indicates the switch is opened or variable SV7T times out indicating the output has been asserted for 5 seconds.

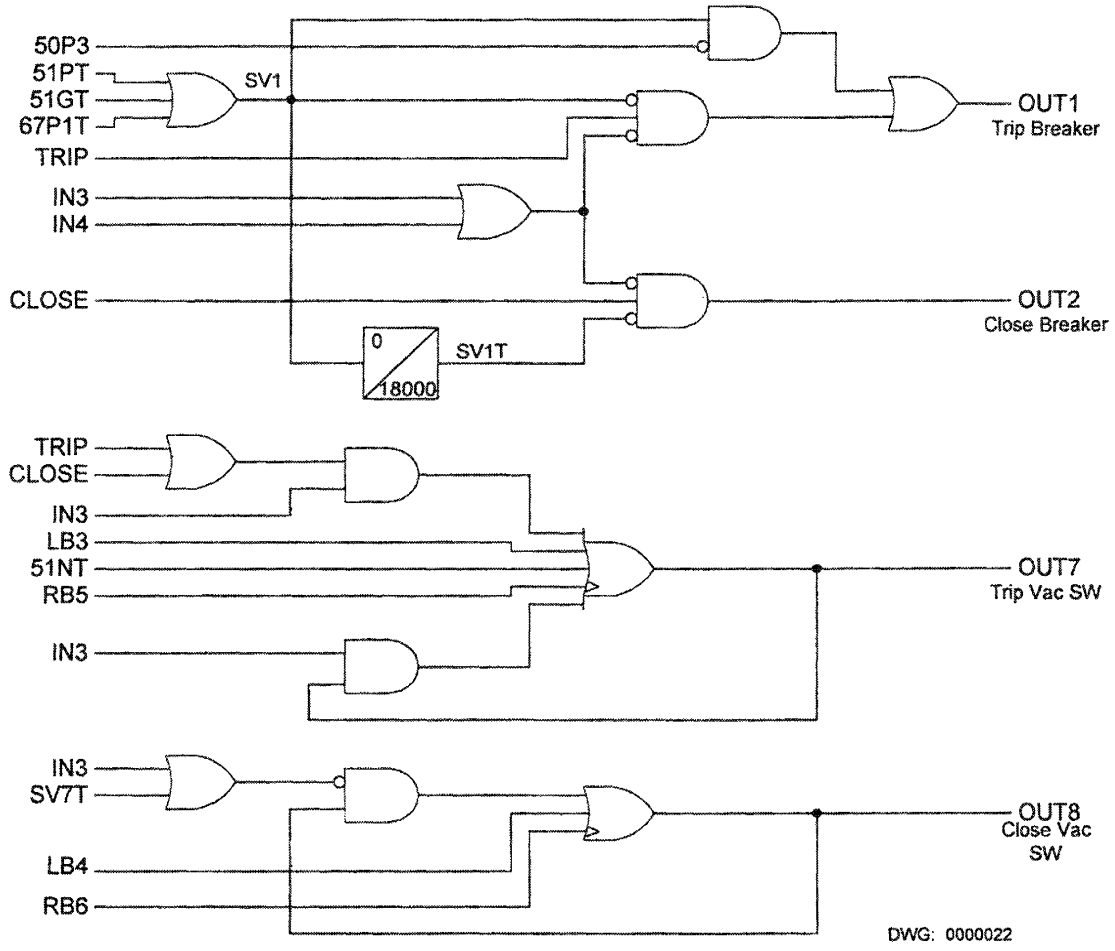

Figure 20: Capacitor Bank Protection/Control Logic

The ability to incorporate these functions in relay logic greatly simplifies the previous electromechanical design. The previous design varied greatly from substation to substation and required a complex arrangement of protective relays, control switches, and auxiliary relays.

SI Control and Data Points

- The primary and backup capacitor bank relays provide the same control, metering, and status points as those listed above for 13 kV feeders.
- The primary and backup capacitor bank relays provide open/close control for each of the vacuum switches, as described above.
- The primary and backup capacitor bank relays receive and report vacuum switch status inputs.
- Both relays incorporate trip circuit monitor alarms and open/close failure timers for each of the two vacuum switches.

Maintenance and Testing Enhancements

The microprocessor-based features of the protective relays used in this substation facilitated the installation and commissioning of the substation in a number of ways:

Relay Settings Management

A relay setting software program provided management and database storage for all of the relay settings derived for all the relays in this substation. The software program establishes serial port communication to each relay either directly through the relay front-panel serial port or by navigating through the communications processor upper and lower tier ports to the rear-panel serial port. The software application is set up as part of the MMI configuration so a relay can have settings downloaded to it from the substation controller. The program compares the downloaded settings against the settings stored in the database. In this manner a total of almost 35,000 relay settings (counting Group 1 settings only) were set and confirmed in the 110 relays used in the substation.

The average time to set each relay was about 10-15 minutes. Entering the same settings manually takes at least twice this time without the accuracy of the automatic method.

Calibration Test

We used a computer-controlled test set with each relay to confirm setting logic and current and voltage threshold values. The test set applies secondary currents and voltages directly to the relay motherboard, bypassing the ac input transformers. This test set works in conjunction with a software application allowing a state-by-state preprogrammed calibration test. This test applies ac currents and voltages as well as dc output voltages to the relay inputs. The test is stored as a software script that is executed against any number of relays of the same type with similar logic settings. The test is used to record output assertions from the relays, store the resultant test times, and record the current or voltage levels when an element picks up.

In this manner, we tested all of the relays thoroughly and quickly. The feeder relays were tested with all of the same test script comprising more than 100 states. The tests took about 10-20 minutes each. These tests would have taken at least one hour per relay using a conventional test method. Since the scripts are stored on disk, the tests can be reexecuted at any time. This method insures consistency. Before, technicians performed tests according to their own philosophy and understanding and obtained inconsistent results.

Loading Test

In addition to the calibration tests, all of the relays were tested under load conditions to confirm phase angle and magnitude values by using the relay meter command. These tests did not require any special test equipment. The test results were stored electronically and analyzed using an analytic software application. The relay microprocessor features, integrated into the remotely accessible SI system, allowed loading tests from a remote location via modem. This remote method resulted in a significant time savings, by eliminating travel time to the substation (about an hour round trip) and test setup time for each relay (about 15 minutes per relay).

CONCLUSION

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 a substation integration (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. Relay failures and breaker trouble, including a number of failure points previously unmonitored, are reported instantly to SCADA operators. Every potential point of data that pertains to a relay operation (i.e., relay elements, current and voltage inputs, auxiliary relay status indications) is instantly available to remote troubleshooters for analysis. This saves engineers and technicians from visiting the substation. The alias feature available in the breaker relay allows intuitive names to be given to programmed elements, facilitating event analysis.

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 MMI controller, and sent to the remote SCADA operators. These features eliminate substation remote terminal units (RTU), transducers, meters, and control switches.

Protection is enhanced by the programmable capabilities of the relays that protect overstressed breakers while minimizing system outages. The 13 kV bus Illegal Zone scheme eliminates the requirement to interrupt all load on a bus for a feeder cable failure. This removes the possibility of an anticipated one Illegal Zone trip per ten years for any of the three Westmoreland busses. 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.

Programmable logic simplifies the design, as in the capacitor bank breaker and vacuum switch control design. This logic eliminates the need for a complex auxiliary relay and control switch design. The Fast Bus Tripping scheme eliminated the need for bus CTs on every feeder and saved about $100,000 in material costs. Relay remote logic bits provided feeder relay Fast Trip and recloser cutoff setting configurations eliminating the need for supervisory control switches. Typical protection scheme designs are reduced, on average, from 4-10 electromechanical relays to two microprocessor-based relays.

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.

All of these features contribute to a more reliable, maintainable, and economical substation.

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BIOGRAPHIES

Mark D. Diehl

Mark obtained his BSEE in 1988 from Drexel University in Philadelphia, PA, a MBA from Villanova University in Villanova, PA in 1994, and a MSEE in Computer Engineering in 1998 from Villanova. He is a Registered Professional Engineer in the state of Pennsylvania and is a member of IEEE. He has worked for PECO since 1988 and has held various positions including Field Engineer, System Engineer, and Relay Engineer.

Robert A. Crognale

Bob obtained his BSEE in 1988 and MSEE in 1996 from Villanova University in Villanova, PA. He is a Registered Professional Engineer in the state of Pennsylvania and is a member of IEEE. He has worked for PECO since 1988 as Field Engineer, Relay Engineer, and now is Project Manager and Lead Responsible Engineer for the Substation Integration project.

James A. Schwenk

After graduating with a BSEE degree from Lehigh University in 1984, Jim was employed by the Philadelphia Electric Company, where he was responsible for distribution and transmission relay engineering for 12 years. In 1996 he was hired as an Application Engineer by Schweitzer Engineering Laboratories, Inc., where his full-time responsibility has been to provide engineering services to PECO and ACC, Inc. for their ongoing substation integration projects.

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