PROTECTING A 138 KV PHASE SHIFTING TRANSFORMER: EMTP MODELING AND MODEL POWER SYSTEM TESTING

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ABSTRACT

This paper describes the protection of a 138 kV, 300 MVA Phase Shifting Transformer (PST) installation, and the issues associated with differential protection stability during external faults that cause PST series winding saturation. In addition, this paper discusses PST modeling using the Electromagnetic Transients Program (EMTP). EMTP modeling is necessary for these complex devices, to verify the protective relaying settings for the particular application and their applicability to different fault scenarios and operating conditions. For the case study detailed in this paper, we verified the relay settings by playing the EMTP transient data back into the protective relays using an open loop approach. From the test data, we made setting changes and other enhancements that increased the PST protection system security for external faults. Finally, we analyzed event report data captured by numerical relays during an actual external line-to-ground fault that occurred after we placed the PST in service.

KEYWORDS

Phase shifting transformer, phase-angle regulator, digital relay, differential protection, transformer protection.

INTRODUCTION

Increased energy demand, deregulation, and privatization of the power supply industry often cause utilities to operate and stress transmission systems to, and occasionally beyond, their original design capabilities. Maintaining reliable, secure, and economical operation of interconnected networks under these conditions requires that transmission operators better control and manage network power flows.

Specially designed power system equipment can control the flow of active and/or reactive power in interconnected power systems by affecting one or more parameters. Traditionally, the only device available to power system operators that controlled both the magnitude and direction of power flow was the PST. Today other devices are also available to control network power flows, such as unified power flow controllers, thyristor-controlled phase-angle regulators, and interphase power flow controllers [1]. This paper focuses on the PST.

Equation (1) shows the equation for active power transferred from sending Bus S in the network to receiving Bus R through Reactance X_L, connecting the two buses.

$$P = \frac{|V_S||V_R|\sin\delta}{X_L} \qquad \text{Equation 1}$$

Where

P = Active power from bus S to bus R
$\overrightarrow{V_S}$ = Sending end bus voltage
$\overrightarrow{V_R}$ = Receiving end bus voltage
X_L = Reactance of the transmission line
δ = Angle by which $\overrightarrow{V_S}$ leads $\overrightarrow{V_R}$

The PSTs control and alter power flows, alleviate line overloads, change parallel-line load sharing, reduce curtailments, and facilitate transfers of energy throughout regional transmission interconnections. The PST controls the flow of active power by varying the phase angle δ between the two buses. The PST varies this phase angle by adding a regulated quadrature voltage to the source line-to-neutral voltage. Note that the PST obtains quadrature voltage for regulating a particular phase from the phase-to-phase voltages of the other two phases. Figure 1 shows how a PST shifts an A-phase angle using the quadrature voltage derived from B-phase and C-phase voltages. Shifting the angle of B-phase and C-phase voltages is similar. The PST load tap changer (LTC), located in the secondary winding of the exciting unit, controls the amount of phase angle shift by changing the magnitude of the quadrature voltage. Note that this quadrature voltage is impressed on the delta secondary winding of the series unit. The exciting-unit secondary winding quadrature voltage is then reflected to the primary winding of the series unit. Depending on LTC tap position and connections, the quadrature voltage adds or subtracts from the source-side primary voltage to create the desired angular phase shift between the source and load side of the PST.

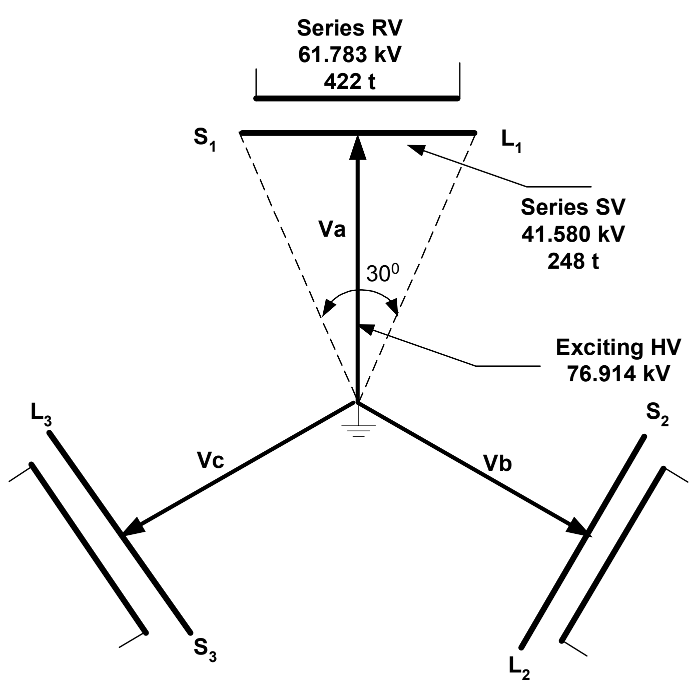

Figure 1 Series- and Exciting-Unit Voltage Phasors

PSTs are built and configured in various ways to provide either a fixed or a continuous variable phase shift [2], [7]. Some designs also control magnitude. The PST described in this paper is the conventional Delta Secondary Series Winding/Grounded-Wye Exciting Winding with LTCs allowing phase angle variations of 30° in a total of 32 steps. This PST also includes windings to provide voltage regulation by controlling the magnitude of the line-to-neutral voltage. The PST is constructed in two units mounted in separate tanks: a series unit and an exciting unit. The series-unit secondary winding is delta connected, while the center tap of the series-unit primary winding is connected to the primary winding of the exciting unit. The exciting unit is connected grounded-wye-grounded-wye. Figure 2 shows the simplified PST connections.

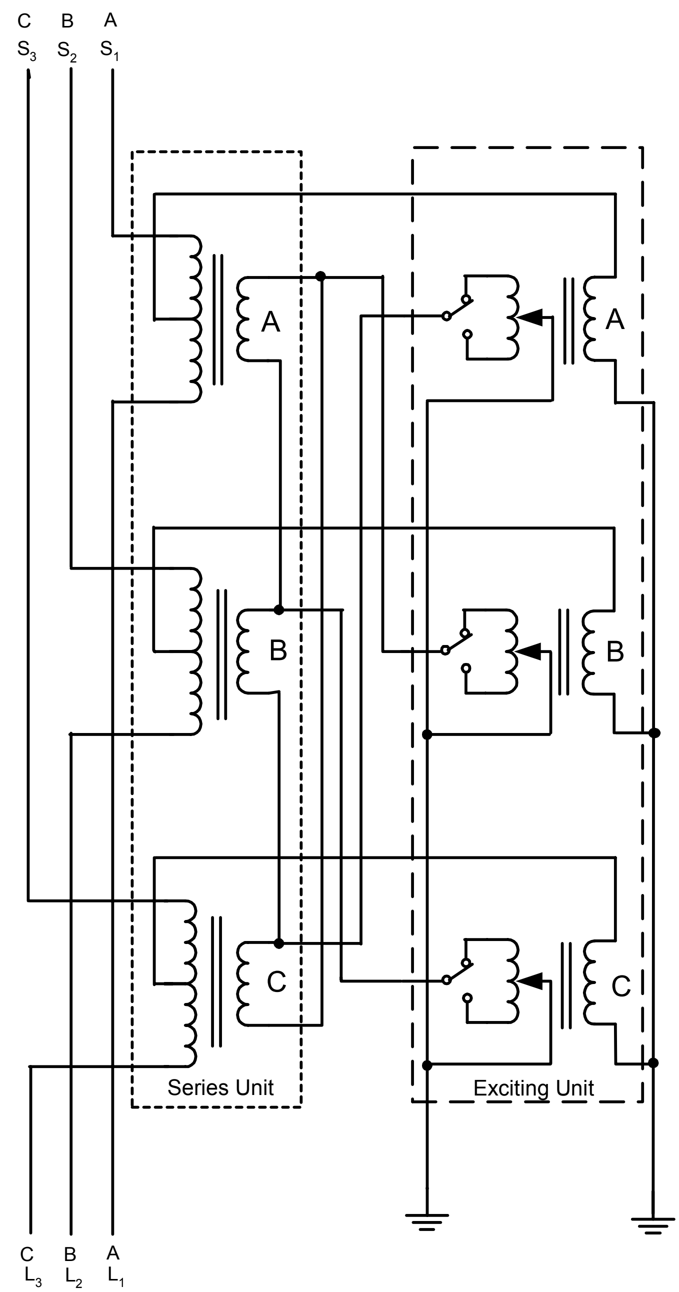

Figure 2 Phase Shifting Transformer Winding Connections

To provide an effective protection scheme for this PST, we must first understand the fundamental operation and electrical characteristics of the phase shifting transformer. From this understanding, we can then evaluate protection schemes.

PHASE SHIFTING TRANSFORMER PROTECTION

The particular PST discussed here is protected by two numerical current differential relay systems, a pair of multifunction distance relays configured in a Permissive Overreaching Transfer Trip (POTT) scheme, two Buchholtz-type relays for the series- and exciting-unit transformer tanks, and LTC sudden pressure relays. Additional protection for some PST faults is also provided by the numerical pilot relaying and distance/ground backup systems that protect a short 138 kV underground cable, which is in series with the PST. The overall PST protection relay system is divided into two subsystems, each with separate ac and dc inputs for increased reliability.

The first relay subsystem receives dc power from the primary dc panel board. Any relay operation picks up the primary lockout relay, which in turn trips the appropriate local circuit breakers, initiates breaker failure protection, sends a transfer trip signal to trip the remote-end circuit breaker, stops local blocking signals of the cable/PST directional comparison blocking pilot relaying system, and inhibits PST fan/pump operation. The second relay system receives dc power from another dc panel board. Any relay operation picks up the secondary protection system lockout relay, which provides functionality identical to that of the primary lockout relay.

Primary Current Differential Relay System:

The primary differential relay (Device 87P) is connected as shown in Figure 3. Its main function is to provide protection for phase-to-ground and multiphase faults in the primary windings of the PST series and exciting units. Device 87P cannot detect faults on the secondary windings of the PST series and exciting units. To provide phase and ground fault protection for the secondary series- and exciting-unit windings, a second differential relay is applied (Device 87S), which is functionally identical to Device 87P, but connected as shown in Figure 4. Device 87P receives its current inputs from the primary windings of the PST. The primary differential relay system is unaffected by series-unit winding saturation caused by overvoltages during nearby external faults.

The current differential relay system has independent restraint and unrestraint current differential elements. The restraint element has a unique dual-slope variable percentage differential characteristic that provides more sensitive and secure protection than traditional current differential protection. The dual-slope characteristic compensates for current transformer ratio mismatch, CT ratio errors, and CT saturation. A separate unrestrained differential element provides fast tripping for high-magnitude internal faults. The differential relay is secure against conditions that could cause incorrect relay operation resulting from system or transformer events. Even harmonic elements (second and fourth), complemented by an element that measures the dc offset, offer security against inrush currents during PST energization. The even harmonic element offers a choice between harmonic blocking and harmonic restraint. A fifth harmonic element is also available, and can be used to prevent incorrect relay operation for allowable overexcitation conditions. The second, fourth, and fifth harmonic element thresholds are independently settable. DC blocking and harmonic restraint features are independently enabled. For each of the four windings, the multifunction differential relay provides overcurrent phase, residual, and negative-sequence elements with instantaneous, definite-time, and inverse-time characteristics. The differential relay also offers current transformer and PST connection compensation programmability to accommodate phase shifts in the transformer or CTs, or to remove zero-sequence currents from the secondary circuits. This same device also offers programmable input and output contacts, and enhanced logic control equations that permit anyone to develop custom control schemes.

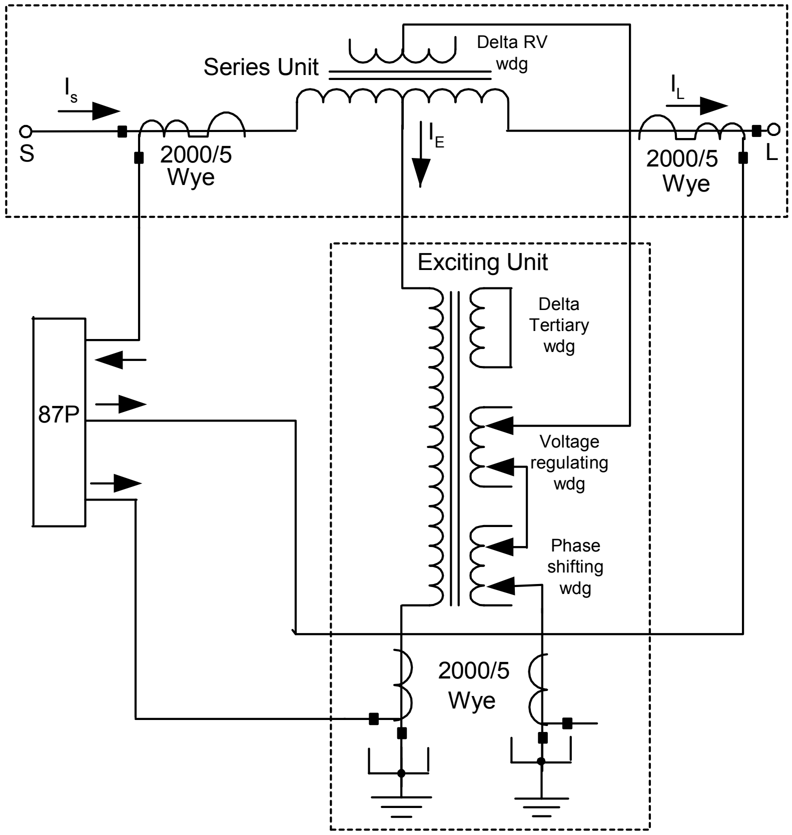

Figure 3 Device 87P Connection Diagram

Three CTs from the neutral side of the exciting unit primary windings are connected to the third input of the 87P. The third winding input of the 87P provides information to the main differential function and is also programmed to provide nondirectional residual overcurrent protection for ground fault protection of the primary windings of the PST exciting and series units.

Secondary Current Differential Relay System:

The secondary current differential system, Device 87S, is functionally equivalent to the primary differential relay system. Its main function is to provide protection for faults in the secondary windings of the PST series and exciting units.

Device 87S receives CT currents from the source and load side of the PST and from the neutral side of the secondary winding of the exciting unit. The relay is connected as shown in Figure 4. The CTs for the secondary differential relay system are connected such that the series-unit source and load currents flow into the polarity side, and the exciting-unit secondary winding currents flow out of the polarity side of Device 87S respective inputs. The exciting-unit secondary winding current is balanced against the sum of the series-unit primary source and load currents in the PST secondary differential relay system. This differs from the approach we use in a conventional three-winding power transformer differential protection system, where the CT ratios and tap selections are based on balancing the differential relay two-windings at a time.

The CT connections and current balancing in the secondary differential relay system are of utmost importance. You must determine the CT ratio requirements and connections under PST full load current conditions and with the LTC set at neutral and at maximum phase shift tap positions. References [2, 5-7] discuss in great detail how to select the CT ratio, relay taps, and CT connections for the secondary differential relay system. In our application, all CTs to the 87S are wye connected as shown in Figure 4. However, individual CT input connection compensation settings in the numerical relay adjust for the fact that the series and load side currents must be delta connected, and the neutral-side exciting-unit secondary CTs must be wye connected.

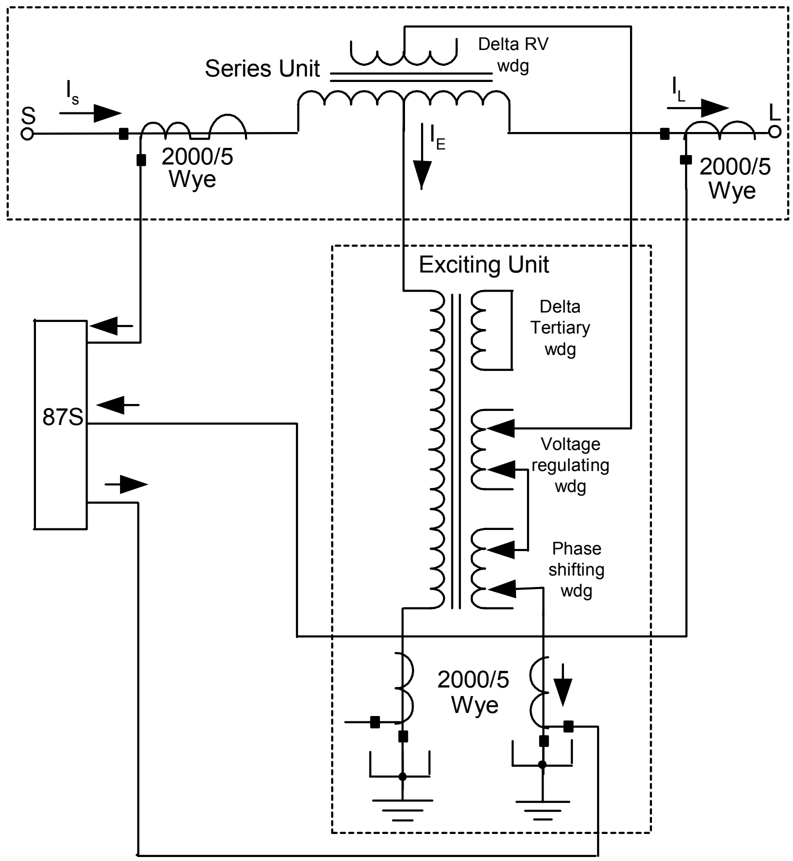

Figure 4 Device 87S Connection Diagram

The voltage presented to the PST series unit for system faults depends on many factors: the system source impedances, fault location, type of fault, and fault point on wave. In addition, PST series-unit impedance, voltage rating, saturation characteristic, and LTC position affect winding voltages. For the PST we modeled, the series-unit winding has an impedance of 3.43 ohms and a 41.58 kV rated voltage. This rated voltage equals the quadrature voltage necessary to produce the desired 30° phase shift. Because this voltage is about 52 percent of the system line-to-neutral voltage, the series-unit transformer windings can be subjected to an overvoltage or overexcitation condition.

An overvoltage condition of the series unit during an external fault can cause series-unit saturation and upset the ampere-turn coupling between the primary source and load windings and the secondary winding of the series unit. Series-unit saturation can cause incorrect 87S operation for external faults because one input of the secondary differential relay system is connected on the secondary winding of the series unit. Therefore, you should evaluate whether series-unit saturation is possible. If series-unit saturation is a problem, determine appropriate relay settings to avoid misoperations for nearby external faults. Some relay settings options are: desensitize the 87S, detect series-unit overvoltage/overexcitation using the presence of fifth harmonics to block tripping of the 87S device during the overvoltage condition, or use information from other devices with directional elements to block operation of the 87S device.

A simple calculation method provides a quick answer as to whether series-unit saturation must be considered. From short circuit studies, determine the voltage developed across the series-unit primary winding for various faults at the series-unit source and load side of the PST. Be sure to consider strong source (lowest source impedance), and minimum and maximum PST impedances. If you determine that series-unit saturation is possible, then you know you must perform further studies to set the 87S properly. EMTP is a valuable tool for performing these studies. We discuss the modeling aspects of the PST later in this paper.

Backup Ground Fault Protection:

Traditionally, two ground overcurrent relays are applied in the neutral of the exciting-unit primary and phase shifting windings for backup PST ground fault protection [5]. You must then determine if the ground overcurrent relays need to coordinate with other nearby ground relays for external faults and whether these same elements require harmonic restraint supervision to prevent overtrips during PST energization [4].

In this application, we take advantage of ground overcurrent elements available in the multifunction differential relays to provide the necessary elements for PST ground fault backup protection. The third winding input of device 87P is programmed as a nondirectional residual overcurrent function to provide ground overcurrent protection for the PST exciting and series units. The PST exciting unit has a tertiary delta-connected winding that provides a low impedance path for zero-sequence current to flow during ground faults external to the PST protection zone. For this reason, the ground overcurrent relay element is coordinated with system ground overcurrent relays.

The current differential relay applied in this installation has second and fourth harmonic percentage restraint elements that can be programmed to supervise the ground overcurrent elements. However, the system operator decided not to apply this particular function based on earlier operating experience with PST protection. This decision may change pending further experience with, and performance analysis of, the design.

Permissive Overreaching Transfer Trip Protection:

Two multifunction numerical distance relays (Devices 11-1 and 11-2) provide an additional level of phase and ground fault protection for the PST. Phase distance, ground distance, and directional overcurrent elements are used in a POTT mode to provide high-speed PST protection for phase-to-ground and multiphase faults. The POTT scheme does not use a communications channel for the permissive signal. Instead, the permissive trip keying and receive signals are hardwired because both relays are located in the same control house panel. Instantaneous and time-delayed phase distance and ground distance elements, and an inverse-time nondirectional ground overcurrent element provide additional PST protection.

Reverse-looking phase and ground distance elements and reverse-looking directional ground overcurrent elements are programmed to block the operation of the secondary differential relay system (Device 87S) during external faults. The dropout time of these elements is extended for a number of cycles to provide additional security to the secondary differential relay system.

Buchholtz and LTC Sudden Pressure Relay Protection:

Buchholtz-type relays are applied in the series and exciting-unit transformers. Sudden-pressure relays are also applied in the LTC compartments of the exciting-unit transformer. These relays provide PST protection for turn-to-turn faults not detected by the PST differential, distance, or overcurrent protection functions. Sudden-pressure relays are very sensitive to low- or high-energy arcs within the transformer LTC. Their inverse-time operating characteristic provides high-speed operation for severe internal transformer faults and a slower operation for low-energy faults.

PHASE SHIFTING TRANSFORMER EMTP MODEL

In our studied PST application, short-circuit fault studies indicated that series-unit saturation was possible. Therefore, we decided to use EMTP modeling of the PST to verify the differential relay stability during series-unit winding saturation, to verify the ability of the protection to properly detect internal transformer faults, and to verify the proposed CT connections. This was the first time the system operator had applied digital relay technology for complete PST protection. To verify the proposed in-service relay settings, we used EMTP data converted to COMTRADE file format using a readily available open-loop playback test system.

Modeling PSTs with EMTP is complicated because it involves several windings and mutual coupling between windings. At minimum, the EMTP model must represent the correct phase shift, the positive-sequence impedance at different exciting-unit secondary winding tap positions, the correct zero-sequence PST impedance, and the series-unit saturation characteristic.

The PST is modeled as two separate units using transformer models and other elements available in EMTP. Interconnection of the series and exciting units is done externally. Transformer manufacturer test reports are used to determine the parameters necessary for modeling development. The biggest challenges in modeling this device were insufficient manufacturer data and converting the actual transformer test report data to the level of data needed to adequately model the PST. The scope necessary to address all of the modeling details is beyond that permitted in this paper. However, we address some important points here because very few references discuss the use of EMTP to model PSTs [8].

We modeled the series unit as a three-winding transformer with the saturation characteristic placed on the delta RV winding of the series unit because 67 percent of the SV winding turns are located closest to the series-unit transformer core. The exciting unit was also modeled as a three-winding transformer with one primary winding and two secondary windings: the phase shifting and tertiary windings. The voltage-regulating winding is not modeled because it does not substantially alter the simulation results. Also, the regulating winding does not pose any additional concerns from a differential protection point of view.

Items needing close attention in modeling the PST in EMTP are:

- Correct representation of the positive- and zero-sequence impedances for the series and exciting units.
- Proper leakage reactance data of the secondary winding of the exciting unit, for the different phase shifting tap positions and turns ratio.
- Correct MVA rating of the series and exciting units.
- Proper external connections between the series- and the exciting-unit phase shifting windings, to provide the correct phase shift at all LTC positions.

- Series-unit saturation characteristic model.
- Appropriate system source voltages and impedance data.

The transformer manufacturer provided the test report data for the overall PST but not for each separate unit. This created a problem in the model development, because we needed to derive other data from these test reports to create an accurate model.

The PST ratings for our application were:

Rated power:	300 MVA
Rated voltage:	138 kV / 138 kV
Rated current:	1255 A / 1255 A
Rated frequency:	60 Hz
Volt. Regulation:	±5%
Phase angle:	$\pm 30^{\circ}$

Series Unit:

SV winding:	(142 + 142) = 248 turns
SV voltage:	41,579 V
RV winding:	422 turns
RV voltage:	61,783 V

Exciting Unit:

Exciting wdg:	414 turns
Phase shift wdg:	192 turns = (16 steps x 12)
Tertiary wdg:	56 turns

You must determine the proper MVA and winding voltage ratings for each unit because the series- and exciting-unit transformers are modeled as two separate transformers in EMTP.

The MVA rating of the series unit is:

$$MVA_{3ph} = 3.0 \text{ x } 41.579. \text{ x } 1.255 = 156.545 \text{ MVA}$$

From Figure 1 we can calculate the voltage ratings of the exciting unit:

$$V_{exc} = (138.0 \text{ kV} /\sqrt{3}) \text{ x } \cos(30°/2) = 76.959 \text{ kV}$$

Similarly, the exciting-unit current rating is given by:

$$I_{exc} = 2.0 \text{ x } 1255 \text{ A x } \sin(30°/2) = 650 \text{ A}$$

Therefore, the exciting-unit MVA is:

$$MVA_{ecx} = 3.0 \text{ x } 76.959 \text{ kV x } 0.65 \text{ kA} = 149.986 \text{ MVA}$$

The positive-sequence impedance of the PST series unit is different at different LTC positions (Figure 5) because of variations of the leakage impedance of the exciting-unit secondary phase shifting winding at different LTC taps. This impedance variation must be reflected in the EMTP model. Because the manufacturer does not provide the phase shifting winding leakage impedance at every tap position, we must derive it from the series-unit positive-sequence impedance values.

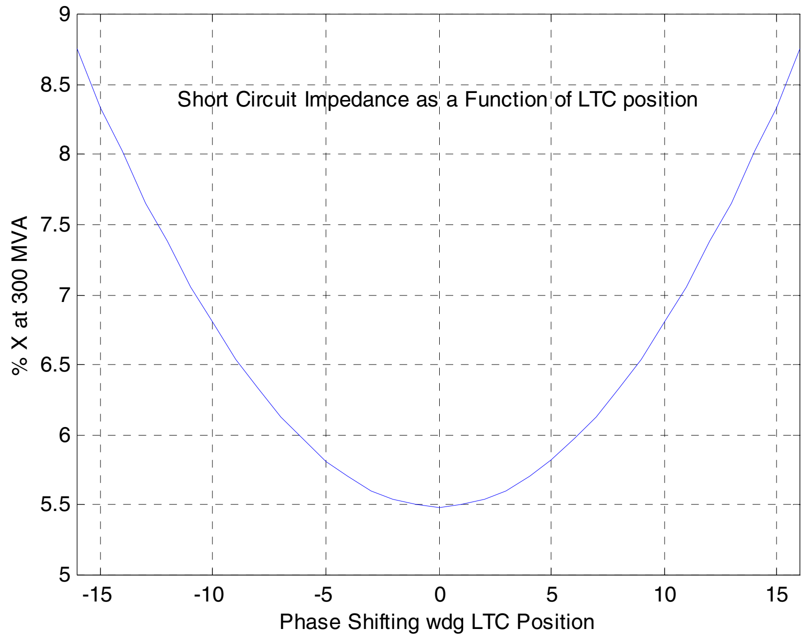

Figure 5 PST Positive-Sequence Impedance Graph

The phase shifting leakage impedance is reflected back to the series-unit positive-sequence impedance by the square of the turns ratio of the series-unit transformer. Therefore, to calculate the exciting-winding leakage ohms at LTC position 16A, first find the impedance difference, ΔX_{S1}, of the series unit between positions 16A and N (neutral or zero position). For this PST, the positive-sequence impedance at position 16A is 8.75 percent at 300 MVA and 138 kV, which is equal to 5.56 ohms. At the neutral position the positive sequence impedance is 5.40 percent, or 3.43 ohms.

$$\Delta X_{S1} = 5.56 - 3.43 = 2.13\ \Omega \text{ primary}$$

Dividing the value for ΔX_{S1} by the square of the turns ratio of the series-unit turns ratio, taking into consideration the fact that the series windings (SV) are wye connected and the regulating windings (RV) are delta connected, yields a value of 1.5676 ohms. This is the appropriate leakage impedance to use for the 16A tap position. You can determine the resistance value at any tap position by multiplying the phase shifting winding ohms/turn resistance by the number of turns in each LTC step. For this particular PST there are 12 turns/step for a total of 192 turns at the 16A LTC position.

The zero-sequence data provided by the manufacturer were given by four different zero-sequence tests involving both the series and exciting units. The manufacturer provided data for the following tests:

1. Series-unit source side excited with zero-sequence voltage with the series-unit load side open. The impedance for this test is 0.691 + j 14.25 ohms.

2. Series-unit source side excited with zero-sequence voltage with the series-unit load side short-circuited. The impedance for this test is 0.076 + j 3.153 ohms.

3. Series-unit load side excited with zero-sequence voltage with the series-unit source side open. The impedance for this test is 0.717 + j 14.89 ohms.

4. Series-unit load side excited with zero-sequence voltage with the series-unit source side short-circuited. The impedance for this test is 0.079 + j 3.153 ohms.

To calculate the zero-sequence equivalent circuit for the series and exciting units, we must consider the fact that the exciting unit has a tertiary winding that is closed during these tests, and that the RV winding of the series unit is also connected in delta. As Figure 6 shows, the resulting zero-sequence equivalent is derived from the test data.

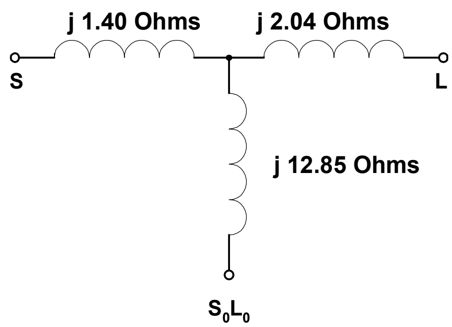

Figure 6 PST Zero-Sequence Equivalent Circuit

Note that the series-unit zero-sequence impedance value is very close to the positive-sequence impedance value and that the exciting unit is a strong source of zero-sequence current for system faults. Therefore, the exciting-unit ground backup element must coordinate with the other ground relay elements in the nearby transmission lines. Also important: the zero-sequence impedance of the PST does not change substantially with the different tap positions of the phase shifting winding. The exciting-unit zero-sequence impedance is placed in the tertiary winding in the model, taking into consideration the appropriate turns ratio between the exciting-unit primary and tertiary windings.

The series excitation characteristic conversion from the manufacturer data to the model is also very important. The series-unit excitation data are listed in Table 1. In addition, the excitation of the series unit at 100 percent voltage is 1.59 Tesla and the air-core reactance is 10.9 ohms/phase at a saturation point of 2.1 Tesla.

Table 1 Series Unit Excitation Data

Rms Voltage in %	Rms Current in Amperes
5.00	0.02
50.00	0.04
100.00	0.31
117.20	1.10
125.80	4.00
132.00	7487.00

You must use an EMTP auxiliary routine to convert the rms saturation data of the PST series unit to peak flux versus peak current data before using it in the model. The input data in the EMTP conversion routine must be given in per-unit voltage and per-unit excitation current. Note that the model requires a point on the excitation curve deep into saturation. This point is very critical in modeling saturation characteristics of iron-core transformers, such as power transformers or CTs. Using a voltage of 9.4 per unit and an air-core reactance value of 10.9 ohms/phase results in a calculated excitation current of 63.248 per unit.

MODEL POWER SYSTEM TESTS

We developed numerous EMTP test cases for various types of faults internal and external to the differential zone of protection. We then converted each EMTP file output to a COMTRADE format. Next, we loaded the COMTRADE file into a playback test system connected to the relay scheme being tested: two differential relay systems and the POTT system. The MPS testing revealed the need to make some setting adjustments for this installation.

Performance of the secondary differential relay (87S) is a concern for this installation because of series-unit saturation for external faults on the load side of the PST. The PST source-side system is stronger than the load-side system in this application. Early stages of testing necessitated a few setting changes such as Winding 1 and Winding 2 compensation settings, and a differential TAP setting for Winding 3 from 5.89 to 1.83. As we discussed earlier, a pair of numerical distance relays provides PST protection using a POTT scheme and backup distance and overcurrent elements. The reverse elements from this pair of numerical relays (Devices 11-1 and 11-2) provide additional security to the secondary differential relay system by blocking the 87S device during external faults.

No incorrect operations occurred during testing of the differential relay systems. However, close inspection of the test reports indicated that the differential relay system could misoperate during external faults in an adjacent transmission line. After the line breaker clears the fault, the series-unit transformer is still recovering from saturation and can cause incorrect 87S operation. Because incorrect operation is possible for several cycles after the external fault is cleared, it is critical that the blocking signal from Devices 11-1 and 11-2 be maintained after reverse element dropout, using the multifunction relay programmable logic and timers. A programmable fifth harmonic element is available in the differential relay for blocking 87S relay operation for a short period of time during series-unit transformer overexcitation conditions. The 87S differential relay system operated reliably for all internal faults. Our testing also showed that increasing the slope from 30 percent to 40 percent in both 87P and 87S was necessary to ensure security. The primary differential relay system performed well for internal and external faults.

The permissive overreaching relaying scheme operated reliably and securely for all tested scenarios.

IN-SERVICE OPERATING EXPERIENCE

The studied PST has been in operation since the fall of 2001. In January of 2002, a single-line-to-ground fault occurred on the 138 kV underground cable that was in series with the PST. This fault was external to the PST zone of protection and within the overall cable/PST zone of protection. Our analysis of current differential event reports indicated correct restraining by both primary and secondary differential relay systems. In addition, our analysis of event reports captured by the pair of numerical distance relays (Devices 11-1 and 11-2) indicated correct operation of the POTT scheme and proper blocking of the secondary differential relay system by the reverse-looking directional elements of Devices 11-1 and 11-2.

Figure 7 and Figure 8 show the performance of the numerical distance relays that make up the POTT relaying scheme. Device 11-2 detects the fault as a C-phase-to-ground fault within the zone of the overreaching Zone 2 element, labeled ZCG, in about one power system cycle. Relay output contacts three and four are programmed as the permissive tripping signal keying contacts. The second digital trace in Figure 7 (labeled OUT 3&4) indicates that Device 11-1 sent a permissive trip signal to Device 11-2. From Trace 1 (labeled IN 7&8) in Figure 8 we see that Device 11-2 receives permission to trip, but never produces a trip because the fault is external to the PST zone of protection and the reverse-looking Zone 3 is picked up as seen in the last digital trace, labeled ZCG.

Further analysis of Device 11-1 and 11-2 relay event reports provided useful data from which we calculated and verified the positive- and zero-sequence impedance of the PST. In addition, we were able to calculate the negative- and zero-sequence source impedance data behind Device 11-1, and the actual LTC tap position during this incident. This additional data helped us create a new EMTP case to represent the system conditions at the time of this fault, and we were able to verify the correctness of the EMTP model by comparing the magnitudes and angles of the fault currents in all the PST windings.

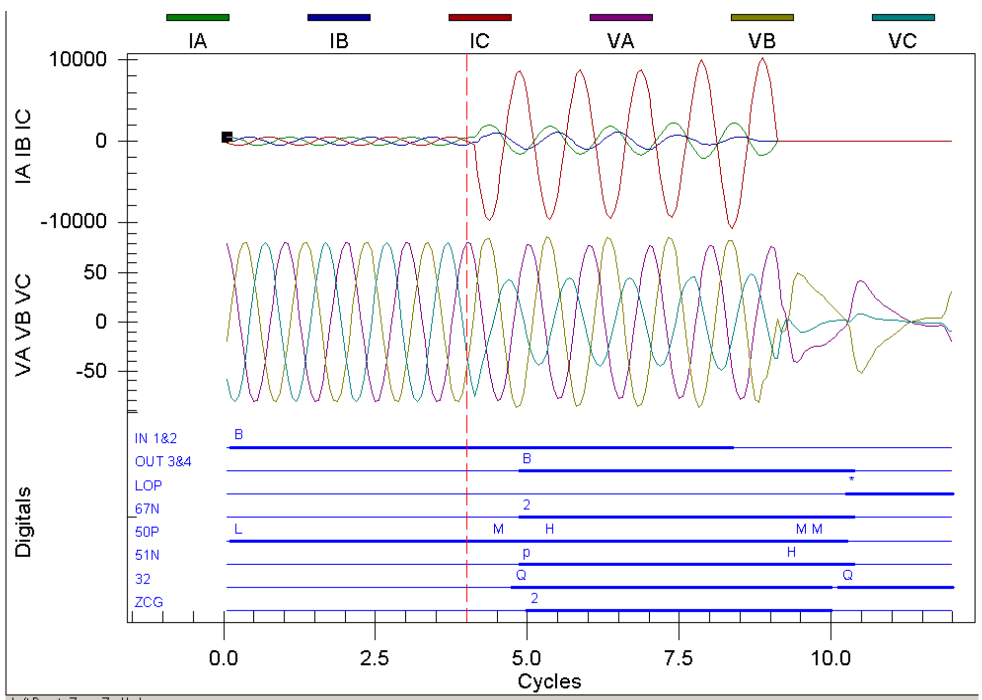

Figure 7 Device 11-1 Event Report (Oscillographic Format)

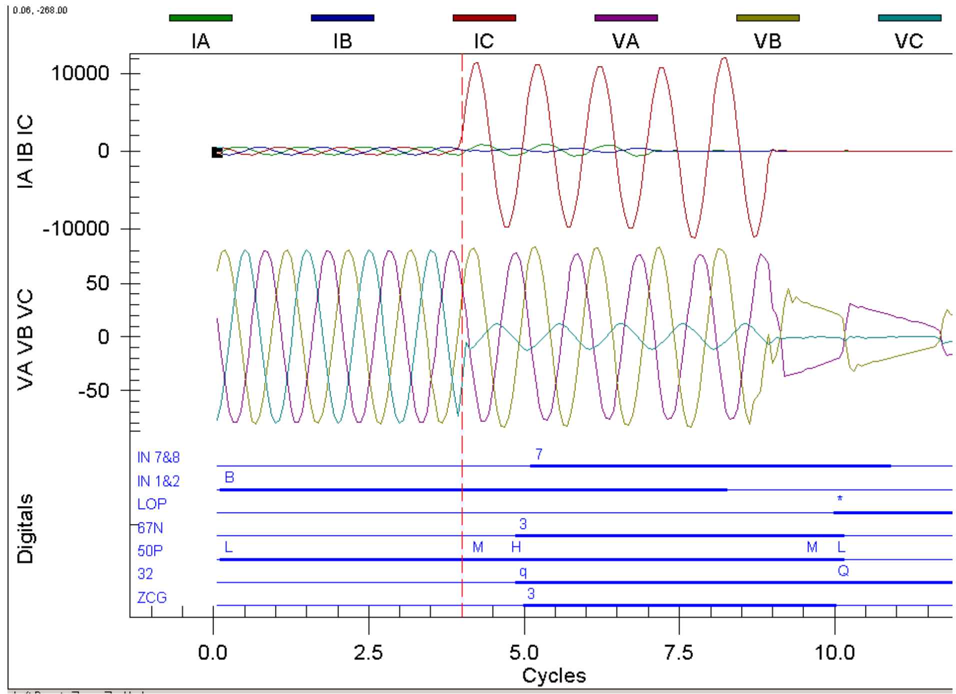

Figure 8 Device 11-2 Event Report (Oscillographic Format)

Conclusions

1. Complete PST protection requires a combination of relay elements such as current differential, distance, ground overcurrent, series- and exciting-unit Buchholz-type relays, and LTC sudden pressure relays.
2. PST differential relay schemes require careful examination to determine CT placement, CT ratio, tap selection, and CT polarity and wiring connections.
3. EMTP modeling of the PST provided data necessary to test the relays, and to verify and enhance the relay settings for this complex protection application.
4. With numerical relays, we can eliminate the additional ground backup overcurrent relays, second harmonic, and volts/hertz relays needed with earlier electro-mechanical or solid-state technologies.
5. Event reports from numerical relays are extremely valuable in verifying correct operation of the relaying systems, and in verifying the power system models used for short circuit or transient studies.

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Biographies

Demetrios A. Tziouvaras received his BSEE degree in 1980 from the University of New Mexico, and his MSEE in 1986 from Santa Clara University. He worked for Pacific Gas and Electric Co. for 18 years in the System Protection Group. He served as a Principle Engineer responsible for the selection of relaying systems, system protection design standards, and application of new technologies in substation automation. In 1998, he joined Schweitzer Engineering Laboratories as a Research Engineer. He is currently a Senior Research Engineer involved in the development of numerical relays. His main interests are protection of power systems, power system transients, and digital relaying. He is the author or co-author of numerous papers in the area of power system protection. He holds one patent and has several patents pending. He is an IEEE senior member, a member of the Power System Relaying Committee, and a member of CIGRE. He is also the convener of CIGRE SC-34 Working Group 15 on “Distance Protection Functions for Modern Applications.”

Ramon Jimenez received his BSEE degree in 1995 from California State Polytechnic University, Pomona, with an emphasis in Power Engineering. He joined the General Electric (GE) Company’s Technical Leadership Program and attended Advanced Power System Engineering Courses in Schenectady, New York. From 1995 to 1997 he worked as an application engineer with GE Power Systems Engineering Department. From 1998 to 1999 he worked as a product support and testing engineer for GE transmission line digital relays in Malvern, Pennsylvania. In 1999, he joined Commonwealth Edison (ComEd) in Chicago, Illinois, as a protection engineer. At ComEd, Mr. Jimenez has been responsible for selection of relaying systems, fault studies for relay settings, protection engineering field support, and contractor design oversight for various projects. This includes relay upgrades, capacity jobs, and various independent power producer interconnection projects. He is currently a senior protection engineer for the ComEd transmission system.

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