New Advancements in Power Flow Regulating Tap-Changer Control Systems for Phase-Shifting Transformers

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Revised edition released May 2018

Previous revised edition released April 2018

Originally presented at the
85th International Conference of Doble Clients, April 2018

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ABSTRACT

This paper describes new developments in power flow regulating tap-changer control systems for phase-shifting transformers (PSTs). These transformers are also called phase angle regulating (PAR) transformers because they control the phase angle across a networked transmission system branch circuit to control the power flowing through it. PSTs regulate the phase angle by inserting a quadrature voltage into each phase by action of a tap-changer mechanism.

This paper discusses advancements in the control technology for use with two 400 MVA PSTs recently installed in parallel in the San Diego Gas & Electric (SDG&E) 230 kV transmission system. It summarizes the further development of the control technology over many projects executed over more than ten years and the further development of the control capabilities to meet the requirements specified by the California Independent System Operator (CAISO) and SDG&E for automatically controlling these parallel PSTs.

INTRODUCTION

Phase-shifting transformers (PSTs) are becoming more common in the networked transmission grid to control power flow. These transformers are also called phase angle regulating (PAR) transformers because they control the phase angle across a networked transmission system branch circuit. However, automatic regulation of the phase angle introduced by the PST has many challenges. Historically, many PST installations have been manually controlled because the regulated quantity, power flow, is only indirectly controlled by the position of the tap changer. Power flow is a function of the sending and receiving voltages and the angle between them. The actual change in power for each tap step is a function of system conditions, and therefore an automatic control could possibly hunt (i.e., control action overshoots the regulation dead band). A previous paper discussed a novel control system that provides automatic regulation to an operator MW set point by utilizing an algorithm that would adaptively set the bandwidth around the set point by learning system conditions, to prevent hunting [1].

PSTs regulate the phase angle between their source and load terminals by inserting a quadrature voltage into each phase. For example, a voltage in phase with VBC or VCB would be combined with VA to produce a phase shift between the Phase A source (S_A) and Phase A load (L_A) terminals of the transformer. Three common configurations for PSTs are described. PSTs are useful in a number of different transmission network topologies to solve operational constraints or improve economics.

This latest project was at the San Diego Gas and Electric (SDG&E) Imperial Valley 500 kV/230 kV substation. Figure 1 illustrates the lines in and out of the substation. This facility provides SDG&E with a 500 kV interconnection to Arizona Public Service (APS) and 230 kV interconnections to Comisión Federal de Electricidad (CFE) and Imperial Irrigation District. The total interconnected generation at Imperial Valley is 1,880 MW, including 1,100 MW of combined cycle and 780 MW of solar generation. In addition, there is 570 MW of wind generation connected at SDG&E's adjacent 500 kV substations. There are two 500 kV lines from Imperial Valley into the San Diego-area load and an underlying 230 kV east-to-west path through the CFE 230 kV system [2]. The implemented PST solution prevents high-level loading of the 230 kV path when a 500 kV line is out of service.

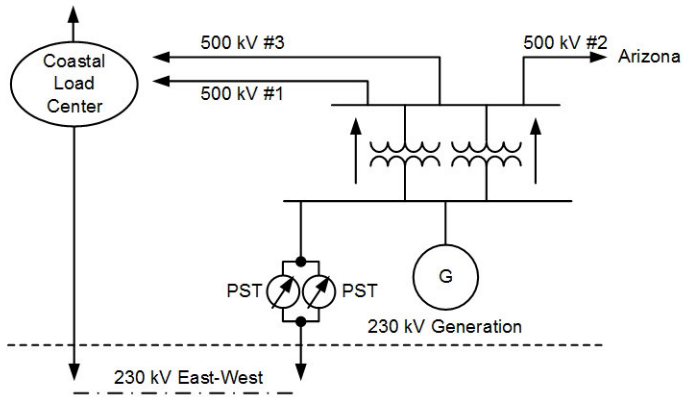

Figure 1
Grid Paths In and Out of Imperial Valley Substation

This paper discusses automatic power flow regulation techniques that have been developed over many years of successful PST projects. The paper provides background information on how PSTs work, what kinds of power system problems they solve, and the different types of PSTs in common usage. With that background, the paper focuses on the challenges and innovative solutions associated with automatic control of the load tap changers (LTCs) that control the angle shift introduced into the transmission network path on which the PST is applied. The paper describes development of a power flow regulating LTC controller that has several control modes and has been adapted for use with a higher level of wide-area control schemes as well. The paper also covers recent advances developed in conjunction with SDG&E to control a particularly challenging application.

PST APPLICATION AND THEORY

The simplified equation (neglecting losses and shunt admittances) for the power flow through a transmission line is shown as (1).

$$P = \frac{E_S \bullet E_R}{X_T} \sin\delta \tag{1}$$

where:

E_S is the sending bus voltage

E_R is the receiving bus voltage

X_T is the reactance of the transmission system between the buses

δ is the angle between the two voltages

Examination of this equation reveals that power flow is largely a function of the angle between the two voltages. In a properly operating power system, E_S and E_R do not deviate significantly from nominal. The impedance of the system, X_T, between the sending and receiving buses is fixed by the transmission grid. For these reasons, if the angle, δ, can be controlled, the power flow can be controlled. By introducing an angle that is additive (advance), power flow is increased. By introducing an angle that is subtractive (retard), power flow is reduced.

Another way of looking at how a PST controls power flow is to go back to basics and write the Kirchhoff's Voltage Law (KVL) equation for the line. The simplified circuit shown in Figure 2 illustrates the concept. The complex transmission network has been reduced to a simple two-source network. The reduced equivalent transmission system consists of the line of interest, X_L, that will have the PST applied to it and a transfer branch, X_T, that represents the rest of the networked system. The transfer branch provides a parallel path between the sending and receiving buses.

Because the impedance of the network is mainly inductive, the voltage drop across the line is mainly in quadrature (lagging by 90°) to the current flow. The voltage at the source terminal of the PST, E_R', is the sending voltage, E_S, minus the voltage drop of the line per (2). The power transfer angle across the line is designated δ' in Figure 2.

$$E_R' = E_S - I_L \bullet X_L \tag{2}$$

where:

E_R' is the voltage at the end of the line terminating at the source terminals of the PST

E_S is the voltage at the sending bus

I_L is the current in the line

X_L is the impedance of the line

The PST injects a quadrature voltage, ΔV_Q, between its source and load bushings. The magnitude of ΔV_Q is the induced quadrature voltage minus the voltage drop of $I_L \bullet X_{PST}$. A later section of this paper shows configurations of common PSTs and their regulating windings. In the example, ΔV_Q causes the load terminal with voltage E_R to lead the source terminal with voltage E_R'. This means that the PST is in advance. The angle across the PST between E_R' and E_R is designated θ in Figure 2. The quadrature voltage, ΔV_Q, effectively cancels some of the voltage drop across the line, which makes it appear electrically shorter and increases power flow. The power flow equation for this line is now per (3). We see that the power flow can be controlled by adjusting angle θ.

$$P = \frac{E_S \bullet E_R}{X_L + X_{PST}} \sin(\delta' - \theta) \tag{3}$$

where:

X_{PST} is the impedance of the PST

The voltage drop across transfer branch X_T is $X_T \bullet I_T$, which can be used to calculate the voltage difference between E_S and E_R and the overall system power transfer angle δ. This is the phasor projected off to the side with the dashed lines to relieve drawing congestion. So, operation of the PST will affect the division of currents I_T and I_L in this KVL diagram and affect the total transferred power as well.

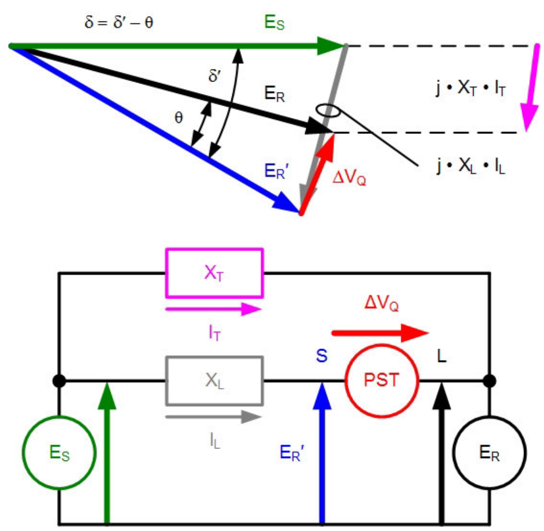

Figure 2
Kirchhoff's Voltage Law for PST Application

PST APPLICATIONS

This section describes PSTs that solve different power system problems:

- Alleviate potential line overloads
- Improve operational flexibility
- Improve economic operation

Alleviate Potential Line Overloads

Improving N-1 contingency operational limits is a common application. The power system must be operated to survive loss of any single element. In many cases, the power transfer between regions must be limited on a high-capacity path if loss of that path would cause extreme overload of the remaining circuits. This was the case for the SDG&E application. For loss of a 500 kV path connecting generation in Arizona to the California coastal load center as shown in Figure 1, the power tended to flow through the CFE 230 kV system. The installed PSTs limit the power flow in the 230 kV path to acceptable limits for that contingency. The PSTs also provide the capability to limit the power flow in the 230 kV path when a single 500 kV path is scheduled to be out of service, operating at a set point that provides acceptable flow if the remaining 500 kV path opens.

Another application is to control loading on a weak third leg of a triangle topology as shown in Figure 3. The three corners of the triangle (1, 2, and 3) represent strong load and generation centers. The tie from 1 to 2 and 1 to 3 are strong. But, the tie from 2 to 3 is limited. The load angles from normal operation of the strong areas of the grid could easily overwhelm the weak link. A PST can compensate for these natural load angles to prevent excessive flows on the limited capacity tie.

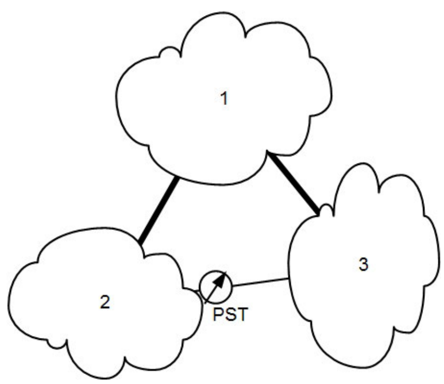

Figure 3
Triangle Topology

Improve Operational Flexibility

In long, sparsely loaded transmission systems, there may be cases where a strong path in the system experiences extreme load flow angles between open terminals, as illustrated in Figure 4. The system is not overload limited. But if the strong line trips, it may not be able to be reclosed because of the extreme angle. In this application, the lead breaker, 1, recloses to re-energize the line and the PST is stepped to reduce the system angle across the follow breaker, 2, so that it can be reclosed without excessive shock to the system. Then, once the path is restored, the PST is stepped back to neutral and bypassed to allow the strong tie to carry the load without the impedance of the PST.

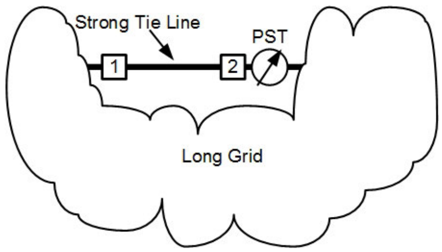

Figure 4
Long, Sparsely Loaded Grid With Strong Tie

Improve Economic Operation

In some applications, wheeling charges (either network or point-to-point) to transmit power across the transmission system may be different for different paths or voltage levels. A PST can be installed to force load flow through the more economical path.

PST CONFIGURATIONS

As mentioned previously, PSTs control phase angle by injecting a variable quadrature voltage into each phase between the source and load terminals of the PST. PSTs can be constructed as single-core or two-core designs.

Figure 5 shows two common single-core designs. Both are shown in the advanced position. Figure 5a is commonly called an extended delta PST. Figure 5b is commonly called a delta-hexagonal PST. Single-core PSTs usually include two LTCs that move the source and load terminals up and down the regulating winding. The winding labeled V_{REG1} is the regulating winding for Terminal 1 (typically Phase A). We see that this voltage is in phase with the winding labeled V_{EX1}, which is connected between terminals 2 and 3 (typically Phases B and C). The line-to-line voltage, V_{BC}, is at 90° from V_A, which is what is meant by quadrature. To move from advance to retard operation, the LTCs pass each other on the regulating winding. Other configurations for single-core PSTs include a single LTC with a conventional plus/minus reversing switch that swaps the polarity of the regulating winding, similar to how an in-phase voltage regulating LTC operates.

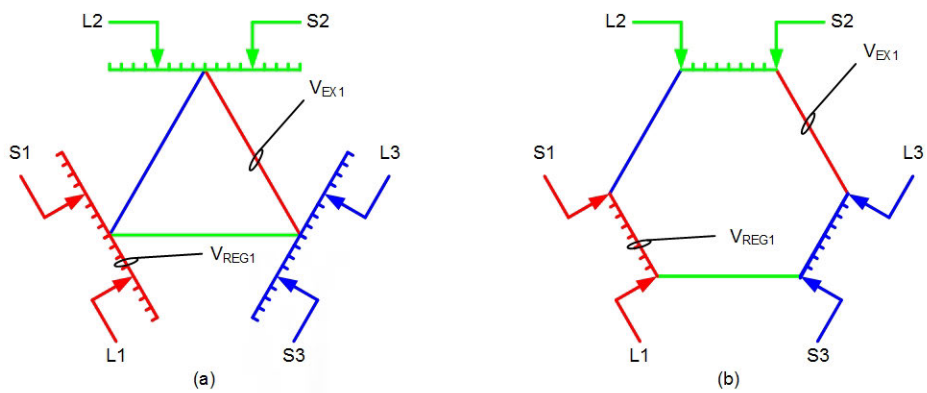

Figure 5
Single-Core PSTs

Normally, when two LTCs are used, the LTC manufacturer configures their LTC control circuits such that the LTC controller only has to initiate an operation in the desired direction and the LTC control mechanism determines which LTC motor to run in which direction to accomplish the operation.

Figure 6 shows the most common two-core design. Again, the PST is shown in the advanced position. This configuration is commonly called a conventional PST. A two-core PST has a single LTC. The voltage applied to the delta secondary winding of the series core, V_{REG1}', is varied from zero to its full value by the LTC, V_{EX1}'. This voltage is induced into the primary winding of the series core labeled V_{REG1}. To switch from advance to retard, the polarity of the regulating winding is reversed by the plus/minus switch as in a conventional in-phase voltage regulating LTC. Following voltage V_{REG1}' from the secondary of the series core to the secondary of the excitation core to the primary of the excitation core, we see that the voltage V_{EX1} is the voltage connected between the midpoints of the terminal 2 and 3 regulating windings of the PST, which is in quadrature to terminal 1.

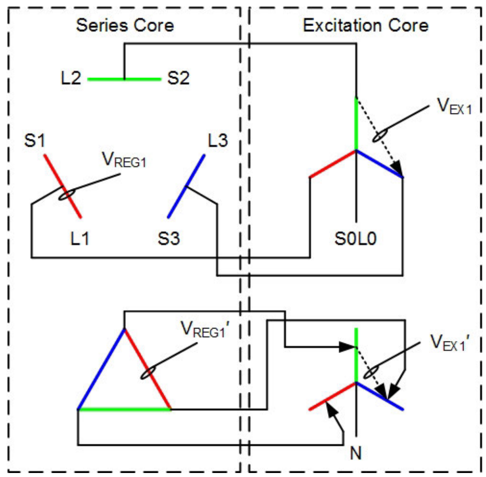

Figure 6
Two-Core PST

POWER FLOW REGULATION CHALLENGES

Unlike an in-phase voltage regulating tap-changer control where there is a relatively well-defined relationship between the ∆V from a tap step and the voltage at the terminals of the transformer, the ∆P associated with a tap step on a PST is influenced by many other parameters. Examining the KVL phasor diagram in Figure 2, we see that the change in angle θ from a tap step change is influenced by the following factors in addition to the induced quadrature voltage:

- The system loading, I_T and I_L, affects voltage drops across the impedances.
- The transfer impedance X_T in parallel with the PST branch, which can change with network contingencies, affects the voltage drops.
- The PST impedance, X_{PST}, varies significantly with tap position.
- The power transfer equation (3) is a sine function.

For these reasons, the ∆P for each tap step will vary throughout the range of regulation and with system conditions.

A discrete step-regulator typically includes an operational set point and a dead band centered on the set point. Because the regulated parameter will change in discrete steps, it is not possible to always operate at exactly the required operational set point. The dead band defines the allowable range around the operational set point before a step change is initiated to bring the regulated parameter closer to the operational set point. If the regulated parameter is within the dead band, no automatic tap changes are required. When the regulated parameter is outside of the dead band for a period, the automatic regulating device will initiate a tap step change in the direction required to return the regulated parameter to within the band limits.

The selection of a bandwidth setting for a discrete step-regulator must be balanced to provide optimal operation. Setting the bandwidth too low can result in excessive numbers of operations. It can also result in hunting. Hunting occurs when a tap step results in a change of the regulated parameter that is near to or even greater than the bandwidth. For each tap step, the regulated parameter can overshoot the dead band and the regulator will soon attempt to step in the opposite direction. Selection of a high bandwidth will reduce the possibility of excessive operations and hunting, but it will result in poor regulation around the regulation set point.

Regulation Modes

The original implementation of this control reported in [1] included regulating the power flow to a set point. We see that selecting a bandwidth setting for the control would be very difficult because, as previously discussed, the ΔP per tap step varies. To address this issue, the control uses an adaptive bandwidth function to optimize regulation while preventing hunting. It does so by measuring the ΔP for the most recent tap changes and averages them to adjust the bandwidth in real time [1].

Controlling the PST to a power flow level is not always the preferred method. In some applications, the PST is operated by placing the LTC at some preset position (typically neutral) and then having the LTC only take action when the N-1 contingency occurs. To accommodate this control strategy, a band limits regulation mode was developed for use in those applications. Instead of selecting a power flow set point for the transmission path, the operator selects an upper and lower band limit. For example, if the PST path is rated for 300 MW, but the path can become overloaded upon loss of a parallel high-capacity transmission path, the upper band limit may be set to +300 MW and the lower band limit is set to 0 MW. Then, if the N-1 contingency occurs and loading goes above the upper band limit, the PST would start stepping to drive the loading back down to +300 MW. Otherwise, the PST does not make any tap changes.

Wide-Area Power Flow Control

In some applications, a wide-area control strategy is desired. For example, a municipal power system with one 230 kV tie line and five 115 kV tie lines made use of a PST to improve operational economics by maximizing wheeling import for the 230 kV tie line. A higher-level power controller was installed to automatically adjust the power set point of the PST LTC controller in real time based on mission priorities. The higher-level power controller monitors loading of critical transmission paths and provides the PST LTC control with visibility of outside conditions. With that visibility, the power control setting of the PST LTC control can be shifted to the most limiting facility in the system while monitoring multiple system operating limits. The LTC control manages and controls the LTC while the MW set point is adjusted in real time by the higher-level control system [3].

The PST tap position for the SDG&E Imperial Valley PST installation is determined by the California Independent System Operator (CAISO). Their control strategy uses the CAISO market-based software application to model the PST and preset the PST tap position to optimize N-1 contingency constraints on economic dispatch in the California interconnected transmission grid. To accommodate this control strategy, the control logic of the LTC control was modified to use the actual tap position as the controlled parameter and the CAISO tap position as the control set point.

CAISO Regulation Implementation

A SCADA heartbeat system is programmed in the SDG&E SCADA Master to ensure that the regulation set point is legitimate as commanded by the CAISO Master. The heartbeat script in the SDG&E SCADA Master periodically writes the CAISO set point to the control. The script also controls a heartbeat bit in the LTC control such that the heartbeat looks like a square wave with a period set in the SCADA Master. The script will stop setting and resetting the heartbeat if it loses communication with the CAISO Master. Similarly, if the link between the SDG&E SCADA Master and LTC controller fails, the heartbeat will also fail to change state. The LTC controllers monitor this condition and go into alarm after not seeing a change of state for 1.5 times the expected period. This alarm condition blocks automatic control and clears itself as soon as a new heartbeat is received.

The control stores the CAISO tap position set point in volatile memory. If the control restarts for any reason, to prevent the control from initiating tap changes to drive the tap position to zero (the default regulation point), the control automatically restarts in the Independent and Off modes. Upon restart of the logic engine, an alarm is latched to indicate why the control has changed its operating mode and state to Independent and Off. This alarm is automatically reset by the SCADA heartbeat system.

The control reads the CAISO set point into active memory on the rising edge of the SCADA heartbeat. This ensures that the active regulation set point is updated soon after a logic restart or after CAISO sends a new set point. It also serves as an integrity poll to refresh the set point periodically to ensure that it is always in synchronism with the CAISO Master. Additionally, the control verifies the validity of the CAISO set point as follows:

- CAISO tap position set point is within the expected range. The PST has 64 tap positions from +16 to –48 where a positive number represents advance and a negative number represents retard.
- Maximum tap difference from present tap position and CAISO set point is less than five steps. If the tap position difference exceeds five steps, an alarm is latched to indicate that the CAISO set point has not been read into active memory because the change was greater than allowed. If the set point change is legitimate, the latched alarm can be reset allowing the set point to be read into active memory on the next assertion of SCADA heartbeat.

This "difference from current position" check is included to prevent a spurious set point (due to a glitch in the DNP3 data message) from being acted upon. If a bad set point is read, we need to guard against moving the tap position too far and causing a power system disturbance.

PST INSTALLATION

Figure 7 shows a typical installation that is similar to the SDG&E Imperial Valley installation. It illustrates the measurements required to support the various control functions. The SDG&E application includes two PSTs in parallel, representing a superset of a typical installation. The figure shows the source terminals of the PST connected to the bus and the load terminals connected to the line. But, it is not unusual for the PST to be installed in the other direction if the normal direction of load flow is into the bus. An example of this configuration is the simplified system illustrated in Figure 2.

PST Installation

The configuration of bypass, load-side, and source-side isolation devices affects the control requirements and operational flexibility. The four common configurations are described as follows:

- Frequently PST installations include three breakers as shown in Figure 7. This configuration offers the most operational flexibility and simplifies the protection of the PST.
- Some installations use a bypass switch for taking the PST out of service instead of a bypass breaker. In general, when a bypass switch is used instead of a breaker, it is necessary to de-energize the PST and associated line to switch the PST in and out of service.
- Some installations use a source-side motor-operated disconnect switch in place of a breaker. In these installations, the load and bypass breakers are used to make and break parallel PST and bypass paths and to pick up load. The source-side disconnect must be used to make and break transformer magnetizing current.
- Some installations include no provision to bypass the PST. If the PST must be taken out of service, the line must also be taken out of service. In these cases, there may or may not be a breaker between the PST and the line, which requires the protection system to include a direct transfer trip scheme to isolate the PST in the event of a fault.

Control Installation

Figure 7 shows the connections to the LTC control, and their purposes are briefly described as follows:

- The load-side current and voltage are brought in to measure the real, P, and reactive, Q, power.
- A second set of inputs measures the currents in the LTC switching contacts to protect against operating the LTC when damaging currents are present. In a two-core PST, these currents can be measured at the neutral bushing CTs in the phases above the star point of the excitation transformer secondary winding. In a single-core PST, this function uses the load terminal CTs.

- The source-side voltages are measured and used in the neutral verification function explained in the next section.
- The tap-changer position is read using a dry contact binary coded decimal (BCD) encoder device on the LTC mechanism.
- Retard Tap and Advance Tap are the contacts that start the LTC motor and "Tap Change in Process" is the feedback from the motor contactor indicating that the motor is running.
- In multiple control applications, one or two serial communications links are installed to exchange information between the two controls. The exchanged data shown in the figure support paralleling of the PSTs. In single PSTs with redundant LTC controllers, a single link that exchanges different information is required.
- The paralleling control uses the real, P, and reactive, Q, power flows in the adjacent PST to calculate circulating apparent power, S_{CIRC}, to alarm when the two PST tap positions are out of synchronism. Similarly, the tap position is also used to alarm for an out-of-synchronism condition.
- The advance and retard commands allow the Master to control the Follower and the motor running status is feedback to the Master that the motor is running in the Follower.

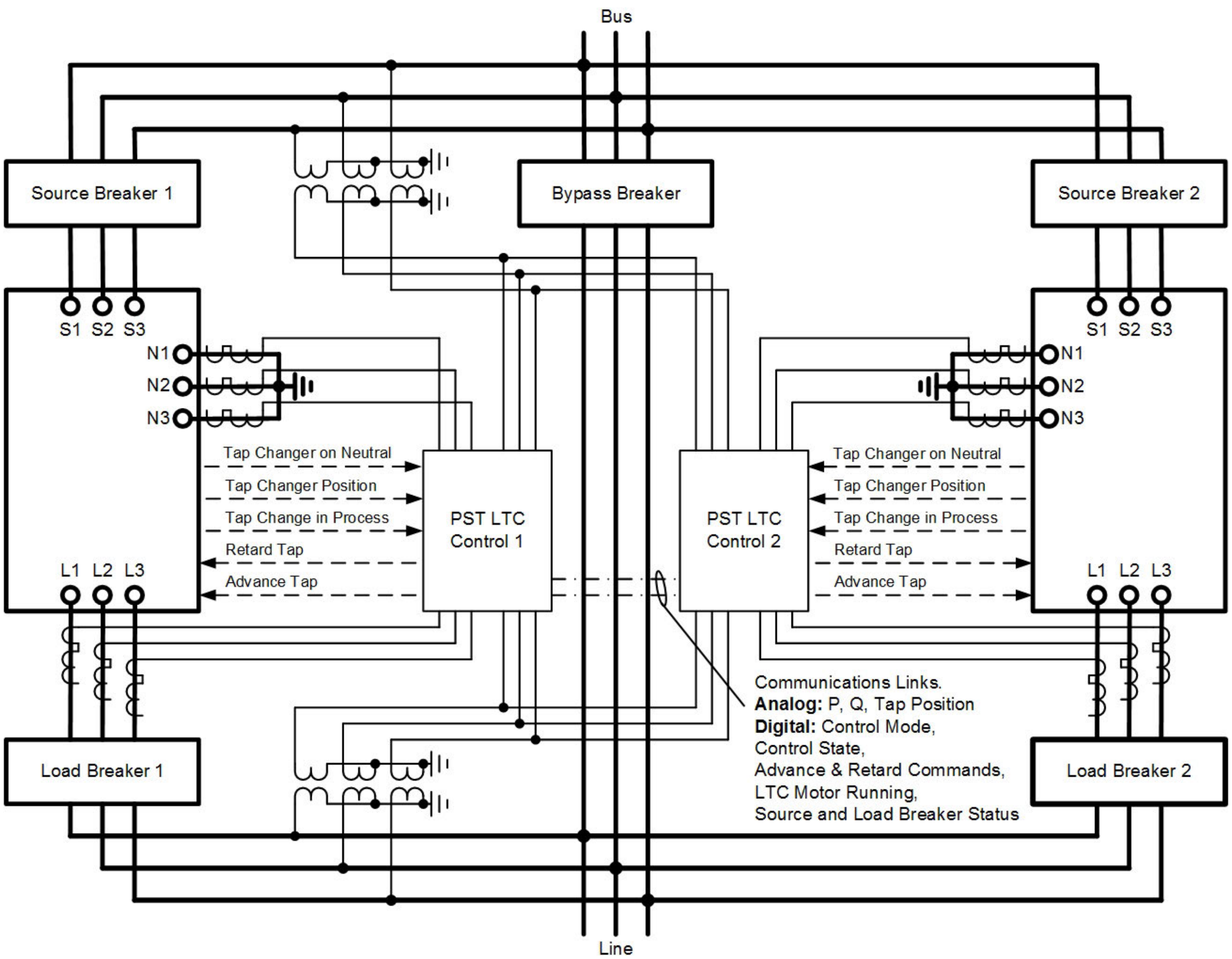

Figure 7
PST Installation

NEUTRAL VERIFICATION

PSTs that have a bypass breaker to switch the PST in and out of service without requiring an outage are vulnerable to the hazard of bypassing off neutral. If a PST is inadvertently bypassed when not in the neutral position, damaging currents flow when the regulating winding is short-circuited. The normal PST differential protection is blind to this high current, so including dedicated bypass-off-neutral (circulating current) protective elements in each phase is recommended [4]. The circulating current element looking at current in the bypass breaker versus current in the load breaker trips only the load-side breaker to break the loop while leaving the transmission path in service via the bypass breaker.

Permissive Conditions

The PST is vulnerable to being bypassed off neutral when closing the bypass to take a PST out of service and when closing the load breaker to place the PST back in service. While protection is a good thing, the best protection is always prevention. The PST control has the best visibility of the status of the PST and its isolation and bypass breakers/switches, so it usually includes permissive logic to supervise the closing of the three breakers/switches.

There are two control strategies that are used depending on the preference of utility operations. The simplest is to design the permissive logic to allow any safe switching operation. Any breaker can be closed if it will not close the loop. Or, if closing the breaker will close the loop, it can only be allowed if the PST is on neutral. The other approach is to use the permissive logic to enforce specific operating procedures. For example, if the line is never to be switched into service via the PST, the logic could only allow closing the load breaker if the bypass is already closed. Another constraint might be to never allow the PST to be energized from the load-side breaker. Doing so will cause the bypass-off-neutral element to misoperate as the inrush current flows through the bypass and into the load breaker, which looks like circulating current.

Because verification of neutral is so important, we use three methods to confirm that the PST is on neutral:

- Neutral contact from the mechanism is asserted
- BCD position indicates that the PST is on neutral
- Voltage angle across the PST indicates that the PST is on neutral

If all three methods indicate neutral, the permissive can be asserted. If any indications are incongruent, a neutral status indeterminate alarm asserts.

Voltage Drop Compensation

Determining that the PST is on neutral using the voltage angle requires more discussion. When the PST is in service, the directly measured angle will not necessarily be zero as a result of the $X_{PST} \cdot I_L$ voltage drop across the PST impedance. Single-core PSTs typically have zero impedance when on neutral. The two LTCs connect the source and load terminals of the PST to the same tap of the regulating winding. So, the angle difference between source and load terminals can be used directly.

Two-core PSTs have the impedance of the series transformer in the circuit—even when on neutral. The control uses the current measured at the load terminals of the PST and the impedance of the PST on neutral, entered as a controller setting, to calculate the voltage drop across the series winding. This, in turn, projects the load terminal voltage to the source terminal voltage so that the angle difference between the source terminal voltage and the compensated load terminal voltage can be calculated.

This method typically uses the positive-sequence voltages and positive-sequence currents in the calculation for best accuracy. But if only a single-phase voltage is available, the scheme uses a single-phase calculation.

In most cases, the load-side VTs are located beyond the load breaker because they are also used for line protection, as configured in Figure 7. In this case, the voltage drop compensated angle difference can only be used when closing the bypass breaker to take the PST out of service. It cannot be used to verify neutral when closing the PST load breaker to place the PST in service. The SDG&E installation actually included a single-phase capacitor voltage transformer between the PST load terminals and the load breaker so that neutral can be verified by checking voltage angle for both switching operations.

Automated Run to Neutral

The neutral verification feature is useful for automatically running the PST LTC to neutral in preparation for switching it in or out of service. The LTC controller typically includes a one-button, automatic-run-to-neutral feature. This function may also be used by the overload mitigation function.

Automated Switching

Another common automatic function to ensure safe switching operations is to automate the switching function with one-button put-in-service and one-button remove-from-service functions. The automated switching sequences are described in detail in [1]. Neutral verification is an important part of that logic as well.

MULTIPLE CONTROL APPLICATIONS

For many applications, features to allow multiple controllers have been developed. The two applications for multiple controllers are:

- Redundant main and hot-standby
- Parallel PST

Redundant Main and Hot-Standby Controls

In many cases, the PST is so vital to the operation of the transmission link, the line must be removed from service if the PST control is out of service. In these applications, redundant controllers are required to prevent a control failure or periodic maintenance testing from disrupting operations. For control functions, multiple controllers active at the same time is an undesirable condition. So, a main and hot-standby approach is used. The communications link between the controls shown in Figure 7 simply exchanges status points to indicate to the other control when it is in manual or automatic mode. This status information is used as an interlock to prevent both controllers from being active at the same time.

Figure 8 shows the user interface for one such application. All of these controls and indications are also available via SCADA communications. To switch which control is enabled, it is necessary to first turn off the other control (i.e., neither AUTOMATIC nor MANUAL mode is enabled) before either AUTOMATIC or MANUAL mode can be enabled in the new control.

To remove a control from service for any reason, simply turn it off (i.e., neither AUTOMATIC nor MANUAL mode is enabled). The PST can still be controlled via turning the other control on (i.e., either AUTOMATIC or MANUAL mode is enabled). To test the control that is not actively controlling the PST, one pole of the isolation test switch is wired to an input on the controller. When this input is de-asserted by opening the test switch, the interlock that forces the control to off when the other control is in either AUTOMATIC or MANUAL mode is defeated. The control that is out of service and isolated from the LTC can then be turned on for testing purposes.

The communications interlock is fail-safe. The communications link is monitored and if it fails, indicating that the control can no longer tell the status of the other control, it switches to off. Under this condition, the control does not know whether the other control is failed or if the communications cable failed or was disconnected. Under the condition that one of the controls has failed, the operator can enable the healthy control.

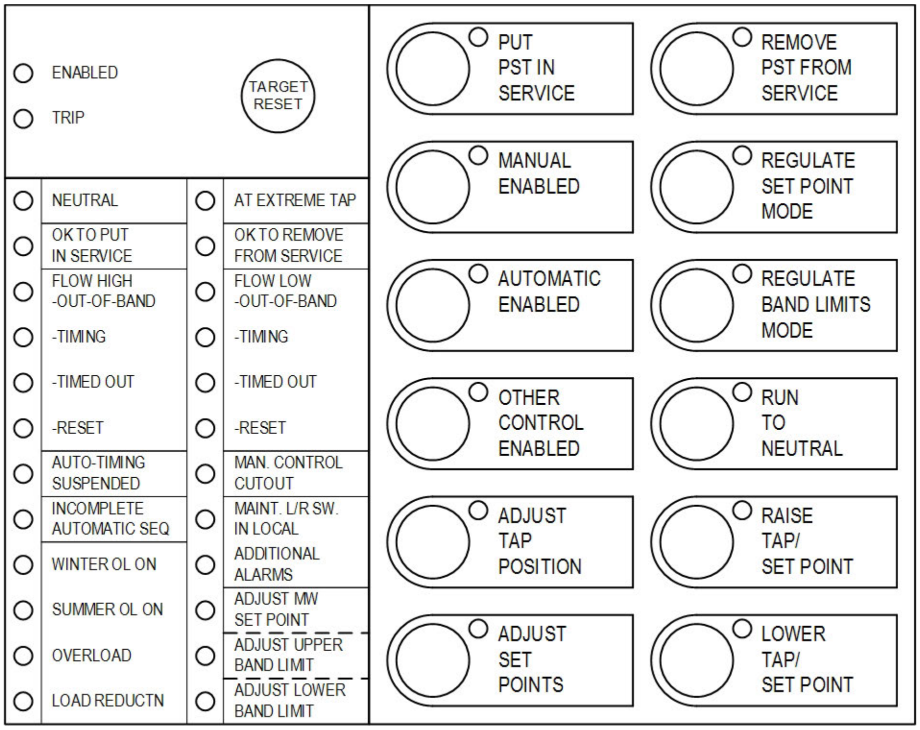

Figure 8
Main and Hot-Standby Controls

Parallel PST Controls

Paralleling controls are required for PSTs that operate in parallel. The SDG&E application included paralleled PSTs bused at their terminals as shown in Figure 7. Another application had PSTs on two separate lines that were closely coupled at both terminals of the lines. This application has a little more impedance in the parallel loop, but requires paralleling controls as well.

The control strategy for paralleling that we recommend is a simple Master/Follower control with monitoring to detect and alarm for an out-of-synchronism condition. The two LTC controllers can operate in a Master/Follower combination or Independent modes. When operating in parallel, one of the controllers is assigned as the Master, while the other becomes the Follower. In this mode, the Follower will simply follow the commands given by the Master. The ADVANCE, RETARD, AUTOMATIC and MANUAL pushbuttons and SCADA commands will not function on the Follower controller. In the event the PST whose controller is the Master trips, the mode of the Follower will automatically change to Independent with the same operating state (Off, Automatic, or Manual) that the Master was in prior to the trip.

The Master/Follower or Independent modes can be chosen locally or via SCADA. When MASTER is selected on either of the controllers, the other controller automatically becomes the Follower. Similarly, if the Follower or Independent command is asserted on either of the controllers, the other automatically becomes the Master or switches to Independent mode respectively. The controllers will also switch to Independent mode if the communications channel (serial cable) fails or if either PST trips. Figure 9 shows the user interface with the MASTER, FOLLOWER, and INDEPENDENT control mode pushbuttons highlighted. When in Follower mode, the control makes no actions to change taps on its own besides executing the master's commands.

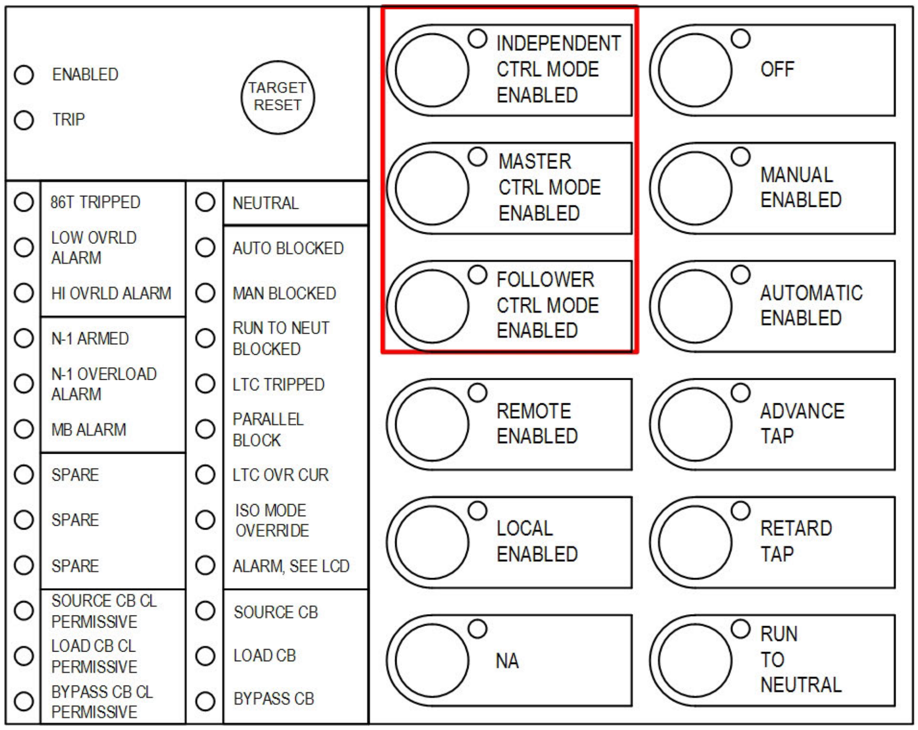

Figure 9
Parallel PST Controls

Monitoring to Detect a Tap Step Out-of-Synchronism Condition

If the tap positions of the paralleled PSTs become unsynchronized, current is driven to circulate between the two PSTs. This increases both real and reactive power losses and can overload one PST while underloading the other. For these reasons, it is important to prevent prolonged operation in this state and to prevent it from getting worse by blocking automatic operation. It should be understood that this circulating current is not nearly as severe as that from a bypass-off-neutral condition. In a bypass-off-neutral condition, the regulating winding is short-circuited and tripping must occur at protection speeds. In a tap step out-of-synchronism condition, there is impedance in the loop that limits the circulating current to reasonable levels. The alarm function is set to alarm for a one-tap-step difference and to block operation for a two-tap-step difference. If the alarm is in a blocked state, it will prevent any automatic operation. But, the control will allow manual steps in the direction that will reduce the mismatch.

The communications link between the two LTC controllers shown in Figure 8 sends three analog signals to the other controller to use in its out-of-synchronism alarm functions. The calculated tap position from the BCD encoder is one measure used to determine if the two PSTs are on the same tap step. But because this is a mechanical measure, it could be erroneous. For this reason, an electrical measure to detect loss of synchronism is also required.

With in-phase voltage regulating LTCs, a popular method to detect a tap step out-of-synchronism condition is to monitor circulating reactive power. The impedance of the paralleled transformers is highly inductive, and the current flowing in the loop lags the voltage driving the loop, ΔV_{DIFF}, by 90°. ΔV_{DIFF} is the difference between the voltages of the two regulating windings on different tap steps. In a voltage regulating transformer, this voltage is in phase with the source and load-side voltages. The circulating current manifests as mainly reactive power. Monitoring reactive power isolates the circulating current from the load current, which is typically of relatively high-power factor. Knowing this, one might conclude that detecting loss-of-tap-position synchronism for a PST would be best done by monitoring circulating real power. This is not the case.

The voltage injected by the PST is in quadrature to the midpoint of the PST. For example, a PST operating at 30° advance would have the quadrature voltage at 90° + (30°/2) = 105° relative to the source voltage and 90° – (30°/2) = 75° relative to the load voltage. The difference in ΔV injected in the loop by the PSTs on different tap steps will be in phase with this quadrature voltage. The circulating current will lag the voltage difference by nearly 90°, which will appear to have a power factor angle of 15° relative to the load-side voltage. So, the circulating current measured will appear to have both real and reactive power components. This effect increases the farther the PSTs are operating from neutral. For this reason, the appropriate method is to use circulating apparent power.

To calculate the circulating apparent power, first total apparent power, S, through the PST zone must be calculated. This is done by summing the real power, P, flowing in each PST and summing the reactive power, Q, flowing in each PST. From that, we calculate the total apparent power flow, S, through the PST zone. Because the two PSTs are identical, we assume that the apparent power flowing in each PST should be half that value. The circulating apparent power, S_{CIRC}, is simply half of the total apparent power minus the measured apparent power in each PST.

Once the circulating apparent power is determined, it is now necessary to compare the measured value to an alarm threshold for a one-step difference and a blocking threshold for a two-step difference. These cannot be fixed thresholds. The circulating apparent power will vary throughout the regulation range for several reasons. The driving voltage in the loop, ΔV_{DIFF}, varies in most PSTs with the number of steps off neutral the PST is. The impedance in the loop also varies with how many steps from neutral the PST is. For this reason, it is necessary to develop a mathematical function for expected S_{CIRC} at each step in the regulating range. In most PSTs, this function can be a simple linear function.

The alarm and block threshold functions for the SDG&E PSTs were much more complex. These PSTs were unusual in that they have an asymmetrical range of regulation, +31.3° to –80.1°. To achieve this range of regulation, the excitation transformers of the PSTs were constructed with three secondary windings designated as fine, coarse, and booster. Each of these windings has the same number of turns, so they each produce the same voltage.

Figure 10 shows the configurations of the windings for the regulation range. The regulation range is broken into four ranges: one in the advance direction and three in the retard direction. The fine winding is the tapped winding that the LTC can insert in 16 steps. The coarse winding is inserted as needed to provide offset from one regulation range to the next. The booster winding is always in the circuit.

Even though each of the three windings has the same number of turns, the physical arrangement of each winding relative to the others on the core is different, resulting in different leakage reactance depending on which windings are in the circuit. Figure 11 shows the PST impedance and phase shift during no-load condition with variation of tap position. The discontinuities are quite evident as different windings are switched in and out.

To obtain a function for the dynamic thresholds of the circulating apparent power alarm and block function, we modeled the PST in a load flow program. The impedance and no-load angle shift for each tap position was modeled. We then adjusted each PST one step at a time to obtain a data point for S_{CIRC} at differences of one and two steps. With those data, we fit a function to calculate the alarm threshold at half way between the one-step-off S_{CIRC} curve and the two-step-off S_{CIRC} curve. For simplicity, the one-step-off alarm curve threshold was simply half of the two-step-off block curve. This curve fit nicely between zero S_{CIRC} and the one-step-off curves.

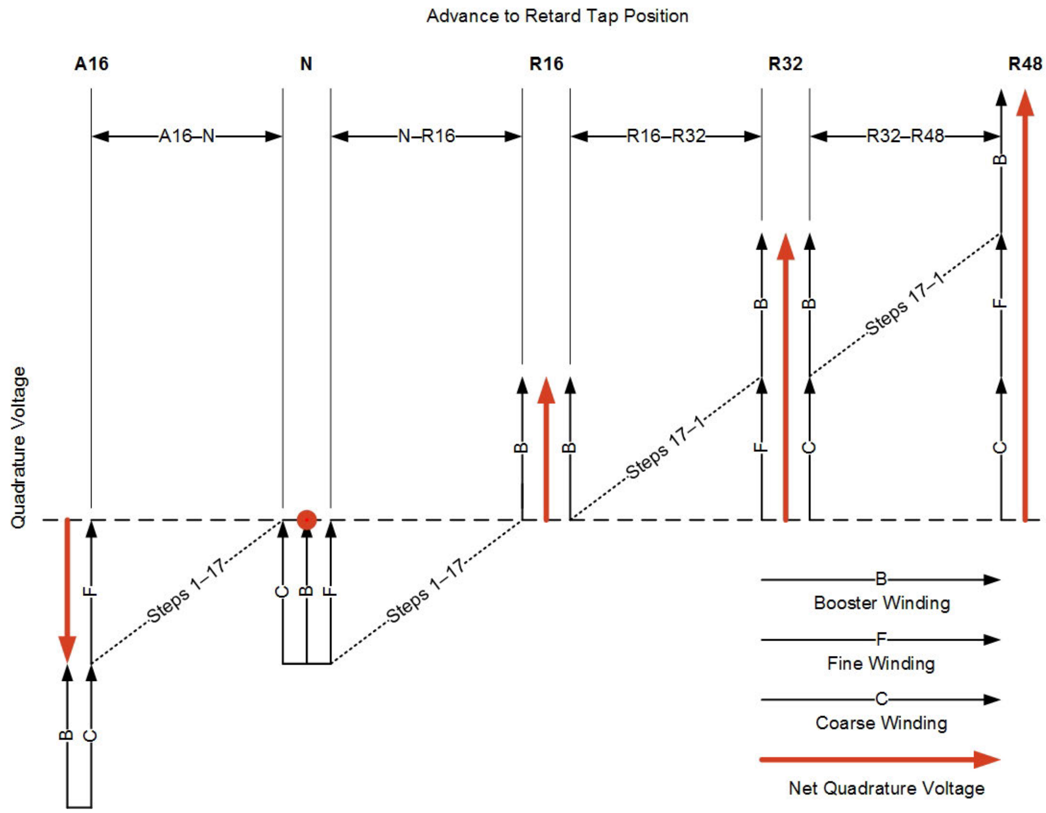

Figure 10
Three Secondary Windings Provide Wide Range of Regulation

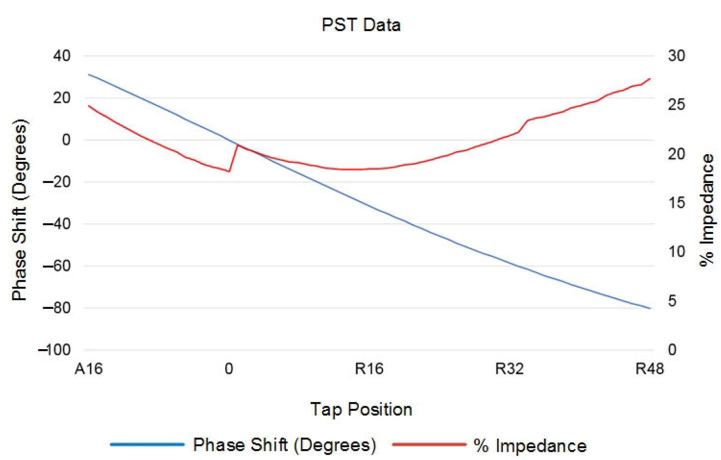

Figure 11
PST Impedance Variation With Tap Position

At the beginning of this discussion about detecting tap step out-of-synchronism conditions, we mentioned that the reason for using an electrical measure to detect a tap step synchronism error is to perform a double check of the mechanical indication. This electrical measure uses thresholds that are dependent on the mechanical position indication. This appears to be a problem. If the mechanical indication is erroneous, the thresholds may not be as required. But, the circulating apparent power will be non-zero.

An erroneous threshold may cause the alarm to be more or less sensitive than it should be—at worst, two steps off to alarm and three steps off to block. The consequences are minimal.

PST OVERLOAD

Operating above nameplate rating for an extended period can prematurely age a PST. Because PSTs can control their own power flow, they can control or mitigate an overload condition by control action. If the PST is under automatic control, the control system will automatically step to reduce the power flow until the apparent power is below the continuous rating of the PST. Alternatively, if a PST is under manual control, an overload alarm may alert the operators so they can manually adjust the tap position to reduce loading to relieve the overload.

The original control included an inverse timing overload function that monitors apparent power [1]. The inverse timing characteristic times out quickly for extreme overload and allows more time for minor overload. The PST control can have both summer and winter continuous ratings available for this function. When the apparent power flow falls below the active continuous rating, the inverse timing overload function starts timing to reset.

Overload Mitigation

If the control is operated in “regulates band limits” mode, the control will likely automatically adjust power flow to within rating without operator intervention upon a system event that causes excessive power flow in the PST. As a result, the PST will never experience an extended overload unless the automatic control system fails to relieve the overload. In the event of extended overload while under automatic control, an alarm alerts the operator to manually attempt to relieve the overload via switching or other adjustments to the networked power system.

If system conditions are such that the PST, even at maximum tap position, cannot reduce the overload condition, the overload can be relieved by running the PST to neutral. For a single-core PST, the neutral position results in no turns of the PST being subjected to heating, which will relieve the overload. For two-core PSTs, this is not the case, so it may also be necessary to automatically close the bypass after the PST reaches neutral to relieve the overload condition.

SDG&E Approach

In the SDG&E application, the CAISO originally specified that if one of the two PSTs was tripped, the second PST must also be tripped and the bypass closed in an open transition to relieve the remaining PST from overload. We advised the CAISO that the remaining PST could easily automatically override its CAISO tap position set point under contingency to address the trip without opening the transmission path. This would provide a more graceful recovery from the loss of the first PST than the proposed action. This mode of operation was called N-1 overload override.

The Imperial Valley PST has the following overload functions:

- N-1 overload override
- Low-set overload alarm
- High-set overload alarm

The N-1 overload override logic will assert if the PST load is above the nameplate rating for a user-settable delay when the second PST is out of service. This logic overrides the CAISO tap position set point and lowers the load on the online PST to maintain the load at nameplate rating or less irrespective of the CAISO set point. The control will remain in N-1 overload mitigation mode until the alarm is reset by the operator.

The SDG&E controller application also includes both low-set and high-set overload alarms. If loading exceeds a low-set threshold (regardless of being in an N-1 state), the controller will alarm after a user-settable delay (e.g., 30 minutes). If the overload exceeds a high-set threshold, (e.g., 600 MVA), the controller will alarm after a user-settable delay (e.g., 5 seconds).

GENERAL CONTROL FEATURES

To create a smart LTC control, additional features are required. This section summarizes some features described in [1].

Local and Remote Control

The control interfaces to SCADA via DNP3 such that all control and indication functions are available remotely. Twelve programmable pushbuttons, 24 programmable LEDs, and a highly configurable LCD with 11 lines of text provide a rich, local user interface. Figure 8 and Figure 9 show examples of two implementations of front-panel interfaces. Figure 12 shows an example of the regulation screen on the LCD.

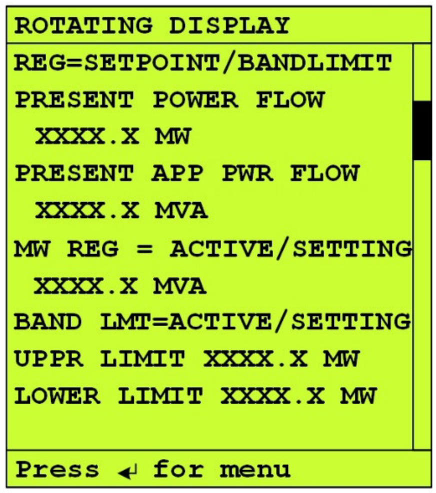

Figure 12
Regulation Screen on the LCD

Integrating Timers

Integrating timers are used to initiate tap changes. The integrating timers count up when the power flow is out of band and count down when the power flow is in band. If automatic control is enabled, once the measured real power flow goes out-of-band high or out-of-band low for a set time delay, a tap change will be initiated in the correct direction to move the power flow closer to the set point.

Refer to Figure 13, reprinted from [1], for the following discussion. One way to understand the characteristics of an integrating timer is to envision a clock hand that moves clockwise or counterclockwise depending upon which input is asserted. When the hand is against the Reset stop, the timer is reset. If the hand is moved clockwise more than it is moved counterclockwise, it will eventually reach the Expired stop. When it does, the expired output asserts. An integrating timer is superior for this type of application where the parameter to be timed can be right on the edge of the band limit and the input continuously sets and resets. An integrating timer will eventually time out and initiate a tap change if the aggregate time that the power flow is out of band is greater than the time that the power flow is in band.

Even though the SDG&E application controls the LTC to make the tap position match the CAISO tap position instead of measured power, we still used the integrating timers and out-of-band comparators to control tap changes to maintain the integrity of the well-proven logic.

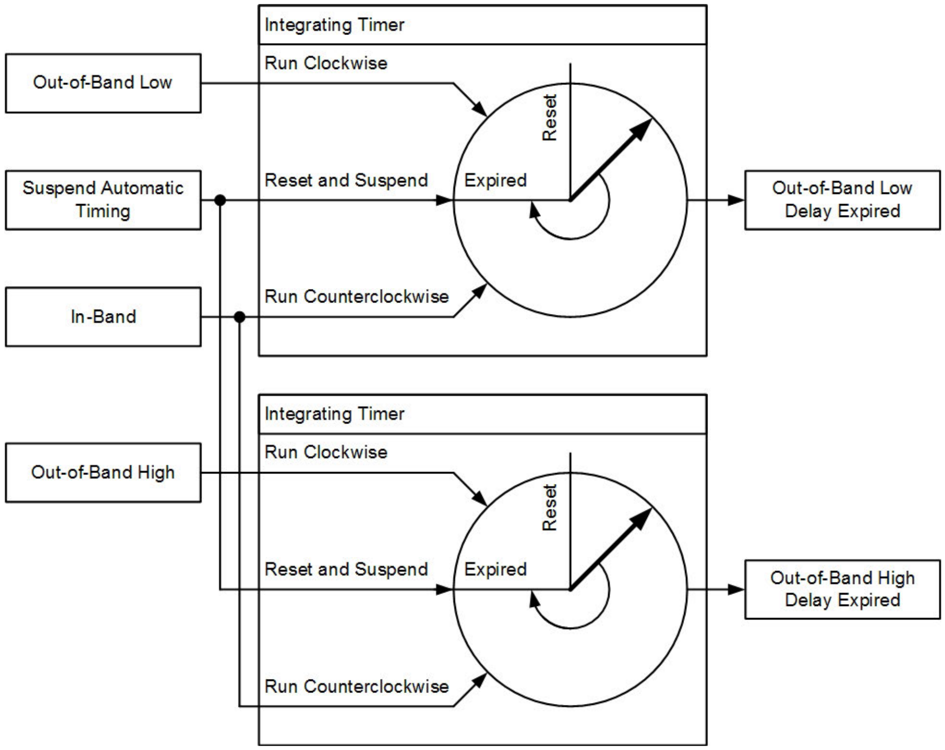

Figure 13
Integrating Timer

Tap Step Wrong Direction Logic

If a problem occurs in the tap-changer control circuits that causes a tap lower or raise operation to have the opposite effect, automatic regulation would continue initiating tap changes in the wrong direction and not stop until the tap reaches its extreme position. The control includes logic to detect a move that is opposite of the expected direction and to suspend operation [1].

Line-Open Logic

Another condition that can result in the LTC running to an extreme position when regulating power flow is when a line is opened—either inadvertently or for a fault condition. In this case, the regulator will sense the power flow going to zero, which may be out of its band limits. Tap changes will not result in moving the operating point off of zero, so the control will continue to call for tap changes until the LTC reaches its extreme position. Then, when the path is restored, the power flow will likely be extremely over the rating of the PST. The control includes logic to detect this condition and suspend operation [1].

Maximum Operations-Per-Hour Logic

In the event that the control does begin hunting, it can operate many times in a short period. This can result in excessive wear on the mechanism and disturbances to the power system. This is unlikely to occur if the adaptive bandwidth function is used; however, this function can be disabled. A maximum operations-per-hour function detects this condition and blocks further operations for the next ten minutes.

CONCLUSIONS

This paper provides a primer on PST application and common installation configurations. Automatic control of the LTC on a PST has many challenges. For this reason, many PSTs are only manually controlled. The paper explains these challenges and introduces many innovative solutions. Extensive experience with many installations accumulated over more than ten years has provided opportunities to develop ever more functions to add to the portfolio of solutions that can be brought to any PST installation.

One of the most challenging installations that the authors have encountered was the SDG&E Imperial Valley parallel PST installation ordered by the CAISO. These PSTs had an extremely wide range of regulation that was asymmetrical around neutral. To achieve this wide range of regulation, the PST designer had to use three regulating windings, switched in and out in such a way to give four ranges of regulation with a total of 64 steps from full advance to full retard. This arrangement of windings made the impedance characteristic of the PST nonlinear across its range of operation which made implementing a circulating apparent power function to supervise the Master/Follower control function very challenging.

The biggest constant we have found in designing and implementing PST control systems is that flexibility is the most important attribute of a successful design. Every PST installation has different strategies for operation that the planning engineers envisioned when specifying a PST as the solution to their power system problem. The PST control that we describe in this paper is extremely powerful and configurable and has always provided the ability to be programmed to whatever the system requires.

ACKNOWLEDGEMENTS

The work described in this paper was funded by California utility customers under the auspices of the California Public Utilities Commission.

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BIOGRAPHIES

Bill Cook is the Project Manager for Grid Operations at San Diego Gas & Electric (SDG&E). Bill started his career at SDG&E in 1976 as an engineer in the SDG&E Control Center. He moved to the field in 1982, working in the Substation and System Protection groups. He moved to the manager position in System Protection and Control Engineering in 1997. In 2014, he moved to his present position in Grid Operations. Bill earned his B.S.E.E. from California Polytechnic State University in San Luis Obispo. He is a registered professional engineer in California and a member of the IEEE. He has been a member of the WECC Remedial Action Scheme Reliability Subcommittee (RASRS) since 1999.

Michael J. Thompson received his B.S., magna cum laude, from Bradley University in 1981 and an M.B.A. from Eastern Illinois University in 1991. Upon graduating, he served nearly 15 years at Central Illinois Public Service (now AMEREN). Prior to joining Schweitzer Engineering Laboratories, Inc. (SEL) in 2001, he was involved in the development of several numerical protective relays while working at Basler Electric. He is presently a Fellow Engineer with SEL Engineering Services, Inc. He is a senior member of the IEEE, member of the IEEE PES Power System Relaying and Control Committee, past chairman of the Substation Protection Subcommittee of the PSRCC, and recipient of the Standards Medallion from the IEEE Standards Association in 2016. Michael is a registered professional engineer in six jurisdictions, was a contributor to the reference book, *Modern Solutions for the Protection Control and Monitoring of Electric Power Systems*, has published numerous technical papers and magazine articles, and holds three patents associated with power system protection and control.

Kamal Garg received his M.S.E.E. from Florida International University and India Institute of Technology, Roorkee, India, and his B.S.E.E. from Kamla Nehru Institute of Technology, Avadh University, India. Kamal worked for POWERGRID India and Black & Veatch for several years at various positions before joining Schweitzer Engineering Laboratories, Inc. (SEL) in 2006. Presently, he is a senior protection engineer at SEL Engineering Services, Inc. Kamal has experience in protection system design, system planning, substation design, operation, remedial action schemes, synchrophasors, testing, and maintenance. Kamal is a licensed professional engineer in the U.S. and Canada and a member of the IEEE.

20180426 • TP6868-01