Abu Dhabi Phase-Shifting Transformer Project: Automatic Parallel Control, Design, and Commissioning

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***Abstract*—Phase-shifting transformers (PSTs) play a crucial role in modern power systems by enabling the control of power flow in a transmission line, improving system stability, and enhancing grid efficiency. 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 the action of a tap-changer mechanism.**

Historically, PSTs were mainly controlled manually for phase-angle regulation, which was often slow, labor-intensive, and prone to human error. This was followed by the introduction of basic automatic controls, which improved operational speed and convenience but still lacked the flexibility to respond to real-time changes in the grid. This paper discusses advancements in adaptive control technology, developed to ensure coordinated operation of two 1,000 MVA, 400 kV PSTs with ±26 degrees of regulation range that were recently installed in parallel in the Abu Dhabi TAQA Transmission system, addressing key challenges in automatic regulation and coordination. To meet the unique requirements of this application, as specified by the utility for automatically controlling these parallel PSTs, a team from the United States of America and United Arab Emirates built on technology that has been developed over nearly two decades of executed projects.

The actual change in power for each tap step is a function of system conditions, and therefore, it is easily possible for an automatic controller to hunt (i.e., the control action overshoots the regulation deadband, which causes the tap position to continually change). The utility desired a control that would provide automatic regulation to an operator set point. This requirement led to the development of a controller with an adaptive bandwidth feature that learns system conditions to prevent the possibility of hunting and improve system stability. A major achievement of this project was refining the controls to ensure that the parallel PSTs remain in step during automatic operation. Additionally, the paper discusses challenges faced during the commissioning of the control system and their resolution.

***Keywords*—Phase-shifting transformer (PST), phase-angle regulating (PAR) transformer, automatic regulation, master-follower control, independent control, parallel PSTs, on-load tap changer (OLTC), advance-retard switch (ARS), factory acceptance test (FAT), site acceptance test (SAT), adaptive control, grid integration**

I. Introduction

The modern high-voltage electrical power grid is continuously evolving to meet the growing demand for clean, reliable, and efficient energy delivery. A key aspect of this evolution is the increasing integration of clean energy sources, such as nuclear, solar, and wind, which are often located far from major load centers due to geographic, environmental, and safety considerations. While long-distance transmission has always been part of power system design, the growing scale, variability, and geographic spread of these sources have made power flow management more complex, posing new challenges for grid operators as transmission networks expand and interconnect [1].

One of the primary challenges in such large-scale grids is the control of steady-state power flow, which is influenced by factors such as the impedance of parallel transmission paths, fluctuations in generation output, and variations in load demand and load center phase angles [1]. Phase-shifting transformers (PSTs) have emerged as a critical solution in this context. By regulating the phase angle across the transmission line, PSTs allow operators to control active power flow effectively without altering generation or load levels. This functionality is essential for mitigating overload conditions, enhancing grid reliability, optimizing grid performance, and maintaining system stability under dynamic operating conditions. In this project, two PSTs are operated in parallel. This introduces complexities such as coordination and synchronization, which require advanced control strategies to prevent conflicting operations and ensure system stability.

In 2024, the Barakah Nuclear Energy Plant was integrated into the United Arab Emirates (UAE) national grid, supplying 5,600 MW of clean, baseload electricity—approximately 25 percent of the national demand and is expected to generate 40 TWh annually [2]. This development significantly enhances grid capacity and supports the UAE’s strategy of net zero by 2050 by displacing fossil-fuel-based generation and reducing carbon emissions by approximately 21 million tons per year [2].

The PSTs being deployed at Substation A play a significant role in the evolving UAE grid. The integration of such large generation sources has further increased the need for robust power flow management tools like PSTs. By dynamically adjusting the phase angle, PSTs enable operators to reroute power flows, thereby alleviating congestion and enhancing grid flexibility. As the UAE grid continues to expand and interconnect regionally, PSTs may become a strategic asset for maintaining long-term stability, efficiency, and adaptability.

Fig. 1 illustrates the newly commissioned parallel PST system at Substation A, operated by the utility. It highlights the well-organized integration of the new PSTs into the existing Substation A-Substation B transmission path. The upgrade includes the installation of associated breakers and isolators, with interconnections routed through gas-insulated switchgear (GIS) buswork, linking the existing and newly constructed GIS buildings.

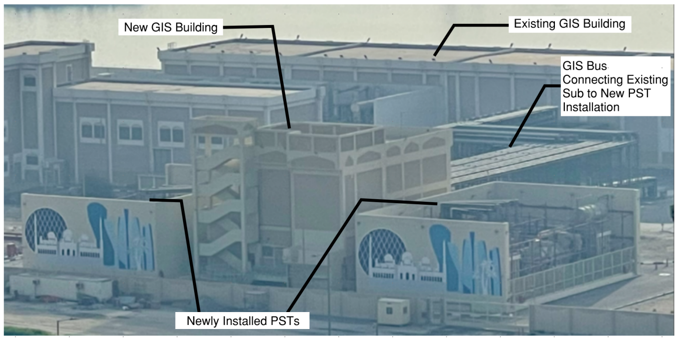

Fig. 1. Substation A overview showing the newly installed parallel PST system.

This paper is organized as follows: Section 2 provides an overview of the PST system and the overall scope of the project. Section 3 and Section 4 outline the control design considerations and strategy, focusing on the design and development of the PST controller logic. Section 5 presents the control panel design, covering the general arrangements and detailed schematics. Section 6 discusses the commissioning process, including the control function verification and communications testing with the existing supervisory control and data acquisition (SCADA) system.

II. Background

A. Project Objectives

The objective of the project is to install two new 400 kV, 1,000 MVA PSTs at the Substation A grid station and integrate them with existing GIS. Additionally, the project includes connecting the PSTs to the underground cable circuits between the Substation A and Substation B grid stations, and incorporating control, protection, and monitoring systems into the National Control Center. This enables the utility to effectively control the power flow in the Substation A and Substation B transmission corridor through phase-angle adjustment using the PSTs' on-load tap changer (OLTC).

The installation of the PSTs enables the utility to mitigate the risk of overloading the 400 kV network by balancing active power flow between the two major transmission corridors supplying Abu Dhabi. This enhances the system stability and operational flexibility across the transmission routes supplying Abu Dhabi during dynamic grid conditions.

The specific objectives of the project discussed in this paper include:

1. To design and develop the PST controller logic for the 400 kV, 600/800/1,000 MVA PST with a phase-angle shift of ±26 degrees.
2. To design a control panel general arrangement and schematics.
3. To conduct commissioning tests, including control function and communications tests, with existing SCADA system through IEC 61850 protocol for telemetry and control.

B. System Overview

The project at the Substation A grid station integrates two newly installed, two-core PSTs connected to two 400 kV transmission lines that operate in parallel. The parallel configuration provides redundancy, ensuring continued operation if one PST is offline for maintenance. These PSTs are rated at 600/800/1,000 MVA and provide a phase-angle regulating (PAR) capability of ±26 degrees with 32 taps in each direction, thereby providing a regulation of 0.8 degree per tap. The PSTs are interfaced with the existing 400 kV GIS at the Substation A station and are connected to the two existing 400 kV cable circuits linking Substation A and Substation B. Their primary function is to regulate active power flow between the Substation A and Substation B grid stations by adjusting the phase-shift angle.

Fig. 2 shows a simplified one-line diagram of the system, illustrating key components, including the line breakers, source breakers, load breakers, and associated disconnect switches. The busbar configuration at Substation A allows the PSTs to be connected to either busbar, Bus 1 (A/B) or Bus 2 (A/B), via disconnect switches, enabling flexible operational arrangements.

During normal system operation, the bus arrangement at both the sending and receiving substations operates with the bus-tie and bus coupler circuit breakers closed such that the PSTs are always operated in parallel. To maintain a true parallel configuration of the PSTs, it is imperative that two transmission circuits remain bussed together at both ends.

Each PST is equipped with a parallel disconnect switch, which enables manual bypass when a PST is out of service. The switches to isolate the PST and insert the bypass path must be operated when the circuit is de-energized.

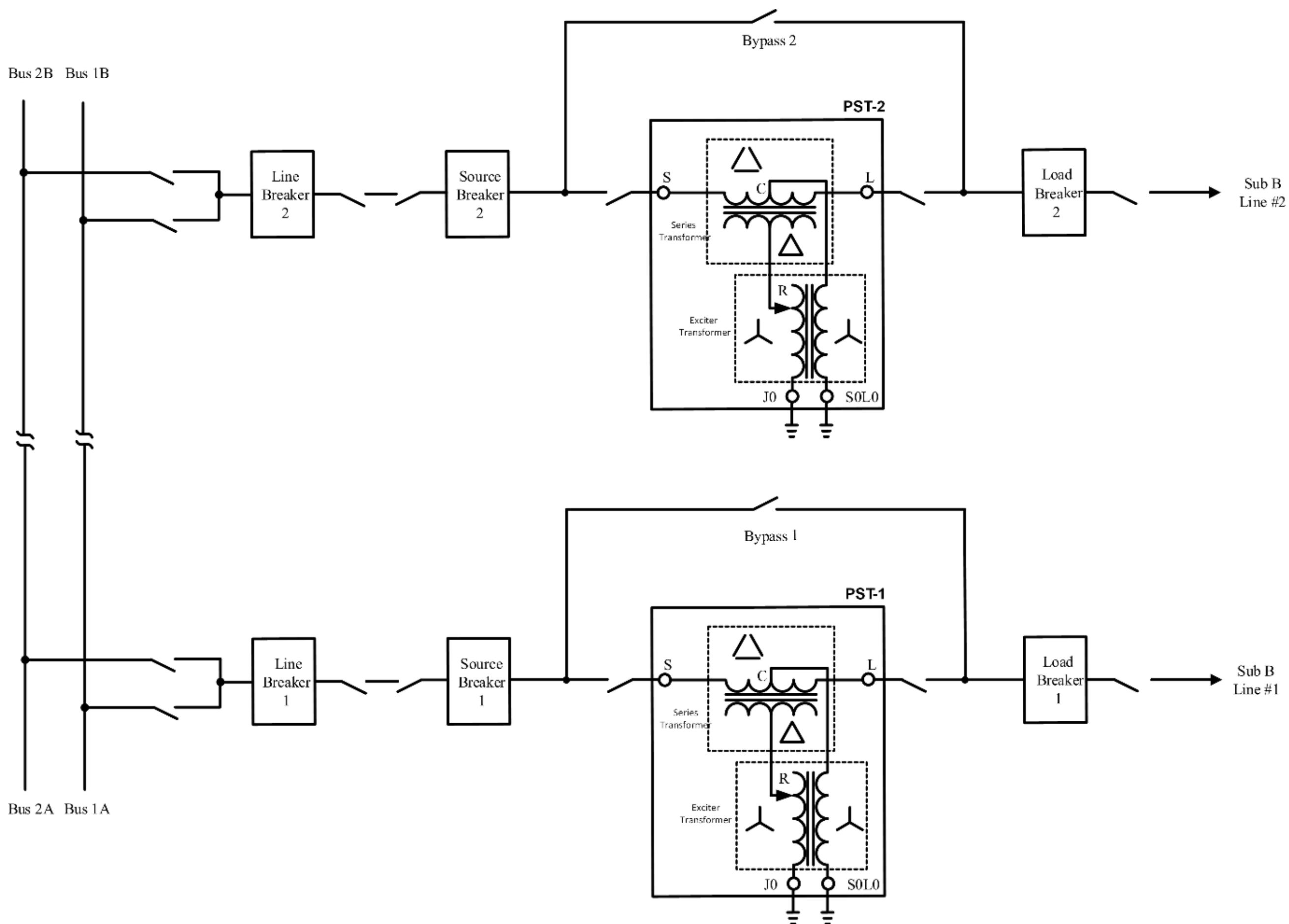

Fig. 2. Simplified parallel system with two-core PSTs at Substation A station.

III. Design Considerations

This section outlines the key design considerations, such as fine regulation requirements, mechanical constraints, coordination complexities, and system limitations faced during the development of the control solution for the utility PST system.

A. Fine Regulation Range

PSTs used in this application are designed with fine resolution, offering approximately 0.8 degree of phase shift per step. The total regulation range spans ±26 degrees, divided into 32 steps in both the advancing and retarding directions, with a neutral position included—resulting in 65 discrete steps. To achieve this desired range, the control hardware infrastructure at the PST has been equipped with a fine- and course-regulating winding in addition to the advance-retard switch (ARS). See the following subsection for more details. This fine granularity enables precise power flow control; however, as the relationship between active power flow and phase angle is nonlinear [3], the control solution for this application must incorporate advanced algorithms capable of dynamically adapting to a changing system to maintain such a desired level of precision.

The controller must be highly responsive and accurate, relying on high-resolution real-time data for its decision making. The effectiveness of fine regulation depends heavily on the precision of the voltage, current, and phase-angle measurements. These parameters are essential for accurately calculating active power flow and determining how much it varies with each step change made by the OLTC. Signal inaccuracies, errors, and delays can further amplify sensitivity of the controller, leading to large deviations in control output and compromising the stability and robustness of the control loop. So, to achieve precise power flow regulation, the controller must continuously assess and operate based on real-time change in power flow that corresponds to each OLTC step—unlike traditional automatic control schemes that rely on fixed threshold values that may not reflect actual system dynamics under varying operating conditions.

The PST controller in this application employs an adaptive control strategy. This approach allows the controller to adjust its internal control factors in real time based on current operating conditions, improving its ability to maintain stable and precise control even within the constraints of a fine regulation range. See Subsection 4.2.3 for further details.

B. ARS and Fine- and Course-Regulating Windings

To obtain the fine degree of control discussed previously, the transformer design incorporates an ARS within the series transformer. This switch enables reversal of the secondary winding polarity during transitions between the advance and retard positions. Fig. 3, as shown following, is derived from Figure 1 and Figure 2 from [4].

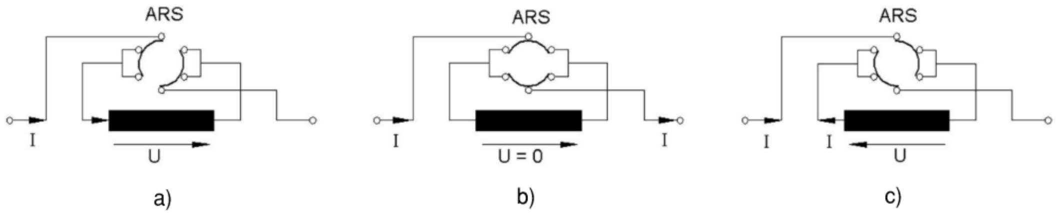

Fig. 3. a) ARS in Operating Position 1; b) ARS during transition; c) ARS in Operating Position 2 [4].

The ARS switch allows the reversing changeover operation to be carried out in two steps without interruption while the regulating winding remains at its neutral position during the whole operation [1]. The limiting parameter for the ARS is the process of commutation, which has to be controlled by the ARS, and it is determined by the commutation of the through current from a small inductive loop to a larger one [1].

The ARS transitions between advance and retard positions by rotating an insulating drive shaft. During tap-change operations that involve transitioning through the neutral position between advance and retard, the ARS motor operates in coordination with the OLTC motor. This mechanical interaction must be explicitly accounted for in the controller design, particularly in systems with parallel PSTs—such as the one described in this paper—in which the synchronized operation of both ARS units is required when operating in parallel.

Further, the PSTs have a fine- and course-regulating winding with the normal reversing switch in the OLTC mechanism repurposed for switching the course winding into and out of the circuit. To move from the neutral position, the OLTC taps up 16 steps along the fine winding. The reversing switch then switches the course winding into the circuit and returns the OLTC to its neutral position. The course winding has the same total number of turns as the fine winding. Positions 17 through 32 are then obtained by the OLTC tapping up the fine winding again. This configuration effectively doubles the number of tap positions, increasing the resolution from 16 to 32 steps. The ARS doubles the total number of steps between full advance and full retard from 32 to 64 plus neutral for a total of 65 possible tap positions.

To ensure accurate monitoring and control of ARS operations, the controller receives the following status and position signals from each ARS mechanism:

- ARS in advance position
- ARS in retard position
- ARS tap change in progress
- ARS incomplete-switching operation
- Voltage monitoring—ARS motor or control circuit

Similar signals are obtained from the OLTC mechanism. These signals are used by the controller to verify that each tap-change operation results in the intended final position. If the ARS or OLTC motor exceeds a configurable runtime threshold or becomes stalled during transition, or if a fault is detected in the ARS or OLTC control circuits, the controller logic will inhibit further automatic operations. This protective measure is intended to prevent mechanical or electrical damage to the transformer and tap-changer assembly. Additionally, the controller is programmed to trigger specific alarms via both the local front-panel interface and the remote SCADA interface to prompt operator intervention.

C. *Parallel PST System*

The utility application involves PSTs operating in parallel, necessitating the implementation of coordinated paralleling control schemes. In such configurations, it is imperative that the controllers operate in a harmonized manner to ensure their control actions are complementary rather than conflicting. Without proper coordination, the controllers may issue opposing commands—such as one increasing and the other decreasing the phase shift—which can lead to control oscillations, suboptimal power flow regulation, or accelerated mechanical wear on the tap changers. These requirements introduce additional complexity to the system control design, demanding the development of robust control algorithms and the deployment of a reliable communications infrastructure to ensure stable and efficient operation. To mitigate these risks, the controllers in this application support real-time communications, shared state awareness, and synchronized decision making. The implementation of these paralleling controls is described in detail in Subsection 4.1.

The PSTs are installed on two separate transmission lines, which are independently bussed at both terminals—Substation A and Substation B. However, due to existing design constraints, the PST controllers located at Substation A do not have access to the bus configuration status. As a result, the controllers are unable to definitively determine whether the PSTs are operating in a truly paralleled configuration. The implications of this limitation are further discussed in Subsection 4.4.

D. *System State Detection and Validation*

The PST controller receives hardwired digital inputs of the open and close statuses of all the high-voltage switching devices, such as disconnectors, circuit breakers, earth switches, and bypass switches, from the local and parallel circuits. Each PST controller has visibility of its PST's state as well as the state of the parallel circuit. The PST circuits can be in one of three defined states—in service on PST, out of service, or in service on bypass—which is determined based on these inputs. To ensure data integrity, the digital inputs are validated for congruence using double point field statuses, as described in Subsection 5.1. The controller is blocked from declaring a system state if an open or close system incongruent status is detected.

Knowing whether a circuit is in service on PST, out of service, or in service on bypass allows the controller to make the right decisions at the right time. Each state represents a distinct physical and electrical condition of the PST and its associated switching devices, which must be accounted for in the control logic.

1) Circuit In Service on PST

All switching devices are closed and power is flowing through the PST:

- This is the normal operating condition.
- The controller can perform automatic or remote manual tap changes, participate in master-follower coordination, and execute the run-to-neutral operations.
- The system calculates power flow and power factor based on the total load in the combined path.
- Alarms related to tap-position mismatch or circulating power are enabled when both PSTs are in service.

2) Circuit In Service on Bypass

The PST is electrically bypassed, and power is flowing directly through a bypass circuit, typically for maintenance or commissioning:

- Automatic or remote manual tap-change functions are blocked, as they would have no effect or could cause damage.
- Power factor or MW/MVAR regulation logic must ignore this path to avoid incorrect calculations.
- Parallel master-follower control logic is suspended.

3) Circuit Out of Service

One or more switches (breakers or disconnectors) are open, and the transmission path is open at any point in the local substation.

- The controller disables automatic or remote manual functions to prevent sending tap-change commands when there is no path for power to flow.
- The control mode typically shifts to independent or OFF.

IV. Control Strategy

This section outlines parallel PST control to ensure coordinated operation, implementation of automatic regulation functions designed to maintain precise phase-angle control under varying load conditions, and overload protection logic designed to continuously monitor transformer loading levels to mitigate the risk of equipment overheating or failure. It also covers circulating apparent power alarm logic for detecting and mitigating imbalances between parallel units.

The PST controller was developed in accordance with the utility requirements to fulfill operational and control specifications aligned with their transmission network standards and system control philosophy.

1. Control Hierarchy
    - The system intends to support both local and remote control operations.
    - Remote control shall be enabled via SCADA system with IEC61850 protocol for load dispatch center (LDC).
2. Operating Control Modes
    - Master mode: Directly regulates the PST based on defined control objectives.
    - Follower mode: Responds to external commands from a master controller.
    - Independent mode: Operates autonomously using internal logic or fallback values when the parallel circuit is unavailable or in an invalid state of control.
3. Operating Control States
    - Local manual control: Manual operation from the local control panel irrespective of the PST controller.
    - Remote manual control: Manual operation via station SCADA system or LDC interface through gateway communications.
    - Automatic control: Automatic control using proven logic according to the selected automatic control state.
4. Command Interfaces and Control Selection

The system allows the control selection for operating control modes, control states, and analog MW set points command from the:

- Controller front-panel interface.
- Station-level SCADA system.
- LDC.

A. Parallel Control of the PSTs

As depicted in Fig. 2, Substation A includes two PSTs connected to parallel transmission lines that operate concurrently. Each PST is equipped with an individual OLTC controller, which provides control feedback to its associated tap-changer mechanism to regulate power flow. In this parallel PST configuration, the primary control objective is to regulate the total active power flow through the PSTs in parallel (total path flow). To achieve this, the control system incorporates the following key features designed to ensure synchronized operation, reliable communication, and alarm monitoring:

- Master-follower control mode
- Independent control mode
- Serial communications links to manage data between OLTC controllers and to support paralleling of the PSTs
- Monitoring control logic to detect and alarm for an out-of-synchronism condition

1) Master-Follower Control

Both the OLTC controllers are capable of operating either in a master-follower combination mode or independent mode. When the two PSTs are operating in parallel—based on system conditions determined by the operators—one controller is designated as the master, while the other controller becomes the follower automatically. In this mode, the follower simply follows the commands given by the master [3]. The automatic and remote manual pushbuttons and associated remote commands will not function on the follower controller. In the event the PST, whose controller is the master, trips, the follower's mode will be changed to independent with the same operating state (off, automatic, or manual) that the master was in prior to the trip [3].

The master-follower and independent control modes can be selected either locally or remotely. Local mode selection is performed via the front-panel user interface on each controller. Remote mode selection is facilitated through the substation control and monitoring system (SCMS) managed by the utility, as well as through the LDC or energy control center for Abu Dhabi. Subsection 5.2 and Subsection 5.3 provide information on the local and remote user interfaces used in this application. When the master pushbutton or associated SCADA command is asserted on either of the controllers, the other controller automatically becomes the follower. Similarly, when the follower pushbutton or associated SCADA command is asserted on either of the controllers, the other automatically becomes the master. When the independent pushbutton or associated SCADA command is asserted on either of the controllers, the other automatically switches to independent mode.

When in follower mode, the controller does not initiate any tap-changing actions on its own. The follower executes control commands governed by the master controller. However, to prevent undesirable operations, the follower controller is blocked from executing control actions under the following alarm conditions:

- The OLTC, or ARS motor, fails to complete its starting, switching, or stopping sequence within the predefined time limit.
- The associated PST is undergoing maintenance.
- The current through the OLTC switching contacts exceeds the configured overcurrent threshold.
- The associated PST trips due to a system fault condition.
- The controller is in the OFF state.
- The controller receives unreliable or inconsistent input signals, preventing it from accurately determining the system state configuration of the parallel system.
- The controller is not in follower mode.

2) *Data Exchange Between Controllers*

For the parallel control system to take desired actions, both controllers that are operating in parallel must have access to pertinent data from their respective local circuits as well as from each other. Each controller receives its local circuit information through its analog and digital input channels, which includes measurement signals from instrument transformers and control signals between the tap-changer mechanism. Additionally, operator commands to the controller, whether issued via local or remote user interface, constitute a vital element of the control strategy. To facilitate coordinated decision making, the local and parallel controllers exchange necessary real-time operational data through a serial communications link, thereby ensuring mutual access to all relevant system and control parameters. The exchanged data are also used to calculate total path loading for automatic control and circulating apparent power to detect and alarm for out-of-synchronism of tap positions of the PSTs in parallel. See Subsection 4.4 for further details.

When reliable data required for coordinated control of the parallel PST system are unavailable, both units automatically switch to independent mode to maintain secure and stable operation. This fallback strategy is triggered under the following conditions:

- Failure of the communications channel (i.e., serial link) between controllers.
- Tripping of either PST due to a system fault condition.
- One or both PSTs rendered unavailable due to the associated local or parallel transmission circuits either being bypassed (placing the PST out of the power path) or taken out of service entirely.
- One or both PSTs undergoing maintenance.
- Tap change initiated manually, bypassing the controller logic.
- Controller initialization events, such as startup or configuration settings changes.

B. *Automatic Regulation Functions*

Automatically controlling an OLTC on a PST is not nearly as straightforward as automatically controlling an OLTC used for voltage control on a conventional transformer. The regulated quantity of a PST is active power flow. However, the OLTC of a PST controls the quadrature voltage, ΔV_Q, inserted between the source and load terminals that only indirectly controls power flow through the PST and associated transmission line.

Another significant concern is designing the automatic control functions so that they will not experience a runaway condition, that is, run the PST OLTCs to an extreme position. This installation controls a major transmission path with a combined capacity of 2 gigavolt-amperes (GVA). If the PSTs experience a runaway condition, the results could be extremely disruptive to the transmission system. The controls must be designed to prevent runaway when in automatic control. This is discussed in Subsection 4.2.4.

Let us consider the problem of automatic control. The simplified equation for the power flow between a sending and receiving bus is (1). We can see that power flow is a function of the sending and receiving voltage magnitudes, the impedance between them, and the sine of the angle, δ, between the voltages. Conceptually, it is an easy-to-understand application of a PST. If we can control δ, we can control power flow. The other variables in this equation are fairly fixed. For example, the voltages operate in a narrow range around nominal and the impedance of the transmission line is fixed.

$$P = \frac{E_S E_R}{X_L} \sin\delta \qquad (1)$$

where:

E_S is the sending-end voltage
E_R is the receiving-end voltage
X_L is the series reactance of the transmission line
δ is the angle between the two voltages

But the actual situation is more complex. It is important to realize that the power flow on the transmission system is driven by the location of sources injecting power into the system and the location of load removing power from the system. Of course, transmission losses must also be considered; but they are neglectable for this discussion. A PST cannot change this fundamental aspect of power flow. The sources and sinks of power have to balance at all times. The simplified two-machine system with a single path connecting them, which we often see accompanying (1), only superficially explains how a PST controls power flow.

We often use the analogy of the power system being similar to a mechanical power transfer system with a rubber shaft. To transfer more power, we have to apply more torque to the shaft. The torsional twisting of the shaft between the sending and receiving ends of the shaft (the angular difference between the source of mechanical power and the driven load) is analogous to the angle δ.

Fig. 4, which is a reproduction of Figure 2 from [3], shows a more useful diagram. A transmission path equipped with a PST is in parallel with all the other paths in the interconnected transmission grid. The parallel transfer impedance branch, X_T, in Fig. 4 represents the rest of the interconnected transmission grid. To use casual language, a PST must have something to twist against to boost or buck power flow. By changing the power flow on its path, of course, the power flow on these parallel paths changes as the total power flow is redistributed. Fig. 4 also includes a Kirchhoff's voltage law phasor diagram around the circuit to better understand how the PST controls power flow in its path.

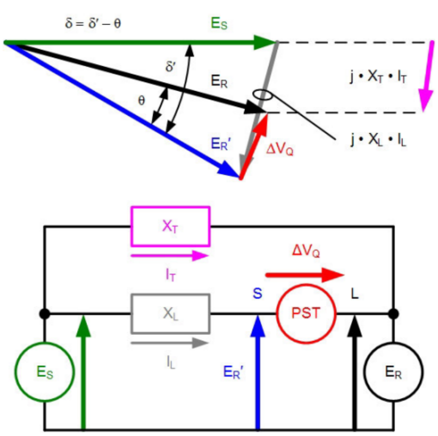

Fig. 4. Kirchhoff's voltage law diagram for PST application [3].

This diagram depicts a condition in which power flow is from sending bus, E_S, to receiving bus, E_R. The PST is in an advanced position, which means that the PST's load terminal, L, is leading the source terminal, S. The quadrature voltage, ΔV_Q, shown between E_R and E_R' is the induced quadrature voltage minus the voltage drop across the impedance of the PST. The resultant effective PST angle is labeled θ. We can see that the angle across the transmission line, δ', is the sum of the system power flow angle, δ, and the effective PST angle, θ. Because δ' is larger than δ, the power flow in the line is boosted over what it would be without the PST. We can easily see that the power flow across the transmission line is increased because the voltage drop across the line, $jX_L \cdot I_L$, is increased. Because jX_L is constant for the line, the PST has increased the magnitude of the line current.

It is important to consider that the angle δ between the sending and receiving terminals of the transmission path is mostly influenced by the power flow demands of the interconnected transmission grid. The system power flow angle, δ, is generally not appreciably affected by this redistribution of power flow caused by the PST.

Variations in system generation and load mix and variations in system topology will affect the PST's action. In addition, we see that the power transfer equation (1) is a sine function, so the effect of changing δ on P will not be the same across the range of regulation. Further, the impedance of the PST varies across the range of regulation, and in some PST configurations, the magnitude of ΔV_Q also changes across the range of regulation. From this discussion, we can see that the parameters that define the relationship between tap position and power flow are quite complex. A power flow regulating the OLTC controller must be able to adapt to the variation in ΔP per tap step to prevent the possibility of hunting.

Each PST control system is unique to the power system it is applied to and the problems that the PST is designed to resolve. In some cases, the PST control algorithm may use a wide-area approach [5] [6]. However, many applications use the power flow through the PST to control the OLTC. In this application, no wide-area control system is provided, so automatic functions are designed to respond to active power flow in the controlled transmission paths.

There are two approaches in common usage for automatic control using measured active power flow in the controlled path. These are described in the following subsections.

1) MW Set-Point Regulation Mode

The most basic automatic control mode is MW set-point regulation. As the name implies, similar to the operator entering a voltage set point for a conventional transformer to hold the bus voltage to a bandwidth around a set value, this regulation mode controls the power flow through the transmission path to a bandwidth around a desired power flow value [7]. This mode requires the adaptive bandwidth function described in Subsection 4.2.3 to prevent hunting. Hunting occurs when a tap step results in a change of the regulated parameter that is greater than the bandwidth setting. For each tap step, the regulated parameter can overshoot the deadband and the regulator will soon attempt to step in the opposite direction. Using a fixed bandwidth in such a system is a compromise. A high bandwidth will reduce the possibility of excessive operations. However, a high bandwidth will also result in poor regulation.

The system operations team looking at power flow conditions on the transmission grid may update the regulation set point several times a day to adjust as system conditions change. This automatic regulation mode is also useful for positioning the PST OLTC at startup. The PST circuits are placed in service (typically on neutral), and then the power flow is automatically ramped up to a desired level. Then the controller can be turned to manual or the other automatic mode.

2) *Band Limits Regulation Mode*

The second automatic control mode is band limits regulation [3]. This mode is useful when the PSTs are being used to respond to contingencies. For example, an outage of a significant generator or parallel transmission path can cause excessive power flows on the controlled transmission path. In such applications, the PST is operated by placing the OLTC at some preset position and then having the controller take action only when the N-1 contingency occurs.

To accommodate this control strategy, the band limits regulation mode is useful. 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 2,000 MW, but the path can become overloaded upon loss of a parallel high-capacity transmission path, the upper band limit may be set to +2,000 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 starts stepping to drive the loading back down to +2,000 MW. Otherwise, the PST does not make any tap changes [3].

3) *Adaptive Bandwidth*

As mentioned previously, the ΔP per tap step is expected to vary with system conditions. A previous paper discussed a novel solution to this problem [7]. The controller adaptively sets the bandwidth by learning system conditions. It does so by measuring the ΔP for the most recent tap changes and averages them to adjust the bandwidth in real time.

The adaptive bandwidth function stores the absolute value of the ΔP from the most recent eight tap changes in memory registers. Fig. 5 shows a functional block diagram of the function. The adaptive +/– bandwidth is calculated as the average ΔP of the most recent tap changes. A user setting is provided to determine how many values are to be averaged in adjusting the +/– bandwidth. This setting is typically left at the default of six. A multiplier setting is included to easily reduce the bandwidth to improve regulation or widen the bandwidth if the number of operations becomes excessive. A user setting is provided to define an initial +/– bandwidth that the controller will use until the ΔP from actual tap-change operations have been recorded. The memory registers are preset to the user setting for initial +/– bandwidth upon the controller being toggled from manual to automatic [3].

1) *Control Runaway*

As mentioned, a control runaway condition must be avoided to prevent significant disruption to the transmission grid. Control runaway can occur if the automatic control calls for an advance or retard operation and the regulated parameter does not respond as expected. The controller can then call for additional tap changes in the same direction. If the condition is not detected, it can continue to issue more tap-change commands because it is never satisfied. It will continue to do so until the OLTC reaches an extreme position. The controller implements a number of features to guard against this condition.

The first function to prevent control runaway is the tap-change failed alarm function. When the controller issues an advance or retard command, it monitors both the change in mechanical tap position and the change in power flow. If the controller detects that the change is in the wrong direction, or if no change is detected, this alarm asserts and automatic control is blocked until the alarm can be resolved and reset. The controller also monitors the OLTC motor circuits for things such as motor fail to start and motor running too long to assert this alarm.

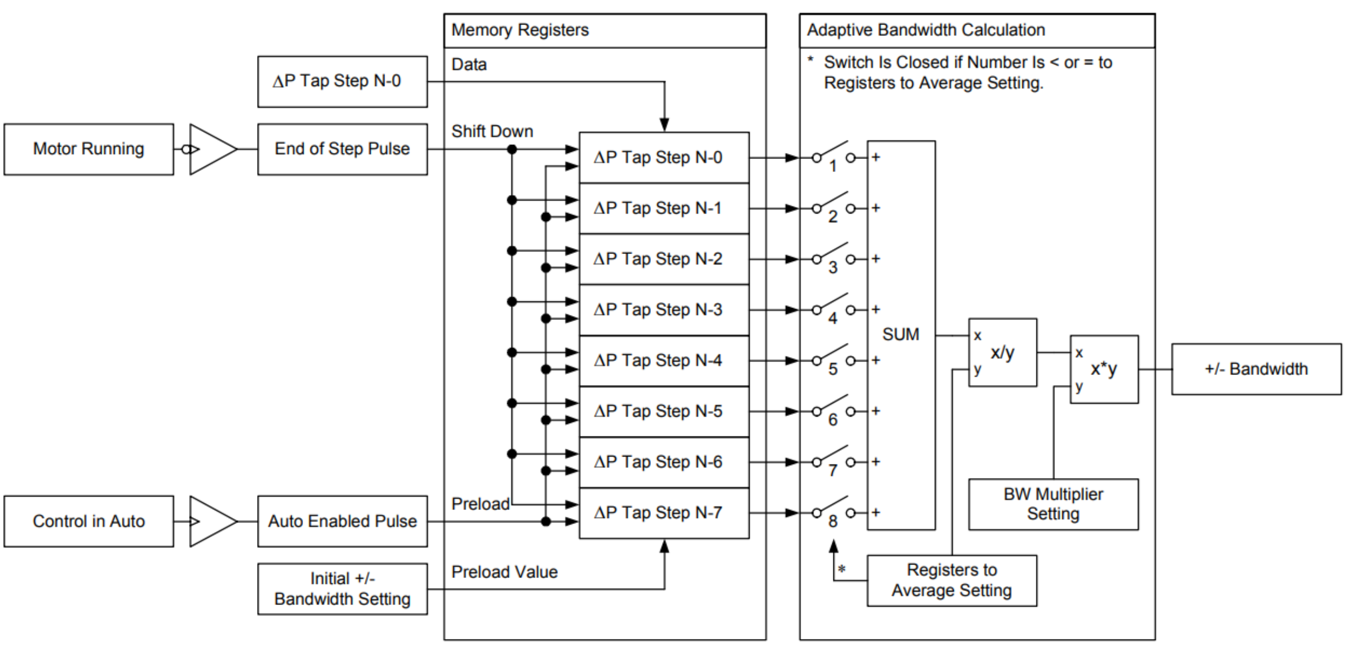

Fig. 5. Adaptive bandwidth function [7].

The second function to prevent control runaway is the detect-line-open function. If the transmission path should become open, the power flow will become zero. This condition could be out of the regulation band, and the controller will issue commands to adjust the power flow back in band. Because the OLTC action will not move the power flow of the open path from zero, the controller could continue to issue commands until it reaches an extreme condition. Then, once the path is restored, the resultant power flow could be excessive and disruptive. An inadvertent path open condition could occur for many reasons, e.g., a protective trip or inadvertent operator control action. The status of the remote terminal is not available to the controller to monitor, so an independent means of detecting this condition is required.

The detect-line-open function asserts when the ΔP from the most recent tap step is less than 50 percent of the expected ΔP and the power flow is less than 50 percent of that value (near zero) as well. For a line open condition, the tap position will only change by one step before being stopped.

Another condition that must be monitored is a case in which the operational set points are lost. The controller stores the operational set point in volatile memory, so if the controller reboots for any reason, the controller restarts with the operational set points at 0 MW. If the controller is in the automatic state when this happens, it may issue commands to step the power flow back to zero. To prevent this, the controller sets this alarm upon first execution of its logic engine. The alarm is automatically reset as soon as the operator sends an operational set point to the control.

Accurate measurement of power flow requires valid voltage signals. The controller has a number of features to monitor for failures in the voltage signals. The controller has a loss of potential function that asserts when there is a change in voltage without an appropriate change in the current signals. Because the controller monitors both source- and load-side three-phase voltage, it also includes a voltage balance function (IEEE C37.2 Device Code 60). If the three-phase voltage signals from the source side and load side of the PST are not similar in magnitude, an alarm is set and automatic operation is blocked. Finally, the controller monitors the voltage transformer circuit miniature circuit breaker and automatic control is blocked if it trips.

C. *Overload Detection*

The overload alarm function asserts when the measured three-phase apparent power is above setting thresholds for a user-settable period. The overload alarm function includes four levels. Overload Levels 2–4 can be disabled. TAQA uses the following levels.

- Level 1 Alarm—occurs when loading is greater than 1.0 per unit (pu)
- Level 2 Alarm—6-hour emergency; occurs when loading is greater than 1.2 pu
- Level 3 Alarm—30-minute emergency; occurs when loading is greater than 1.3 pu
- Level 4 Alarm—short-term emergency; occurs when loading is greater than 1.4 pu

The function uses integrating timers. Integrating timers are required for an overload function. The power flow may be near an overload threshold causing the timer to continuously pick up and drop out with small fluctuations. An instantaneous reset timer may never time out and provide the needed protection. An integrating timer will integrate the amount of time when load is over the threshold versus the time below the threshold, and if the time over the threshold is greater, it will eventually time out.

Operating over the nameplate rating for an extended period of time can prematurely age the PST. A PST is unique in that it can be adjusted to control its own loading. Because the controller allows the automatic regulation set point to be set above the continuous rating, if necessary for the operational requirements, the controller includes a feature to automatically reduce the operational set point to the maximum continuous rating to allow the PST to cool when the controller is in automatic mode. The utility decided not to use this function and relies on operators at the control center to respond to an overload condition.

D. *Circulating Apparent Power Alarm and Block*

Large circulating apparent power (S_{CIRC}) may flow if the two PSTs operate at different tap positions. The magnitude of the S_{CIRC} is a function of the impedance of the PSTs, impedance of the transmission lines, and the voltage in the loop, which varies with tap position. Two methods are used to detect an undesired operating condition in which both PSTs are at different tap positions:

- Tap-position measurement (mechanical indication of symmetry).
- Circulating apparent power measurement (electrical indication of symmetry).

Tap-position difference logic compares the tap position of the two controllers for alarm and block functions. The present tap positions of the two controllers are exchanged over the serial communications channel. If the absolute value of the tap-position difference is equal to 1, then a parallel alarm is asserted. If the tap position difference is equal to 2, then a parallel block is asserted.

The circulating apparent power logic uses apparent power measurements for alarm and block. Voltage-regulating OLTCs insert an in-phase voltage, which results in the circulating current being almost 100 percent reactive power (VARs). Thus, circulating VARs are a good way to monitor and alarm for an OLTC position mismatch [5]. However, the PST inserts a quadrature voltage, but, for a symmetrical PST, the quadrature voltage is quadrature to the midpoint between the source and load terminals. Hence, the circulating apparent power is a combination of the P and Q components in the case of a PST. In this project, it was decided to use apparent power S. Because the two PSTs have similar impedances, P and Q divide equally when the PSTs are paralleled and on the same step. S_{CIRC} is defined by subtracting the measured power from half of the total power as shown in (2) and (3). S_{CIRC} is then determined by the square root of the sum of the squares of the quadrature components per (4).

$$P_{CIRC} = P_{LOCAL} - \left(\frac{P_{LOCAL} + P_{PARALLEL}}{2}\right) \quad (2)$$

$$Q_{CIRC} = Q_{LOCAL} - \left(\frac{Q_{LOCAL} + Q_{PARALLEL}}{2}\right) \quad (3)$$

$$S_{CIRC} = \sqrt{P_{CIRC}^{\ 2} + Q_{CIRC}^{\ 2}} \quad (4)$$

where:

P_{LOCAL} and Q_{LOCAL} are the active and reactive power measured by the OLTC controller.

$P_{PARALLEL}$ and $Q_{PARALLEL}$ are the active and reactive power measured by the adjacent OLTC controller.

The magnitude of S_{CIRC} is a function of the impedance of the lines, the impedance of the PSTs, which varies by tap position, and the voltage in the loop, which also varies by tap position. Fig. 6 shows the S_{CIRC} characteristic programmed for this application. The expected S_{CIRC} for a one-step difference (alarm) and a two-step difference (block) varies depending on where in the range the PSTs are operating.

Three settings define the alarm (one step off symmetry) and block (two steps off symmetry) characteristics:

- The calculated S_{CIRC} at neutral, which is the Y intercept of the characteristic.
- The slope of the line connecting the calculated S_{CIRC} at neutral to the calculated S_{CIRC} at full advance.
- A margin factor to offset the characteristics from the expected values.

The dynamic alarm and block thresholds, based on the mechanical tap-position reading, are calculated using the simple slope times X + Y intercept equation for a straight line. Because the expected values in the advance and retard positions are mirrored, the characteristic is practically implemented by using the absolute value of the tap position so changing the sign of the slope depending on whether in advance or retard is not necessary.

Analysis was performed in an Excel spreadsheet to calculate the expected S_{CIRC} characteristic shown in Fig. 6. It allows us to enter the impedance of the PST for each tap position and calculates the ΔV_Q at each tap step based on the ratios of the series and exciter transformers and trigonometric principles.

Once the parallel block asserts, further tap change is prevented in automatic state. Manual tap changes are blocked only in the direction that will increase the out-of-step condition. The directional blocking logic uses the sign of P_{CIRC} to determine which direction manual tap changes are blocked. If the sign of P_{CIRC} is positive, it indicates that the PST is in advance of the other PST and, therefore, only manual commands to retard the tap position are allowed. Similarly, if the sign of P_{CIRC} is negative, it indicates that the PST is in retard of the other PST and, therefore, only manual commands to advance the tap position are allowed.

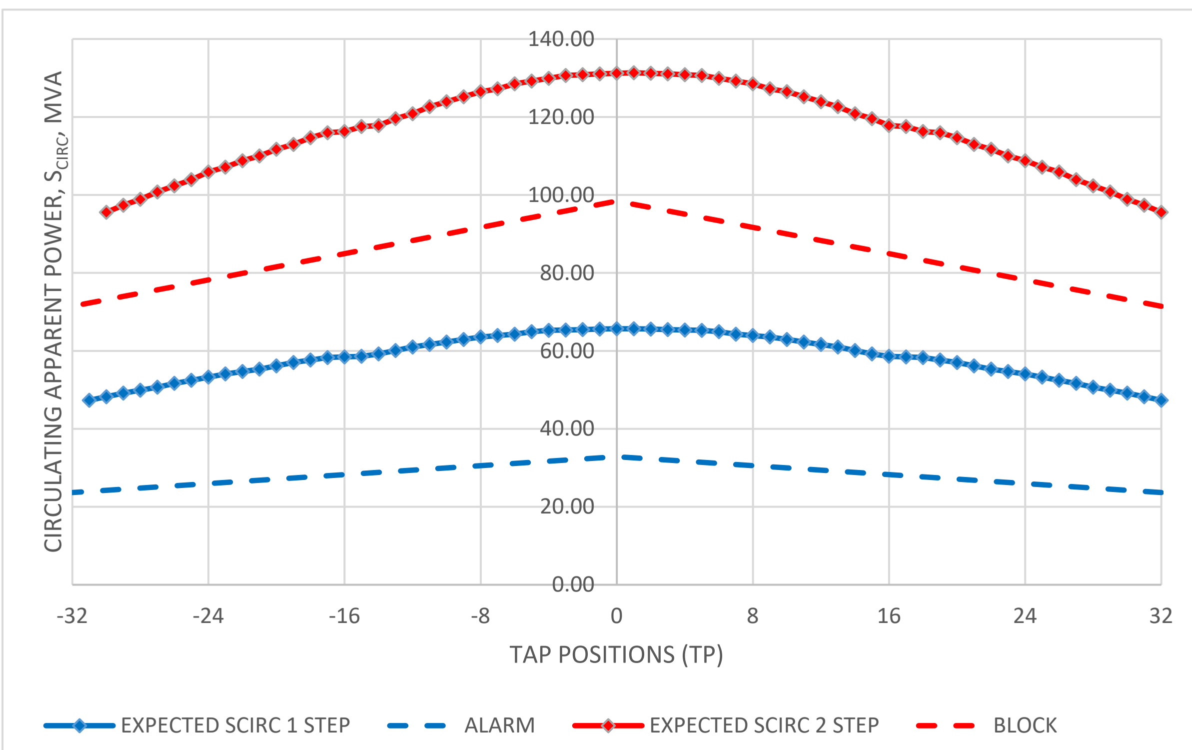

Fig. 6. Circulating apparent power alarm and block curve.

Parallel PST circulating alarm and block will not assert under normal conditions when the two PSTs are in service, in synchronism with each other, and in a parallel state. If a bus tie or bus sectionalizer is open, the PSTs may not actually be in parallel. The circulating apparent power function will not be able to tell why the PST power flows are not the same if this condition happens and will provide a circulating alarm when the situation is actually that the PSTs are not operating in parallel. The utility agreed that the operators must have system situational awareness to identify this abnormal condition. The controls were designed with the assumption that the operators would never operate the system with the buses split. During such abnormal conditions, the operator can place the controller in independent mode locally via pushbutton or remotely via SCMS and LDC. The parallel circulating apparent power alarm and block functions are disabled when the controls are in independent mode.

In summary, the following functions are disabled on parallel block:

1. Automatic control
2. Run to neutral
3. Remote manual raise or lower (that increases circulating apparent power)

V. Panel Design

The design of the control panel is a critical component in ensuring reliable, safe, and efficient operation of the system. It includes a user-friendly interface with real-time status displays, alarm notifications, and manual override options. This section outlines the key elements incorporated into the panel architecture to meet both functional and operational requirements. It begins with the integration of the PST power flow controller, a PST monitoring unit, a local annunciator followed by the implementation of manual control capabilities in addition to discussion on both local and remote interfaces. Visual references such as panel drawings and photographs are included to provide clarity on layout and component placement. Finally, the section concludes with a summary of the factory acceptance test (FAT).

The free-standing control panel was designed per the IEC standard and utility specifications. The panel includes the PST power flow controller, PST monitoring device, local annunciator, local or remote selector switch, test switches, local control pushbuttons, supply supervision relays, indication lamps, and terminal blocks. The control circuits were assembled according to the utility standard.

A. Input and Output (I/O) Requirements

1) HV Switchgear

The PST controller control logic acquires digital inputs from the open and close statuses of all control devices in the high-voltage switchgear, including disconnectors, circuit breakers, earth switches, and bypass switches. Inputs are taken from both the local and parallel circuits to determine the overall system state.

2) OLTC Marshalling Box

The following signals are acquired from the OLTC marshalling box:

- OLTC local or remote selector status
- ARS position
- Tap-change operation in progress or incomplete
- PST on neutral position status
- Maximum advance or retard tap limit reached
- Binary-coded decimal (BCD) inputs for decoding tap position
- Protection trip signals from the protection panels

3) Analog Inputs

- Three-phase voltage measurements from both the source and load sides of the PST
- Three-phase current from the load terminals of the PST
- Current from the secondary phases of the excitation transformer above the star point of the PST neutral bushings

4) Digital Outputs

- Advance and retard command signals to the OLTC motor control circuit
- Overcurrent cutout signal to the OLTC motor circuit

5) Transformer Monitoring Unit (TMU)

The TMU provides monitoring of tap position, oil, and winding temperatures. It requires 4–20 mA analog inputs from field-mounted transducers for accurate parameter measurement.

The previously stated requirements are fulfilled by the PST controller, which is configured with 103 digital inputs and 40 digital outputs. In compliance with the utility specifications, an additional 20 percent I/O capacity is reserved for future expansion or contingencies.

B. Local Interface and Control

The local interface and control provide a critical layer of operational redundancy for the PST, enabling field-level control in the event of controller out-of-service or communication failure. They are designed to eliminate any single point of failure in the control path and allows the field operator to safely adjust tap positions using simple, robust control interfaces.

The selector switch is set to local mode, control signals from PST power flow controller are bypassed, and the system is forced into independent mode and OFF state, suspending automated coordination.

For safe and effective manual control, it is essential that the operator has access to real-time tap position and loading information (e.g., MW and MVAR). These values are monitored through the PST monitoring unit and the power flow controller display, enabling the operator to monitor the impact of each tap movement.

Manual operation is performed using panel-mounted pushbuttons to advance or retard the tap position. These controls are directly wired to the tap-changer mechanism, ensuring it remains functional regardless of the controller's status. With the absence of automatic master-follower logic in this mode, tap adjustments across parallel PSTs must be manually coordinated to maintain synchronism.

The interface also includes basic configuration options using the controller's front panel. These allow the selection of:

- Operating modes (master, follower, independent)
- Control states (automatic or manual)
- Regulation set points (power flow limits)

To support local coordination between units, PST power flow controllers communicate over a serial link, which automatically shares operating status and key measurements like MW, MVAR, and tap position. This helps ensure consistency between parallel PSTs, even during local control.

In conclusion, the availability of accurate tap position and loading information is fundamental for the safe execution of local manual control. While this mode lacks the automated coordination features of centralized systems, it ensures the operational continuity and system resilience under degraded control conditions.

C. Remote Interface and Control

The PST power flow controller is interfaced with an existing station-level SCADA system via IEC 61850 Manufacturing Message Specification (MMS) protocol. The controller has been configured in accordance with the utility control philosophy, utilizing the IEC 61850 MMS protocol for data exchange and command execution.

The local and remote switch on the control panel is set to remote mode, and the following control functions are transferred to the station-level SCADA system or LDC:

- PST tap-changer control
- Selection of control modes (master, follower and independent)
- Selection of control state (automatic and remote manual)
- Regulation mode operational set points

This configuration enables full remote operation and supervision of the PST, ensuring integration into the broader network control system while maintaining local control capabilities as a fallback.

1) Manual Run-to-Neutral Control

In manual mode, it is possible to operate the run-to-neutral control function. This function initiates tap changes in the appropriate direction upon initiation. Once the first tap change is initiated, the function continues to issue additional tap steps following the expiration of the delay between steps timer, provided the run-to-neutral in-process signal remains high. The process completes when the tap position on neutral is detected.

The run-to-neutral control function can also be initiated locally by pressing the run-to-neutral pushbutton on the controller front panel.

Remotely, the run-to-neutral control function can be initiated via SCADA or the LDC interface. For safety and equipment protection, the run-to-neutral process operation is blocked under several alarm conditions to prevent damage to the transformer and tap-changer mechanism. Run to neutral is blocked under the following conditions:

- The OLTC or ARS motor fails to complete its starting, switching, or stopping sequence within the predefined time limit.
- The associated PST is undergoing maintenance.
- The current through the OLTC switching contacts exceeds the configured overcurrent threshold.
- Tripping of the associated PST due to a system fault condition.
- The controller detects tap-changer mechanism failure or circulating alarm condition.
- The controller is in follower mode.
- The controller is not in a manual state.
- The controller receives unreliable or inconsistent input signals, preventing it from accurately determining the system state configuration of the parallel system.
- The number of tap changes in the previous hour exceeds the maximum allowed operations threshold.

D. Factory Acceptance Test

The FAT is a crucial quality assurance step conducted before delivery of the PST control panel. It involves a series of visual, mechanical, and functional inspections to verify that the panel meets approved specifications and performs as intended. During both the internal and user-witnessed FAT, the panel was examined for build quality, component conformity, and wiring accuracy based on approved schematics. Mechanical inspections included checks for dimensions, paint finish, and assembly integrity. Electrical safety was verified using insulation resistance and high-voltage dielectric test in compliance with IEC standards, ensuring no insulation breakdown. Functional testing was performed on key components such as supervision relays, LEDs, switches, heaters, and protective devices to confirm correct operation. The PST power flow controller was tested using a simulator to validate control logic, I/O behavior, operation modes, alarms, and communication functions.

Similarly, the PST monitoring unit was tested using simulated analog signals to confirm measurement accuracy and system responsiveness. Once all the tests were successfully completed, the results were documented and the panel was packed and cleared for shipment to the project site for installation and commissioning.

VI. Commissioning

After the PSTs' controls were thoroughly tested in a laboratory environment during the FAT, a detailed site acceptance test (SAT) plan was created to commission the PSTs safely and without any unintended operation. The commissioning included functional tests of the control logic, verification of communication with the SCADA system, and validation of adaptive control features under various operating scenarios. It was intended to verify the controller's actions with the physical equipment at the field to satisfy the PSTs' controller's functions before putting the PSTs in service. The field testing was performed in two stages. The first stage was to verify PSTs testing in offload condition with controllers and assess whether any adjustments were required on controllers. The second stage was in-service testing when the PSTs were energized and on load to verify the performance of the PSTs' control system. Challenges encountered during commissioning, such as signal delays and synchronization issues, were addressed through iterative testing and controller tuning.

The goals of the tests were to:

- Verify wiring to and from the PSTs and associated circuit breakers and isolators.
- Verify PST OLTC control settings with PST OLTC motors.
- Operate the PST OLTCs over their full range, from +32 advance to −32 retard tap positions.
- Verify the run-to-neutral commands and operations.
- Verify ΔP settings.
- Verify the local, LDC, and SCMS and automatic and manual functionality, proving set-point and band limit mode control.
- Verify master-follower control.
- Verify the interlocks and alarms functions.
- Perform LDC and SCMS point-to-point testing, proving all LDC and SCMS controls, statuses, and metering.
- Develop Sequence of Events recording data to document the PSTs' operation.

A. *Site Acceptance Test*

PSTs offload testing was conducted two weeks before the energization, which took place after all the wiring was completed. One of the purposes of offload field testing was to determine the motor running time for each tap-position change and verify operation at each tap position. The motor running time is dependent upon design and cannot be determined only from a lab test. Several other functions were verified during testing, as per the SAT explained following.

To verify the controller's functions and PSTs interface the following tests were performed as per the approved SAT plan before energization, with the help of an injection-testing kit for (current, voltage, and power) injection cases.

The test setup shown in Fig. 7 shows the secondary injection kit for voltage, current, and power injection. Further, controllers are showing the interface with the PST-1 on the left and parallel PST-2 on the right. VZ is the voltage injection points, and IW is the current injection points of the PST controllers.

One of the critical evaluations conducted during the SAT was the actual measurement of tap-change operation timing using the field-installed apparatus. Given that the PSTs in this application have two motors, ARS and OLTC, the controller must accommodate two independent timing sequences to account for scenarios where the motors run multiple times to go through +/–16 steps, when the reversing switch inserts or removes the course-regulation winding and for the sequential operation of the ARS and OLTC motors when transitioning through the neutral tap position. Accurate detection of tap step completion is essential for capturing pre- and poststep tap positions and the corresponding power flow data. Given the variability in motor operation—sometimes requiring a single run, other times multiple—the controller must know the appropriate moment to log poststep data. These inputs are critical for the adaptive bandwidth automatic function and the functions to prevent runaway.

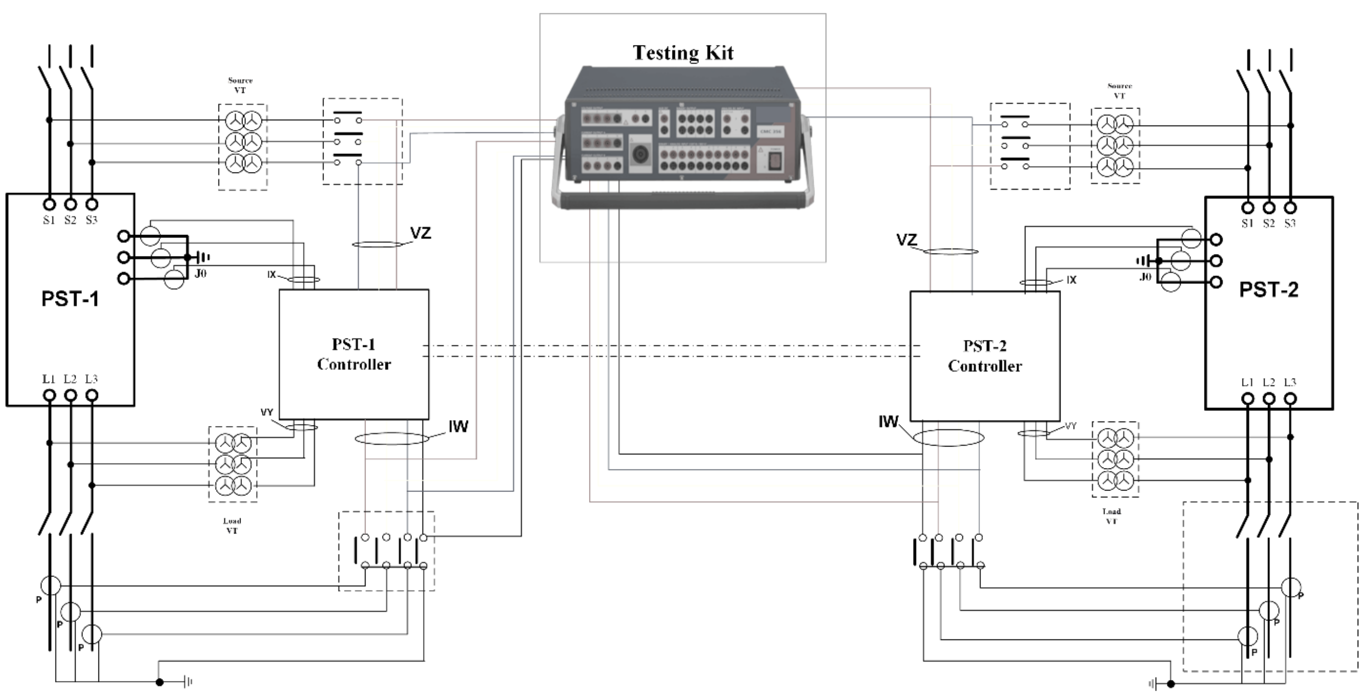

Fig. 7. SAT test setup for PSTs' control system.

The actual carried-out time from the OLTC motor run is possible with the physical equipment connected to the controller, and this test should be performed before the in service of the PST. If motor time does not tune properly then the result will block the PST controller's functions. For example, in Fig. 8, if the proper motor running timing setting is not tuned then the motor running too long false alarm asserts and motor incomplete sequence error will block automatic, manual, run-to-neutral, and follower modes.

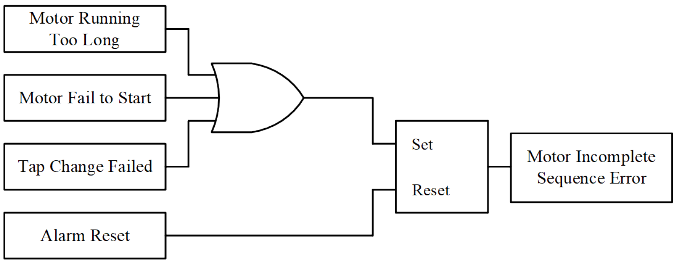

Fig. 8. Motor incomplete sequence alarm.

Operational data from both PST controllers were systematically recorded to support detailed analysis and archival for future diagnostic and performance evaluation purposes. See Fig. 9.

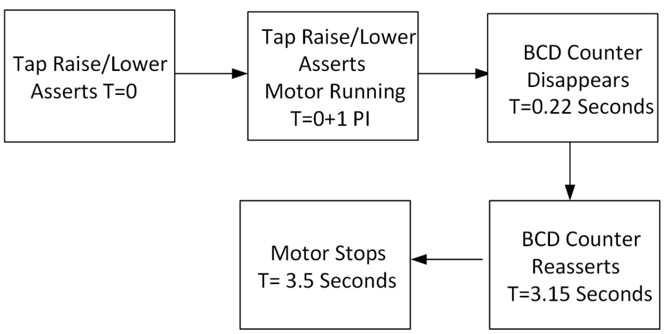

Fig. 9. PST typical tap-change operation timing diagram.

Additional tests performed during the SAT are shown in Appendix A.

B. *In-Service Testing*

Initially, PST-1 was energized on neutral position with remote manual control state, and LDC verified the set point set through the control center. While PST-2 was not energized, PST-1 was set to independent control mode during energization. To achieve the desired power flow from the PST-1 circuit, the tap advance control commands were sent from the control center.

A few days later, PST-2 was energized on the same tap positions as PST-1 and the total path power flow from both circuits in the parallel state was verified, including circulating apparent power measurement; hence, after acceptable performance and equal power transfer, as required, both controllers then switched to the master-follower mode. PST-1 was configured in master mode while PST-2 operated in follower mode. A tap-position change was initiated from the master controller, and it was verified that PST-2 accurately mirrored the tap change via its OLTC mechanism, confirming proper synchronization and control coordination between the units.

The next step was to verify the automatic function of the control system and circulating apparent power. The following tests were performed:

1. The regulation set point was configured to maintain a combined line flow of 500 MW with the PSTs initially in the neutral position. Once the controllers were switched to automatic mode, they began issuing commands to their OLTCs, which brought the active power flow within the controller's regulation deadband, causing the control action to stop as the total path flow approached 500 MW.
2. Forced the paralleled PSTs to 1 and 2 steps off symmetry at neutral and took load and S_{CIRC} readings.
3. Forced the PSTs to 1 and 2 steps off symmetry at the midposition in the regulation range and took load and S_{CIRC} readings.
4. Verified that the S_{CIRC} readings and the calculated alarm and block thresholds from Step 2 and Step 3 were as expected from the calculated values shown in Fig. 6.

This experience confirmed the importance of incorporating an adaptive bandwidth function in PST control. In this application, the controller adjusts the bandwidth by averaging the ΔP values from the six most recent tap changes. Without this adaptive feature, the controller tends to overshoot the deadband when out-of-band timers trigger adjustments under such conditions [7]. The operational outcome also highlighted the necessity of capturing actual ΔP measurements during the initial parallel operation to fine-tune the controller's initial bandwidth setting.

C. *Challenges*

The project was commissioned in stages. Initially, PST-1 was independently tested and commissioned, followed by the separate testing and commissioning of PST-2. Subsequently, both PSTs were verified to operate correctly in a parallel configuration.

During one of the commissioning phases, the system was configured such that PST-2 was de-energized and under construction while PST-1 remained in service. As previously discussed, each PST controller was designed with full visibility of the parallel circuit to determine its operational state and enable coordinated control decisions. However, this configuration introduced operational complexity, particularly in managing breaker and isolator statuses and executing switching operations from the control panels under various test scenarios.

To address these challenges, a dedicated control switch was integrated into each PST control panel. This switch, operable only by qualified maintenance personnel, indicates whether the associated PST is in a test state. With this enhancement, each controller is now aware of both its own and the parallel PST's test status.

Using this information:

- The in-service PST-1 controller calculates the actual parallel path power by disregarding the power data received from the PST-2 controller, which is under test.
- Conversely, the PST-2 controller, while under test, forces its transmitted power data to the PST-1 controller to zero.

This logic ensures that the in-service PST can operate independently of the PST under test. Test signals can be injected without affecting the live power flow in the energized circuit. This approach enables safe and accurate testing while maintaining system integrity and operational continuity.

VII. Conclusion

This project successfully implemented a proven yet innovative control solution to manage active power flow within the TAQA transmission network, adapting technologies that have been in use for nearly two decades. The deployment faced and overcame unique challenges specific to the TAQA system and its operational requirements. This paper detailed the control strategy, panel design, and the rigorous testing processes—both at the factory and onsite—that ensured a robust and reliable implementation.

The integration of PSTs has significantly enhanced the operational flexibility of the UAE power grid. By enabling more precise control of power flows, the solution supports improved grid stability and efficiency. As the UAE continues to expand its transmission infrastructure, the success of this project sets a strong precedent for the broader adoption of PSTs across the national grid, aligning with the country's evolving energy landscape and strategic goals.

VIII. Appendix A: Site Acceptance Testing (Pre-Energization)

Local Manual Mode PST-1/PST-2	**Remote Manual Mode PST-1/PST-2**	**Auto Mode PST-1/PST-2**	**Overload Alarms PST-1/PST-2**	**Parallel Block PST-1/PST-2**	**Additional Alarms and Interlocking Testing**
Verified advance and retard commands from controller front-panel pushbuttons, run from Position 0 (neutral) to 2 and from 2 to 0 (neutral). Individually for PST-1 and PST-2	Verified advance and retard commands from SCMS/LDC, run from Position 0 (neutral) to 2 and from 2 to 0 (neutral). Individually for PST-1 and PST-2	Verified master-follower modes	Verified overload alarms with 6 hrs, 30 min and short-term emergency loadings	Verified tap positions difference is 1 between PSTs (parallel alarm)	Protection trip feedback from PSTs' protection system
Verified run-to-neutral operations from controller front-panel pushbuttons, run from position +32 to 0 (neutral) and from –32 to 0 (neutral). Individually for PST-1 and PST-2	Verified run-to-neutral operations from SCMS/LDC, run from position +32 to 0 (neutral) and from –32 to 0 (neutral). Individually for PST-1 and PST-2	Verified band limits set points		Verified tap position difference is 2 between PSTs (parallel block)	Suspend automatic mode
Verified control mode selection master-follower when both PSTs are in service from controller front-panel pushbuttons and verified advance-retard and run to neutral that the follower follows the master commands	Verified control mode selection master-follower when both PSTs are in service from SCMS/LDC by toggling RB10/RB11 and verified advance-retard and run-to-neutral commands that the follower follows the master commands			Circulating power > 33 MVA (parallel alarm)	Follower control cutout
Verified control state selection automatic/off from controller front-panel pushbutton	Verified control state selection automatic/manual/off from remote SCMS/LDC by toggling RB03/RB04/RB07, respectively			Circulating power > 98.5 MVA (parallel block)	Remote manual control cutout
					OLTC motor overcurrent protection
					Voltage balance
					Test switch enabled
					Line open

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