Real-Time Automation Control of a Phase-Shifting Transformer Based on Mission Priorities

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***Abstract*—The Silicon Valley Power (SVP) system is connected to the area transmission system via one 230 kV interconnection and five 115 kV interconnections. To reduce the active power import from the 115 kV interconnections and increase the active power import from the 230 kV interconnection (and therefore reduce the cost of active power import), SVP installed a 420 MVA, 230/230 kV phase-shifting transformer (PST) at Substation A. The PST operation at SVP should satisfy N-1 contingencies in that a loss of any important transmission line within the SVP network should not overload any other lines.**

This paper presents mission-priority-based active power control (P control) of a PST to achieve the optimal cost of the active power import and satisfy predetermined N-1 contingencies. A mission priority is an established control algorithm for different preset conditions. The proposed mission-priority control is tested in a closed-loop environment to demonstrate its effectiveness.

***Index Terms*—Mission-priority control, N-1 contingency, phase-shifting transformer, power control, system operating limits**

I. Introduction

As the name implies, a phase-shifting transformer (PST) can create a phase shift between the primary and secondary side of a transformer and hence control the active power flow for various technical or economic reasons [1] [2] [3]. Silicon Valley Power (SVP) intends to install and operate a phase-shifting transformer (PST) on its interconnection to the area transmission system. SVP will install the PST in series with their single 230 kV interconnection and in parallel with their five 115 kV interconnections. SVP will use the PST to import more power on the 230 kV interconnection and less power on the 115 kV interconnections. To achieve maximum return on investment and reduce SVP's transmission access charges, a load-following control system is required to maximize these goals. The authors developed a new active power control (P control) system to allow SVP to capture the intended economic benefit while also ensuring the safe, reliable operation of the PST and the area transmission system. The P control system also provides a resource for SVP to control the power flow when called upon during planned or unplanned contingency conditions.

II. Requirements

A. PST Control and P Control

SVP's PST control system is based on a protection, automation controller as the core of a transformer tap changer control system. In addition to controlling power flow at the PST, the tap changer control system provides automatic detection of improper tap operation sequences and system events and is designed to operate independently of P control.

Two redundant P controllers, based on real-time automation controllers, are installed at SVP. The P controllers provide the PST controllers with visibility into outside conditions so that the P control setting of the PST controllers can be shifted to the most limiting facility in the system while monitoring multiple system operating limits (SOLs). The logic solution settings are designed to be completely configurable, avoiding any reprogramming, and are grouped into mission-priority settings that are defined to control the PST during particular system conditions. These conditions can vary from "all systems normal," to a set defined for a particular planned outage or anticipated N-1 condition. The P controllers provide an updated power regulation set point to the PST control that allows the PST to operate at maximum efficiency while not exceeding defined SOLs.

B. System Operating Limits

SOLs are values (such as MW, MVAR, ampere, frequency, or volts) that satisfy the most limiting of the prescribed operation criteria for a specified system configuration to ensure operation with acceptable reliability criteria. The SOLs included in the SVP control system are designed specifically for monitoring the MW values of facilities using 24-hour and

4-hour ratings. SOLs are developed as linear equations as follows:

$$\mathrm{SOL} = \mathrm{MW_{LF}} + \mathrm{B} \bullet \mathrm{MW_{N-1}} \quad (1)$$

where:

SOL is the calculated value of the limiting facility in the most limiting N-1 condition.

MW_{LF} is the real-time megawatt value of the limiting facility.

B is the distribution factor at the limiting facility for the facility causing the N-1 contingency.

MW_{N-1} is the real-time megawatt value of the facility causing the N-1 contingency.

III. P Control System

This section provides a detailed functional description of the P control system. Core functions and supporting algorithms are discussed. The primary goal of the P control system is to import more power from the 230 kV interconnection and less on the 115 kV interconnections while satisfying the constraints of preset mission priorities, PST maximum capacity (PST Max), and maximum active wheeling power (PWheeling).

A. P Control Mission Priority

A mission priority is an established control algorithm for different preset conditions. The operators can define 16 mission priorities in the HMI of the P control system. However, only one mission priority can be activated at a time for each system operating scenario. For each mission priority, there are three SOL requirements for active power (PSOL1, 2, and 3), one PWheeling requirement, and one PST Max requirement. These five requirements are the five objectives that each mission priority tries to optimize. The PSOL equation for each mission priority considers the transmission loading based on N-1 conditions. This is described in the following equation:

$$\mathrm{PSOLk_i} = \sum_{j=1}^{20} \mathrm{Ck_{ij}} \mathrm{MW_j} + \mathrm{Offsetk} \quad (2)$$

where:

$PSOLk_i$ is the k^{th} PSOL of mission priority *i*.

PSOLk represents PSOL1, PSOL2, and PSOL3 (*k* = 1, 2, and 3, individually).

i is the number of the mission priority.

j is the transmission line number.

Ck_{ij} is the mission priority *i* coefficient for PSOLk of transmission line *j*

MW_j is the measurement value (analog-point, MW) of transmission line *j*.

The maximum constraint of PWheeling, the sum of the exported MW power out of the SVP system through five 115 kV lines, is another mission-priority requirement. The value of PWheeling can be calculated as:

$$\mathrm{PWheeling_i} = \sum_{j=1}^{5} \mathrm{MW_j} \quad (3)$$

PST Max, the fifth objective, is used to limit the maximum MW flow going through the PST transformer.

The operators are required to enter the upper and lower limits of each objective. If the objective value is lower than the lower limit, its indication will display yellow on the HMI; if the objective value is greater than the lower limit but less than the upper limit, its indication will display green on the HMI; if the objective value is greater than the upper limit, its indication will display red on the HMI.

B. Optimized P Control Philosophy Based on Mission Priority

The optimized P control philosophy based on the mission priority settings is explained as follows.

If the PSOL1, PSOL2, PSOL3, PWheeling, and PST Max values obtained by the P controllers are all less than their respective MW lower limits provided by the operators, their alarm colors on the P control status screen will display yellow and the P controllers will send a Higher Power Requested set point to the PST controllers to increase the power imported from the 230 kV transmission line until one of the PSOL, PWheeling, or PST Max values obtained by the P controllers is greater than the respective MW lower limit. In this case, PST controllers will tap up the PST to achieve the requested power set point and the number of taps will respect the maximum raise operations per hour limit provided by the P controllers.

If any of the PSOL1, PSOL2, PSOL3, PWheeling, or PST Max values calculated by the P controllers are greater than their provided MW upper limit, the respective unit on the P control status screen will be displayed in red and P controllers will send a Lower Power Requested set point to the PST controllers to decrease the power imported from the 230 kV transmission line until none of the upper limits are violated. In this case, the PST controllers will tap down the PST to achieve the requested power set point. Tapping down control is not constrained by the maximum raise operations per hour limit but is constrained by total operations per hour, which is set at SVP to 18 taps per hour. This total operation per hour limit constrains the number of total taps within an hour, including both tapping up and tapping down.

If one of the PSOL1, PSOL2, PSOL3, PWheeling, or PST Max values reaches a green indication and none of them are red after PST tapping, the PST has two options: either continue tapping or hold tapping based on whether or not the Tap to Middle logic is enabled. If Tap to Middle logic is disabled, the PST will hold the taps once one of its five optimized objectives reaches a green indication and none of them are red. If the Tap to Middle logic is enabled, when one of the PST’s five optimized objective indicators turns green and none of them are red, the PST may continue tapping in the same direction as the previous tap to reach a “more green” position based on where the PST is. A more detailed explanation is in the Tap to Middle Logic subsection.

As explained previously, P controllers regulate the power imported from the 230 kV transmission lines by sending a requested power set point to the PST controllers. The tap of the PST is discrete, and the PST controllers have a dead band to tap the PST. If the requested power set point is within the dead band of the PST controllers, the controllers will not take any action to tap the PST. Therefore, in order to tap effectively, the power requested set point should be set to greater than the average PST step (dead band) sent by the PST controllers plus the current PST MW. The average PST step is computed using eight samples in the PST controllers and is sent to the P controllers.

C. PST Tap Timer of P Controller

For different control purposes, P controllers use two different maximum raise operations per hour settings to allow the PST control to get to the regulation set point efficiently. The operators set one small value and one large value in the HMI. Either the small value or the large value will be transmitted to PST controllers as the maximum raise operations per hour from P controllers based on the various control objectives. The PST controllers have default timers to space tapping. The implementation of using a small number or a large number of maximum raise operations per hour for different PST control purposes are explained as follows:

- When P control is enabled in the HMI while the PSOLs, PWheeling, and PST Max indicators are all yellow (which means PST is not loaded enough), the P controllers send a large number of maximum raise operations per hour to the PST controllers to quickly tap the PST until one of the objectives is indicated in green.
- If one of the five objectives is indicated in green, which means the PST is controlled close to the requested set point, the P controllers will send a small number of maximum raise operations per hour to the PST controllers to avoid excessive operation of the PST.
- If the only objective indicator that is green returns to yellow while the other objective indicators are all yellow, the P controllers will wait a certain time before sending a new power requested set point to the PST controllers. The reason for this time delay is to avoid PST operation because of a transient load variation.
- If any of the objective indicators turn red because of a load change, the P controllers will wait a certain time before sending the lower new power requested set point to tap down the PST. The reason for this time delay is also to avoid operation because of a temporary load variation.

D. P Control Raise Suspend

The P control raise block alarm restricts the P controllers from tapping up the PST; however, tapping down the PST will not have any restriction in this case. There are three situations that will bring up this alarm:

1. If the MW upper and lower limits of PSOL1, PSOL2, PSOL3, PWheeling, or PST Max are set too small, it may create hunting of the PST. To prevent hunting, the P controllers restrict the PST from tapping up.
2. The raise up option of the P control will be suspended if the average steps of the PSOLs and PWheeling are considered trustworthy (the number of average steps recorded is greater than six) and the P controllers predict that the next PST raise action will result in a red alarm of at least one of the five mission priority objectives (PSOL1, PSOL2, PSOL3, PWheeling, and PST Max).
3. If the operator selects to reject a raise up power request set point provided by the P controllers, the raise up action of the P control will be suspended.

E. Average Step Calculation

There are five P optimization objectives. The average steps for four of them (PSOL1, PSOL2, PSOL3, and PWheeling) are calculated inside the P controllers. The average steps of PST MW are calculated inside the PST controllers and transmitted to the P controllers. There are two main purposes for calculating average steps:

- They are displayed in the HMI to help operators set up an appropriate bandwidth (the difference between the MW upper limit and lower limit) for each objective. It is recommended that the bandwidth of each objective is set up no less than 1.5 times the average steps.
- The average steps could be used inside P controllers to implement various intelligent logic. For example, they are used in Tap to Middle logic to help the PST stay in the "middle of the green" and avoid transients. They are also used in the next step above upper limit alarm to help P controllers predict the position of the next step and avoid the PST jumping to a red alarm.

F. Tap to Middle Logic

The purpose of Tap to Middle logic is to tap the PST to the middle of green when the dead band of the five P control objectives set up by the operator is very large. The middle of green is defined as the middle point between the MW upper limit and the MW lower limit. For example, if the MW upper limit of PSOL1 is 300 MW and the MW lower limit of PSOL1 is 160 MW, the middle of green position for PSOL1 is 230 MW. This logic can be enabled or disabled in the HMI. The Tap to Middle logic only starts when five of the P control objective indicators are all yellow and the PST is tapping up or at least one of the five objectives indicators is red and the PST is tapping down.

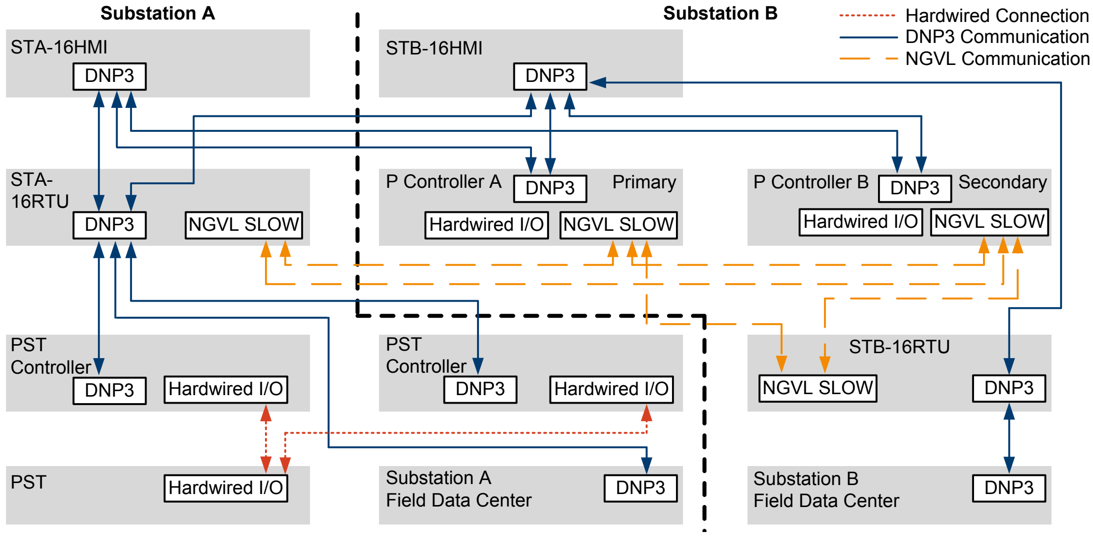

Figure 1. Data Flow Diagram (DFD) of P Control System

IV. System Architecture

This section explains the P control system architecture, including the DFD, redundancies, and hardware.

A. *Data Flow Diagram*

The SVP DFD indicates the conceptual flow of data between devices in the P control system. A DFD contains the following types of critical information:

- The route of communications signals between intelligent electronic devices (IEDs).
- Ethernet and serial networks.
- Protocols between IEDs.
- Information exchanged.

The DFD of the SVP P control system is shown in Figure 1. The P control logic and algorithms are implemented inside P Controllers A and B. They receive system measurements and data from STA-16RTU and STB-16RTU, process the data, make decisions, and send commands back to the PST controllers via STA-16RTU. There are two HMIs in the diagram. One is located at Substation A, and the other one is located at Substation B.

Three different types of communications are implemented for this system: hardwired communication, Distributed Network Protocol 3 (DNP3) [4] communication, and Network Global Variable List (NGVL) communication. NGVL protocol is a powerful, fast, and economical protocol to address the sharing of data between controllers within a decentralized control architecture [5]. The communications between the PST controllers and the PST use hardwired I/O. The decimal number of the PST tap position is represented by a six-digit binary code, which is called binary-coded decimal (BCD) code. Hence, the digital communications between PST controllers and the PST include tapping up or down commands, tap position BCD code, and digital alarms. The communications between the P controllers and the 16RTUs use NGVL, which allows the data to be transmitted on a configurable cyclic transmission interval, on the change of a variable or on a change of Boolean state. All the other communications use DNP3.

B. *Redundancy*

The P control system contains several levels of physical redundancy, including network equipment, controller hardware, and I/O redundancies. These redundancies protect the designed control system from single-point failures.

The redundant P controllers are working in hot standby. In this form of redundancy, both controllers are turned on, communicating, processing logic, and making decisions. These two controllers have communications channels to synchronize their internal variables to ensure they will make the same decision. One of the controllers is primary and its control decision will be sent out; the control decision of the other, secondary, controller will be held. If the primary controller fails, the secondary controller will pick up the control immediately and send out its control decision.

V. Case Study

To test the effectiveness of the mission-priority-based active power control at SVP, two days of real data from the field were selected for closed-loop testing: 08/01/2015 (Saturday) and 08/03/2015 (Monday). The upper and lower limits of the five objectives are shown in Table I. The equation coefficients are as follows: for PSOL1, $C1_7 = 0.8$ and $C1_{11} = 1.0$; for PSOL2, $C2_7 = 1.0$ and $C2_{11} = 0.3$; for PSOL3, $C3_{11} = 1.0$ and $C3_{12} = 0.3$. The other equation coefficients are all zeros.

TABLE I
MISSION PRIORITY SETTINGS

Objective	Upper Limit	Lower Limit
PSOL1	220	205
PSOL2	250	230
PSOL3	300	280
PWheeling	20	0

A. Results of 08/01/2015, Saturday

This is a weekend day, and the power import to the SVP system does not change much. Figure 2 shows that the lowest import is 185.6 MW at 4:00 a.m. and the highest import is 245.3 MW at 6:00 p.m. The tap position does not change much during the weekend either. It only changes from Tap 8 to Tap 9 at 10:00 a.m. and changes from Tap 9 to Tap 8 at 12:00 a.m., midnight.

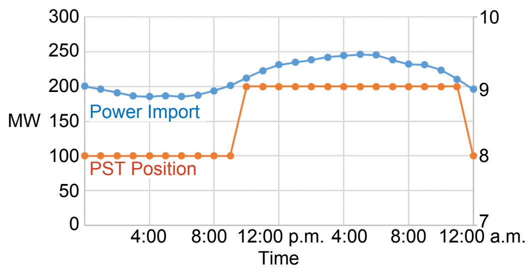

Figure 2. SVP Power Import and PST Tap Position for 08/01/2015

Figure 3 shows PSOL1 and Figure 4 shows PWheeling for the day. Between 12:00 a.m. and 10:00 a.m., power wheeling is in-band (green) and is the constrained variable; between 10:00 a.m. and 11:00 p.m., PSOL1 becomes in-band (green) and is the constrained variable; between 11:00 p.m. and 12:00 a.m., power wheeling again becomes in-band (green) and is the constrained variable.

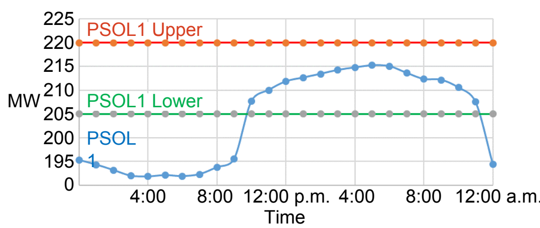

Figure 3. PSOL1 of SVP for 08/01/2015

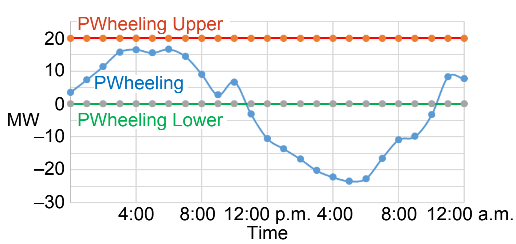

Figure 4. Power Wheeling of SVP for 08/01/2015

B. Results of 08/03/2015, Monday

This is a weekday, and the power importing into the SVP system changes more than the weekend. Figure 5 shows that the lowest import is 176.4 MW at 4:00 a.m. and the highest import is 279.6 MW at 4:00 p.m. The tap position also changes more frequently than during the weekend.

Figure 6 shows PSOL1 and Figure 7 shows power wheeling for this day. Between 12:00 a.m. and 7:00 a.m., power wheeling is the constrained variable; between 7:00 a.m. and 11:00 p.m., PSOL1 is the constrained variable; between 11:00 p.m. and 12:00 a.m., power wheeling is the constrained variable.

The results of the two-day closed-loop testing also show that the operating point of the PST is close to the upper limit of PSOL1 or power wheeling.

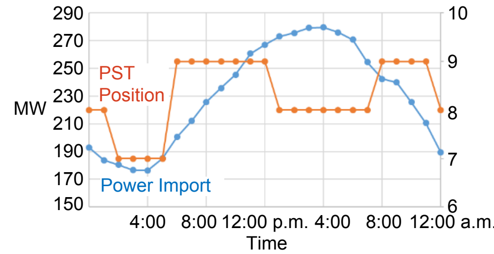

Figure 5. SVP Power Import and PST Tap Position for 08/03/2015

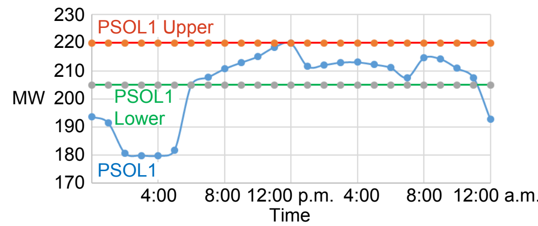

Figure 6. PSOL1 of SVP for 08/03/2015

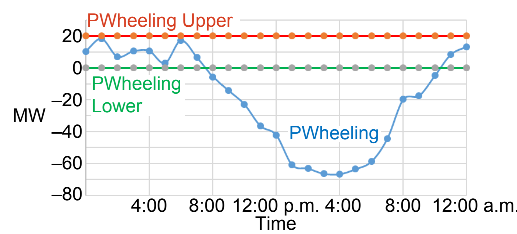

Figure 7. Power Wheeling of SVP for 08/03/2015

VI. Conclusion

This paper presents an active power control system for a PST based on mission priorities. The objective of this control system is to import more power from a 230 kV transmission line and less power from 115 kV transmission lines to reduce the SVP operating cost and satisfy predefined N-1 contingencies. The paper also discusses functional design, technical details, system architecture, and implementations of P controllers. A case study presents the effectiveness of the proposed controllers, showing that they could maximize the power import from a 230 kV line while satisfying predefined mission priorities.

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