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### **Design Considerations in Phase-Shifting Transformers to Enhance Loadability and Controllability of the Connected Grid**

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#### **SUMMARY**

The phase-shifting transformer (PST) is a classic power-flow control device that has been deployed for controlling power flows and for solving unexpected grid congestions in transmission networks up to 500 kV level. The PST offers excellent features in terms of the ability to control active power (P) flow while operating by using reliable load tap changers (LTCs) and advance-retard switch (ARS).

Increasing connection of renewables has posed a new challenge in power flow control and voltage stability. With some key design considerations, the PST will be very effective in improving grid operational reliability.

This article describes the principles of active power flow control, and also the important design aspects of PSTs. The design aspects are outlined as follows:

- Types and categories of PSTs - focusing on the most frequently used single-core and two-core symmetric type PSTs
- Fundamental design parameters - emphasizing the rated throughput power, rated main unit design power, and the range of phase-shift angle regulation
- Important design considerations - on phase angle rating, MVA rating, PST types, overload conditions, LTC and ARS applications, and special considerations for two-core PST design
- Circuit arrangements - mainly focusing on PSTs long-term deployment, operational flexibility with easiness of PST during maintenance or outages
- Operational likelihood - addressing operational flexibility with several viable options

This article also addresses essential factors specific to the PST project.

#### **KEYWORDS**

Phase-shifting transformer (PST), phase-angle regulator (PAR), quadrature booster, symmetric, asymmetric, single-core, two-core, phase shift angle, throughput power, regulation winding, overfluxing, on-load tap changer (OLTC), advance-retard switch (ARS)

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## BACKGROUND

The modern power grid, especially in AC transmission networks, is facing challenges to enhance grid controllability and power transfer capability due to the increasing number of renewable generation penetrations. In recent decades, a large number of flexible AC transmission system (FACTS) devices controlled by power electronics (e.g., thyristors, IGCTs, IGBTs, and GTOs) have been utilized to improve voltage stability as well as power flows control. Utilities are exploring viable options with most suitable cost-effective power-flow controllers that can offer grid-operational reliability, high efficiency, minimum operation and maintenance (O&M) costs, component non-obsolence and interoperability to fulfill power grids constraints for the integration of renewable energy generation sources.

A phase-shifting transformer (PST), also known as phase-angle regulator (PAR), is a specialized type of transformer that controls active power ( $P$ ) flow in the electric power grid while operating by reliable load tap changers (LTCs) and advanced-retard switch (ARS). A PST regulates the voltage phase-shift angle difference between source and load terminals. The principle relies on a phase-shifted voltage source injection into the line segment by a series transformer unit, which is fed by a shunt or main transformer unit. The configuration of the shunt and series transformer windings establishes the phase shift.

PSTs are well proven and robust devices being deployed for controlling active power flows and for solving unexpected grid congestions in transmission networks up to 500 kV level. The addition of reactive elements can extend control capability of the PSTs and support for other applications. There are a number of unconventional applications of the PSTs (e.g., substation uprating, substation reserve sharing, network decoupling, line power flow control using Assisted PSTs and HV transmission line de-icing), made possible by adding series reactive elements as discussed in [1]. In US power grids, there are approximately one hundred PSTs in service to improve loadability and controllability of certain transmission network segments.

## PRINCIPLES OF ACTIVE POWER FLOW CONTROL

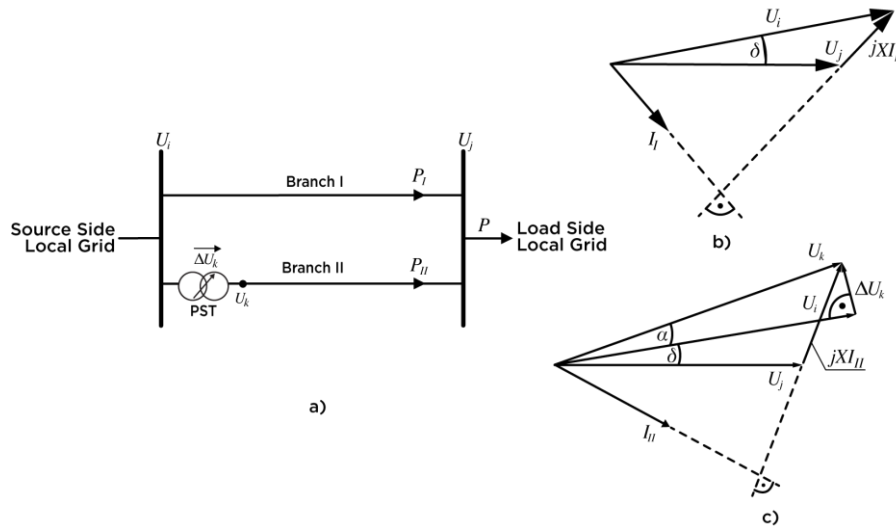


Fig. 1. Active power flow control in PST by adjusting  $\delta$ : a) system one-line with a series and a shunt unit, b) phasor diagram for branch I, c) phasor diagram for branch II [2]

Active power flow ( $P$ ) through a single branch of inductive reactance ( $X$ ) can be expressed using the power angle equation as:

$$P = \frac{U_i U_j}{X} \sin \delta$$

Where:

$P$  – active power flow through the branch reactance  $X$ ;  $U_i$ ,  $U_j$  – voltages at the sending and receiving end of the line, and  $\delta$  – load angle (the difference of phases between  $U_i$  and  $U_j$  of the line,  $\delta = (\theta_i - \theta_j)$ )

As illustrated in Fig. 1b), the active power flow through the branch can be adjusted by changing the voltages at  $U_i$  and  $U_j$ , the reactance  $X$ , and the load angle,  $\delta$ . The ability to control active power flow using changes in the voltages,  $U_i$  and  $U_j$  are relatively small, mainly due to limitations in the regulation of these voltages. Larger adjustable power flow can be possible through a branch reactance change, a so-called series compensation (using series capacitor banks). However, the full extent of active power flow through the branch can be changed by adjusting load angle,  $\delta$  (not only change the value of active power flow but also change the direction of power flow).

The concept of adjusting the load angle, using a PST, is shown in Fig. 1. It is assumed that parallel branches  $I$  and  $II$  have the same parameters and as a result of power flow across the network, the voltages at the source (S) and at the load end (L) take the values  $U_i$  and  $U_j$ , and the difference of load angle is  $\delta$ . Phasor diagram of the branch is shown in Fig. 1b). With the assumed voltages and load angle, the active power ( $P_I$ ) in the branch is determined as:

$$P_I = \frac{U_i U_j}{X} \sin \delta$$

The phasor diagram of the branch  $II$  is shown in Fig. 1c). A PST is installed on branch  $II$ . In this case, voltages,  $U_i$  and  $U_j$  are the same as for branch  $I$ , but a perpendicular voltage,  $\Delta U_k$  is added to the initial voltage  $U_i$  as discussed in [2]. As a result of this, the voltage after the booster transformer (i.e., series unit of the PST) is equal to  $U_k = U_i + \Delta U_k$ , and load angle for branch  $II$  equals to  $(\delta + \alpha)$ . Active power ( $P_{II}$ ) in the branch  $II$  can be represented as:

$$P_{II} = \frac{U_k U_j}{X} \sin(\delta + \alpha)$$

Since  $(\delta + \alpha) > \delta$ , the active power flow  $P_{II}$  is greater than  $P_I$ .  $\Delta U_k$  (i.e., booster voltage) can be adjusted from  $(-\alpha)$  to  $(+\alpha)$ .

## TYPES AND CATEGORIES OF PSTS

A PST can be of symmetric or non-symmetric type; it can also be a quadrature or a non-quadrature type, with a single-core or a two-core design, and finally with a single tank or a dual tank design. The term ‘‘symmetric’’ means, that under no load condition the voltage magnitude at the load side (L) is always equal to the voltage magnitude at the source side (S), independent of the phase angle. Alternatively, a symmetrical design will not change the voltage magnitude between the source and load bushings in the process of advancing or retarding the phase angle. A quadrature type phase shifter is a unit where the boost voltage, which creates the phase shift between source and load terminals, is perpendicular to the line voltage at one terminal, or to a combination of the line voltages at source and load terminals.

According to IEEE Std C37.245:2018 [3], PSTs can be grouped into five categories.

- a) Single-core asymmetric, with tap winding outside the delta
- b) Single-core symmetric, with tap winding outside the delta
- c) Single-core, symmetric, polygon (delta hexagonal)
- d) Two-core symmetric with wye-wye exciting unit (conventional)
- e) Two-core, asymmetric with wye-wye exciting unit (quadrature booster)

Single-core PSTs are used for low voltages and small power ratings and designed as symmetric or non-symmetric. The symmetric design unlike the non-symmetric one provides an output voltage independent of the phase angle shift at no load, and therefore it is the most used design. For most cases, the non-symmetric design can be extrapolated by cutting half of the symmetric one. These transformers consist of an excitation winding and one or more regulation windings wound on the same core.

In the past, many studies [3]-[9] have demonstrated different types of PSTs and their design requirements on a case-by-case application. With an intention to provide a quick grasp of this topic, this article briefly explains the most frequently used single-core and two-core symmetric type PSTs.

**Single-core symmetric, with tap winding outside the delta**

A single-core symmetric PST with tap winding outside the delta (in the advanced position) is shown in Fig. 2a) and Fig. 2b) [3]. The delta excitation winding is fixed at the midpoint of the regulating windings. Two tap changers move the S and L terminals along the regulating windings. This is a symmetrical design as long as the two LTCs are operated such that they always remain within one step of being the same number of taps from either side of the midpoint of the regulating winding. The relative positions of the LTC and reversing switch determine whether the PST is in advanced or retard mode operation.

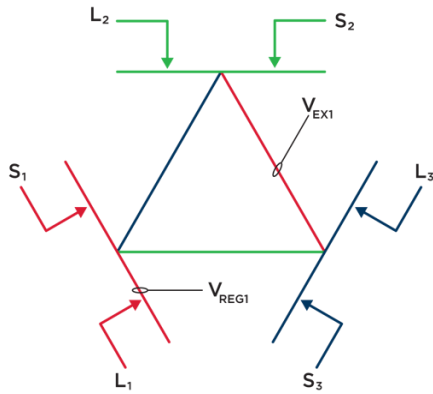


Fig. 2a). Nameplate diagram [3]

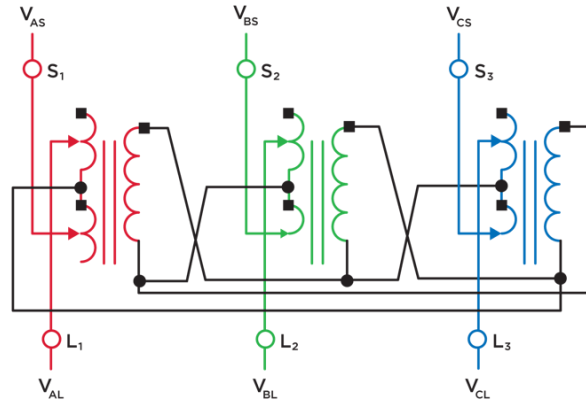


Fig. 2b). Three-line diagram [3]

**Two-core symmetric with wye-wye exciting unit (conventional)**

Fig. 3a) and Fig. 3b) show the nameplate and three-line diagram of a two-core symmetric PST [3].

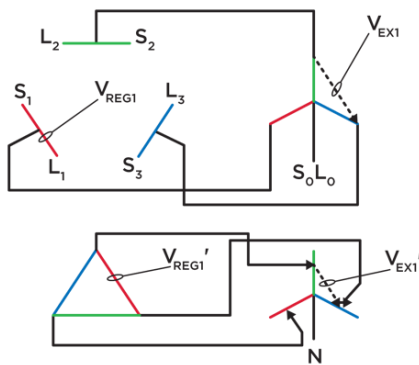


Fig. 3a). Nameplate diagram [3]

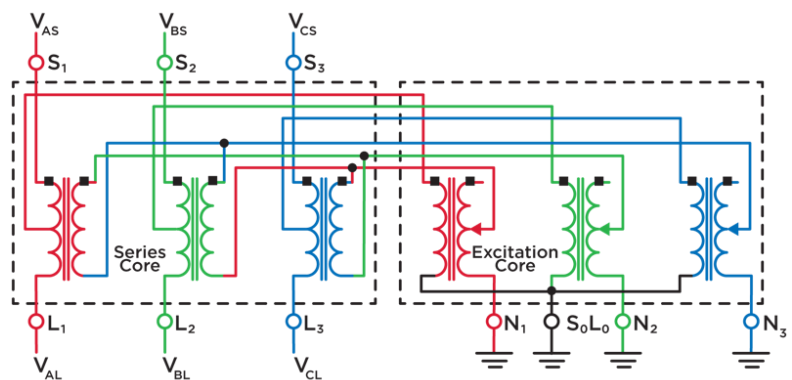


Fig. 3b). Three-line diagram of a two-core symmetric PST in the advanced position [3]

The primary winding of the excitation core is tapped to the midpoint of the primary winding of the series core. The secondary winding of the excitation core has an LTC on each phase that regulates the secondary voltage of the series core winding. When the LTC is at neutral, no voltage is applied to the series core secondary. When the LTC is at its highest tap, full voltage is applied to the secondary winding of the series core. The secondary winding of the series core is connected in delta as shown in Fig. 3a) and Fig. 3b). The quadrature voltage is applied to each phase, which is  $\pm 90^\circ$  out of phase with the midpoint to ground voltage halfway between the source (S) and load (L) terminals. Such arrangement helps to ensure that the symmetrical S and L voltage magnitudes for the full range of LTC positions are achievable. A reversing switch in the secondary of the excitation winding (not shown in Fig. 3a) and Fig. 3b)) determines whether the PST will be controlled in advanced or retard position [3].

The advantage of a two-core design over a single-core is the flexibility in selecting the step voltage and the current of the regulating winding be optimized in line with the voltage and current ratings of the LTC. LTCs have limitations in current ratings, step voltages per phase, and switching capacity; they are the main regulating features for the maximum possible PSTs rating. For very large PSTs, more than one LTC per phase may be utilized.

## FUNDAMENTAL DESIGN PARAMETERS

As discussed in [3]-[9], PSTs can be of different types and categories based on application and design considerations.. Most frequently used design solution for high power devices is of symmetric PSTs. Such a PST includes two transformers with separate cores (refer Fig. 4). The main transformer (shunt or exciting unit) has two wye-windings (one primary and one secondary). The primary winding of the main transformer is powered from the midpoint of the primary winding of the series unit; the secondary wye-winding is regulated by load tap-changers (LTCs). The primary winding of the series unit (or booster transformer) connects in series with the line, for which the phase-shift angle is regulated, and passes the rated through-current (i.e., load current) out of the series windings' L terminal.

The main parameters of a symmetric PST consist of:

- Rated throughput power,  $S_n = 3 * V_1 * I_{1L}$ , where  $V_1$  is the midpoint voltage of the primary winding of the series unit (as derived in subclause 4.5.1 of IEEE Std C57.135-2011 [8])
- Rated main unit design power,  $S_{MU} = 2 * S_n * \sin \frac{\alpha}{2}$
- Range of phase-shift angle regulation,  $\alpha$

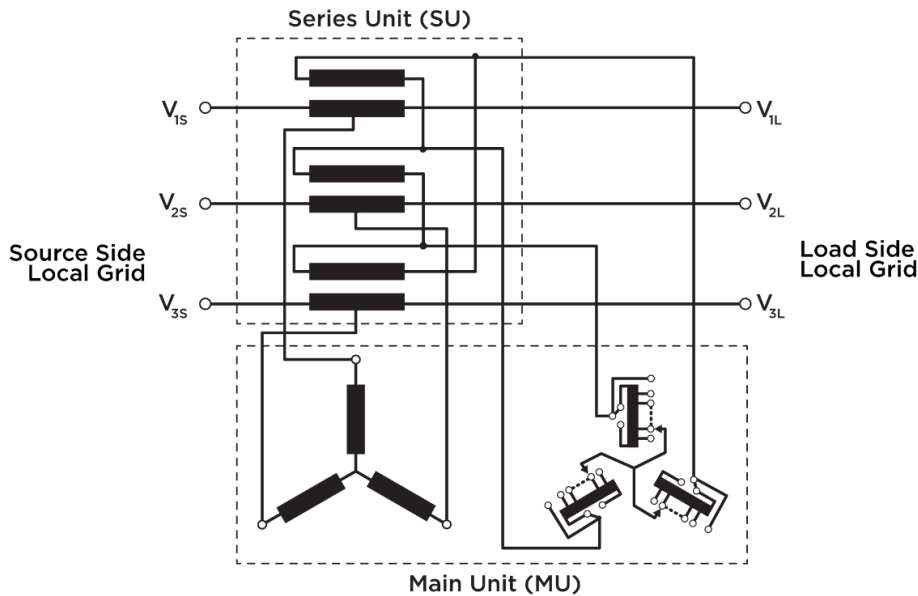


Fig. 4. Connection diagram of a symmetrical two-core PST [2]

The throughput power of a PST is obtained from its rated voltage and rated current flow through terminal L of the booster transformer (i.e., the current flow from S to L bushing terminals). In turn, the rated design power results from the booster voltage produced by the booster transformer (series unit) and the current flow through its winding. The rated design power of series and main unit is associated with the dimensions of PST.

Fig. 5 shows the winding arrangement of a symmetric two-core PST. The main transformer (exciter) unit is powered by the source voltage supplied from the midpoint of the primary winding of the series (or booster) transformer. This winding arrangement injects a quadrature voltage between the source and load bushings. To advance the phase angle of  $V_1$ , a voltage in phase with  $V_{32}$  (the tapped voltages

of neighboring phases of the shunt transformer's secondary) is added to the  $V_1$  voltage of the series unit's delta winding as shown in Fig. 5. Likewise, to retard the phase angle of  $V_1$ , a voltage in phase with  $V_{23}$  is added to the  $V_1$  voltage.

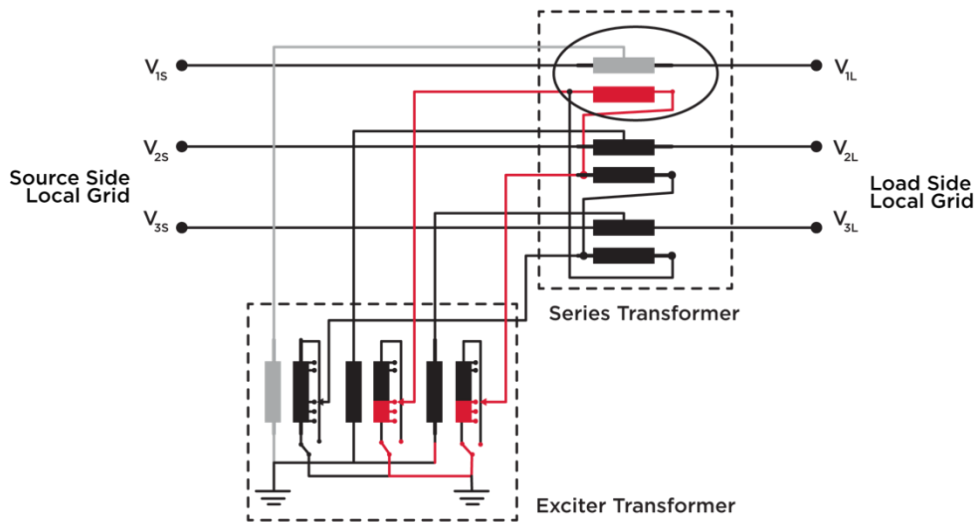


Fig. 5. Winding arrangement of a symmetric two-core PST in advanced position [10]

## IMPORTANT DESIGN CONSIDERATIONS

The following design aspects may be considered:

- **Phase angle rating:** For PST deployment, a thorough study and analysis must be performed to determine the permissible limits of the phase-shift angle. The maximum achievable phase angle of a PST is limited. A higher total phase angle can be achieved when multiple PSTs are connected in series.

The rated phase angle is defined under no-load condition. The PST is unlikely to operate at this phase angle under load in the advanced phase-shift position because of the voltage drop in the series unit. In retard position, the phase-shift angle should not go beyond the no-load phase angle limit. Exceeding such limit can cause a certain degree of overexcitation in transformers cores.

- **MVA rating:** The design capacity of a PST is defined as the apparent power (i.e., MVA) at rated voltage. To determine the rated MVA rating, a comprehensive study shall be necessary. The nameplate MVA rating of a PST is associated with the power flow over the range of regulation from neutral to full advanced and full retard position. The actual MVA rating of the transformer core is associated with the range of regulation that a PST can provide. Thus, for estimating inrush in a PST, it is essential to determine the equivalent MVA rating.

The capacity of future load growth must be considered. A higher total throughput power can be achieved if multiple PSTs are connected in parallel.

The MVA rating of the PST main unit (shunt transformer) and series unit shall be determined based on system's specific power flow control and other applications needs. The MVA rating of individual shunt and series unit can be different for project specific design requirements. Reference [11] describes design and installation experience of the first PST (with 315 MVA, 400/220/55/33 kV shunt unit and 105 MVA, 35/55 kV series unit) in Indian power network.

- **PST types:** PSTs with shunt and series transformer units can be built in a common tank or different tanks according to the requirements for a single-core or two-core design, respectively. Transportation limitations demand for two-core PST design. This is frequently

the case for system voltages equal to or greater than 400 kV. For higher MVA rating, the single-phase solution is necessary to fulfill transportation requirements.

The single-core design is less complex and has fewer windings than the two-core designs; but it has some limitations with respect to the two-core design. In a single-core design, the load tap changer (LTC) and the tapped winding are in the line end of the windings and are directly exposed to the system overvoltages.

Two-core designs consist of a series and shunt units. For smaller rating and lower voltage, PST can be built into a single tank, while for larger rating and higher voltage PST requires a dual-tank design solution. A few examples of PSTs are as follows:

- 1) 100 MVA, 110/110 kV,  $+7^\circ$  (no load degree) in 32 steps, built into a single tank, installed by Municipality of Ulm, Germany in 2005,
- 2) 336 MVA, 138/138 kV,  $\pm 15^\circ$  (no load degree), voltage regulation  $\pm 5\%$ , built into a dual tank, installed by Commonwealth Edison, Chicago, USA in 2000,
- 3) 450 MVA, 138/138 kV,  $\pm 58^\circ$  (no load degree) in 64 steps with a series reactor, built into a dual tank, installed by Keyspan, Long Island, USA in 2002, and
- 4) 1630 MVA, 400/400 kV,  $+18^\circ$  (no load degree), built into a dual tank, installed by TERNA Rondissone, Italy in 2003.

- **Overload conditions (above nameplate rating):** Overloading of a PST increases the internal phase angle  $\beta$  and consequently also the load phase angle,  $\alpha_{(r)}^*$  in the retard position [8]. This may result in a load phase-shift angle that exceeds the maximum rated no-load phase angle. The voltage across the regulating winding and consequently also the voltage per step of a single-core type as well as the voltage across the series winding of a two-core type will exceed the rated voltage.

Moreover, with a two-core design, the main transformer (i.e., exciter unit) will experience a certain degree of overexcitation with the same consequences for the regulating (i.e., tapped) winding. The degree depends on the ratio of the impedances of series and exciter (or shunt) transformer units.

Besides the cores' overfluxing effect, the other parameters, such as permissible voltage per step, current, and switching capability, etc., should be checked whether they are within the limits of the LTC design [8].

- **LTC and Advanced-retard switch (ARS) application:** PSTs are normally designed to change the angle between the source and load voltage; the load voltage is either in-phase with the source voltage, in advance, or in retard direction with respect to the source voltage. Step changes in angular regulation are achieved by using load tap-changers (LTCs) that add or subtract from the number of winding turns in the regulating winding of the PST [8]. Transitions from advance to retard regulation, or vice versa, are accomplished by reversing the connection of one of the PST windings or a portion of one of the overall windings. This polarity inversion is performed by either using the LTC's reversing change-over selector switch or through a separate ARS switch as discussed in [3][8].

The selection of on-load tap-changers (OLTCs) for the PSTs differs from the standard power transformers. The required switching capacity as well as the step voltage of an OLTC are the most important parameters beside the throughput current flow. The permissible step voltage in a PST may vary over a wide range depending on the load and the switching position of the OLTC [7][8].

Special features of the OLTC for many PST configurations, both with and without an ARS, as well as configurations with multiple LTCs used for coarse and fine tap changes may be used as described in [3][7][8].

In two-core PST design, the winding connection inversion to achieve an advance or a retard transition can either be provided in the series transformer secondary winding via an ARS or in

the secondary winding of the excitation unit via one or more LTC reversing change-over selectors and sometimes via an ARS switch.

Therefore, the selection of OLTCs for use in PSTs designs should be determined wisely because of some specific duties' requirements.

- **Special considerations for two-core design:** In two-core type PST, the transmission of transient voltages caused by switching or lightning impulses is rather complex [8]. There may be high-voltage oscillations of the connecting leads depending on the capacitive voltage control of the series winding. High transient voltages will be transferred to other windings coupled to the series winding or to the excitation winding. Therefore, it is essential to compute the transient voltages using a comprehensive computer model to determine precise dielectric level for this configuration.

Likewise, when a two-core design is made with multiple tanks, special precautions must be taken to design connections between the tanks. The connection leads must be insulated for the overvoltages that may occur under transients and power frequency environment. A short circuit between the connections of the two units would trigger severe damages. A short-circuit proof PST design for this special case may be recommended, even at a significant cost increase.

Therefore, the use of appropriate metal enclosures to protect the leads against lightning strikes and other possible sources of short circuit can withstand the mechanical, electrical, and thermal stresses produced by external short-circuit events [8].

## CIRCUITS ARRANGEMENTS

The operational flexibility of one or more PSTs is determined by the circuit arrangements and layout of feeder bay. A variety of arrangements along with circuit breakers, disconnectors and bypass switches may be possible for an ideal operation of the PST as described in [3][12]. In case, the PST deployed for the transmission line (T-line) segment needs maintenance, it will be required to bypass the PST and bring the T-line back into service. For permanent deployment, a detailed circuit arrangement with the PSTs in the feeder bay is essential. A few possible circuit arrangements with one PST, two-PSTs in series, and two-PSTs in parallel are demonstrated in Fig. 6a-e).

Fig. 6a) shows the circuit arrangement of one PST connected with two circuit breakers (CBs), one bypass switch and four disconnectors.

Figs. 6b-c) show the circuit arrangements for two PSTs in series connected with one and two bypass switches, respectively. If two or more identical PSTs are connected in series, the phase-shift angles and impedances from each PST add together to produce a total equivalent phase shift and impedance. The MVA rating of the bank of series connected PSTs is equivalent to the MVA rating of each PST.

Figs. 6d-e) show the circuit arrangements for two PSTs in parallel with one bypass switch, and one CB and one bypass switch combined, respectively. If two or more identical PSTs are connected in parallel, the impedances from each PST combine in parallel to provide a reduced total impedance. The MVA rating of the bank of parallel-connected PSTs is equivalent to the sum of the MVA ratings of all parallel-connected PSTs. Under such an arrangement, phase-shift angle of the bank will remain unchanged. When operating two or more PSTs in parallel, influence of circulating currents that can occur during tap changes should be evaluated during the design phase.

In many situations, maintenance of disconnectors and circuit breakers (CBs) will lead to an outage of the PST-connected circuit, but the assigned bypass solutions will support for the maintenance of the PSTs without outage of the T-line.

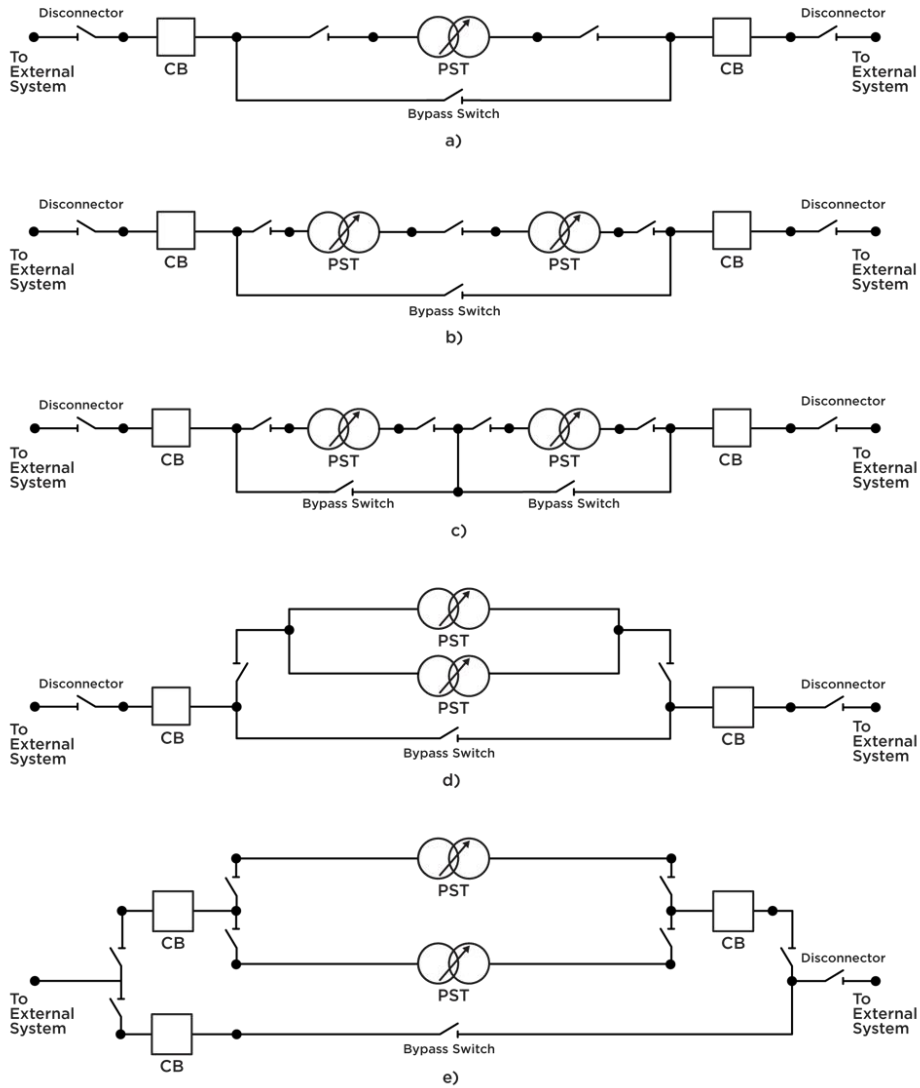


Fig. 6. Circuit arrangements of PSTs [12]

- a) One PST, connected with two CBs, one bypass switch and four disconnectors,
- b) Two PSTs in series, connected with one bypass switch and five disconnectors,
- c) Two PSTs in series, connected with two bypass switches and six disconnectors,
- d) Two PSTs in parallel, connected with two CBs, one bypass switch and four disconnectors,
- e) Two PSTs in parallel, connected with three CBs, one bypass switch and eight disconnectors.

## OPERATIONAL LIKELIHOOD

Operational flexibility of the PSTs can be improved with the following mode of operation [12]:

- Parallel operation of PSTs can reduce MVA rating of each transformer. However, for parallel operation, the effect of circulating currents must be taken into consideration.
- Serial operation of PSTs extends combined phase-shift angle. Under such a configuration, the rated phase-shift angle of each PST will be reduced.
- Bypassing option of the PSTs with disconnector switches and circuit breakers can reduce line losses when the regulated power flow control with PSTs is not necessary. Additionally, it can be beneficial to bypass PSTs when it is unavailable due to failures or maintenance.
- Changeable line arrangement allows flexibility in PST's position to different power lines and may be required due to power flow situation changes. Fig. 7 shows an example with changeable line arrangement.
- Flexible node topology can be formed for changing the power flow situations. PSTs can be assigned between various electrical nodes with different voltage phasor angles (requiring

additional busbar sections). This is required whenever transit flows are induced into other lines, transformers or entire grids.

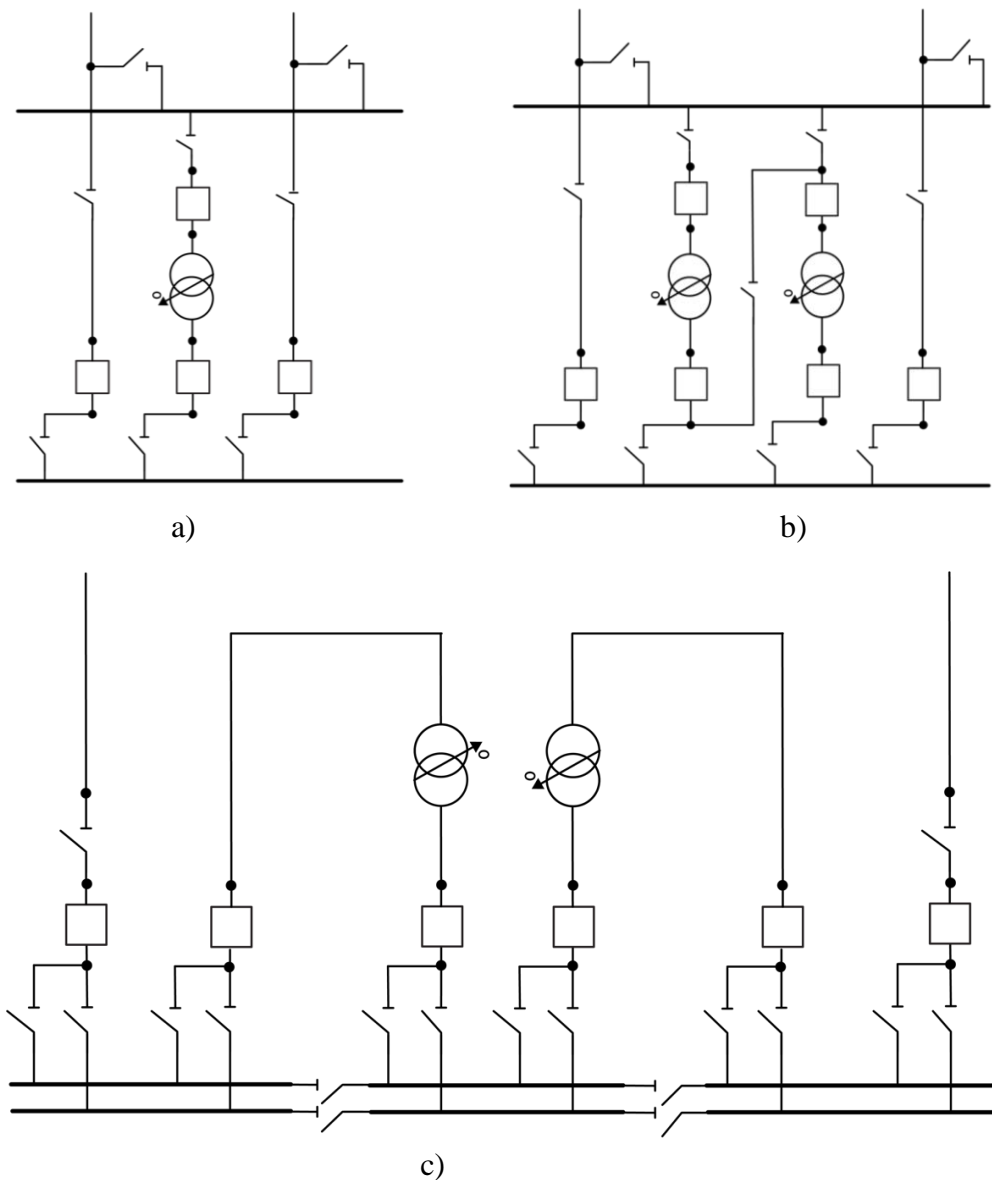


Fig. 7. Circuit arrangements of PSTs with additional transfer busbar [12]

- Energized switching is necessary when the network is already stressed due to overloads. Switching operations that require a short discontinuity to get from one of the above states to another, will eventually lead to inadmissible differences in phasor angles. This can be avoided by the integration of additional circuit breakers to allow discontinuity-free switching operations as described in [12]. Fig. 7 shows circuit arrangements of PSTs with additional transfer busbar. These configurations enable energized switching.

## CONCLUDING REMARKS

The PST can control the power flow between different networks and protect T-lines from thermal overload and improve the power system stability. PSTs can be designed for a discrete phase angle shift or continuously variable phase shift, or a combination of both. Some designs support for controlling the voltage magnitude as well as the phase angle shift. Various winding arrangements (e.g., symmetric or asymmetric) are possible depending on the rated voltage, the rated throughput power, the amount of

phase shift, and whether or not a linear voltage control is also required. Discrete phase-angle PSTs normally provide settings for a fixed  $+\alpha$  or  $-\alpha$  and zero degree. A variable phase shift operation can be possible by using OLTCs and ARS [3][8].

One PST design can have many solutions. The customer's needs and the manufacturer's preference generally determine the PST design. Preferences of a manufacturer as to the type of transformer (core or shell) or type of tank (single or dual), and other design characteristics (e.g., symmetric or non-symmetric, quadrature or non-quadrature) will play an important role for selecting a PST design.

The major factors specific to the PST design shall include [3][7][8]:

- Rated throughput power and phase-shift angle ( $\alpha$ ) requirements
- Rated voltage
- Impedance variation across the regulating taps and its influences on voltage drop under load, phase shift under load, and saturation effects in retard mode
- Short circuit capability of the PST connected line
- OLTCs performance requirements
- Load tap changers margins on step voltage, rated current, short circuit currents, step switching, and transient voltage withstand, and the duty of advance-retard switch
- Transient voltage distribution during lightning impulse
- Single command features [13][14] for bypass and tap changers (OLTC and ARS) operation
- PST installation costs
- Test capability

Other factors shall include [7][8]:

- Footprint requirement in the substation
- Oil spill containment volume
- Transportation limitations
- Protection challenges and costs for relays

All these factors would determine whether a single- or a two-core, symmetric or asymmetric type PST design solution is feasible for any project-specific application.

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