CIGRE US National Committee
2022 Grid of the Future Symposium

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

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# Outline

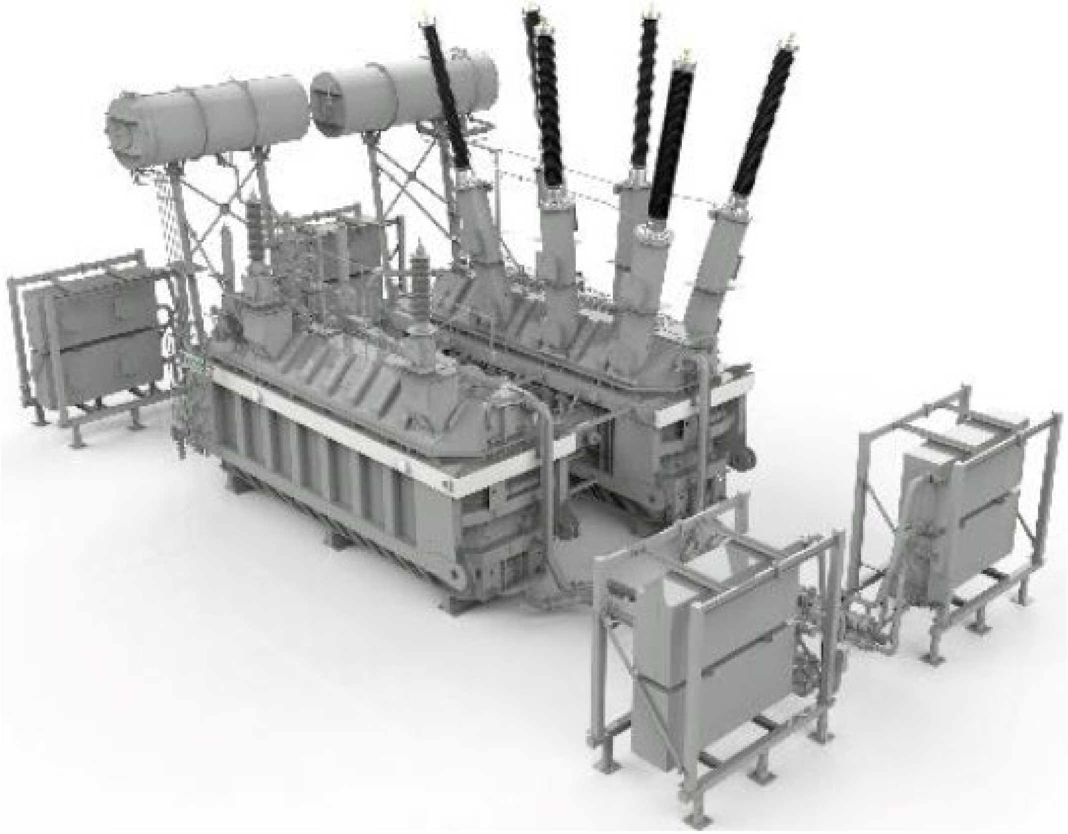
- Background
- Principles of Active Power Control
- Types and Categories of PSTs – single-core and two-core symmetric
- Fundamental Design Parameters
- Important Design Considerations
- Circuit Arrangements of PSTs
- Operational Likelihood – flexible assignment of PSTs
- Concluding Remarks

# Background

- Modern power grid facing challenges to enhance grid controllability and power transfer capability due to the increasing number of renewable generation penetrations.
- Utilities are exploring viable options with suitable power-flow controllers to offer grid-operational reliability and meet power grids constraints.
- PST - a specialized type of transformer that controls active power (P) flow in power grid while operating by reliable LTCs and advanced-retard switch (ARS) application.
- PST regulates the voltage phase-shift angle difference between ‘S’ and ‘L’ terminals - depends on a phase-shifted voltage source injection into line segment by a series transformer unit, fed by a shunt transformer unit.

# Phase-Shifting Transformers


Phase-shifting transformer (photo courtesy of ABB)



Phase-shifting transformer (photo courtesy of Siemens)

# Principles of Active Power Control

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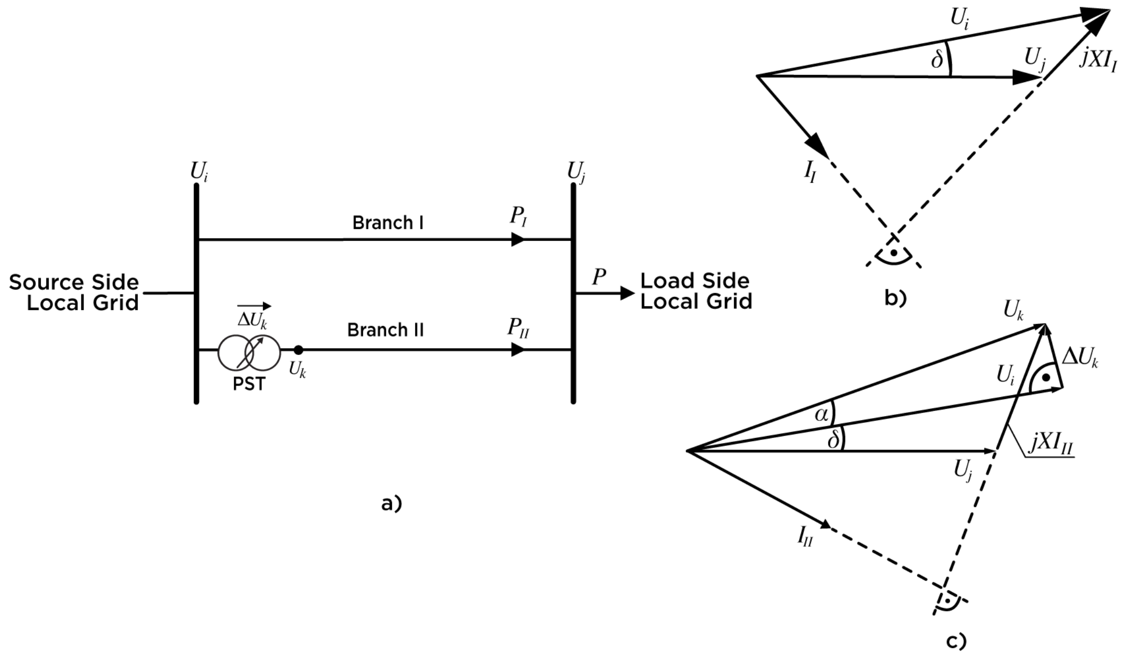



Active power flow control by adjusting $\delta$: a) system one-line with a PST, b) phasor diagram for branch-I, c) phasor diagram for branch-II

- Active power flow ($P$) through a single branch of inductive reactance ($X$)

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

- $U_i$, $U_j$ – voltages at sending and receiving end, and δ – load angle (diff. of phases between $U_i$ and $U_j$, $\delta = (\theta_i - \theta_j)$)

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

$$P_{II} = \frac{U_k U_j}{X} Sin(\delta + \alpha) \text{ where, } U_k = U_i + \Delta U_k$$

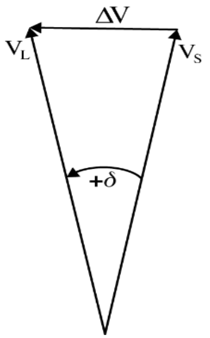
- Since $(\delta + \alpha) > \delta$, $P_{II} > P_I$.
- $\Delta U_k$ (i.e., booster voltage) can be adjusted from (-α) to (+α)

C1-108_2014: Improving the Cross-border Transmission Capacity of Polish Power System by Using Phase Shifting Transformers, *CIGRE 2014*

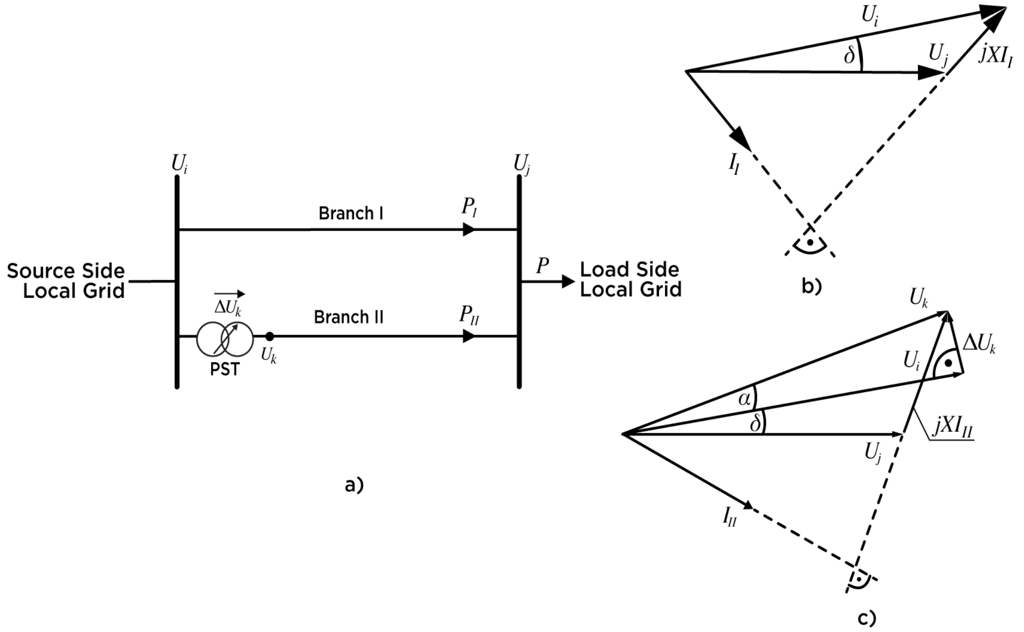
# Types and Categories of PSTs

Symmetric or non-symmetric type; 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 L-bushing is always equal to the voltage magnitude at S-bushing, independent of the phase shift angle.




Quadrature voltage across a PST causes a shift in angle δ




A quadrature type PST is a unit where the boost voltage, which creates the **phase shift** between **S and L bushings**, is **perpendicular** to the line voltage at S- terminal, or to a combination of the line voltages at S and L terminals.

# Types and Categories of PSTs

PSTs can be grouped into five categories:

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

IEEE Std C37.245:2018 Guide for the Application of Protective Relaying for phase-Shifting Transformers

# Single-Core Symmetric - with Tap Winding outside the Delta

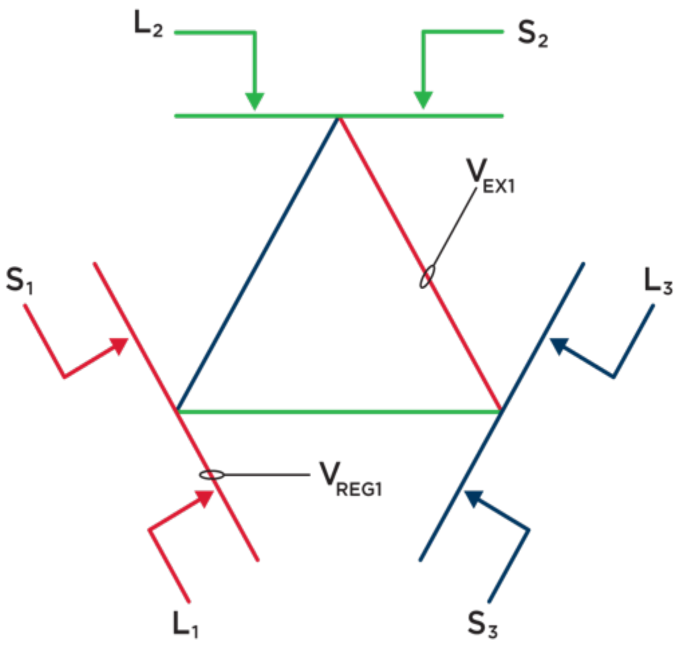



Fig. Nameplate diagram

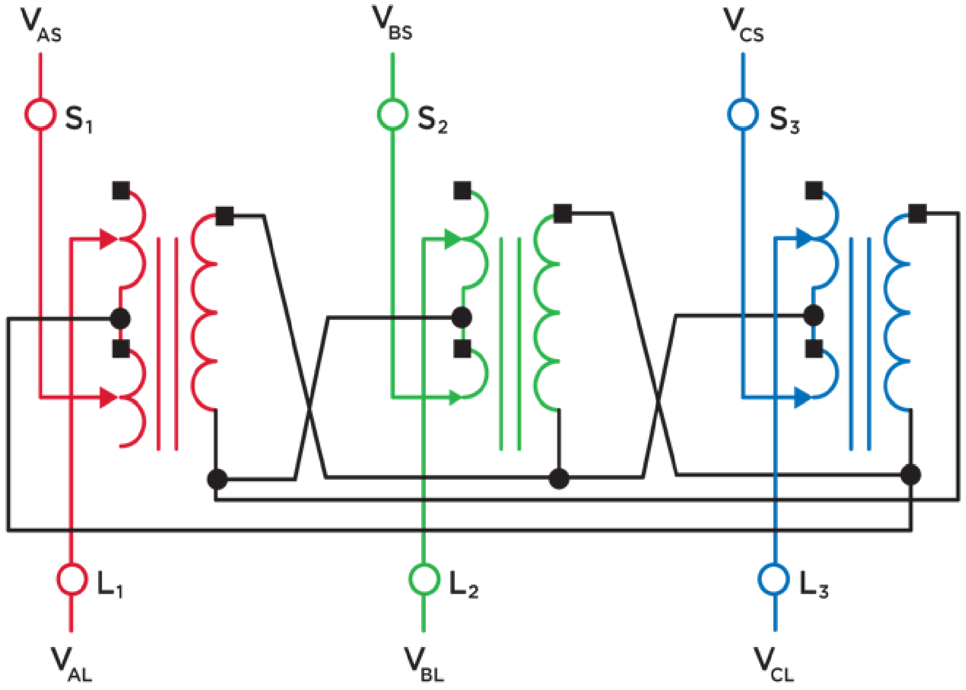



Fig. Three-line diagram

IEEE Std C37.245:2018 Guide for the Application of Protective Relaying for phase-Shifting Transformers

# Two-Core Symmetric - with Wye-Wye Exciting Unit (Conventional)

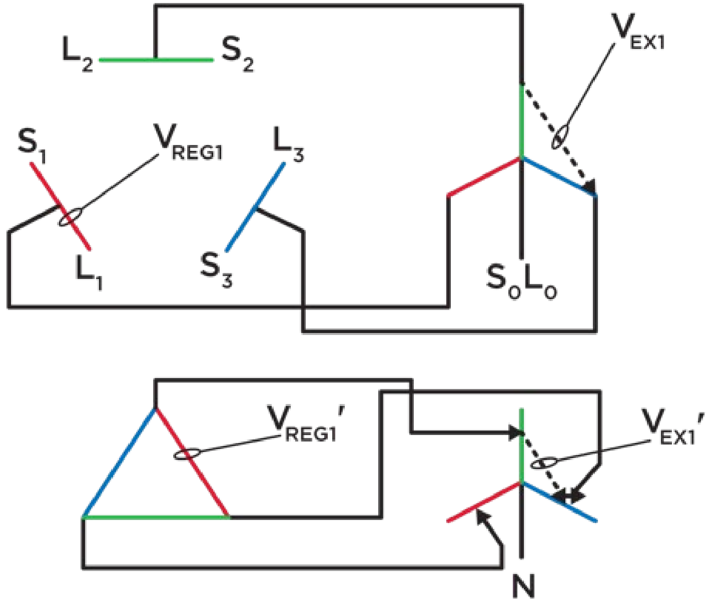



Fig. Nameplate diagram

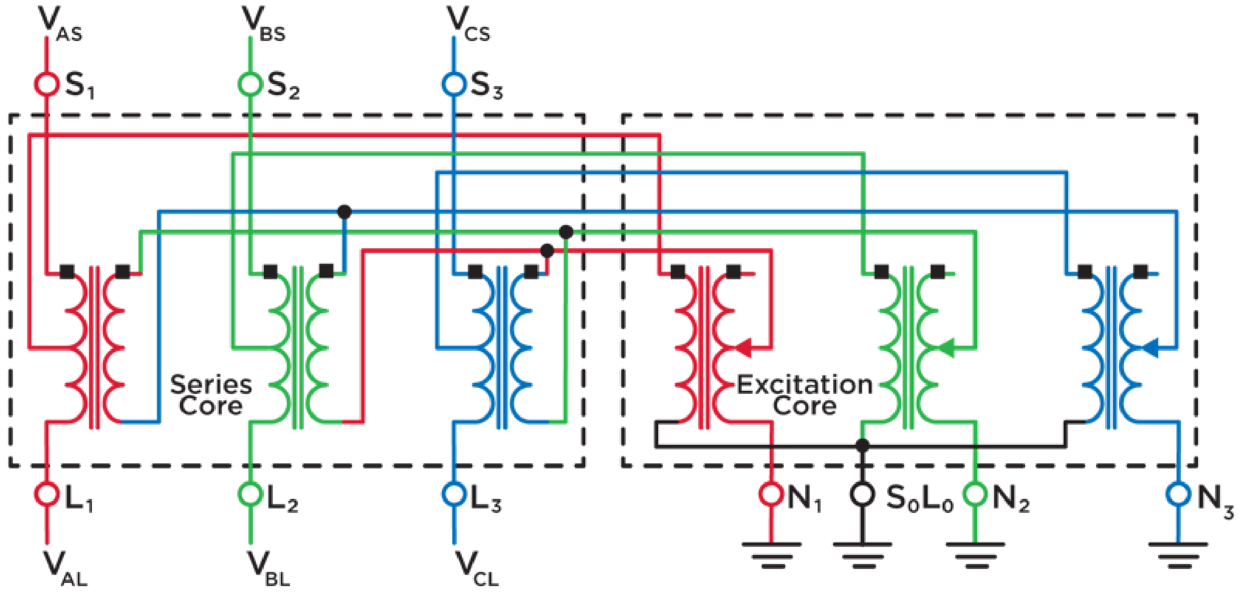



Fig. Three-line diagram of a two-core symmetric PST in the advanced position

IEEE Std C37.245:2018 Guide for the Application of Protective Relaying for phase-Shifting Transformers

# Fundamental Design Parameters

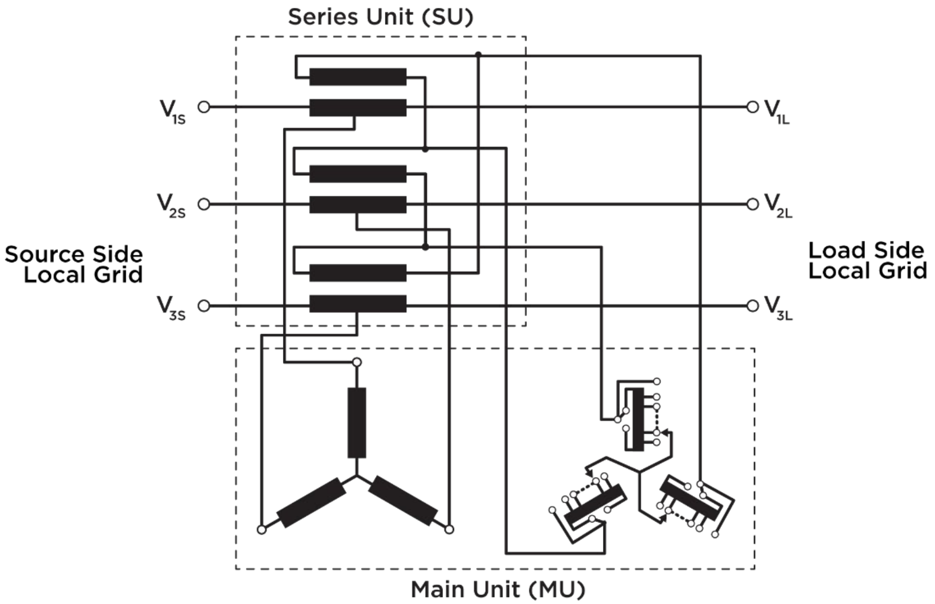



Fig. Connection diagram of a symmetrical two-core PST

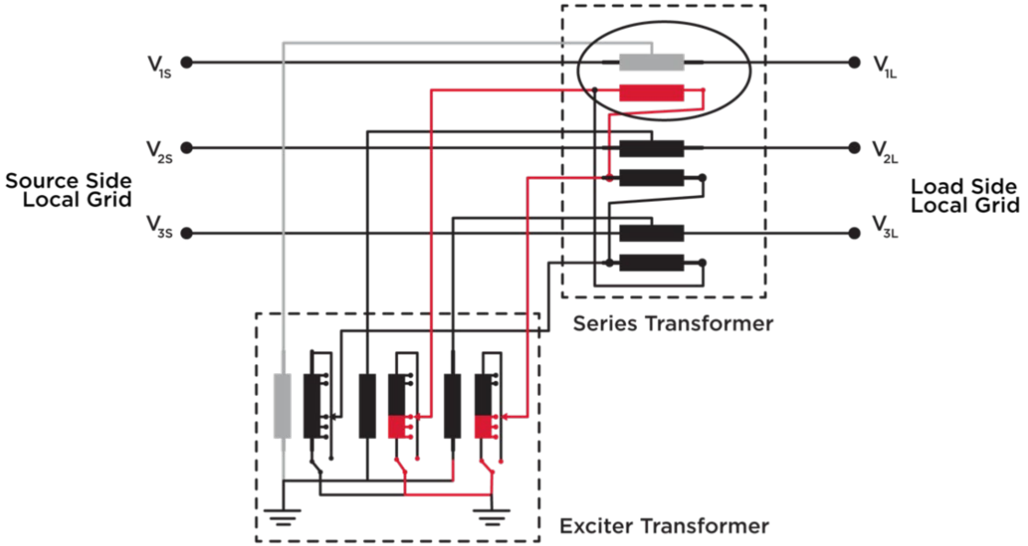



Fig. Winding arrangement of a symmetric two-core PST in advanced position

The main parameters of a 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
- Rated main unit design power, $S_{MU} = 2 * S_n * Sin\frac{\alpha}{2}$
- Range of phase-shift angle regulation, α

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.

Phase-Shifting Transformers Application and Technology, ABB AG, Germany


[1] C1-108_2014: Improving the Cross-border Transmission Capacity of Polish Power System by Using Phase Shifting Transformers
[2] IEC 62032/IEEE Std C57.135:2012 Guide for the Application, Specification and Testing of Phase-Shifting Transformers

# Important Design Considerations

**Phase angle rating:** Defined under **no-load condition**.

Note: *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.*

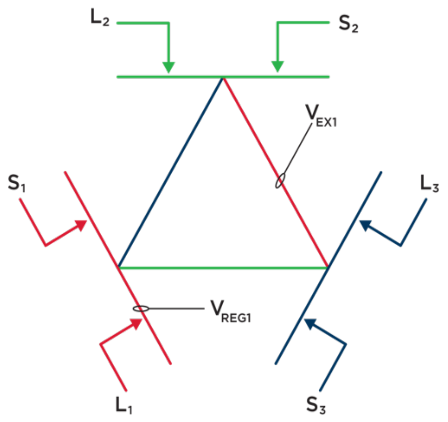
**MVA rating:** Defined as **the apparent power** (MVA) at rated voltage.

*The nameplate MVA rating is associated with the power flow over the range of regulation (tap) from neutral to full advance and full retard position. The MVA rating of shunt and series unit shall be determined based on system's specific power flow control needs.*

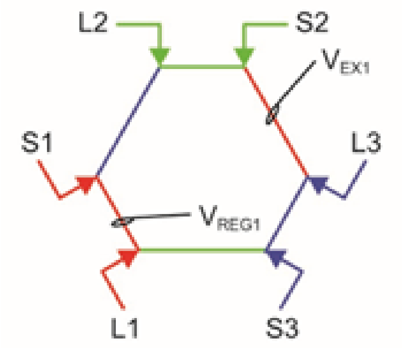
# Important Design Considerations

**PST types:** PSTs with shunt and series unit can be built in a common tank or different tanks according to the needs for a single-core or two-core design.

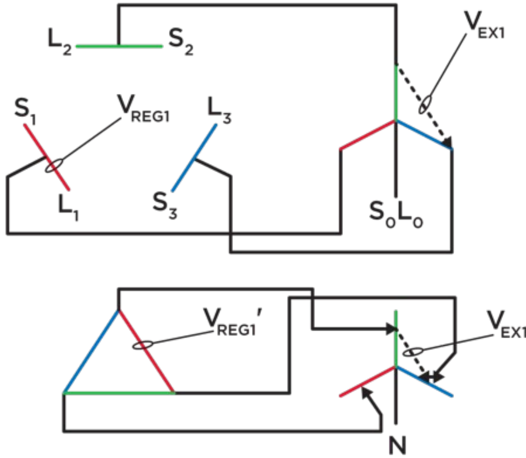
In single-core design (extended delta and delta hexagonal), the LTC and the tapped winding are in the line end of the windings and are directly exposed to the system overvoltages.




Single-core symmetric, extended delta




Single-core symmetric, delta hexagonal




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

Two-core designs consist of a series and excitation 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. Transportation limitations demand for two-core design. This is frequently the case for system voltages equal to or greater than 400 kV.

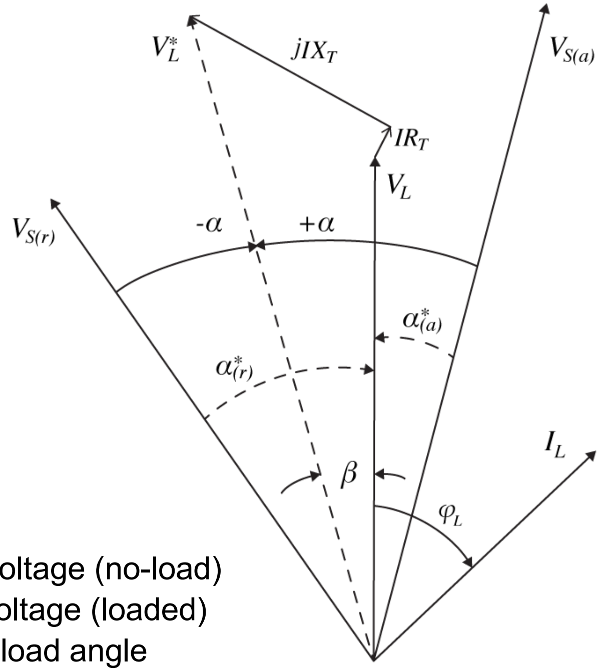
# Important Design Considerations

**Overload conditions (above nameplate rating):** Overloading increases β (transformer load angle) and consequently also the load phase angle, $\alpha^*_{(r)}$ in the retard position.

**Note:** *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 (shunt) 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 (shunt) transformer units.

**Note**: *Besides the cores' overfluxing effect, the other parameters, such as voltage per step, current, and switching capability, etc., shall be checked whether they are within the limits of the LTC design.*




Where:
$V_L^*$ = load-side voltage (no-load)
$V_L$ = load-side voltage (loaded)
β = transformer load angle
α = phase-shift angle
$\varphi_L$ = load power factor angle

Fig. PST under load

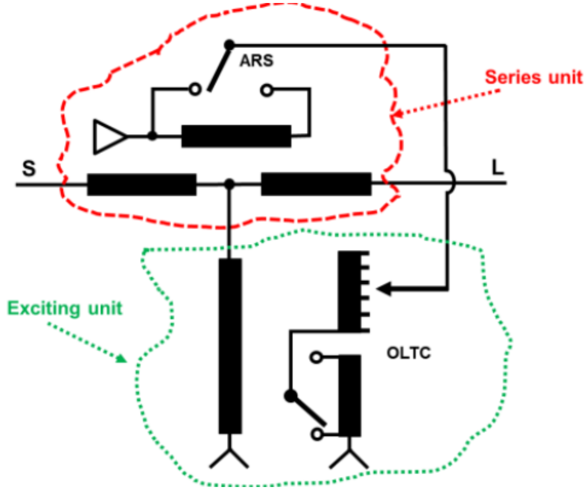
PST adds ±α, and so, $\alpha^*_{(a)}$ and $\alpha^*_{(r)}$ - varied as:
$\alpha^*_{(a)} = (\alpha - \beta)$: is phase-shift angle (loaded) advance
$\alpha^*_{(r)} = -(\alpha + \beta)$: is phase-shift angle (loaded) retard.

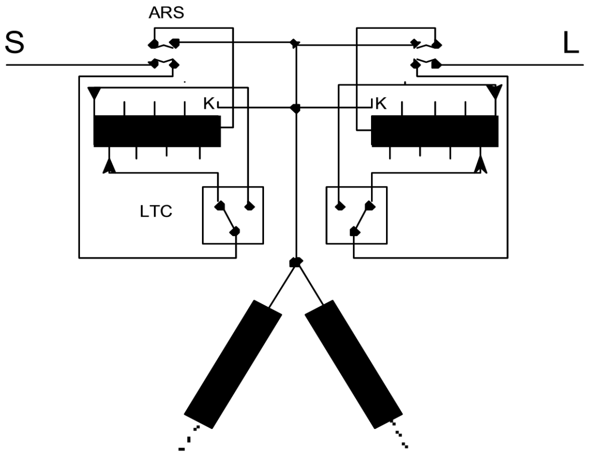
IEC 62032/IEEE Std C57.135:2012 Guide for the Application, Specification and Testing of Phase-Shifting Transformers

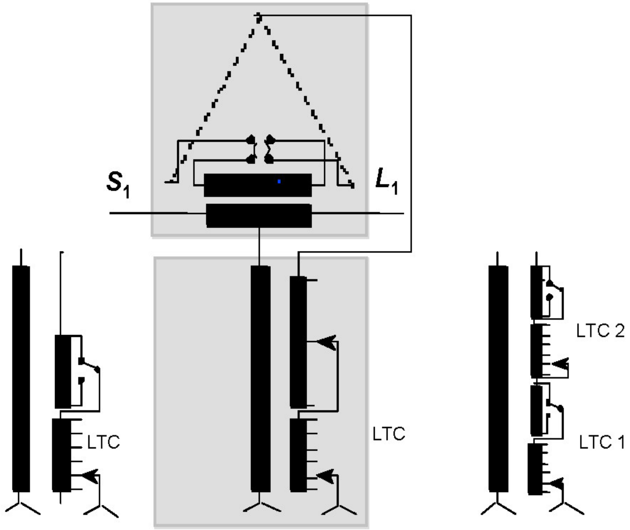
# Important Design Considerations

**LTC and ARS (Advance-Retard Switch) application:** The selection of 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.

In two-core 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...





[1] A2-207_2014: New Phase Shifting Transformers in the Italian Transmission Network - Design, Manufacturing, Testing and Electromagnetic Transients Modelling
[2] IEC 62032/IEEE Std C57.135:2012 Guide for the Application, Specification and Testing of Phase-Shifting Transformers

# Important Design Considerations

**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. 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.

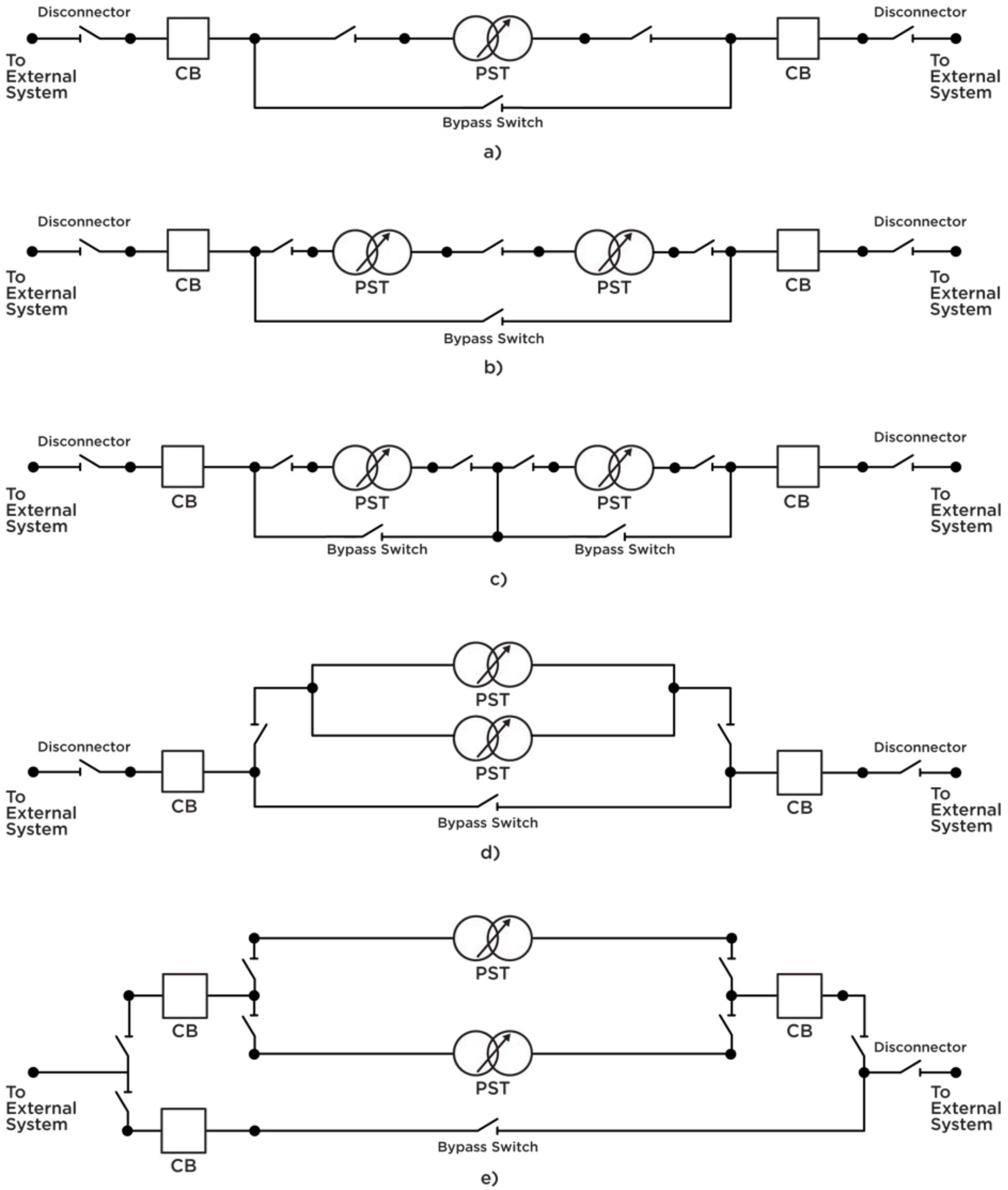
Likewise, when a two-core design is made with multiple tanks, special precautions must be taken to design connections between the tanks. The connection leads must be insulated for the overvoltages that may occur under transients and power frequency environment. A short circuit between the connections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


A2-207_2014: New Phase Shifting Transformers in the Italian Transmission Network - Design, Manufacturing, Testing and Electromagnetic Transients Modelling

# Circuits Arrangements

## Circuit Arrangements of PSTs

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.




B3-108_2020: Flexible Integration of Phase-shifting Transformers in AIS Substations - Comparisons of Approaches, *CIGRE Session 2020*

# Operational Likelihood

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

- Parallel operation of PSTs can reduce MVA rating of each transformer. Effect of circulating currents must be taken into consideration.

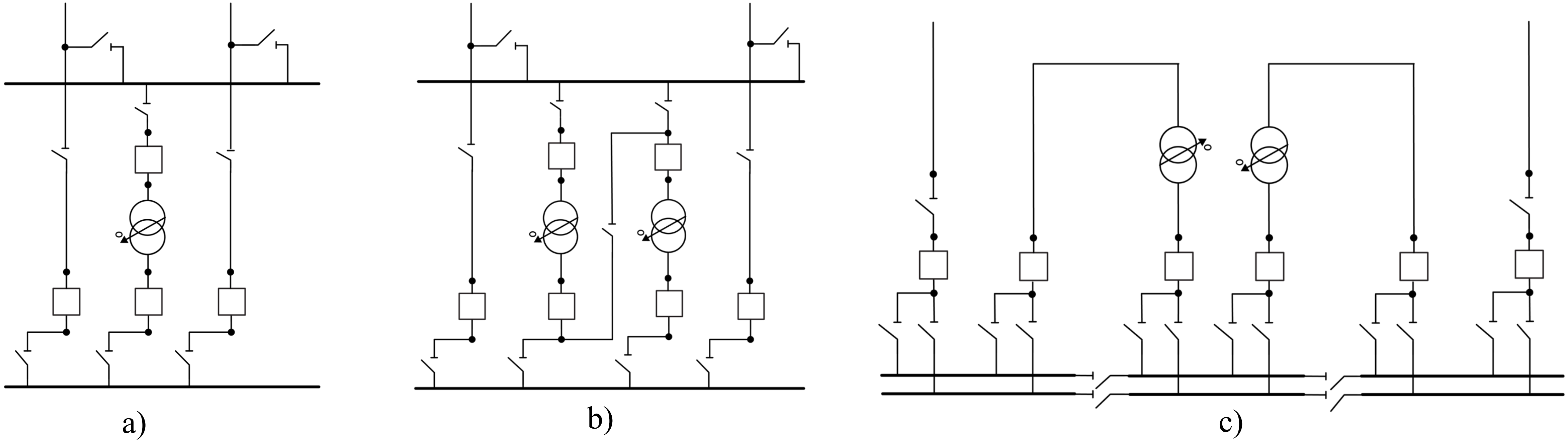
- Serial operation of PSTs extends combined phase-shift angle. Under such a configuration, the rated phase-shift angle of each PST will be reduced.

- 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 or when 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.

# Operational Likelihood

## Flexible Assignment of PSTs




Circuit arrangements of PSTs with additional transfer busbar

B3-108_2020: Flexible Integration of Phase-shifting Transformers in AIS Substations - Comparisons of Approaches, *CIGRE Session 2020*

# Operational Likelihood

- 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 – refer previous figure]. This is required whenever transit flows are induced into other lines, transformers or entire grids.

- 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 inadmissibly differences in phasor angles. This can be avoided by the integration of additional circuit breakers to allow discontinuity-free switching operations.

# Concluding Remarks

- The major factors specific to the PST design shall include:
  - Rated throughput power, phase-shift angle (α) requirements  and 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 - LTC 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 for bypass and tap changers (OLTC and ARS) operation
  - PST installation costs
  - Test capability

# Concluding Remarks

- Other factors shall include
  - 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.

[1] IEEE Std C37.245:2018 Guide for the Application of Protective Relaying for phase-Shifting Transformers
[2] A2-205_2006: Special Considerations on the Selection of On-Load Tap-Changers for Phase-shifting Transformers, *CIGRE 2006*
[3] IEC 62032/IEEE Std C57.135:2012 Guide for the Application, Specification and Testing of Phase-Shifting Transformers

# References


[1] A2-203_2006: Innovative Applications of Phase-Shifting Transformers Supplemented with Series Reactive Elements, *CIGRE 2006*

[2] C1-108_2014: Improving the Cross-border Transmission Capacity of Polish Power System by Using Phase Shifting Transformers, *CIGRE 2014*

[3] IEEE Std C37.245:2018 Guide for the Application of Protective Relaying for phase-Shifting Transformers

[4] 12-306_1998: Phase Shifting Transformers - Discussion of Specific Characteristics, *CIGRE Session 1998*

[5] J. Verboomen, D. Van Hertem, P. Schavemaker, W. Kling, and R. Belmans, "Phase Shifting Transformers: Principles and Applications," *International Conference on Future Power System*, Amsterdam, Netherlands, November 2005

[6] A2-204_2006: French Experience in Phase-Shifting Transformers, *CIGRE 2006*

[7] A2-205_2006: Special Considerations on the Selection of On-Load Tap-Changers for Phase-shifting Transformers, *CIGRE 2006*

[8] IEC 62032/IEEE Std C57.135:2012 Guide for the Application, Specification and Testing of Phase-Shifting Transformers

[9] IEC/IEEE 60076-57-1202:2017 Power Transformers - Part 57-1202: Liquid Immersed Phase-Shifting Transformers

[10] Phase-Shifting Transformers Application and Technology, ABB AG, Germany

[11] A2-205_2014: Design, Testing and Commissioning of First Phase Shifting Transformer in Indian Network, *CIGRE 2014*

[12] B3-108_2020: Flexible Integration of Phase-shifting Transformers in AIS Substations - Comparisons of Approaches, *CIGRE Session 2020*

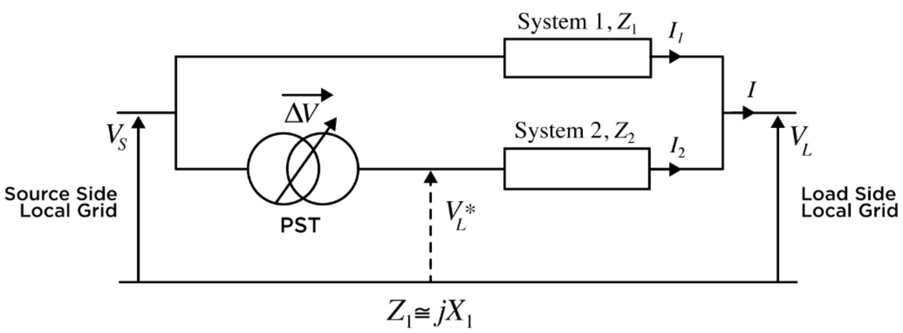
[13] M. J. Thompson, H. Miller and J. Burger, "Innovative Power Flow Regulating Tap-Changer Control Installed on Multiple Phase-Shifting Transformers," *IEEE PES T&D Conference and Exposition in Chicago, IL*, April 21-24, 2008

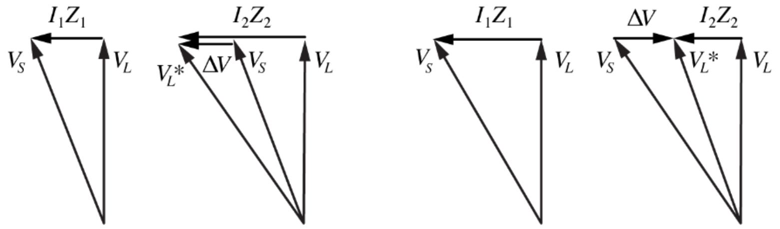
[14] A2-207_2014: New Phase Shifting Transformers in the Italian Transmission Network - Design, Manufacturing, Testing and Electromagnetic Transients Modelling, *CIGRE Session 2014*

# Q&A

https://cigre-usnc.org/papers-presentations/

# Principles of Active Power Control



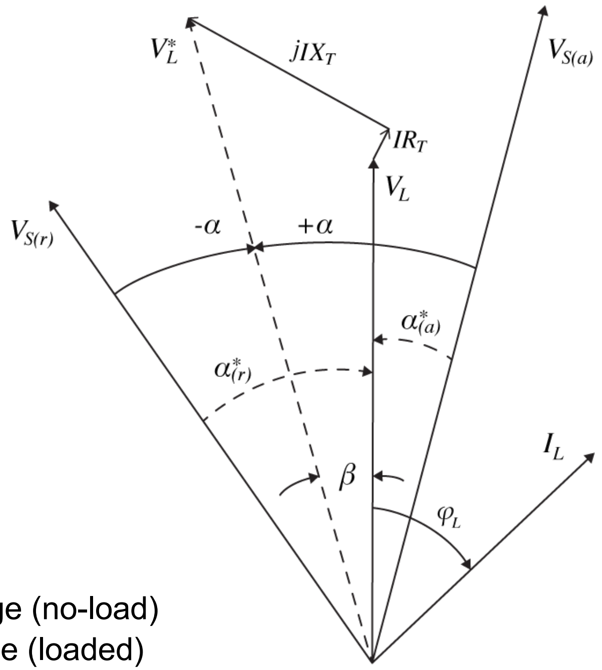




$I_1Z_1 < I_2Z_2$
Advanced: $V_L^*$ leads $V_S$

$I_1Z_1 > I_2Z_2$
Retard: $V_L^*$ lags $V_S$

## Load side power factor of 1.0

$V_L^*$ = Load-side no-load (or preload) voltage
$V_L$ = Load-side loaded voltage
$\alpha_{+(adv)}$ : *when* $V_L^*$ leads $V_s$
$\alpha_{-(retd)}$ : *when* $V_L^*$ lags $V_s$




PST under load

Where:
$V_L^*$ = load-side voltage (no-load)
$V_L$ = load-side voltage (loaded)
β = transformer load angle
α = phase-shift angle
$\varphi_L$ = load power factor angle

PST adds ±α, and so, the load phase-shift angles $\alpha^*_{(a)}$ and $\alpha^*_{(r)}$, respectively, can be varied as:
$\alpha^*_{(a)}$ = (α – β): is phase-shift angle (loaded) advance, and
$\alpha^*_{(r)}$ = −(α + β): is phase-shift angle (loaded) retard.

IEC 62032/IEEE Std C57.135:2012 Guide for the Application, Specification and Testing of Phase-Shifting Transformers

# Single-Core Symmetric, Polygon (Delta Hexagonal)

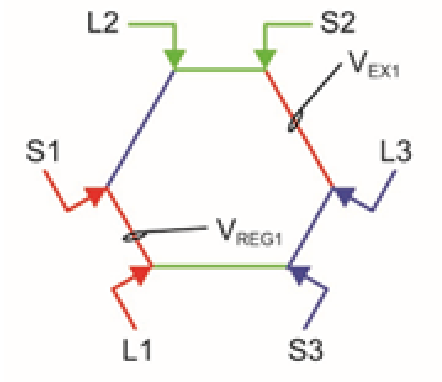



Fig. Nameplate diagram

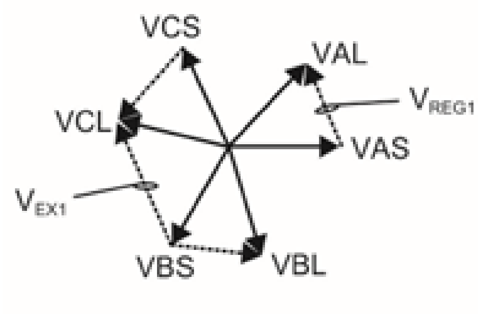



Fig. Phase shift diagram

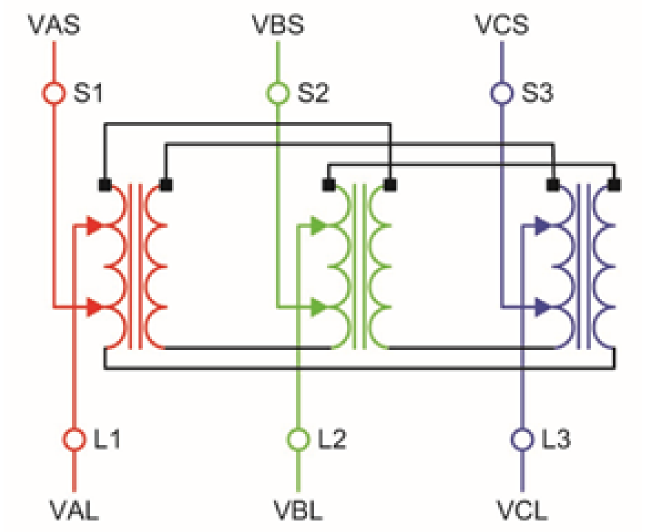



Fig. Three-line diagram of a single-core delta hexagonal, shown in the advanced position

IEEE Std C37.245:2018 Guide for the Application of Protective Relaying for phase-Shifting Transformers

# Design Considerations - Overloading in Retard Position

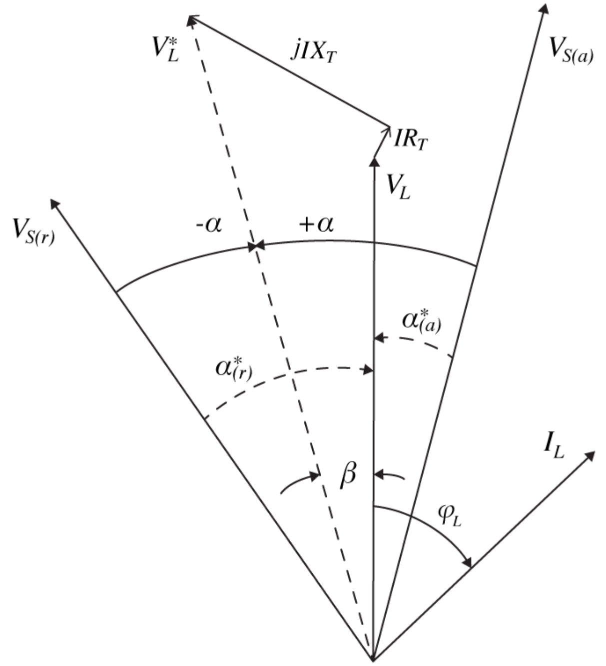



Fig. PST under load

Overloading of a PST increases the internal phase angle β and consequently also the load phase angle, $\alpha^*_{(r)}$ in the retard position.

Where:
$V_L^*$ = load-side voltage (no-load)
$V_L$ = load-side voltage (loaded)
β = transformer load angle
α = phase-shift angle
$\varphi_L$ = load power factor angle

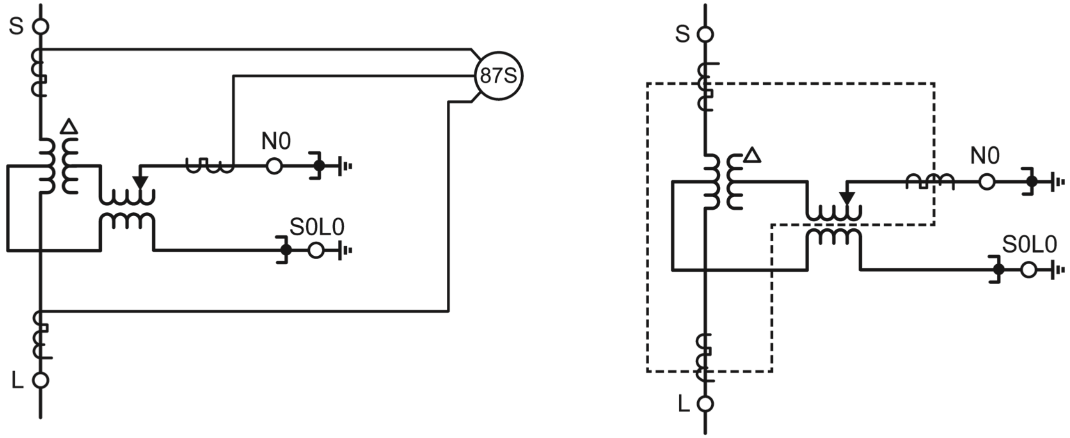
PST adds ±α, and so, the load phase-shift angles $\alpha^*_{(a)}$ and $\alpha^*_{(r)}$, respectively, can be varied as:

$\alpha^*_{(a)} = (\alpha - \beta)$: is phase-shift angle (loaded) advance, and

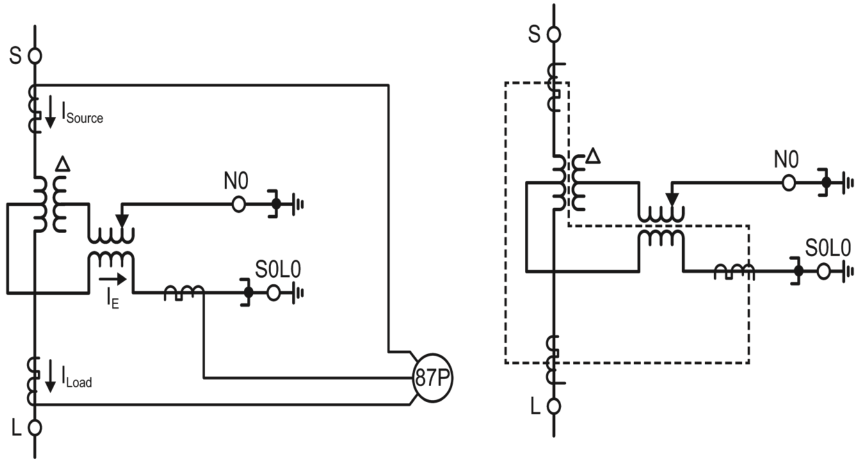
$\alpha^*_{(r)} = -(\alpha + \beta)$: is phase-shift angle (loaded) retard.

IEC 62032/IEEE Std C57.135:2012 Guide for the Application, Specification and Testing of Phase-Shifting Transformers

# Highlights on PST Protection (forthcoming article)



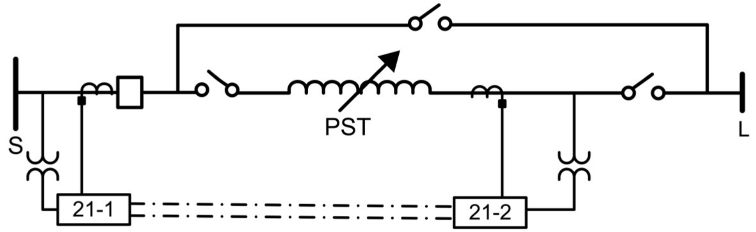

87S (ATB) connection diagram
of a two-core symmetric PST




87P (KCL) connection diagram
of a two-core symmetric PST

Other protections include:

- Short Circuit Protection
- Through Fault Protection
- Thermal Overload Protection
- Backup Ground Fault Protection
- Buchholtz and LTC Sudden Pressure Relay Protection




Permissive Overreaching Transfer Trip Protection