Phase Shifting Transformers – Principles, Design Aspects and Operation

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Purpose and function of PSTs

A Phase Angle Regulator >
Controls power flow through specific lines
Creates a driving force onto power transmission networks

Basic function of a PST

- In principle, a phase shifting transformer creates a phase shift between primary (source) & secondary (load) side
- Usually, this phase shift can be varied under load
- Sometimes, it can be made advance and retard
How does phase shift influence power flow?

The „natural“ current distribution is dependent on the impedance of the lines

\[ i_{\text{total}} \]

\[ V_S \]

\[ V_L \]

\[ i_1 \]

\[ i_2 \]

\[ X_1 \]

\[ X_2 \]

\[ \Delta V \]
The „natural“ distribution may be rather inefficient, if $X_1$ and $X_2$ are extremely different. For example if $X_1 = 2X_2$: 

\[ \Delta V \]

\[ V_S \]

\[ V_L \]
Equalization of currents:

An additional voltage source must be introduced
Purpose and function of PSTs

This additional voltage source, perpendicular to the phase voltage, generates a „circulating“ current, increasing $\imath_1$ and decreasing $\imath_2$:
Purpose and function of PSTs

Another control need –

Power transfer between nodes with fixed voltage
Categories and types

Phase shifting transformers can be classified for different parameters:

- symmetrical – non symmetrical
- quadrature - non quadrature
- single core - two core
- single tank - two tank
Categories and types

**Non-symmetrical single core solution:**

- Delta-connected exciting winding,
- One tap winding
- One LTC
- One reversing change-over switch

**Reversing switch operation is critical**

**Advantageous for small phase angle and rating**
Categories and types

**Symmetrical single core solution:**

- Delta-connected exciting winding
- Two tap windings
- Two tap changers
- Two advance retard switches

**Rating strongly limited by LTC**

**Load tap changers exposed to system disturbances**
Categories and types

**Alternative symmetrical option:**

- Hexagonal connection of exciting winding and tap winding
- One LTC
- Two ARS

**Delta- hexagonal design**

Often used for lower voltage level

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**Winding Scheme with Advance-Retard Switch:**

```
L1 S1 L2 S2 L3 S3
```

Additional Impedance

RW

EW

**Phasor Diagram:**
Categories and types

Classic solution:

- Symmetrical two core design
- Series unit and exciting unit
- One LTC

Phase Shifting Transformer (PAR)

Widely used in USA
Operational considerations

**Phase shifting transformers in Operation:**

Variation of load voltage due to load current, ohmic components neglected

\[
V_{L0} + jX_{PST}i_L
\]

\[
V_{L0} + V_{PST} = V_L = V_{PST} + jX_{PST}i_L = V_S
\]

\[
\Delta \alpha = \phi
\]

\[
\alpha
\]

\[
\varphi
\]
Operational considerations

Effect of load on effective phase angle

![Graph showing effect of load on effective phase angle]
Operational considerations

For a given phase shift under load, design optimization is necessary:

- Impedance as low as possible, minimum value determined by short circuit requirements
- With lower impedance, no load phase angle can be reduced
- Lower no load phase angle means lower design rating, lower weight, lower cost.
Purpose and function of PSTs

Power needed to reach a certain displacement in phase angle

\[ P_{\text{alpha}} = 2 \times P_{\text{thr}} \times \sin \frac{\alpha}{2} \]

Is proportional to the throughput power and almost proportional to the phase angle.

- \( P_{\text{alpha}} \): rating of the series winding resp. phase shifting power (MVA)
- \( P_{\text{thr}} \): throughput power (MVA)
- \( \alpha \): no-load phase angle (degree)
**Tap changer application**

- PST’s can be designed with fixed or variable phase angle. For a variable phase angle design, a load tap changer (LTC) and a regulating winding is required.
- In general, the regulating winding and therefore the LTC must be designed for the **maximum design rating** of the PST.
- The maximum regulating capacity (switching capacity per step times the number of steps) is limited by the capacity of available tap changers.
Tap changer application

**Maximum throughput rating** $P_{\text{max}}$ **versus maximum regulating capacity** $R$

![Graph showing the relationship between maximum throughput rating $P_{\text{max}}$ and maximum regulating capacity $R$. The graph compares three configurations: Single core, with two tap changers; Single core, with hexagonal winding connection; and Dual core, with series and exciting unit.](Image)
Tap changer application

Throughput power versus no-load phase angle
step capacity 5000 - 6000 kVA, +/32 steps

The graph shows the relationship between throughput power (MVA) and no-load phase angle (degrees) for different step capacities (5500kVA, 5000kVA, 6000kVA) with 32 steps.
Operational considerations

**Power transformer**

Flux distribution at rated load, \( \cos \varphi \sim 1 \)
Testing

Testing phase shifting transformers:

Specific requirements:

Heat run
- PST fully assembled
- minimized deviation of loss distribution during short circuit condition
- access to all windings for resistance measurement

Induced voltage test
- PST fully assembled
- tests at zero and maximum phase shift
Testing

Heat run test:

Temporary bushings inserted at all connections between series and exciting unit

For resistance measurement, all these connections can be opened
Design consideration - Heat run test settings

Note difference in loss distribution for nominal operation vs. condition for heat run test

<table>
<thead>
<tr>
<th>No Load Losses (kW)</th>
<th>α = 0</th>
<th>α = maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Series Unit</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>Exciting Unit</td>
<td>100</td>
<td>70</td>
</tr>
<tr>
<td>Load Losses (kW)</td>
<td>α = 0</td>
<td>α = maximum</td>
</tr>
<tr>
<td>Series Unit</td>
<td>400</td>
<td>400</td>
</tr>
<tr>
<td>Exciting Unit</td>
<td>0</td>
<td>400</td>
</tr>
<tr>
<td>Total Losses (kW)</td>
<td>α = 0</td>
<td>α = maximum</td>
</tr>
<tr>
<td>Series Unit</td>
<td>400</td>
<td>500</td>
</tr>
<tr>
<td>Exciting Unit</td>
<td>100</td>
<td>470</td>
</tr>
</tbody>
</table>
Induced voltage test:

Temporary bushings are connected to the regulating winding
Application of an additional step-up transformer is avoided by proper tap selection
Operational considerations

**Bypass breaker considerations**

- Due to the PST’s impedance, inserting the PST with phase angle zero normally reduces the load flow.
- A minimum advance phase angle is necessary to restore the original load flow condition.
- Therefore, by-passing the PST might be advantageous in certain conditions.
- On the other hand, lightning strikes can also appear with the PST by-passed.
- Internal stresses have to be investigated carefully for this condition.
Testing

**Lightning impulse test:**

**Standard LI test:**

![Diagram of Standard LI test]

**Special LI test:**

![Diagram of Special LI test]

Only the primary windings of one phase are shown.

Recommended test if by-pass breaker is provided - at least for tap position zero (0°).
Lightning impulse stresses in the series winding

Applied voltage and typical wave shape of voltage at crossover during lightning impulse test with source and load side terminals connected.
Phase shifting transformer protection

In general, PST protection is similar to power transformers. There is one exception > differential relaying

In PST, difference between source & load current @ normal operating condition becomes too large for conventional differential protection.

Therefore, specific differential schemes for PST’s are required, different for single core and dual core designs.

CTs required for protection often located inside tank of the PST.

NOTE > protection scheme must be finalized @ design stage.
Differential protection scheme for dual core design (example)
Recent PST units

Phase Shifting Transformer

- 700 MVA, 230 kV, 60 Hz
- ±32° no load (± 24 Taps); 22.2° ..-41.8° load
- uk: 11.1% Tap 0; 17.4% Tap 24
- Noise Level < 74 dB(A) with fans

Classical design PST

- Two-tank design
- Two-core design
Recent PST units

Phase Shifting Transformer

- 800MVA, 230kV, 60Hz
- ±35° no load (± 32Taps); load 25.3°..-44.9°
- uk: 11.4% Tap 0 ; 17.6% Tap 32
- Noise Level < 77dB(A)

Classical design PST

Two-tank design
Two-core design
650 MVA, 525 kV, ±24°, Largest PSTs in world, (2) for SRP, Arizona and (2) for NPC, Nevada
LEAPS
Transmission One-Line

To SCE Serrano Sub
16.5 miles

Lee Lake Substation
12.7 miles

To SCE Valley Sub
30 miles

Lake Elsionre Pump House
16.5 miles

To SDG&E Talega Sub
10 miles

Camp Pendleton Substation

To SG&E Escondido Sub
37 miles

500 kV
230 kV
115 kV
13.8 to 20 kV
Existing
New Additions
Further Additions

Siemens Energy, Inc.
Recent PST units

**Phase Shifting Transformer**

- 300 MVA, 138 kV, 60 Hz
- $\pm 25.0^\circ$ at no load ($\pm 16$ taps);
- $14.4^\circ$ at rated load - extreme advance
- $-5.4^\circ$ at rated load - mid tap
- $-35.6^\circ$ at rated load - extreme retard
- $u_k$: 9.5% Tap 0; 18.6% Tap 16
- Noise level < 70 dB(A)

**Classical design PST**

- Single-tank design
- Two-core design
Recent PST units

Phase Shifting Transformer

- 1200MVA, 400kV, 50Hz
- ± 24° no load (±16 taps);
- 16.6° at rated load - extreme advance
- -5.3° at rated load - mid tap (0)
- -31.4° at rated load - extreme retard
- uk: 9.25% Tap 0; 13.0% Tap 32
- Noise power level < 80 dB(A) - sound house

Classical design PST

Two-tank design
Two-core design
Phase shifting transformers >

- Look like normal power transformers
- Manufactured using the same technology

However, several special aspects only in PST’s

PST issues appear in both design and testing.

Therefore special expertise required.
Conclusion

- The classical two-tank two-core solution:
  Offers greatest operational security @higher voltage
  This because LTC not directly exposed to system disturbances.

- The single-core solution offers economic advantages
  at lower system voltage levels (and lower MVA).
Thank you!

Questions?