Phase Shifter Application Workshop

Siemens Energy, Inc.

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Phase Shifter Application Workshop

Phase Shifting Transformers – Principles, Design Aspects and Operation

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Purpose and function of PSTs

Power flow in power systems may need control, due to

- technical reasons (e.g. line overloading)
- economical reasons (e.g. committed power transfer at network node)

The need for power flow control is becoming more common, due to deregulation effects

This control can be achieved with a Phase Shifting Transformer (PST)
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.
The “natural“ distribution may be rather inefficient, if $X_1$ and $X_2$ are extremely different. For example if $X_1 = 2X_2$: 
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 $i_1$ and decreasing $i_2$:
Another control need –

Power transfer between nodes with fixed voltage
Purpose and function of PSTs

Phase Shifting Transformer between 2 system nodes

\[ \Delta V = I_2 \cdot j(X_{PST} + X_{Line}) \]

\[ V_1 = V_S \]

\[ \Delta I_{PST} \]

\[ V_{L0} \]

\[ V_L \]

\[ V_2 \]
Purpose and function of PSTs

Phase Shifting Transformer between two system nodes

\[ V_L = V_{PST} \]

\[ V_{L0} = V_1 = V_S \]

\[ I_2 \]
Phase shifting transformers can be classified for different parameters:

- symmetrical – non symmetrical
- quadrature - non quadrature
- single core - two core
- single tank - two tank
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
Alternative symmetrical option:

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

Delta-hexagonal design

Often used for lower voltage level
Categories and types

**Classic solution:**

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

**Phase Shifting Transformer (PAR)**

Widely used in USA

**Winding Arrangement and Connections:**

- Primary circuit: $L_1$, $S_1$, $S_3$, $L_2$, $L_3$
- Secondary (regulating) circuit: $a$, $b$, $c$

**Phasor Diagram:**

- $L_1$, $S_1$, $L_2$, $S_2$, $L_3$ Primary circuit
- $a$, $b$, $c$ Secondary (regulating) circuit
Operational considerations

Phase shifting transformers in Operation:

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

\[ V_{L0} \rightarrow jX_{PST}i_L \rightarrow V_{L} \rightarrow V_{PST} \rightarrow V_{S} \]

\[ \Delta \alpha = \phi \]

\[ i_L \]

\[ V_{L0} \]

\[ V_L \]

\[ V_{PST} \]

\[ V_{S} \]
Operational considerations

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

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

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

<table>
<thead>
<tr>
<th>P_{\text{alpha}}</th>
<th>rating of the series winding resp. phase shifting power (MVA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P_{\text{thr}}</td>
<td>throughput power (MVA)</td>
</tr>
<tr>
<td>\alpha</td>
<td>no-load phase angle (degree)</td>
</tr>
</tbody>
</table>
Tap changer limitations @Max MVA and regulating angle

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 maximum throughput rating $P_{\text{max}}$ versus maximum regulating capacity $R$. The graph displays three different configurations: Single core, with two tap changers; Single core, with hexagonal winding connection; and Dual core, with series and exciting unit. The x-axis represents the maximum phase angle (deg), and the y-axis represents $P_{\text{max}}/R$. The graph illustrates the relationship between $P_{\text{max}}/R$ and the maximum phase angle for each configuration.](image-url)
Tap changer application

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

![Graph showing throughput power versus no-load phase angle for different step capacities.](image-url)
Tap changer @Max MVA and regulating angle
Tap changer Application– depends on MVA & phase angle being switched

OLTC operations can range from 300,000 to 1.2M but might be lower on large OLTC models seeing large phase shifter duties.

Inspection intervals also depend on size of OLTC model.

For moderate step capacities (up to 3000kVA per phase), maintenance intervals can be up to 300,000 operations. For larger tap changer duty, inside reactors used to enforce equal current splitting & achieve up to 6000kVA per phase.
Tap changer limitations @Max MVA and regulating angle

**Tap changer maintenance intervals**

<table>
<thead>
<tr>
<th>On-load tap-changer</th>
<th>Transformer rated current</th>
<th>Number of tap-change operations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>without MR oil filter</td>
</tr>
<tr>
<td>R III 1200</td>
<td>up to 600 A, up to 1200 A</td>
<td>80 000</td>
</tr>
<tr>
<td>R I 1201</td>
<td>up to 600 A, up to 1200 A</td>
<td>80 000</td>
</tr>
<tr>
<td>R I 2002</td>
<td>up to 2000 A</td>
<td>40 000</td>
</tr>
<tr>
<td>R I 2402</td>
<td>up to 2400 A</td>
<td>40 000</td>
</tr>
<tr>
<td>R I 3000</td>
<td>up to 3000 A</td>
<td>40 000</td>
</tr>
<tr>
<td>R I 3600</td>
<td>up to 3600 A</td>
<td>40 000</td>
</tr>
</tbody>
</table>

*Table II* Inspection intervals for
- OLTC type R in star-point connection (Y)
If switching @maximum (rated) current, contacts will be replaced at approx 300K operations.

**Maintenance Intervals:**
After every 50,000 operations, the diverter switch contacts have to be exchanged between phases.

**Inspection:** Every 6 years or 50,000 operations whatever comes first.
First inspection: After 2 years or 20,000 operations.
Operational considerations

Special considerations for reverse load flow

The effective phase angle is increased, as is the voltage across the PST. This can cause over-excitation in the core of the PST!
Voltage across PST

Advance

\[ jX_{PST} \cdot i_L \]

\[ V_{L0}, V_L, V_{PST}, V_S \]

\[ \alpha, \Delta \alpha \]

Retard

\[ jX_{PST} \cdot i_L \]

\[ V_{PST}, V_L, V_{L0}, V_S \]

\[ \alpha, \Delta \alpha \]
Operational considerations

Power transformer

Flux distribution at rated load, $\cos \varphi \sim 1$
Operational considerations

PST
Single phase scheme and phasor diagram

3-phase connection

U_1

U_2

PST

U_1

U_2

U_Z

I

I

U_1

U_2
Operational considerations

Series transformer of a PST

Flux distribution at maximum angle, $\cos \varphi \sim 1$
Design consideration – Stray Flux in Series Winding

Ampere - turn balance in the series unit

Separation of ampere-turns into two components:

Series unit (one phase only):

Phasor diagram components

longitudinal transversal
Influence of the current phase shift on the magnetic stray flux

- The transversal current component creates additional stray flux
- Dependent on the arrangement of windings, this stray flux can
  - create additional eddy current losses in windings and steel structure
  - generate specific axial forces under short circuit condition
- Both effects have to be taken into account carefully
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
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></th>
<th>( \alpha = 0 )</th>
<th>( \alpha = \text{maximum} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Load Losses (kW)</td>
<td></td>
<td></td>
</tr>
<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></td>
<td></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></td>
<td></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 with S2 and L2 connections](image)

Special LI test:

![Diagram of Special LI test with S2 and L2 connections](image)

Source- and load-terminal connected

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.

CT’s 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**

- 700MVA, 230kV, 60Hz
- ±32° no load (± 24Taps); 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
- $\pm 35^\circ$ no load ($\pm 32$Taps); load $25.3^\circ$ ..-$44.9^\circ$
- $\text{uk}$: 11.4% Tap 0; 17.6% Tap 32
- Noise Level $< 77$dB(A)

**Classical design PST**

- Two-tank design
- Two-core design
650 MVA, 525 kV, ±24 deg, only 500kV PSTs in world, (2) for SRP, Arizona and (2) for NPC, Nevada
LEAPS
Transmission
One-Line

Lee Lake Substation

Camp Pendleton Substation

To SCE Serrano Sub
12.7 miles

To SCE Valley Sub
16.5 miles

Lake Elsionre Pump House

To SDG&E Talega Sub
16.5 miles

To SG&E Escondido Sub
12.7 miles

Existing

New Additions
Further Additions

500 kV
230 kV
115 kV
13.8 to 20 kV

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Recent PST units

**Phase Shifting Transformer**

- 300 MVA, 138 kV, 60 Hz
- $\pm 25.0^\circ$ at no load (± 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
- uk: 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**

- 575 MVA, 345 kV, 60 Hz
- \( \pm 37.8^\circ \) no load (\( \pm 16 \) taps);
- \( 27.6^\circ \) at rated load - extreme advance
- \( -4.9^\circ \) at rated load - mid tap
- \( -48.0^\circ \) at rated load - extreme retard
- uk: 8.5\% Tap 0 (NR); 17.94\% Tap 32 (16R)
- Noise level \(< 68 \) dB(A) @ 345 kV

**Classical design PST**

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

**Phase Shifting Transformer**

- 234 MVA, 138 kV, 60 Hz
- ±25° no load (± 16 taps)
- 14.4° at rated load - extreme advance
- -5.4° at rated load - mid tap (0)
- -35.6° at rated load - extreme retard
- uk: 7.62% Tap 0; 18.25% Tap 16
- Noise limit - Octave Band
  
  Limits M1-R New York
  
  125  250  500  1000  2000 [Hz]
  <74  <66  <59  <53  <47 [dB]

**Classical design PST**

**Single-tank design**

**Two-core design**
Recent PST units

**Phase Shifting Transformer**

- 150MVA, 138kV, 60Hz
- $\pm 32.9^\circ$ no load ($\pm 16$ taps)
- $30.1^\circ$ at rated load – tap 1
- $0.0^\circ$ at rated load – tap 17
- uk: 5% tap 1; 0% tap 17

**Delta hexagonal PST**

- Single-tank design
- Single-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).
Conclusion

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

Questions?

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