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Phase Shifter Application Workshop

Siemens Energy, Inc.

PJM Power Pool, March, 2015

Phase Shifting Transformers – Principles, Design Aspects and Operation

James McIver

SIEMENS Energy, Inc.
SIEMENS Transformers Austria, Weiz

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

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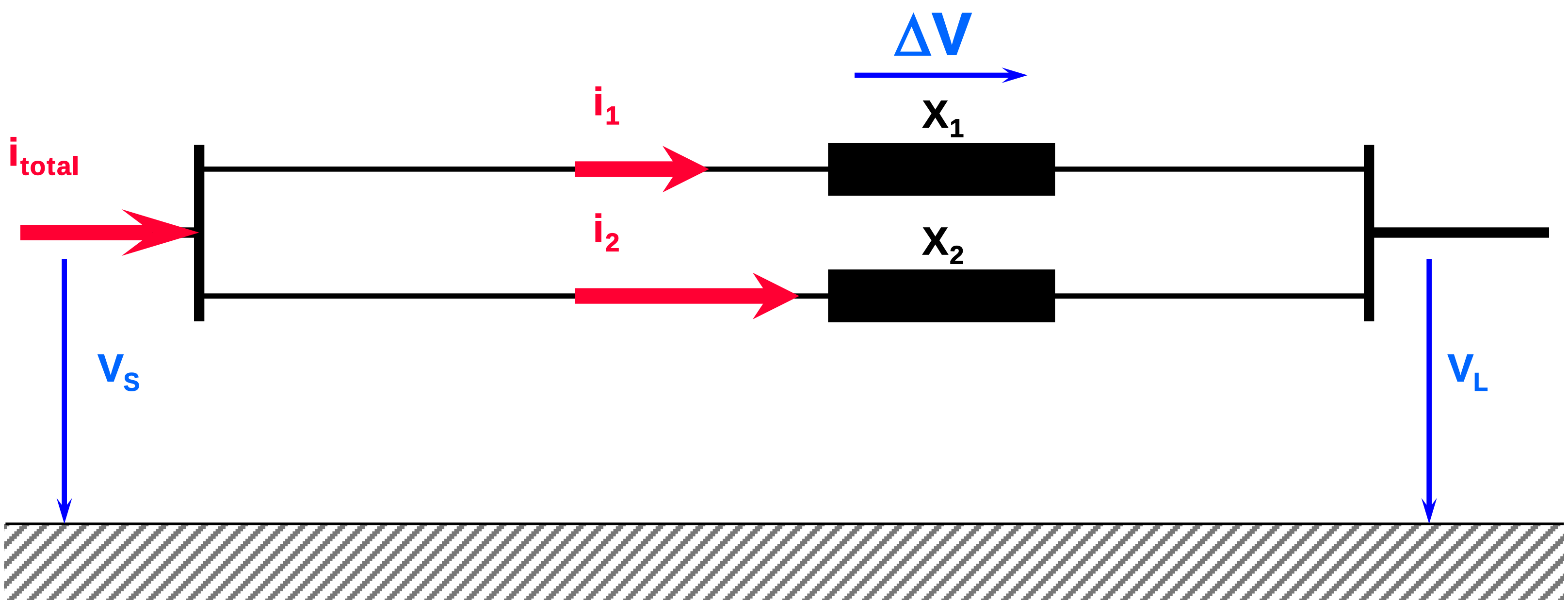
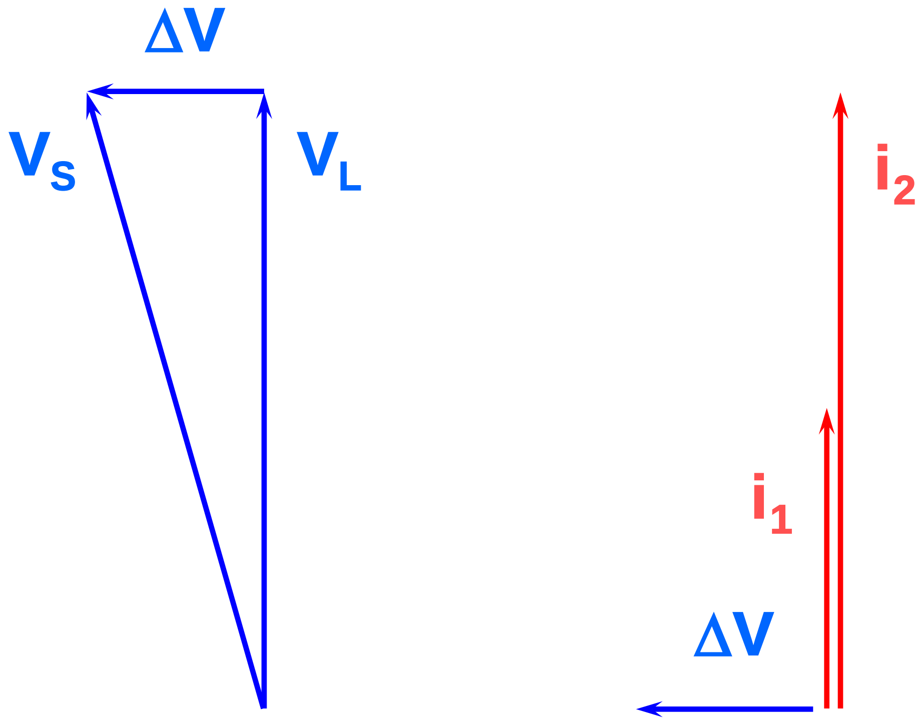
How does phase shift influence power flow?

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



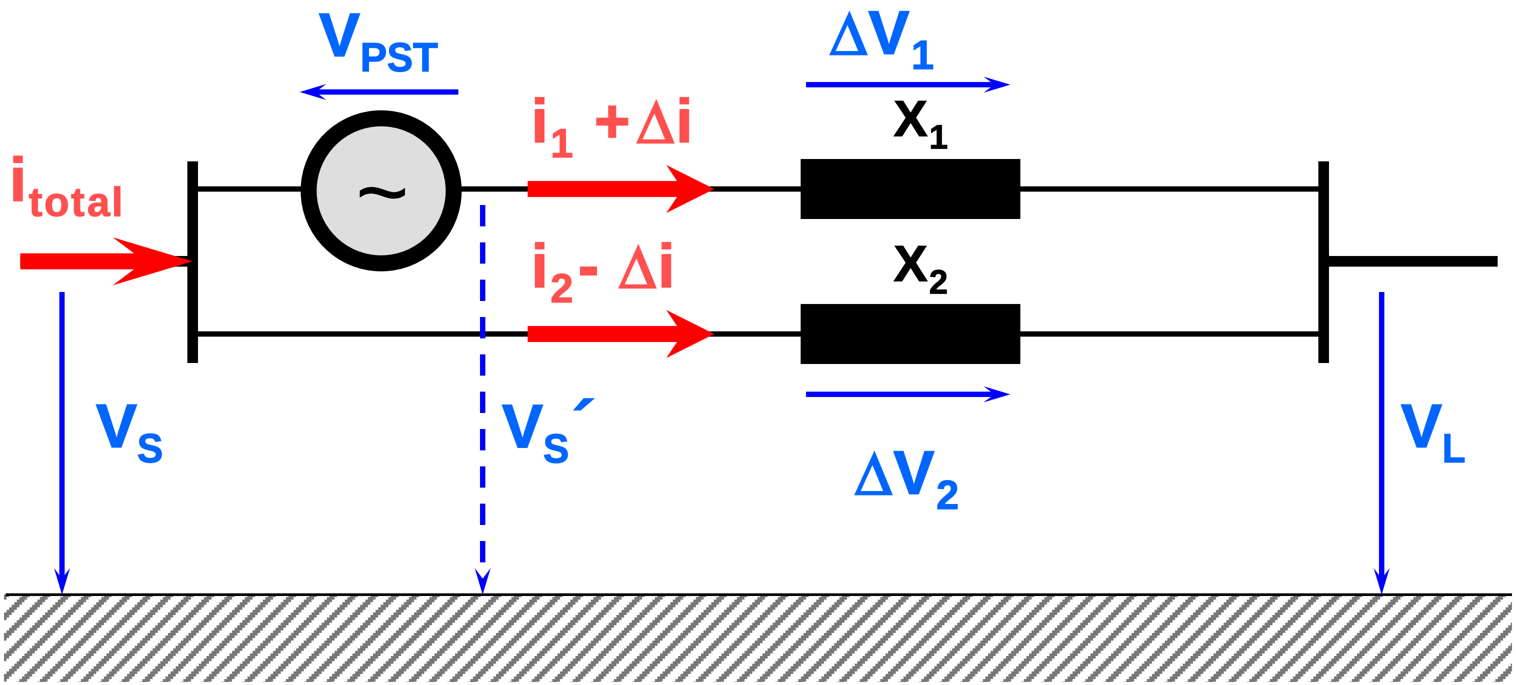
Purpose and function of PSTs

The „natural“ distribution may be rather inefficient, if X_1 and X_2 are extremely different.
For example if $X_1 = 2^*X_2$:



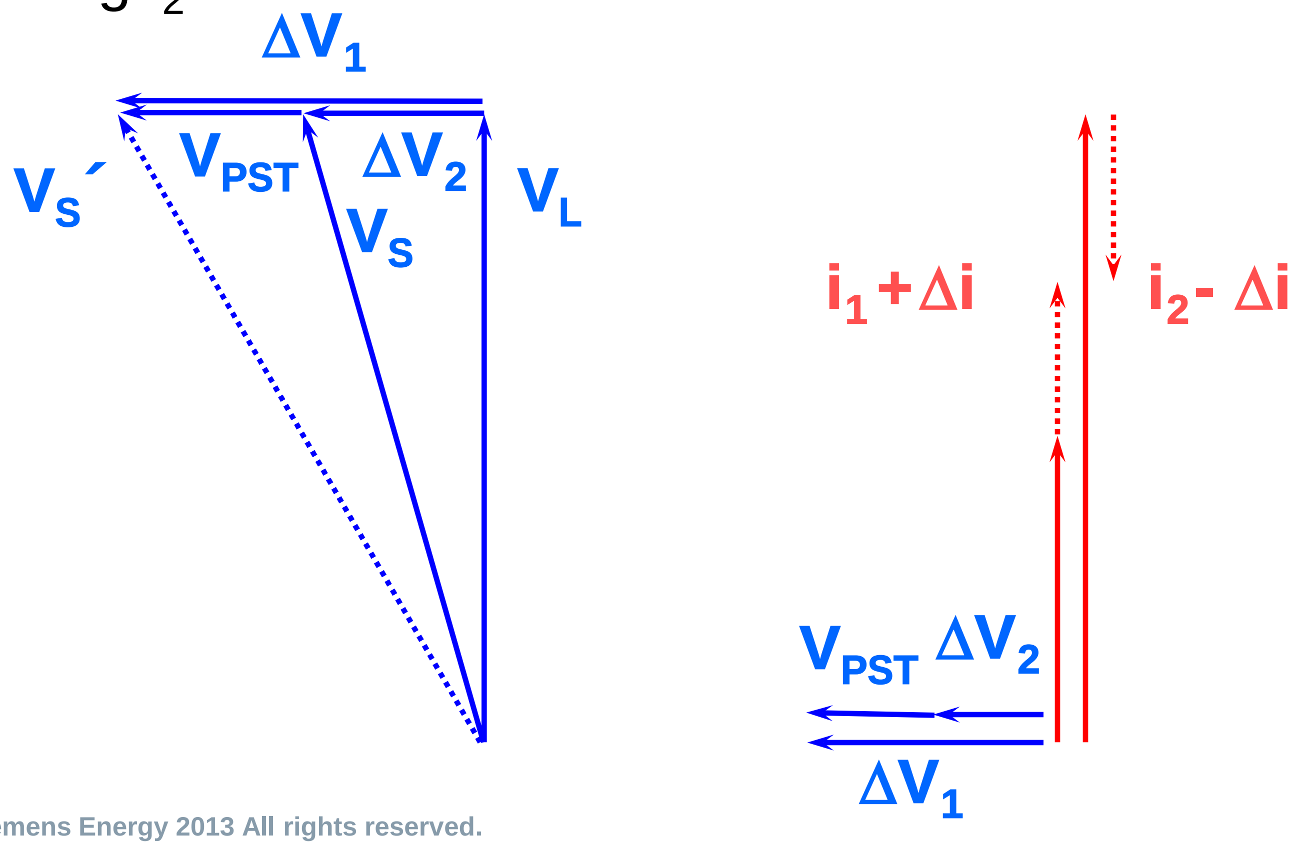
Equalization of currents:

An additional voltage source must be introduced



Purpose and function of PSTs

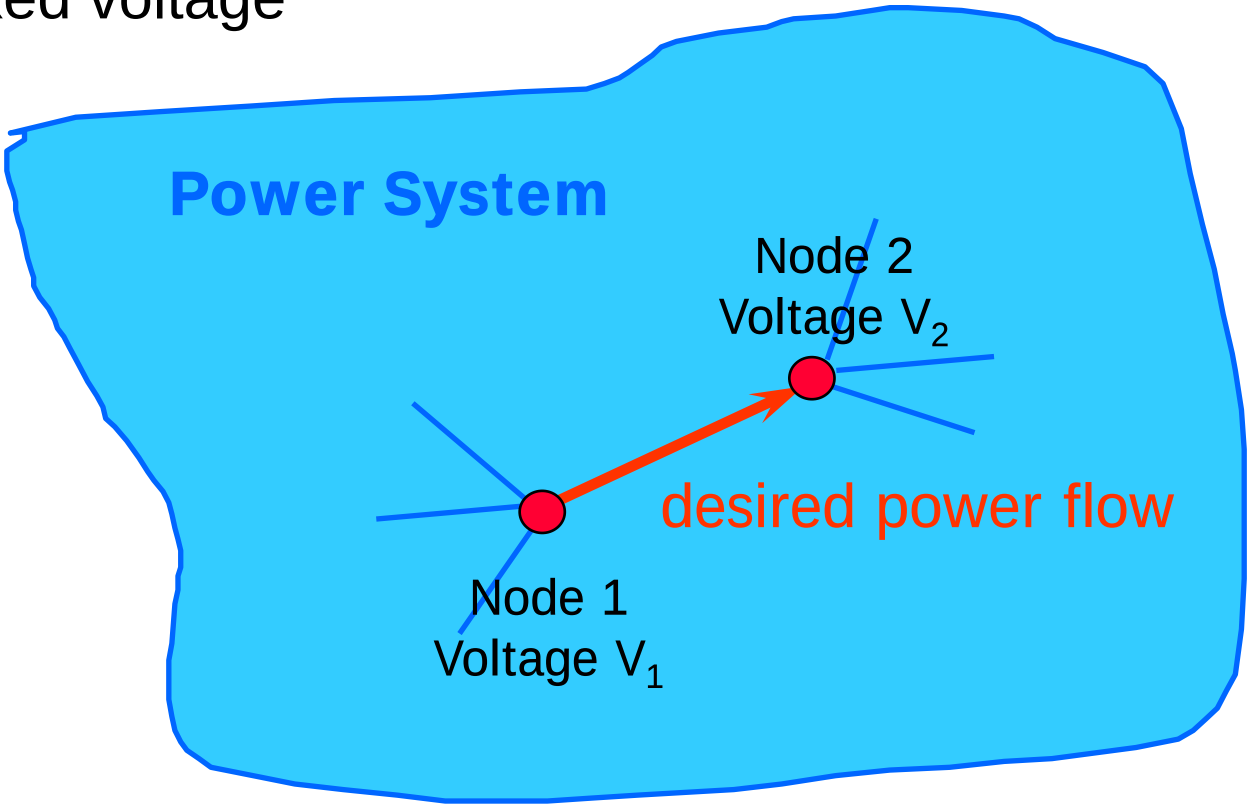
This additional voltage source, perpendicular to the phase voltage, generates a „circulating“ current, increasing i_1 and decreasing i_2:



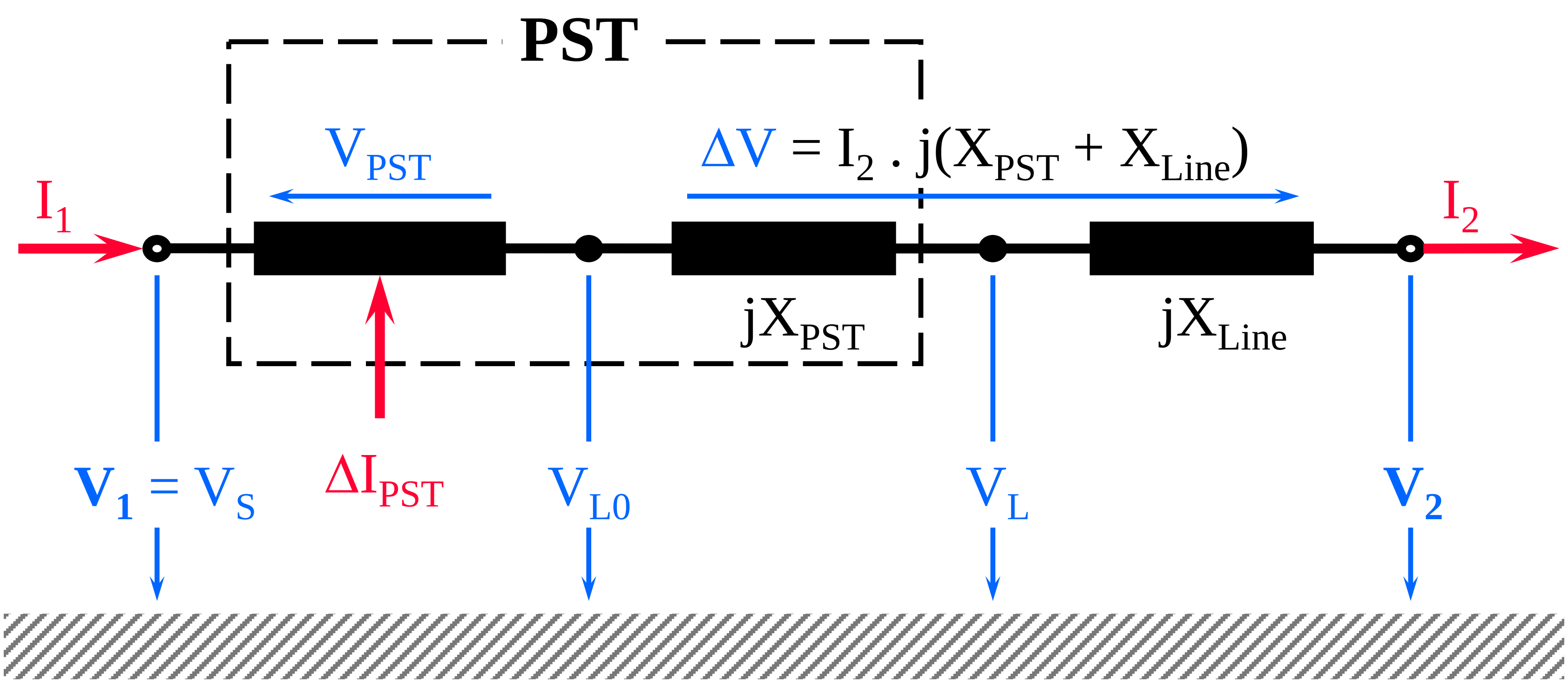
Purpose and function of PSTs

Another control need –

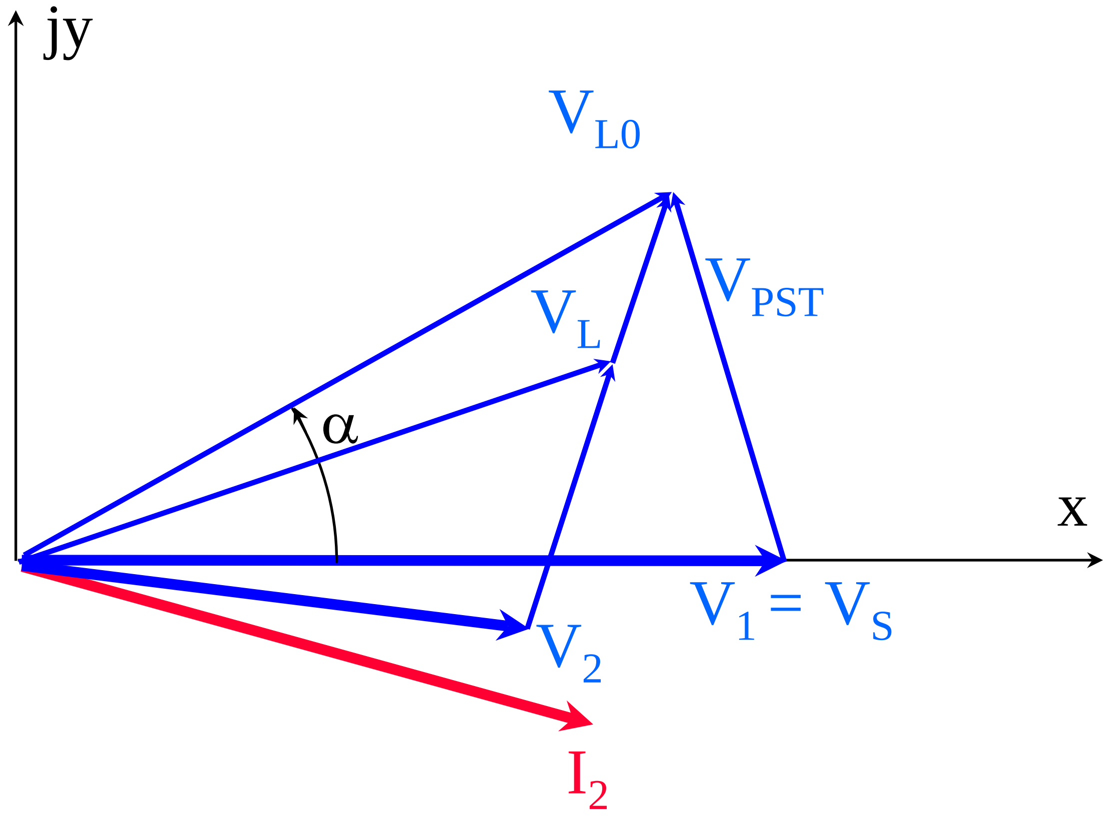
Power transfer between nodes
with fixed voltage



Phase Shifting Transformer between 2 system nodes



Phase Shifting Transformer between two system nodes



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

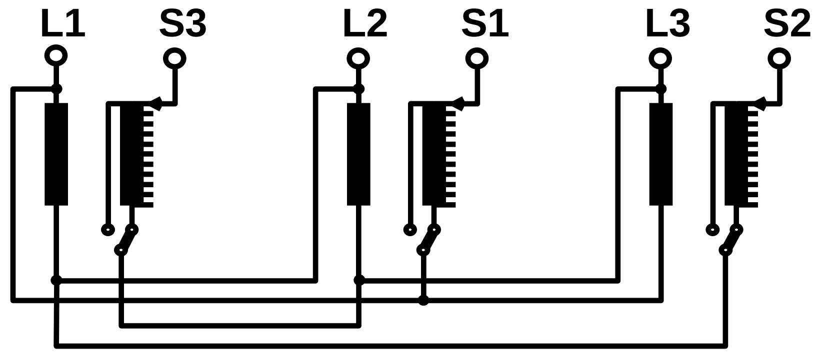
Non-symmetrical single core solution:

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

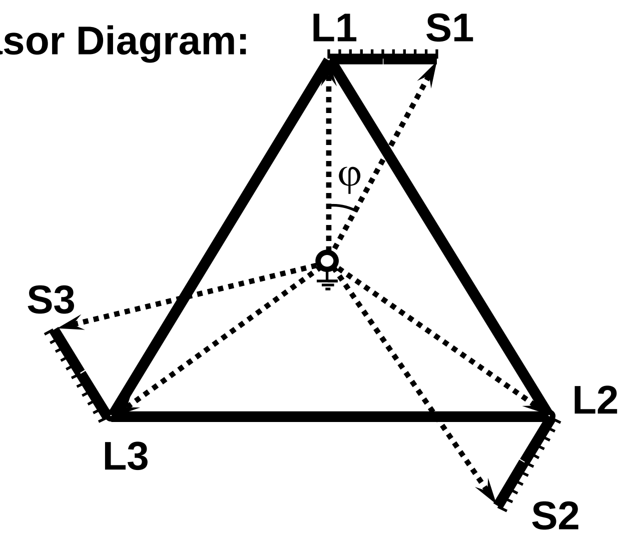
Reversing switch operation is critical

Advantageous for small phase angle and rating

Winding Connection with Reversing Switch:



Phasor Diagram:



Categories and types

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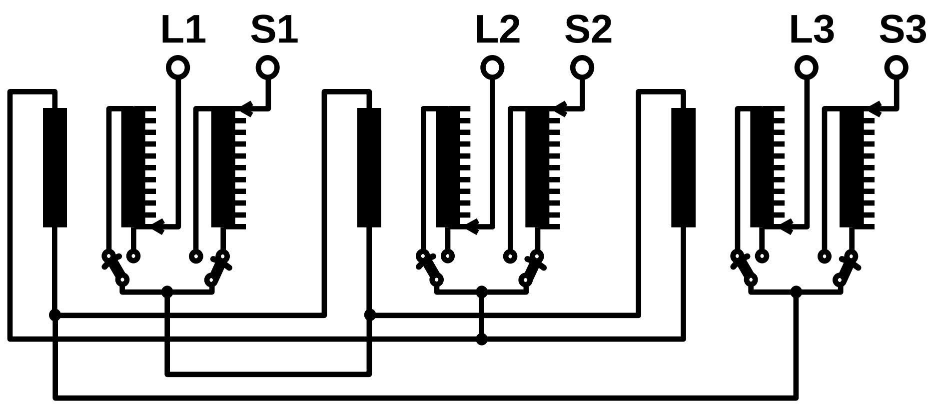
Symmetrical single core solution:

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

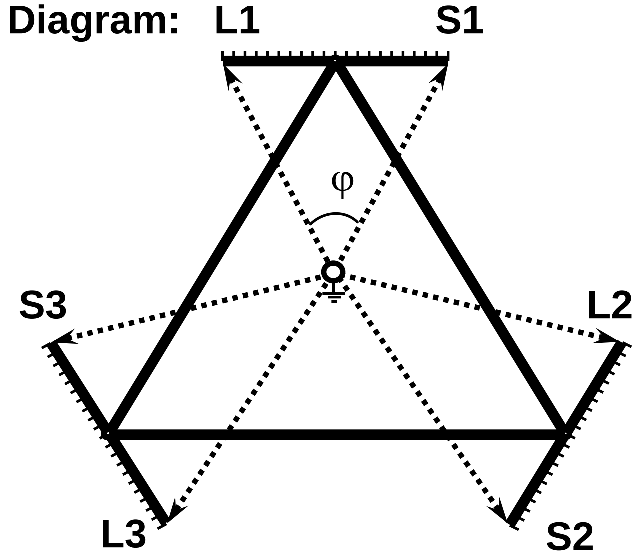
Rating strongly limited by LTC

Load tap changers exposed to system disturbances

Winding Connection with two ARS Switches:



Phasor Diagram:



Categories and types

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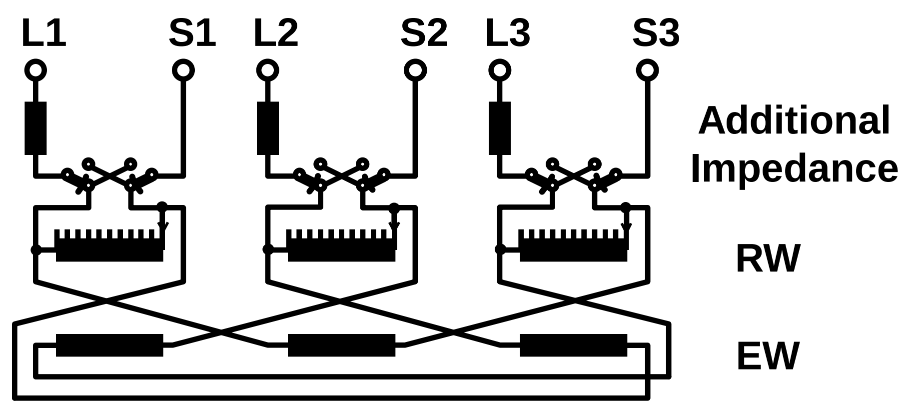
Alternative symmetrical option:

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

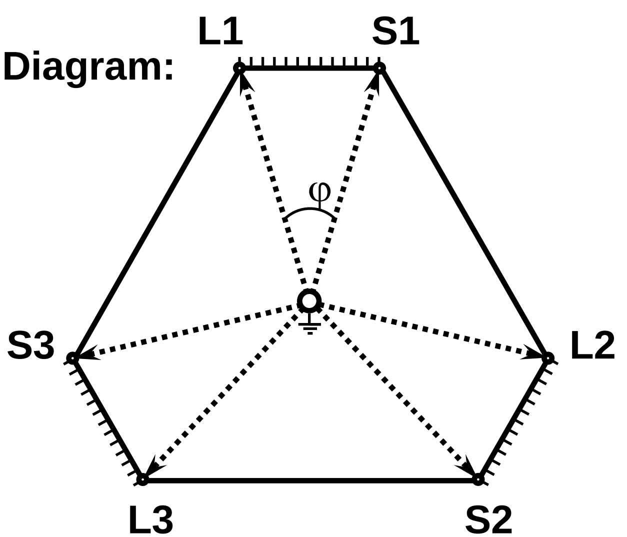
Delta- hexagonal design

Often used for lower voltage level

Winding Scheme with Advance-Retard Switch:



Phasor Diagram:



Categories and types

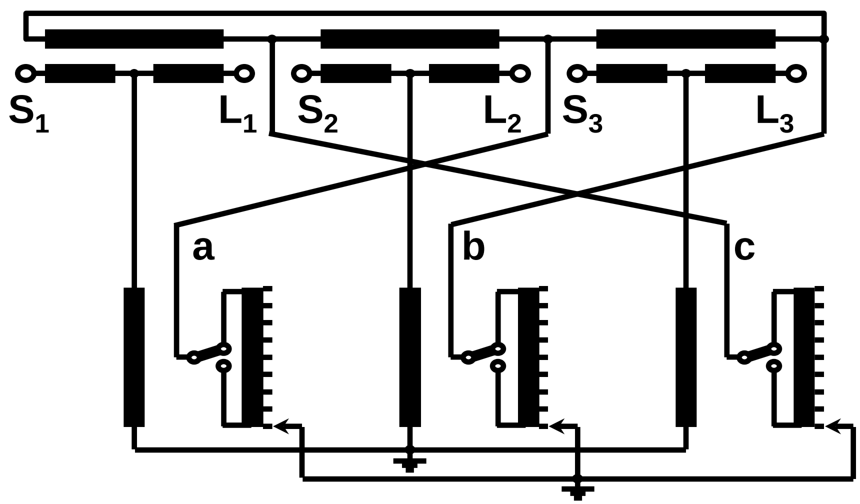
Classic solution:

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

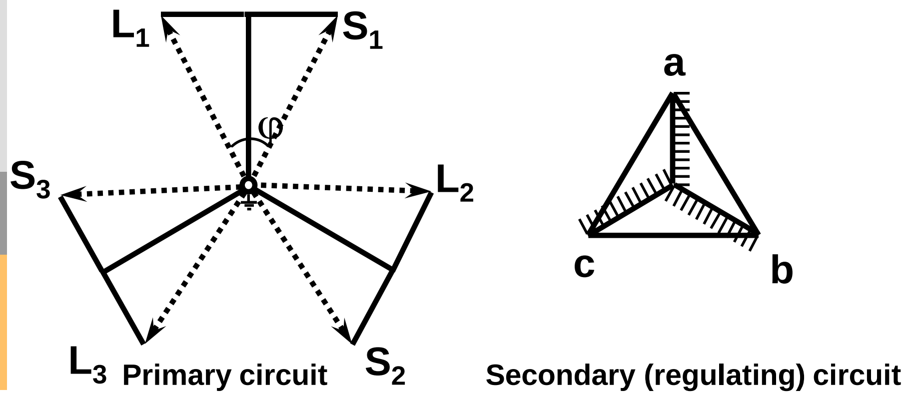
Phase Shifting Transformer (PAR)

Widely used in USA

Winding Arrangement and Connections:



Phasor Diagram:



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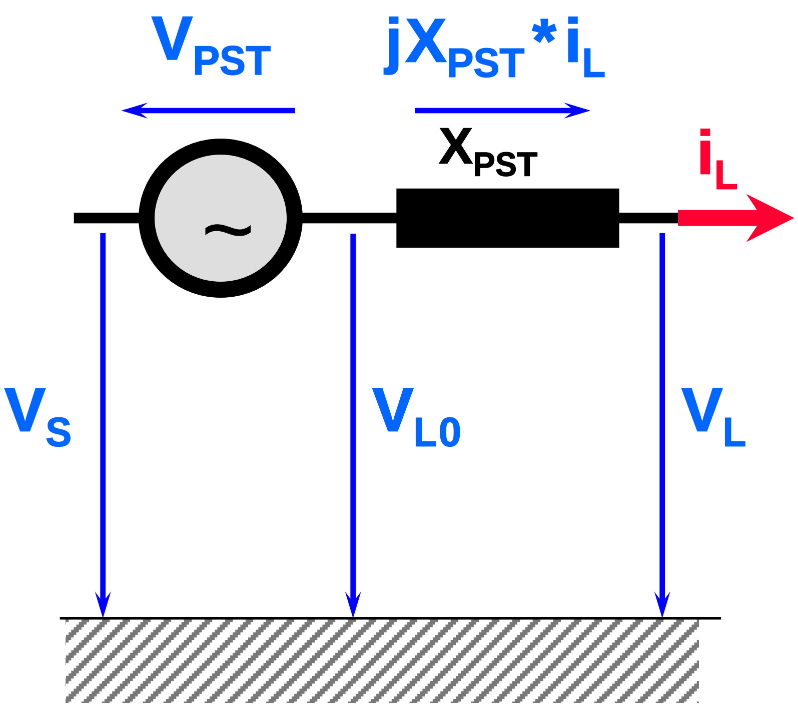
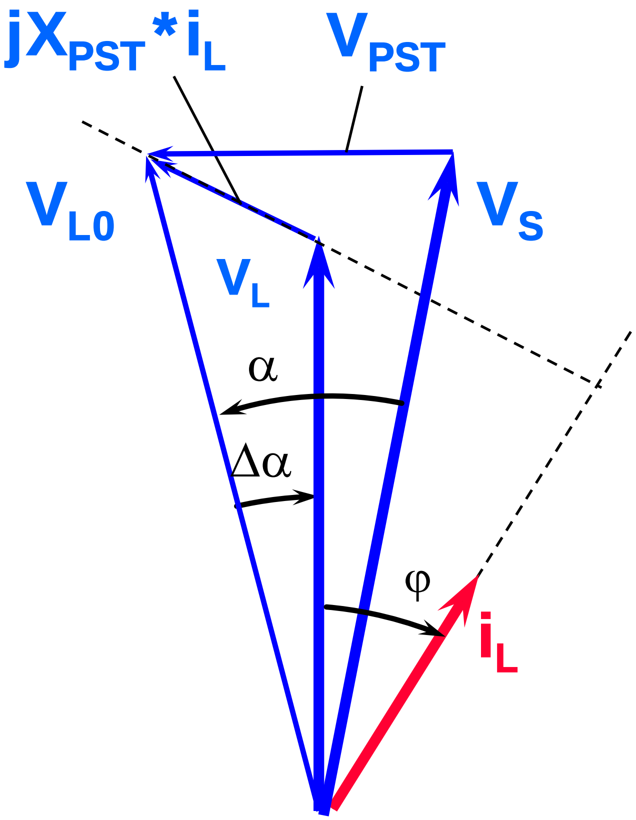
Phase shifting transformers in Operation:

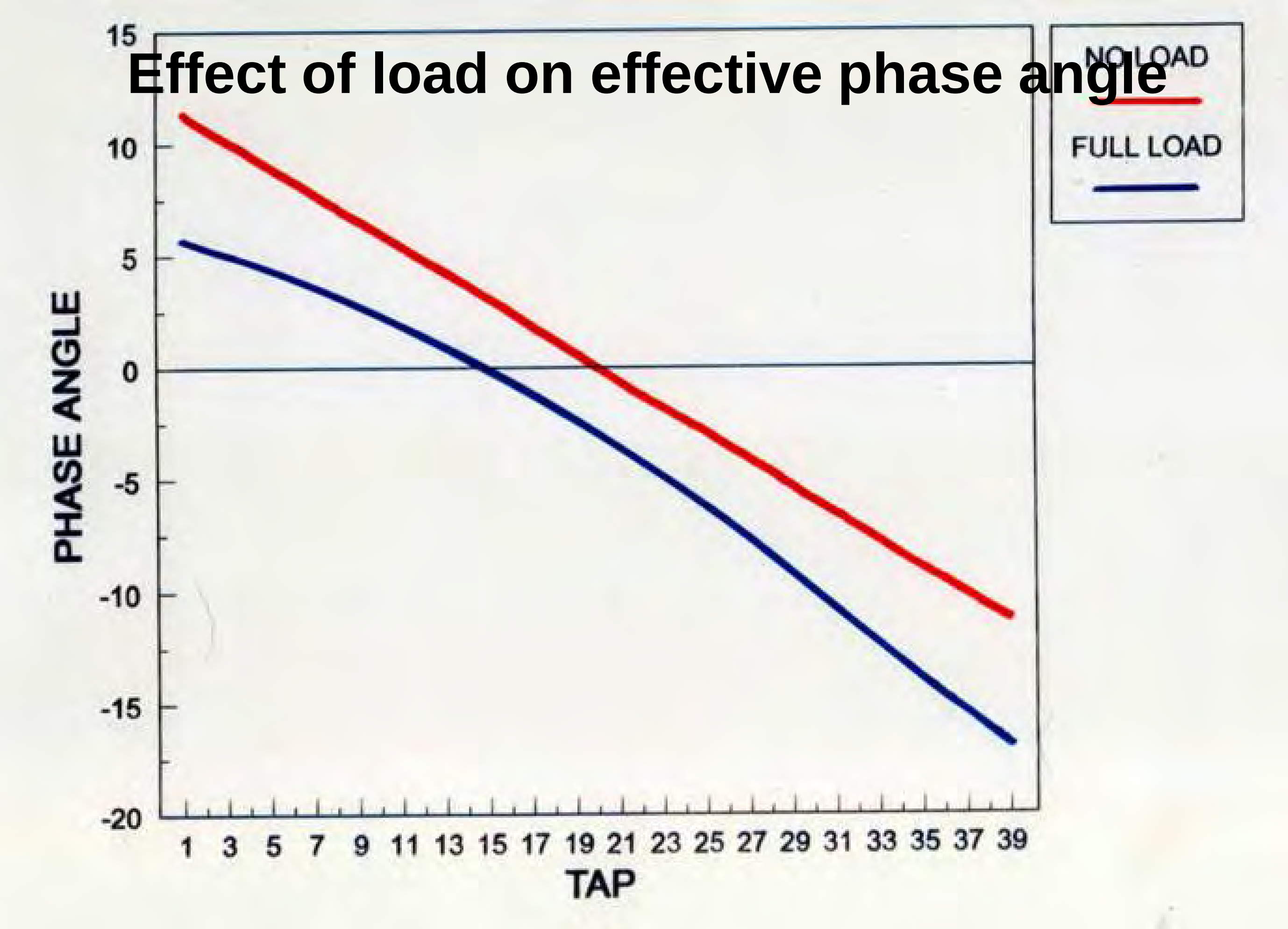
Variation of load voltage due to load current, ohmic components neglected





Operational considerations

Effect of load on effective phase angle



Operational considerations

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

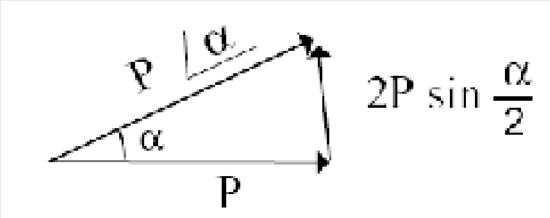
- Impedance as low as possible, minimum value determined by short circuit requirements
- With lower impedance, no load phase angle can be reduced
- Lower no load phase angle means lower design rating, lower weight, lower cost.

Purpose und function of PSTs

Power needed to reach a certain displacement in phase angle

Palpha = 2 x Pthr x sin alpha/2

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



Palpha	rating of the series winding resp. phase shifting power (MVA)
Pthr	throughput power (MVA)
alpha	no-load phase angle (degree)

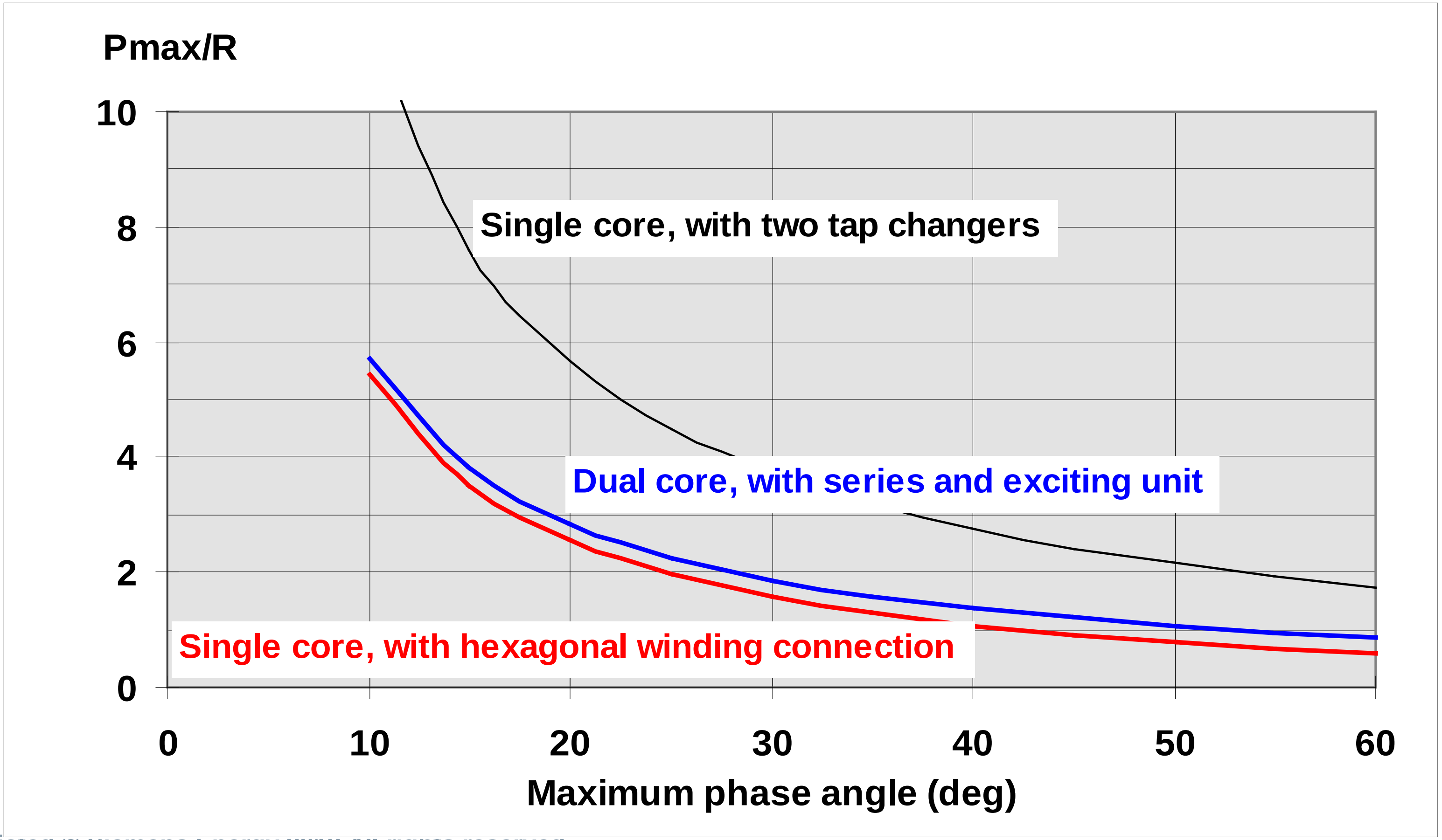
Tap changer limitations @Max MVA and regulating angle

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_{max}
versus maximum regulating capacity R



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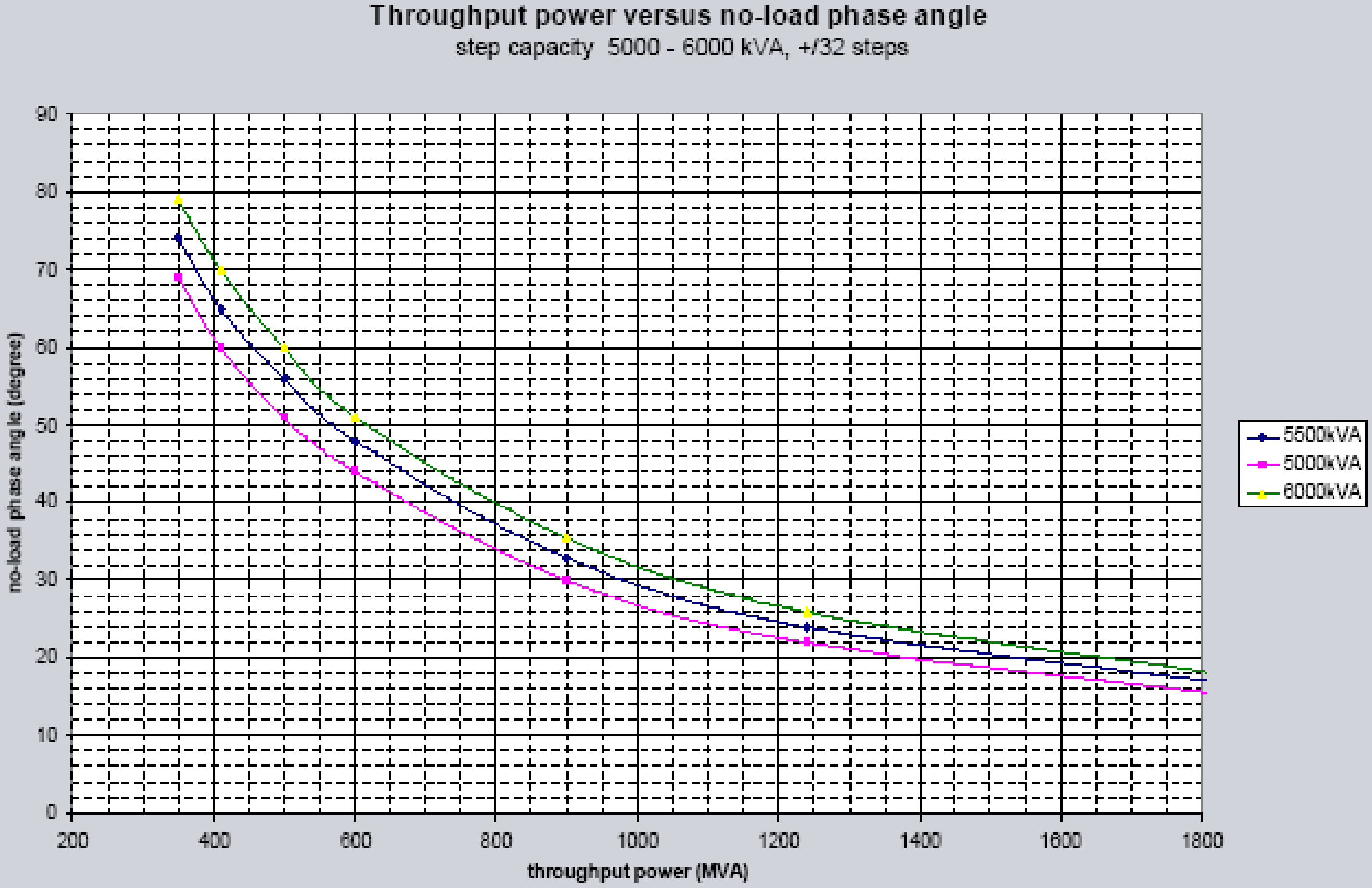
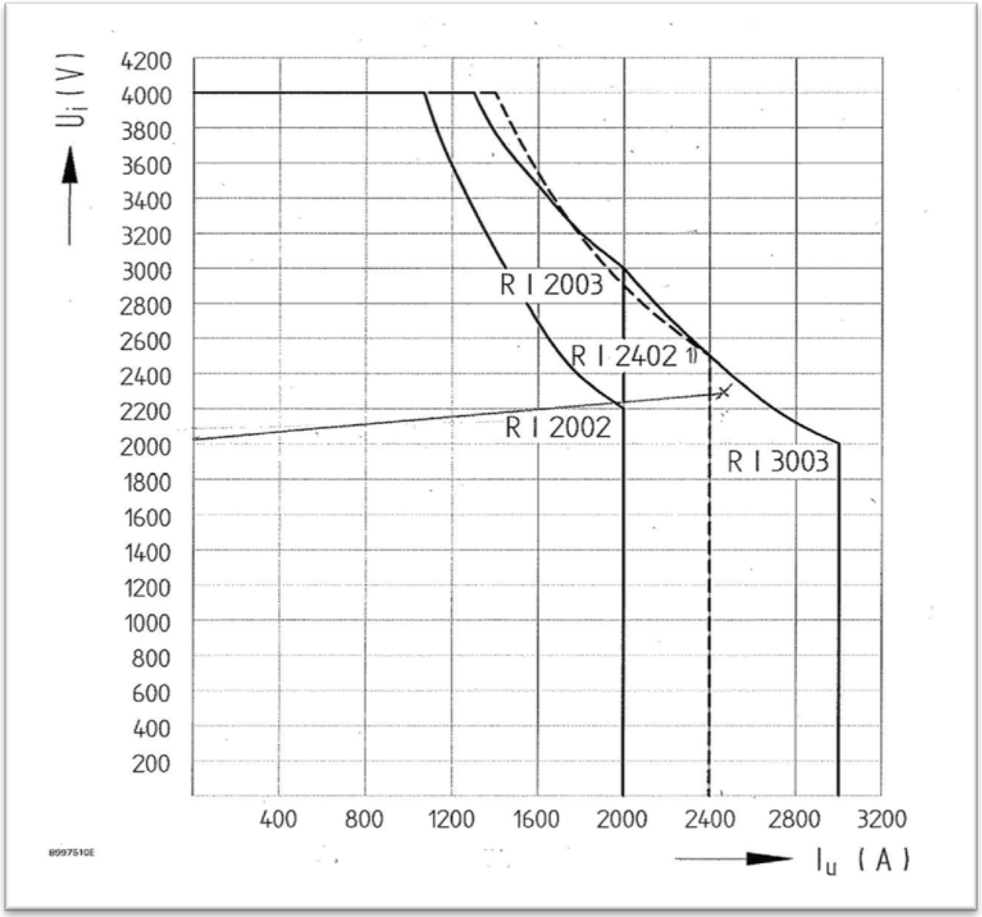
Tap changer application



Tap changer @Max MVA and regulating angle



Tap changer Application– depends on MVA & phase angle being switched

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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

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Tap changer maintenance intervals-

On-load tap-changer	Transformer rated current	Number of tap-change operations without MR oil filter	with oil filter
R III 1200	up to 600 A up to 1200 A	80 000 60 000	100 000 100 000
R I 1201	up to 600 A up to 1200 A	80 000 60 000	100 000 100 000
R I 2002	up to 2000 A	40 000	80 000
R I 2402	up to 2400 A	40 000	80 000
R I 3000	up to 3000 A	40 000	80 000
R I 3600	up to 3600 A	40 000	80 000

Table II Inspection intervals for
– OLTC type R in star-point connection (Y)

Tap changer operations @Max MVA and regulating angle

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If switching @maximum (rated) current, contacts will be replaced at approx 300K operations.

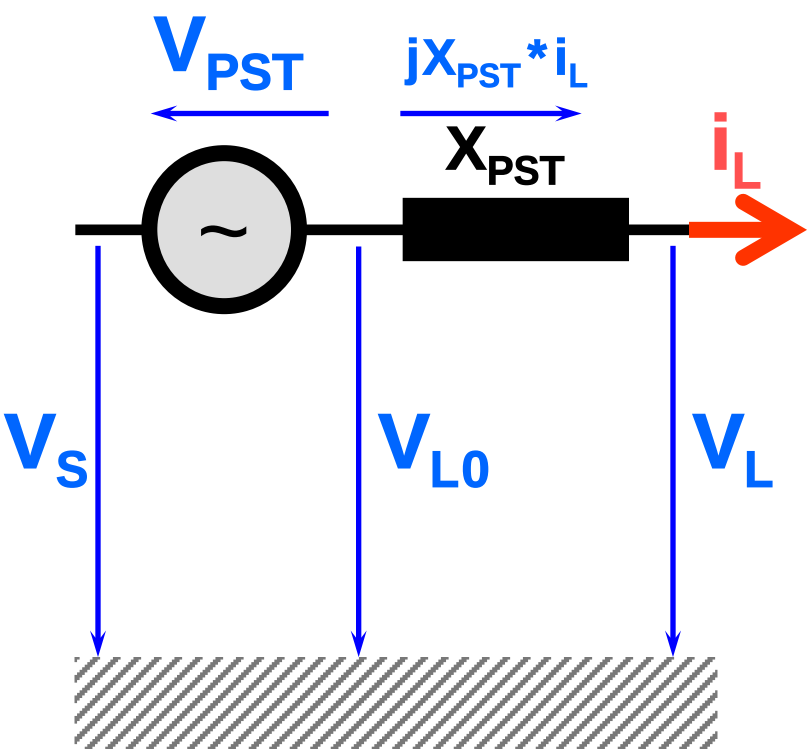
Maintenance Intervals:
After every 50,000 operations, the diverter switch contacts have to be exchanged between phases.

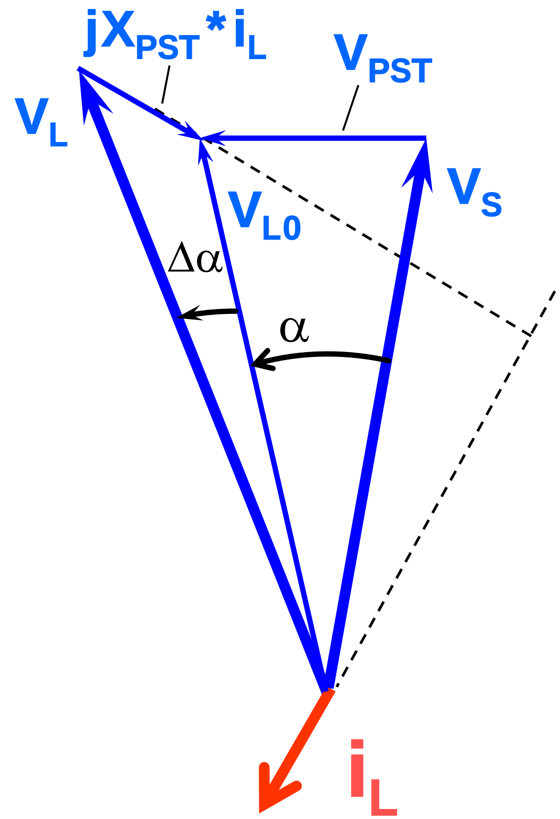
Inspection: Every 6 years or 50,000 operations whatever comes first.
First inspection: After 2 years or 20,000 operations.

Operational considerations

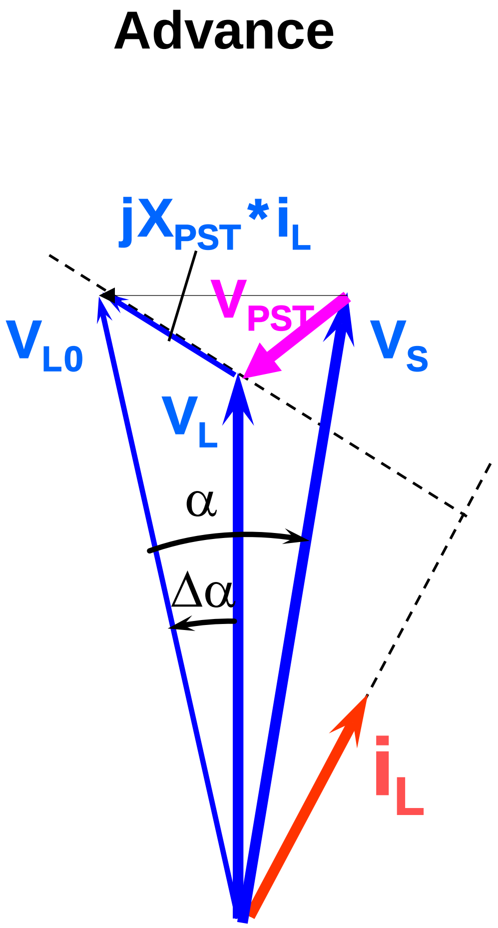
Special considerations for reverse load flow

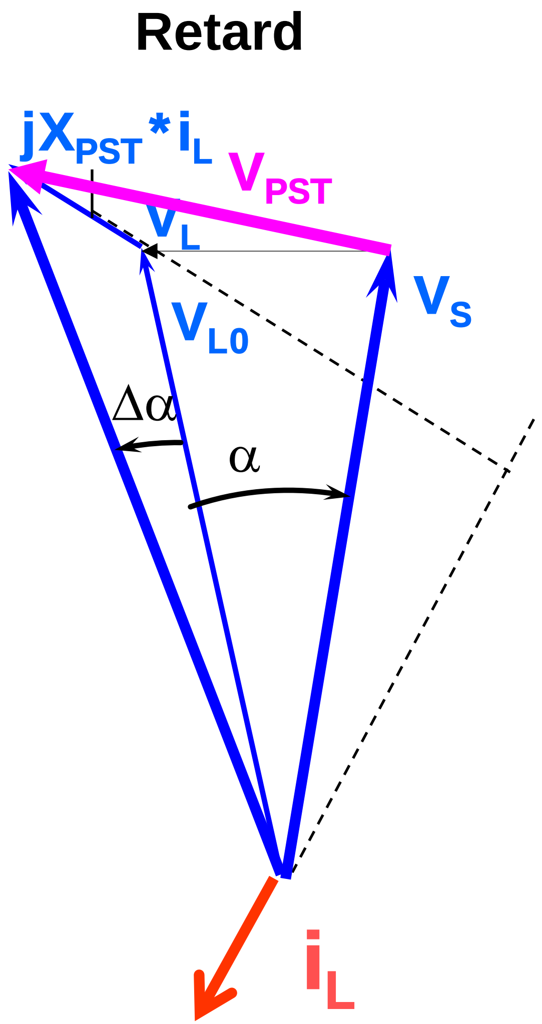
The effective phase angle is increased, as is the voltage across the PST. This can cause over-excitation in the core of the PST!





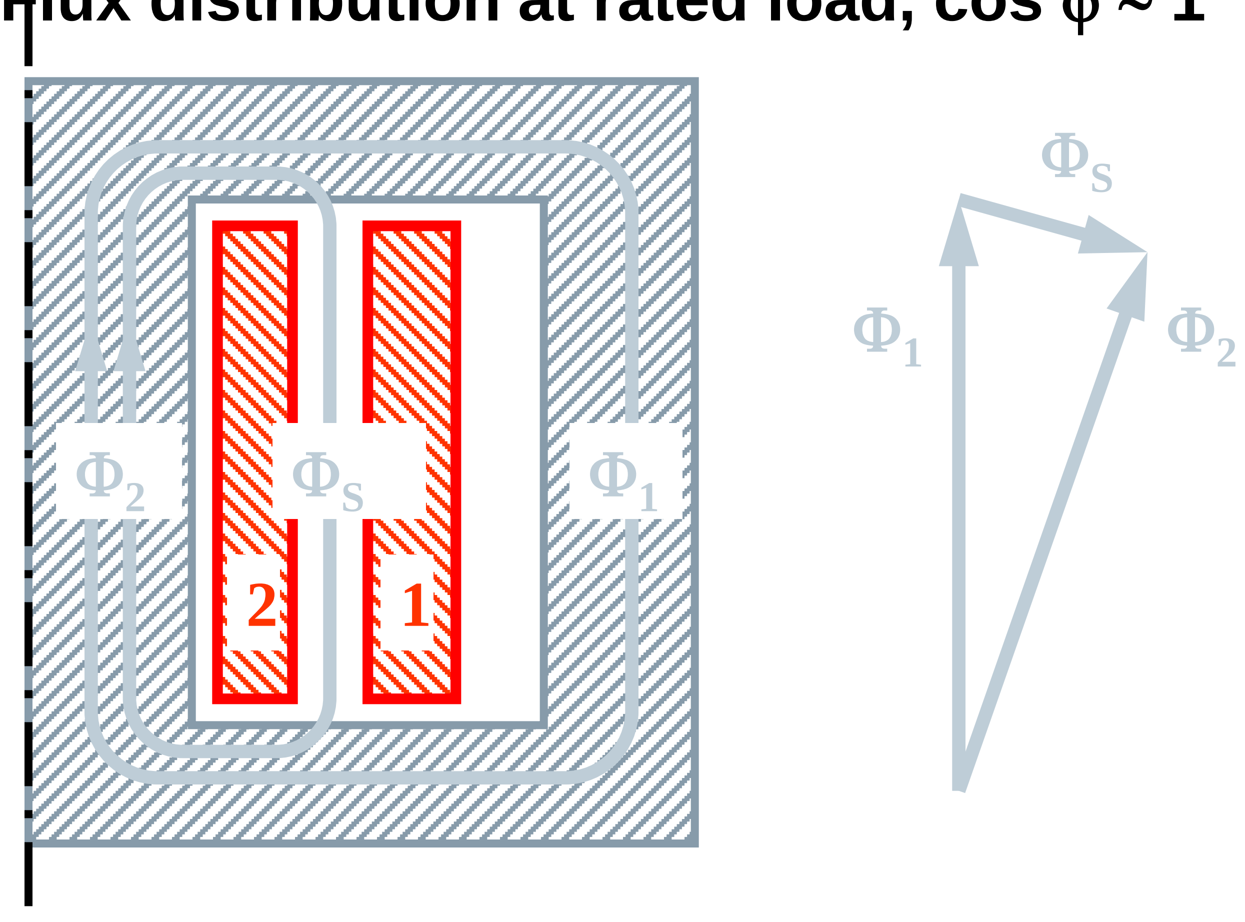
Voltage across PST





Power transformer

Flux distribution at rated load, cos φ ~ 1



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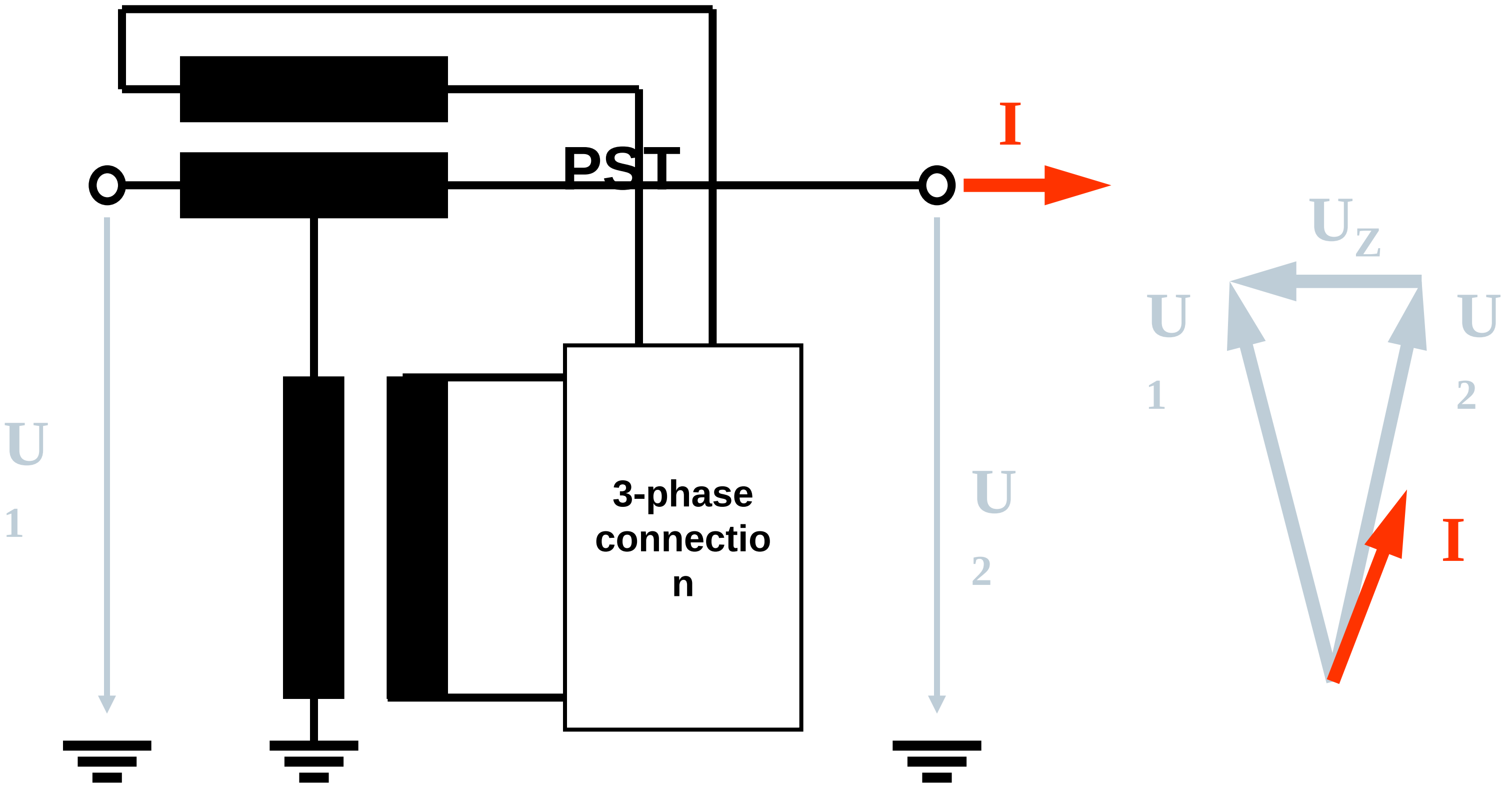
PST
Single phase scheme and phasor diagram



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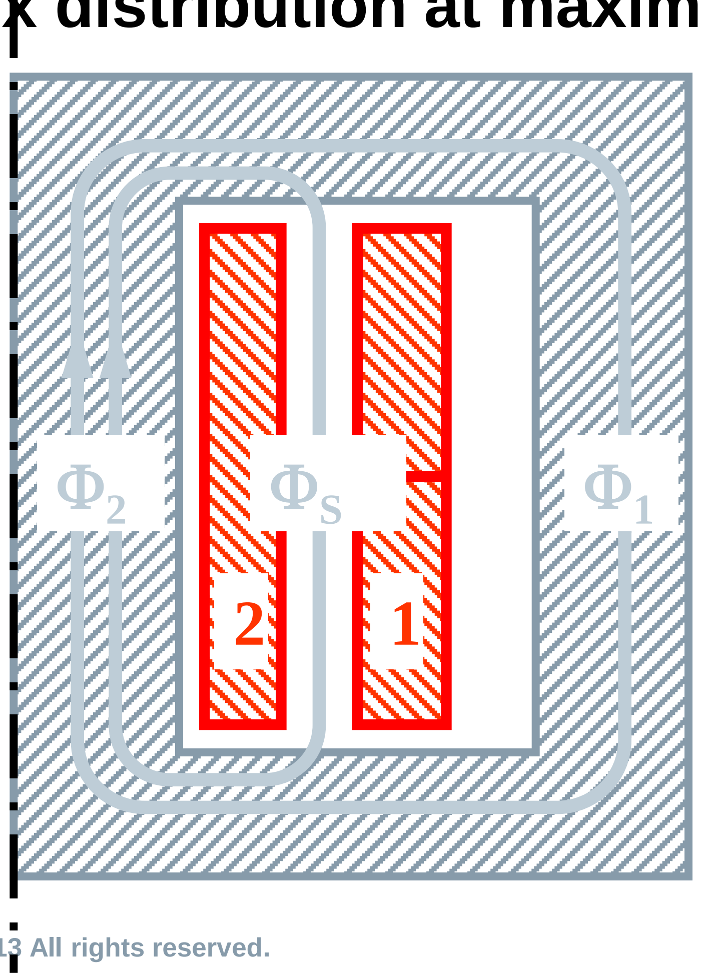
Series transformer of a PST

Flux distribution at maximum angle, cos φ ~ 1

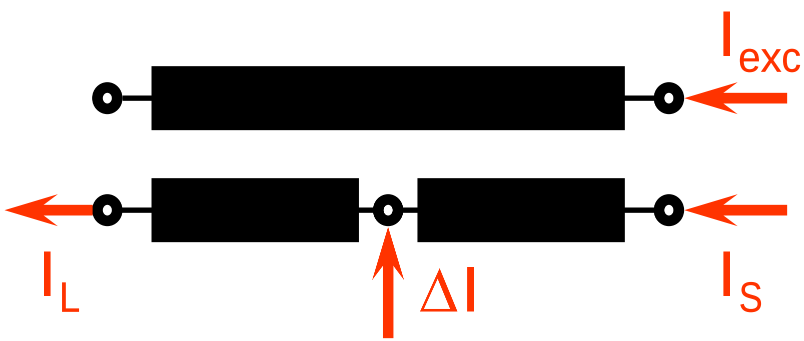


Design consideration – Stray Flux in Series Winding

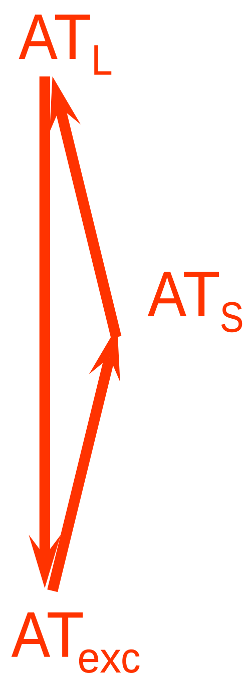
Ampere - turn balance in the series unit

Separation of ampere - turns into two components:

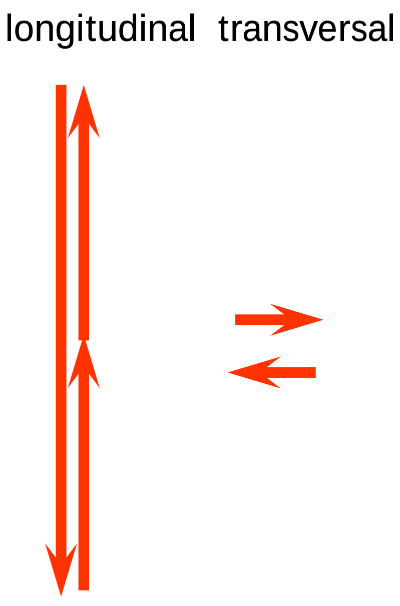
Series unit (one phase only):



Phasor diagram



components



Design consideration – Transverse Current

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

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Testing phase shifting transformers :

Specific requirements:

Heat run

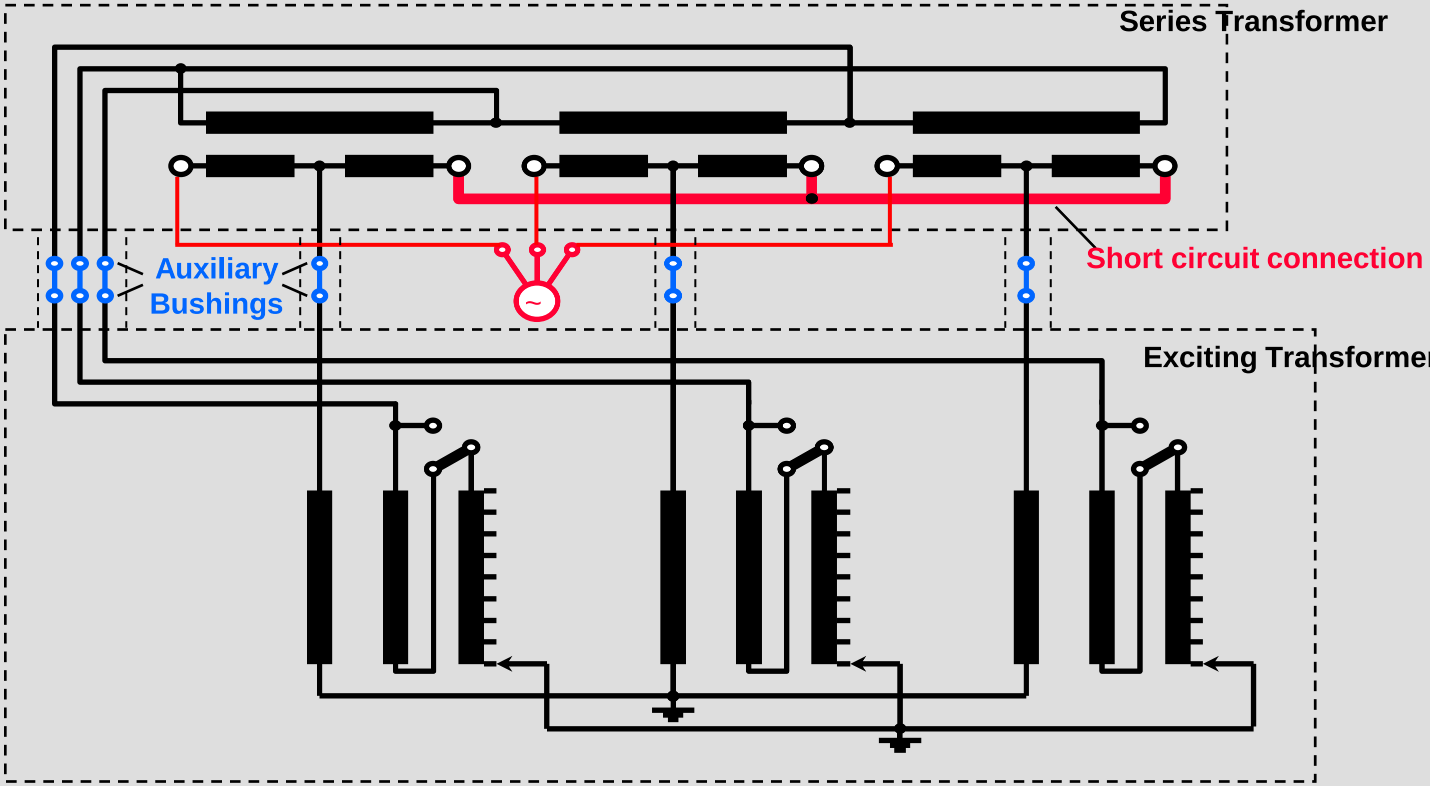
- PST fully assembled
- minimized deviation of loss distribution during short circuit condition
- access to all windings for resistance measurement

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

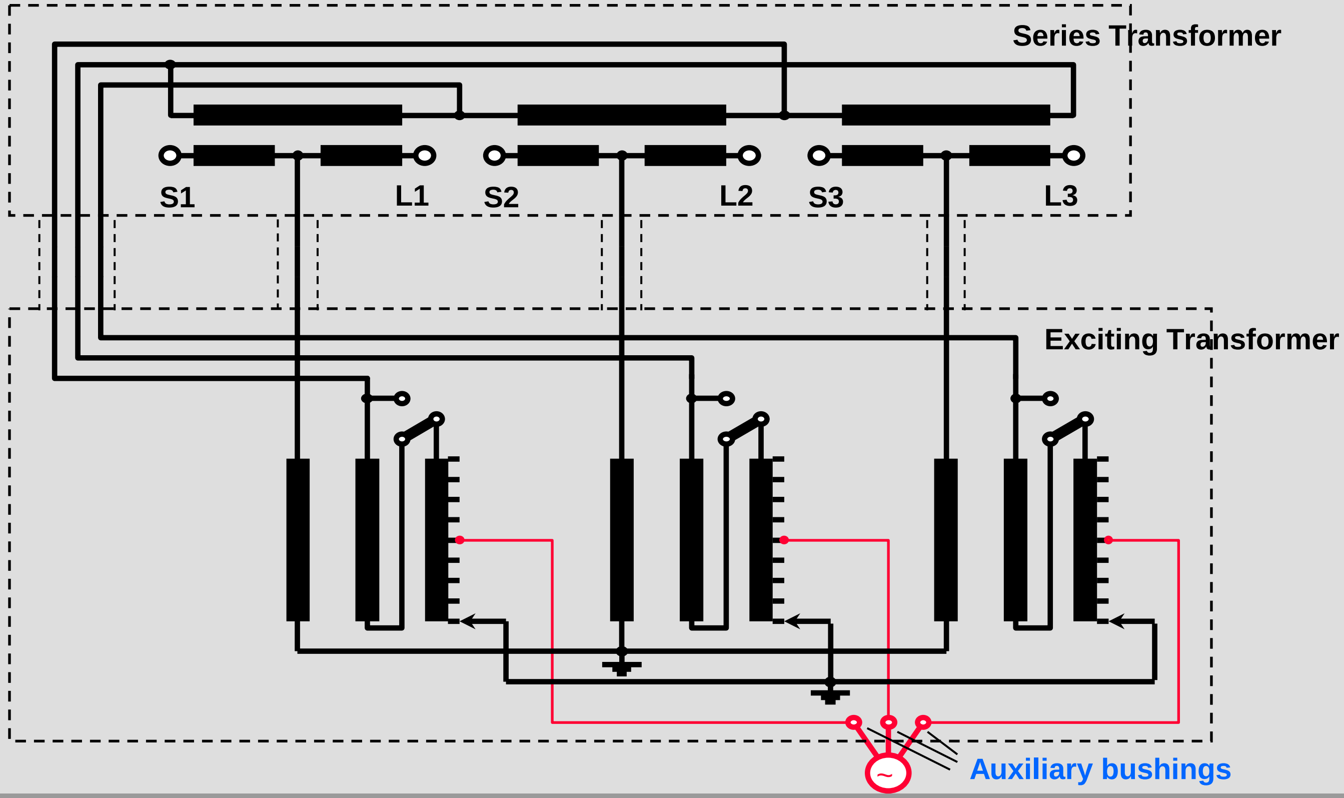
For resistance measurement, all these connections can be opened

Design consideration - Heat run test settings

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

No Load Losses (kW)	**α = 0**	**α = maximum**
Series Unit	0	100
Exciting Unit	100	70
Load Losses (kW)	**α = 0**	**α = maximum**
Series Unit	400	400
Exciting Unit	0	400
Total Losses (kW)	**α = 0**	**α = maximum**
Series Unit	400	**500**
Exciting Unit	100	**470**

Induced voltage test:



Temporary bushings are connected to the regulating winding

Application of an additional step-up transformer is avoided by proper tap selection

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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

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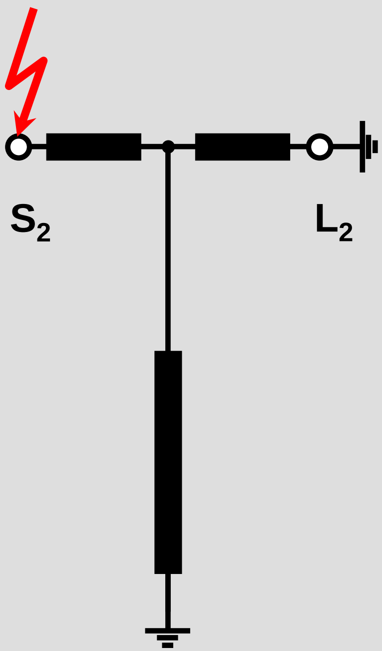
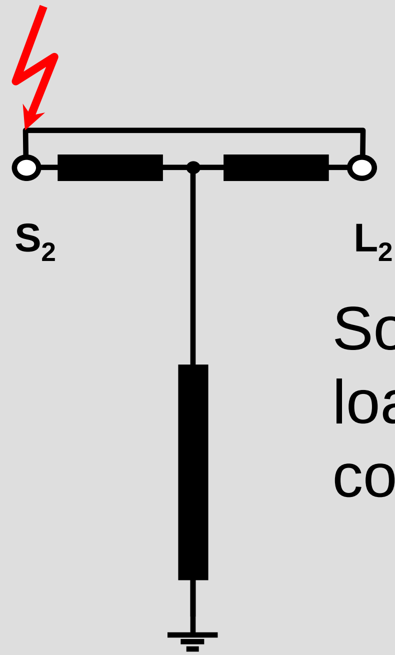
Testing

Lightning impulse test:

Standard LI test:



Special LI test:

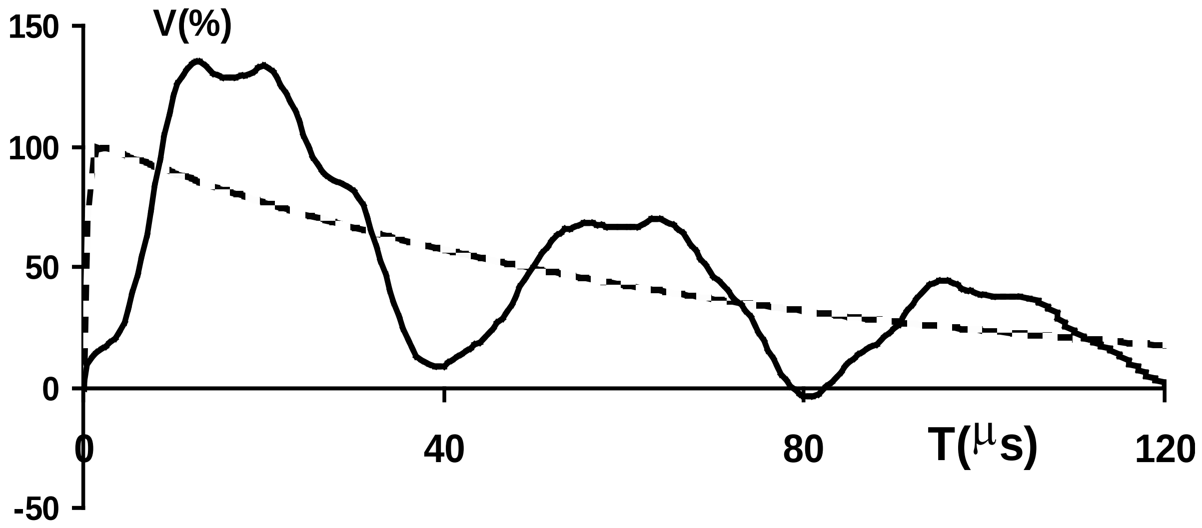


Source- and load- terminal connected

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

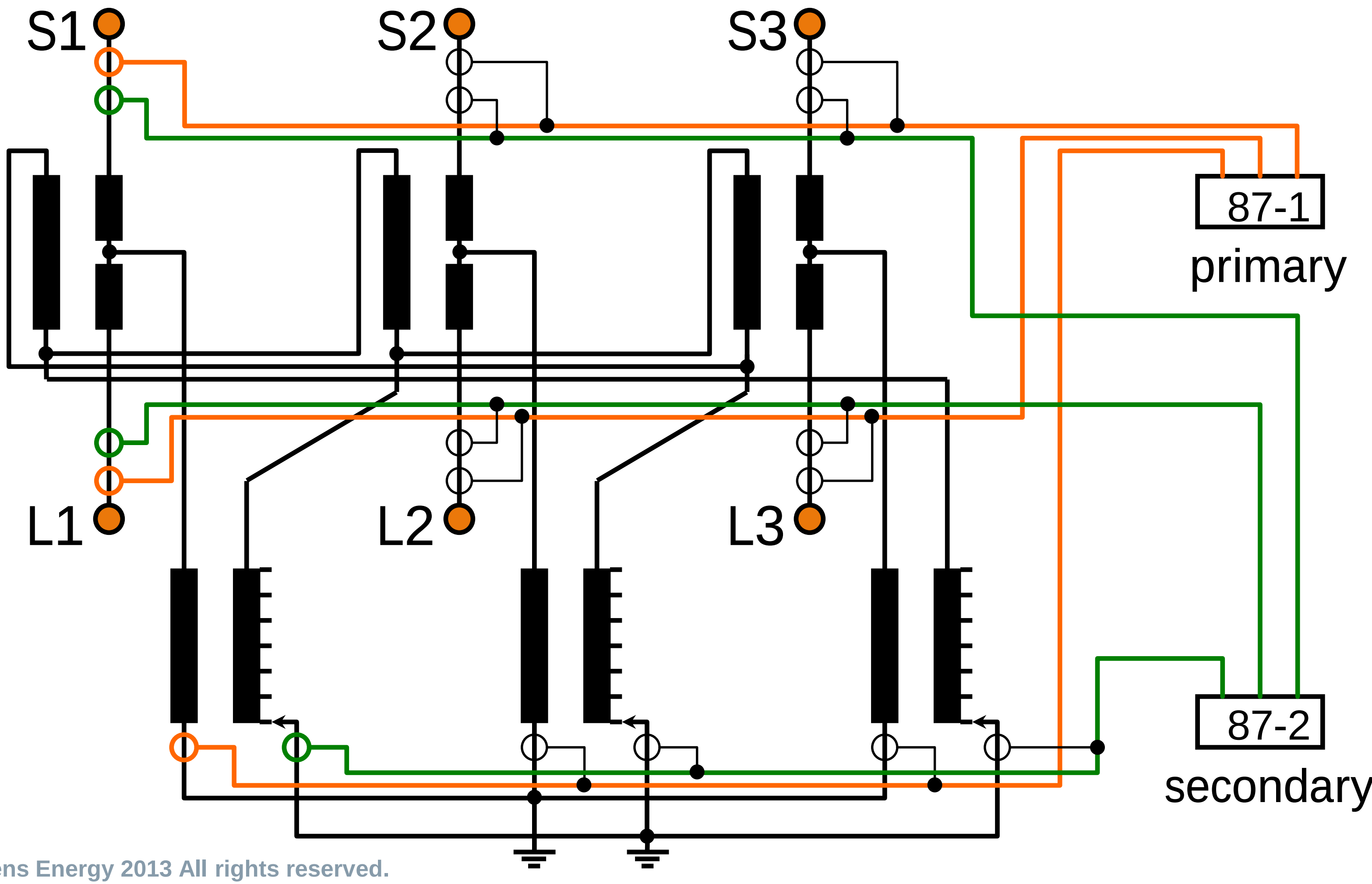
In PST, difference between source & load current @ normal operating condition becomes too large for conventional differential protection.

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)



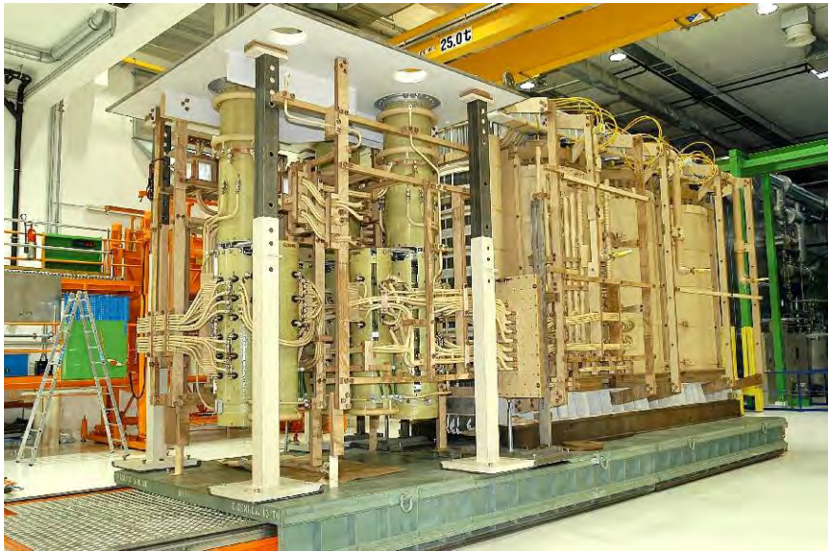
Recent PST units

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

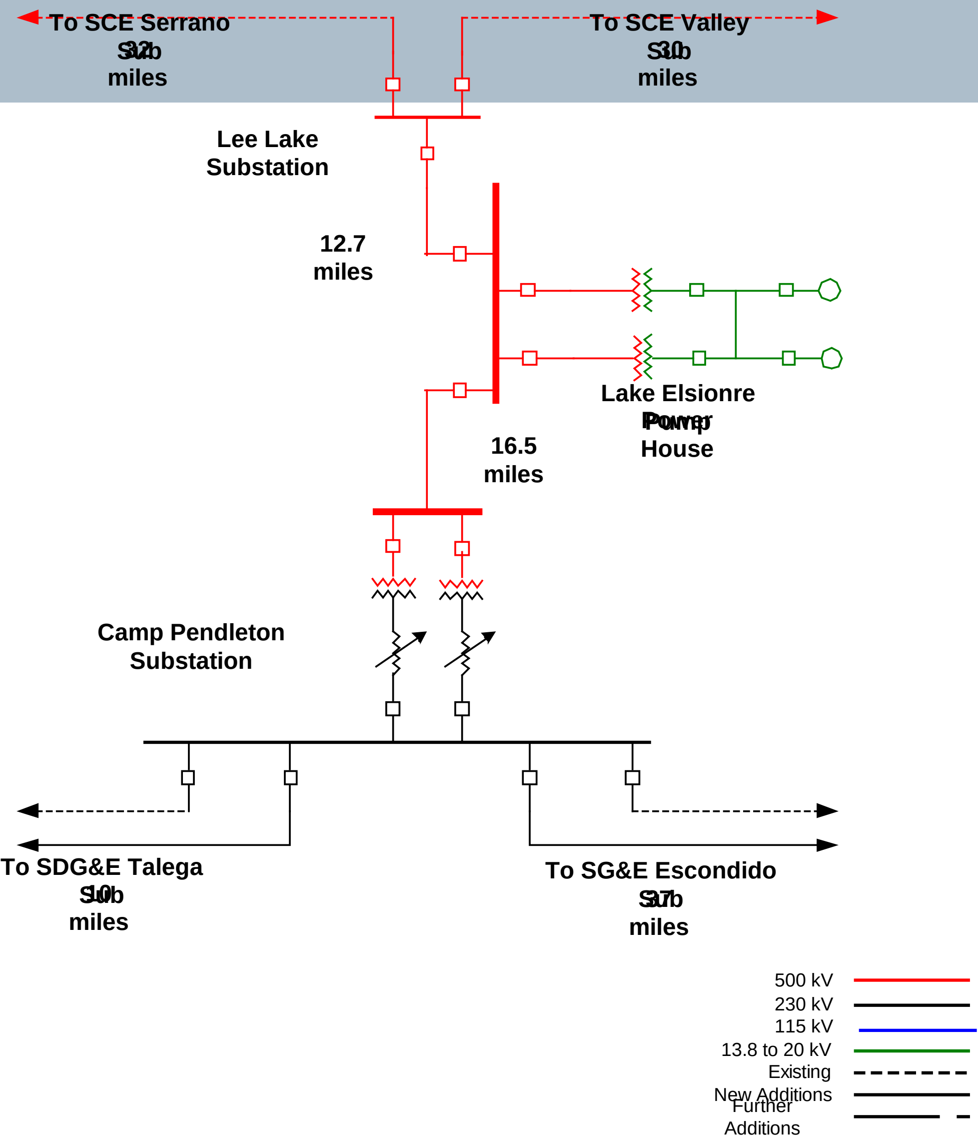
- 800MVA, 230kV, 60Hz
- ±35° no load (± 32Taps); load 25.3° ..-44.9°
- uk: 11.4% Tap 0 ; 17.6% Tap 32
- Noise Level < 77dB(A)

Classical design PST

Two-tank design
Two-core design

650 MVA, 525 kV, ±24 deg, only 500kV PSTs in world, (2) for SRP, Arizona and (2) for NPC, Nevada

LEAPS Transmission One-Line



Recent PST units

Phase Shifting Transformer

- 300 MVA, 138 kV, 60 Hz
- $\pm 25.0^\circ$ at no load ($\pm$ 16 taps);
- 14.4° at rated load - extreme advance
- -5.4° at rated load - mid tap
- -35.6° 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
- ±37,8° no load (±16 taps);
- 27.6° at rated load - extreme advance
- -4.9° at rated load - mid tap
- -48.0° 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
- ±32.9° no load (± 16 taps)
- 30.1° at rated load – tap 1
- 0.0° at rated load – tap 17
- uk: 5% tap 1; 0% tap 17

Delta hexagonal PST

Single-tank design
Single-core design

Recent PST units

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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

Conclusion

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).

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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?

james.mciver@siemens.com