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Guide for the Application, Specification, and Testing of Phase-Shifting Transformers

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Guide for the Application, Specification, and Testing of Phase-Shifting Transformers

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International Standard IEC 62032/ IEEE Std C57.135-2011 has been processed through IEC technical committee 14: Power transformers, under the IEC/IEEE Dual Logo Agreement.

This second edition cancels and replaces the first edition, published in 2005, and constitutes a technical revision.

The text of this standard is based on the following documents:

IEEE Std	FDIS	Report on voting
IEEE Std C57.135-2011	14/710/FDIS	14/714/RVD

Full information on the voting for the approval of this standard can be found in the report on voting indicated in the above table.

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- withdrawn,
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IEEE Std C57.135™-2011
(Revision of
IEEE Std C57.135-2001)

IEEE Guide for the Application, Specification, and Testing of Phase-Shifting Transformers

Sponsor

Transformers Committee
of the
IEEE Power & Energy Society

Approved 16 June 2011

IEEE-SA Standards Board

Abstract: Theory, application of phase-shifting transformers, and the difference of specification and testing to standard system transformers are described in this guide. Various types of phase-shifting transformers and how to select the optimal design to achieve required control of power flow are covered. An understanding of the terminology, types, construction, and testing specific to phase-shifting transformers is provided.

Keywords: advance phase angle, dual-core design, IEEE C57.135, main transformer, phase-shifting transformer, power transfer, retard phase angle, series transformer, single-core design, special tests

IEEE Introduction

This introduction is not part of IEEE Std C57.135-2011, IEEE Guide for the Application, Specification, and Testing of Phase-Shifting Transformers.

This guide describes the application, specification, and testing of phase-shifting transformers. It is intended for the following:

- Organizations responsible for the application and specification of phase-shifting transformers for electric transmission systems to control power flow.
- Organizations responsible for testing phase-shifting transformers.

This guide is designed to help organizations:

- Understand the various types of phase-shifting transformers and how to apply them to obtain required control of power flow.
- Prepare specifications for the purchase of phase-shifting transformers.
- Standardize tests and test methods for phase-shifting transformers.

This guide is intended to satisfy the following objectives:

- Promote consistency within organizations for the application and specification of phase-shifting transformers.
- Provide an understanding of the terminology, types, construction, and testing relating specifically to phase-shifting transformers.
- Promote the standardization of testing procedures for phase-shifting transformers.

Since this guide was first published in 2001, several recommendations from users and manufacturers were made to revise it to improve accuracy and applicability. Some of the revisions are as follows:

- Figure 1, Figure 3, Figure 4, Figure 7, and Figure 11 were improved.
- Equation (1) was divided into two parts to show the difference between advance and retard operations.
- A new section on minimum information requirements for specifying a PST was inserted.
- Various editorial changes were made to clarify the contents of the guide.

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Guide for the Application, Specification, and Testing of Phase-Shifting Transformers

1. Overview

1.1 Scope

This guide covers the application, specification, theory of operation, and factory and field testing of single-phase and three-phase oil-immersed, phase-shifting transformers (PSTs).

This guide is limited to matters particular to PSTs and does not include matters relating to general requirements for power transformers covered in existing standards, recommended practices, or guides.

1.2 Purpose

The terminology, function, application, theory of operation and protection, and design of PSTs are not covered by existing transformer standards and guides. The purpose of this document is to provide guidance to those specifying, designing, and using PSTs.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

IEC 60076-1, Power Transformers—Part 1: General.[1]

IEC 60076-3, Power Transformers—Part 3: Insulation Levels, Dielectric Tests and External Clearances in Air.

IEC 60076-5, Power Transformers—Part 5: Ability to Withstand Short Circuit.

IEC 60076-7, Power Transformers—Part 7: Loading Guide for Oil-Immersed Power Transformers.

IEEE Std 693™, IEEE Recommended Practice for Seismic Design for Substations.[2,3]

IEEE Std C37.90.1™-1989, IEEE Standard for Surge Withstand Capability (SWC) Tests for Relays and Relay Systems Associated with Electric Power Apparatus.

IEEE Std C57.12.00™, IEEE Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers.

IEEE Std C57.12.80™, IEEE Standard Terminology for Power and Distribution Transformers.

IEEE Std C57.12.90™, IEEE Standard Test Code for Liquid-Immersed Distribution, Power, and Regulating Transformers, and IEEE Guide for Short-Circuit Testing of Distribution and Power Transformers.

3. Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary: Glossary of Terms & Definitions*[4] should be consulted for terms not defined in this clause.

All other definitions, except as specifically covered in this guide, shall be in accordance with IEEE Std C57.12.80™.[5]

advance phase angle: The phase angle expressed in degrees that results when the load (L) terminal voltage leads the source (S) terminal voltage.

excitation-regulating winding: A two-core phase-shifting transformer (PST) design in which the exciting unit has one winding operating as an autotransformer that performs both functions listed under excitation and regulating winding of a two-core PST.

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[4] The *IEEE Standards Dictionary: Glossary of Terms and Definitions* is available at http://shop.ieee.org.
[5] Information on references can be found in Clause 2.

excitation winding: The winding of a phase-shifting transformer (PST) that draws power from the source to energize the PST.

excited winding of a two-core phase-shifting transformer (PST): The winding of the series unit that is excited from the regulating winding of the exciting unit.

exciting unit of a two-core phase-shifting transformer (PST): The core and coils that furnish excitation to the series unit.

L terminal: The L terminal is the terminal that is used to measure the voltage phase-shift angle when compared to the S terminal of the phase-shifting transformer (PST).

primary winding of the exciting unit of a two-core phase-shifting transformer (PST): The winding on the high-voltage side of the exciting unit.

phase-shifting transformer (PST): A transformer that advances or retards the voltage phase-angle relationship of one circuit with respect to another.

rated kVA of a phase-shifting transformer (PST): The apparent power at rated voltage for which the PST is designed.

rated phase angle of a phase-shifting transformer (PST): The phase angle measured between the S and L terminals at maximum advance and/or retard tap position under no-load condition.

rated voltage of a phase-shifting transformer (PST): The phase-to-phase voltage to which operating and performance characteristics are referred. The voltage ratings are to be defined at no-load and based on turn ratios.

regulated circuit of a phase-shifting transformer (PST): The circuit on the output side of the PST in which it is desired to control the voltage, the phase relation, or both.

NOTE—In the regulated circuit the voltage may be held constant, or may vary with or without relation to the phase angle depending on the type of PST.[6]

regulating winding: The winding of a single-core phase-shifting transformer (PST) or of the exciting unit of a two-core PST in which taps are changed to vary the phase angle.

retard phase angle: The phase angle expressed in degrees that results when the L terminal voltage lags the S terminal voltage.

series unit of a two-core phase-shifting transformer (PST): The core and coil unit that has one or more windings connected in series with the line circuit.

series winding(s) of a two-core phase-shifting transformer (PST): The winding(s) of the series unit that is(are) connected in series in the line circuit.

single-core design: A single-core phase-shifting transformer (PST) has all windings mounted on a single core.

S terminal: The S terminal is the terminal that is used as the fixed reference point when measuring the voltage phase angle of a phase-shifting transformer (PST).

[6] Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

two-core design: A two-core phase-shifting transformer (PST) consists of a series unit and a exciting unit. The series and the exciting unit can be either in one tank or in separate tanks.

4. Application and theory of PSTs

4.1 Introduction

The development of large, high-voltage power grids has enabled power consumers to enjoy the benefits of more reliable and efficient service and has allowed generation sources to be, in some cases, located long distances from large load centers. Although large interconnected grids strengthen a power system's reliability, complications can arise with the control of steady-state power flow along certain segments of the system. These complications can be attributed to several factors, including the impedance of parallel paths in the power grid, variation in power generation output, and variation in loads and load center phase angles.

4.2 Basic principle of application—advanced and retard phase angle

PSTs are used to control the power flow in electrical power systems. When power flows between two systems, there is a voltage drop and a phase-angle shift between the source and the load that depends upon the magnitude and power factor of the load current. If the systems are connected together in two or more parallel paths so that a loop exists, any difference in the impedances will cause unbalanced line loading. Figure 1 shows an example with the load side power factor assumed to be 1 and the system resistances being negligible with respect to their reactances. An arbitrary power flow distribution can be obtained by inserting a PST into one of the branches. Dependent upon whether the PST is installed in the branch with the higher or lower impedance, an advanced or a retard phase angle is needed. *Advanced* means that the L terminal voltage (V_L) leads the S terminal voltage (V_S); *retard* means that the L terminal voltage (V_L) lags the S terminal voltage (V_S).

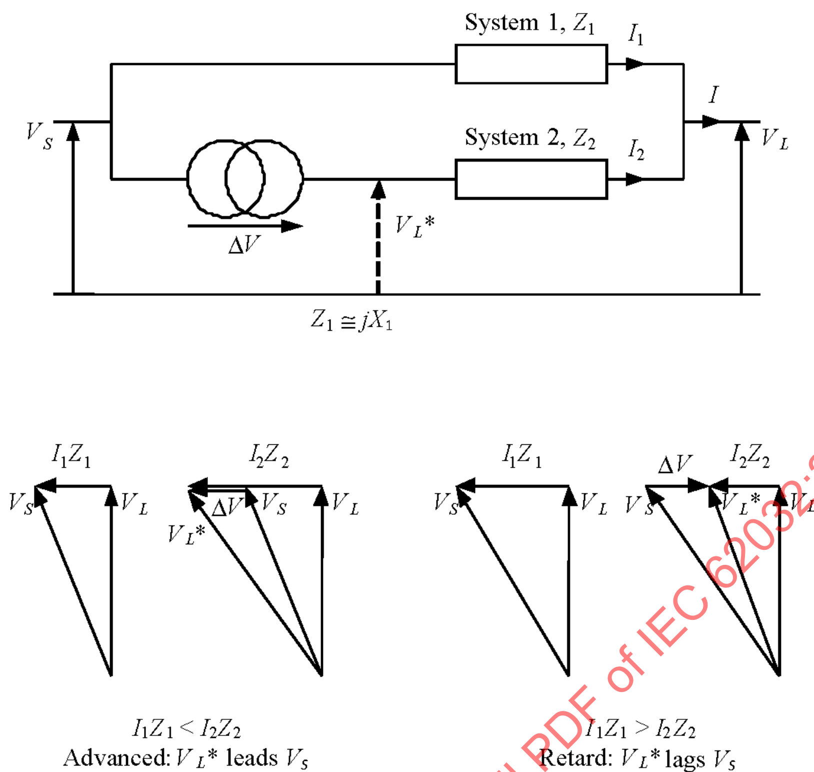

Figure 1—Load side power factor of 1

Equation (1a) and Equation (1b) illustrate the advance and retard operations shown in Figure 1.

$$I_2 * Z_2 - \Delta V - I_1 * Z_1 = 0 \quad \Rightarrow \quad \Delta V = I_2 * Z_2 - I_1 * Z_1 \tag{1a}$$

$$I_1 * Z_1 + \Delta V - I_2 * Z_2 = 0 \quad \Rightarrow \quad \Delta V = I_2 * Z_2 - I_1 * Z_1 \tag{1b}$$

A numerical example should illustrate this. If it is required that both systems are loaded with 50% of the total transferred power 2xS and the impedances are assumed to be z_1 = 0.02 and z_2 = 0.30, related to S, the necessary additional voltage becomes ΔV = 0.30 – 0.02 = 0.28. Hence, a load phase angle (advanced) of about 15.6° (≈arctan(0.28)) is necessary. The total angle between source and load becomes minus 1.1°. In case with z_1 = 0.30 and z_2 = 0.02, the same load phase angle (retard) would be needed, but the total phase angle between source and load would become 16.7°. If no measures were taken, then the load distribution between system 1 and 2 would be 0.9375 to 0.0625 instead of 0.5 to 0.5.

A second important application is the use of a PST to control the power flow between two large independent grids. An advanced phase-shifting angle is necessary to achieve a flow of active power from system 1 to system 2 (Figure 2).

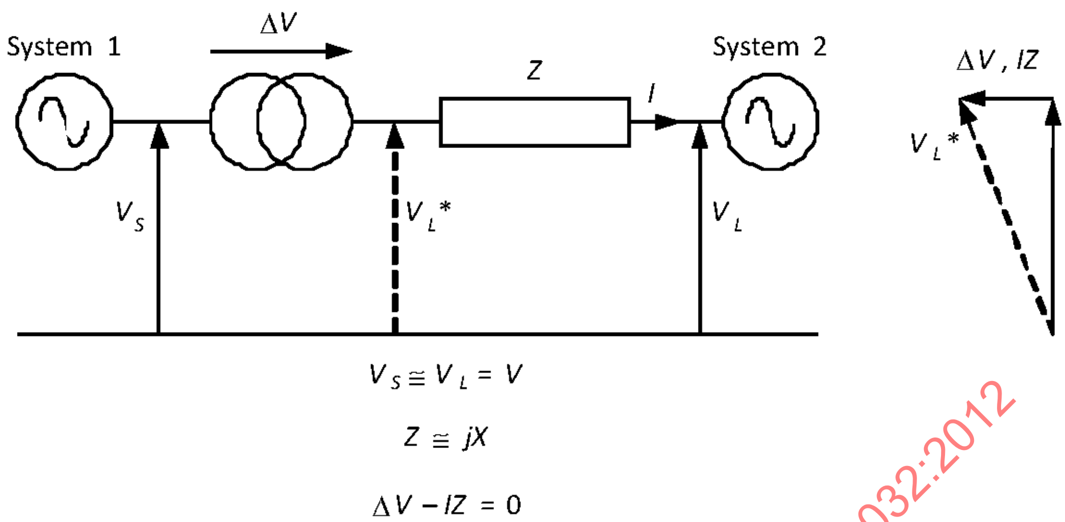

Figure 2—Advanced phase-shifting angle

4.3 PST under load

So far an "ideal" PST (i.e., a transformer with an impedance $z_T = 0$) has been dealt with. To demonstrate load conditions, an equivalent circuit phasor diagram is used as shown in Figure 3 with an ideal PST with $z_T = 0$ and an additional transformer with a turns ratio of 1:1 and an impedance $z_T = R_T + jX_T$.

where

- V_L* is load-side voltage (no-load)
- V_L is load-side voltage (loaded)
- $V_{S(a)}$ is source-side voltage (advanced)
- $V_{S(r)}$ is source-side voltage (retard)
- I_L is load current
- cos φ_L is load power factor
- z_T is transformer impedance
- β is transformer load angle
- α is phase-shift angle
- \+ advanced
- – retard

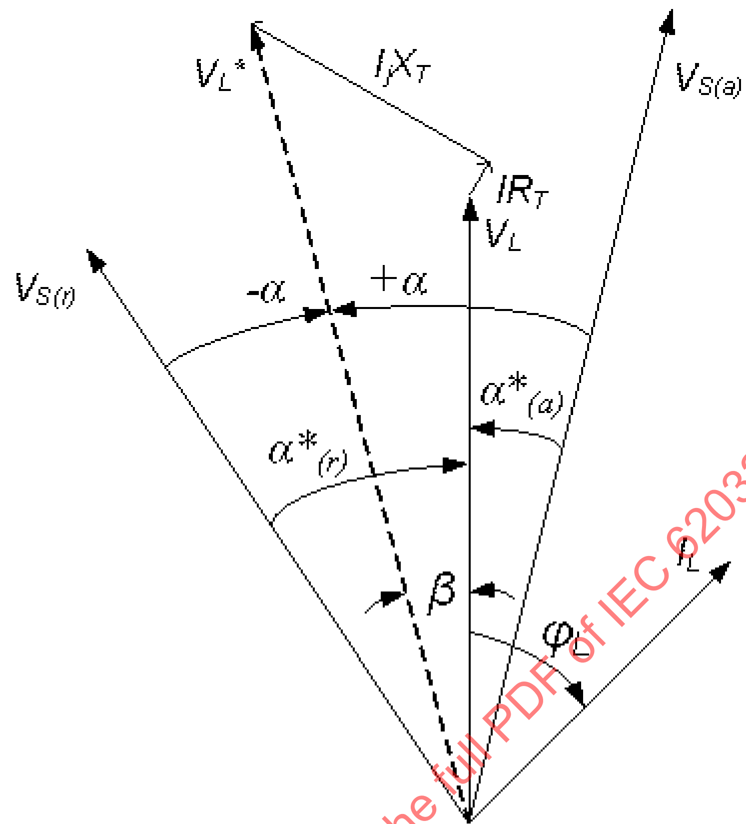

Figure 3—Demonstration of load conditions

Next, the phasor diagram of the PST can be drawn. Starting with the load voltage V_L and calculating the ohmic and reactive voltage drop in the 1:1 transformer, the load voltage V_L* can be obtained. The load phase angle β can be calculated with Equation (2):

$$\beta = \arctan \frac{I_L \times X \times \cos \varphi_L - I_L \times R \times \sin \varphi_L}{V_L \times I_L \times X \times \sin \varphi_L + I_L \times R \times \cos \varphi_L} \cong \arctan \frac{Z_T \times \cos \varphi_L}{100 + Z_T \times \sin \varphi_L} \quad (2)$$

The PST adds ±α, and so, finally, the load phase angles of the transformer $\alpha^*_{(a)}$ and $\alpha^*_{(r)}$, respectively, are obtained as shown in Equations (3) and (4):

$\alpha^*_{(a)} = \alpha - \beta$ is phase-shift angle (loaded) advance (3)

$\alpha^*_{(r)} = -(\alpha + \beta)$ is phase-shift angle (loaded) retard (4)

On the one hand, to obtain an advanced phase angle $\alpha^*_{(a)}$ under load, the no-load phase angle α has to be chosen properly under consideration of the phase angle $\alpha^*_{(r)}$ of the PST. On the other hand, the retard phase angle $\alpha^*_{(r)}$ is increased under load. This has an impact on transformer and tap changer as discussed in 4.8.4.

4.4 Power transfer

A PST has two separate effects on power flow. First, the no-load phase angle creates an additional voltage that drives additional current through the line. Second, the PST's additional impedance is added to the circuit. These two effects may work against each other. Therefore, a minimum phase angle is usually required to compensate for the additional voltage drop across the PST's impedance in the advanced position. To ease the following considerations, the impedance of the PST has been assumed to be constant over the whole regulating range, a tolerable approximation for two-core designs (the impedance of single-core designs is commonly zero at 0° phase shift).

With the denotations used in Figure 3 and

P_0	is active power transferred when $\alpha = 0$	(preload)
Q_0	is reactive power transferred when $\alpha = 0$	(preload)

the power components at the source side are calculated using Equations (5) and (6):

$$P(\alpha) = P_0 \times \cos\alpha - Q_0 \times \sin\alpha + \frac{V_S^2}{X_T} \times \sin\alpha \tag{5}$$

$$Q(\alpha) = P_0 \times \sin\alpha + Q_0 \times \cos\alpha + \frac{V_S^2}{X_T} \times (1 - \cos\alpha_0\ ) \tag{6}$$

Figure 4 explains the effect of the introduction of the phase-shift angle α. In the formula, the first two terms reflect the effect of the phase angle on the original power flow as easily can be derived from Figure 4. The last term represents the additional power flow generated by the additional voltage ΔV across the impedance jX of the PST. Taking into consideration that the real component of ΔV ($-\Delta V$* cos(α/2)) drives a current with a positive imaginary component and the imaginary component of ΔV ($-\Delta V$*sin(α/2)) is a current with a positive real component and that $\Delta V = 2 * V_s$ * sin((α/2), the last terms in Equations (5) and (6), respectively, can be confirmed without difficulties.

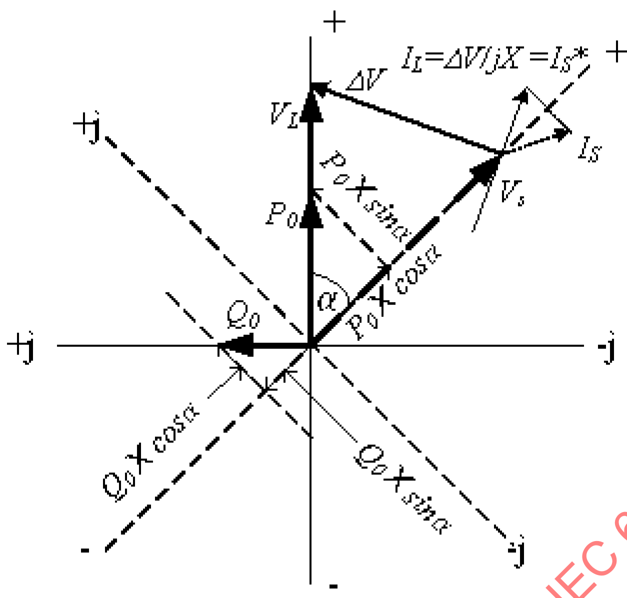

Figure 4—Effect of phase-shift angle α

Figure 5 shows the variation of the additional power flow (assumption: $P_0 = Q_0 = 0$, $Z_T \approx jX_T$, $V_s^2/X_T = 1$) with the PST angle α.

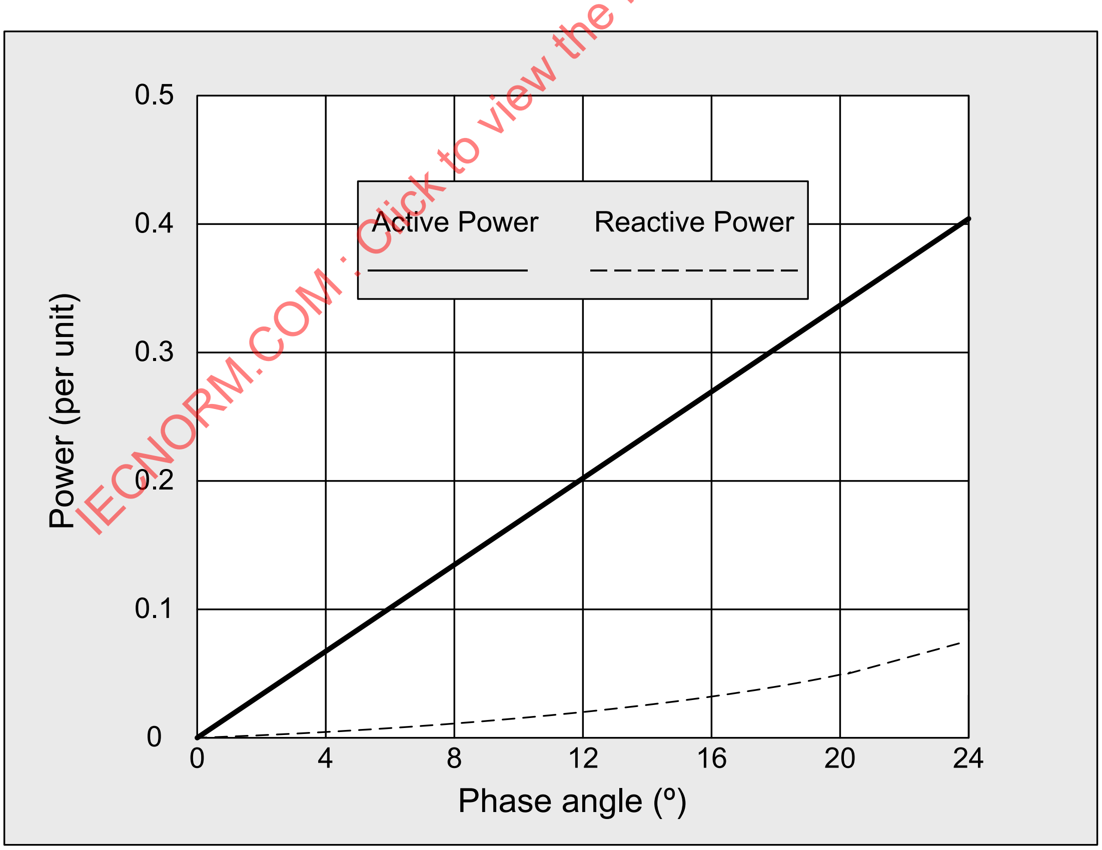

Figure 5—Variation of additional power flow with the PST angle α

Figure 6 shows as an example the variation of the power flow at the source side with the phase angle α, depending on different preload conditions. The maximum additional power transferred has been assumed to be 1.

It can be seen how the power flow is influenced when the no-load phase angle of the PST is changed from zero to maximum leading phase shift. The highest increase of active power for the same phase shift appears when a negative reactive power flow exists, i.e., with high capacitive load. An inductive load (positive reactive power) decreases the effect of the PST.

The reactive power flow is also influenced by the preload condition. The active power has a major impact on the influence of the PST angle.

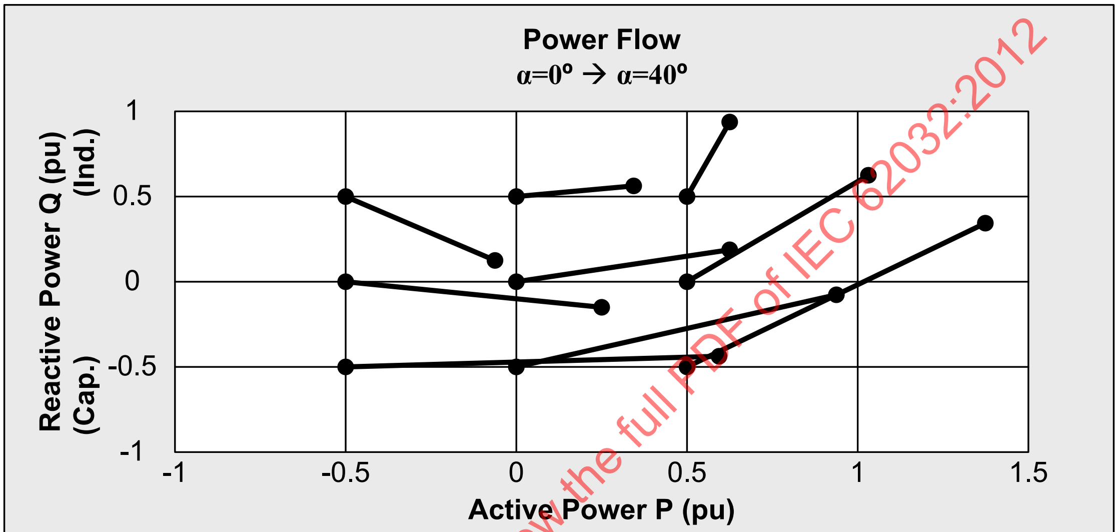

Figure 6—Variation of power flow with the phase angle α depending on different preload conditions

4.5 Types of PSTs

4.5.1 Introduction

The basic principle to obtain a phase shift is to connect a segment of one phase into another phase. Figure 7 shows an elementary arrangement; the phasor diagrams are drawn for a no-load condition. A PST is used with the exciting winding delta connected. The regulating winding of phase V_2–V_3 is connected to phase V_1 and so on. The scheme has been plotted for subtractive polarity of the windings, and the tap position has been chosen so that the transformer produces an advanced phase angle. Under the no-load condition, the regulation is symmetrical, i.e., the absolute values of source and load voltage are the same.

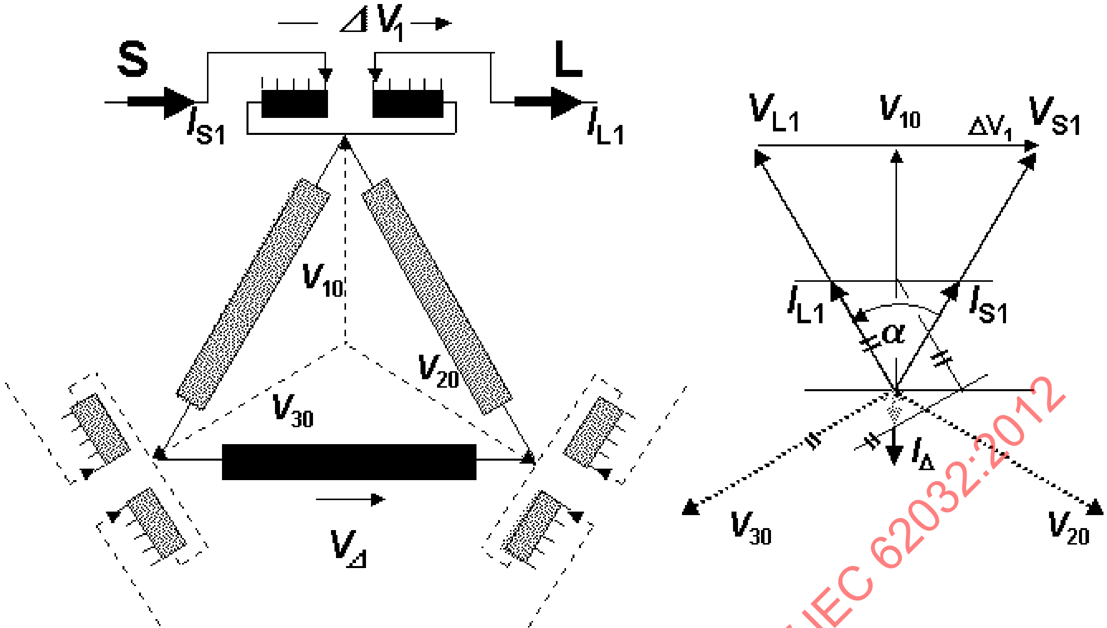

Figure 7—Phasor diagram for the no-load condition

Equation (7) through Equation (9) can be used to calculate V_S, V_L, and V_Δ:

$$V_{S1} = V_{10} + \frac{\Delta V_1}{2} \tag{7}$$

$$V_{L1} = V_{10} - \frac{\Delta V_1}{2} \tag{8}$$

$$V_{\Delta 1} = V_{20} - V_{30} \tag{9}$$

With consideration of these formulas, the phasor diagram can be drawn and absolute values can be determined using Equation (10) through Equation (15):

$$V_{S1} = V_{L1} - V_1 \tag{10}$$

$$V_{10} = V_1 \times \cos\frac{\alpha}{2} \tag{11}$$

$$\Delta V_1 = V_1 \times 2 \times \sin\frac{\alpha}{2} \tag{12}$$

$$V_{\Delta} = V_{10} \times \sqrt{3} = V_1 \times \sqrt{3} \times \cos\frac{\alpha}{2} \quad (13)$$

$$I_{S1} = I_{L1} = I_1 \quad (14)$$

$$I_{\Delta} = I_{L1} \times \frac{\Delta V_1}{V_{\Lambda}} \times \cos\frac{\alpha}{2} = I_{L1} \times \frac{2}{\sqrt{3}} \times \sin\frac{\alpha}{2} \quad (15)$$

The rated throughput power of the PST is determined with Equation (16):

$$P_S = 3 \times V_1 \times I_{L1} \quad (16)$$

whereas the rated design power that determines the size of the unit is determined with Equation (17):

$$P = 3 \times \Delta V \times I = P \times 2 \times \sin\frac{\alpha}{2} \quad (17)$$

In practice, many solutions are possible to design a PST. The user's electric power system requirements and the manufacturer's preference generally determine the design. The major factors determining the type of PSTs are listed subsequently.

The factors specific to the PST design are as follows:

- PST purchasing price or the first cost
- Cost of capitalization of losses
- Impedance variation across the tap range
- Angle at full load
- Electrical arrangement of on-load tap changers
- On-load tap changers margins on step voltage, rated current, fault current and switching capacity and duty of changeover selector [advance-retard switch (ARS)]
- Test capability

The factors specific to the project are as follows:

- Foundations and the space requirement in the substation
- Oil spill containment volume
- Shipping weights and shipping dimensions
- Protection and relay costs

These factors decide whether a single-core or a two-core type has to be chosen. These two types are described in more detail in 4.5.2 through 4.5.3.

4.5.2 Single-core design

The single-core design is less complex and has fewer winding segments than two-core designs but has some disadvantages as follows.

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.

The short-circuit impedance of the single-core design PST is very low at tap positions near 0° phase shift. Therefore, the ratio between external fault currents passing through the PST and rated current may become very high, especially in systems with low fault current impedance. This has to be taken into account when selecting the tap changers and when calculating the forces in the windings.

With the design outlined in Figure 7, symmetrical conditions are obtained. The LTC can also be equipped with a reversing changeover selector. This solution permits changing from an advanced phase angle to a retard phase angle. With the single-core design, it is generally accepted practice to supply two sets of three single-pole tap changers: one set connected to the S terminals and the second set connected to the L terminals. As a simplified solution, it is also possible to use only one half of the tapped winding. But in such a case, the load voltage increases with respect to the source voltage (Figure 8).

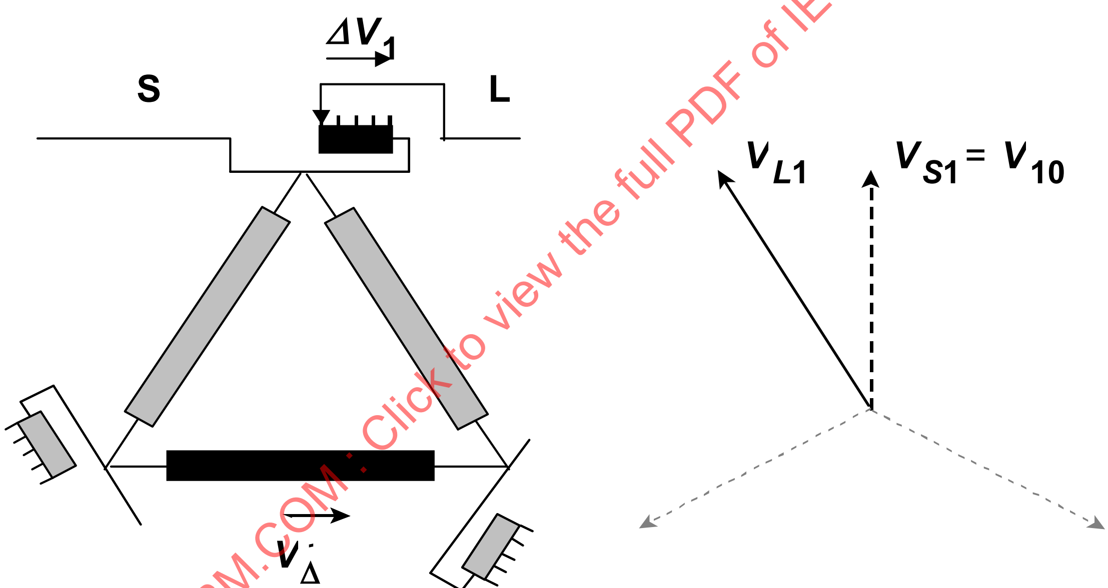

Figure 8—PST with half tap winding

In the case of a small rated switching capacity (step voltage × through current), a solution with one two-phase LTC per phase is possible, using an LTC assembly according to Figure 9.

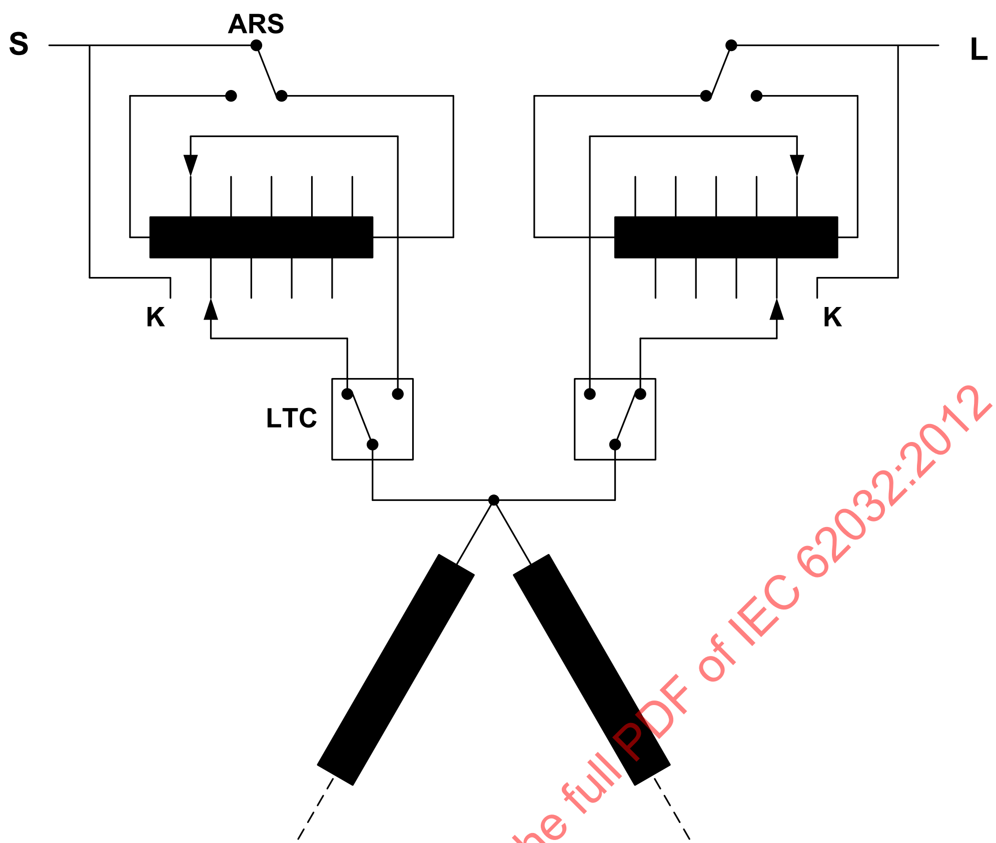

Figure 9—PST with small switching capability

As another example,[7] Figure 10 shows the connection diagram and the phasor diagram of a "delta-hexagonal" PST. These transformers have LTCs with linear regulation, i.e., without an ARS.

A non-LTC, delta-hexagonal PST can also be configured with a deenergized changeover selector switch and a deenergized phase-shift selector switch. Because of complications of interconnecting windings, such a fixed phase-shift design is restricted to only a limited number of phase shifts for system connections. However, for systems anticipating fewer and infrequent phase-shift changes, such a PST has significant benefits of simplistic design and operation.

[7] There are numerous other possibilities, e.g., also designs with deenergized operation.

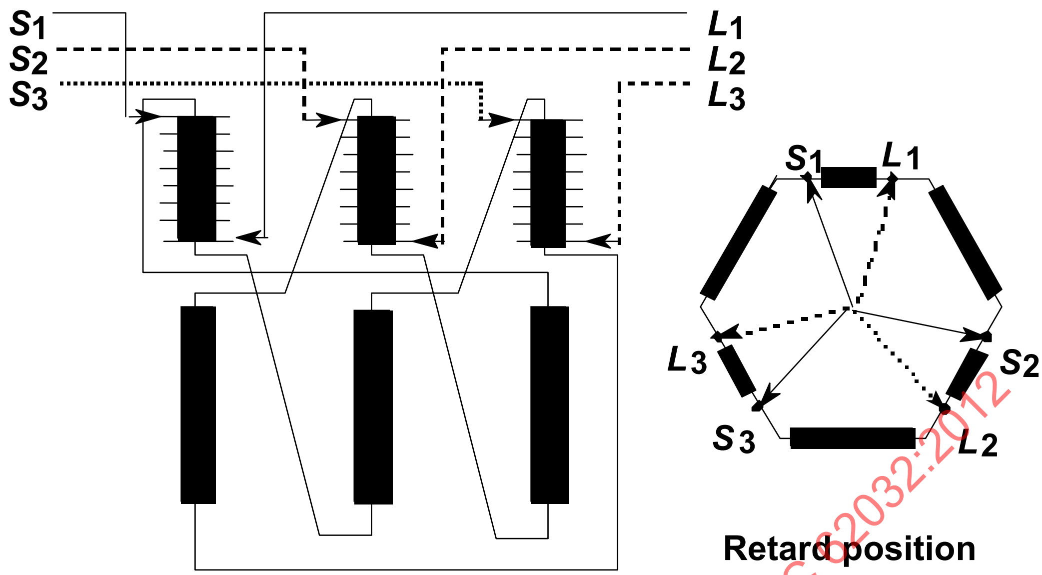

Figure 10 —Connection diagram and the phasor diagram of a "delta-hexagonal" PST

The single-core design is less complex and has fewer winding segments than two-core designs but has some disadvantages, as follows:

— The LTC and the tapped winding are in the line end of the windings and are directly exposed to the system overvoltages. Depending on the overvoltages and isolation levels, the use of internal surge arresters to protect the tap winding can become useful, or necessary.

— Voltage per tap and current are determined by the phase-angle requirement and rating of the PST, and they cannot be adjusted to obtain optimum switching conditions. If one of these parameters exceeds its limit, then the solution would not be possible although the required switching capability may still be given.

4.5.3 Two-core design

The most commonly used circuit for two-core designs is shown in Figure 11. This configuration consists of a series unit and an exciting unit. For smaller ratings and lower voltages, two-core PSTs may be built into one single tank, whereas large ratings and high-voltage PSTs require a two-tank design.

The advantage of a two-core design is the flexibility in selecting the step voltage and the current of the regulating winding. They can be optimized in line with the voltage and current ratings of the LTC. Because LTCs have limited current ratings, step voltages per phase, and switching capacity, they are the main limiting feature for the maximum possible rating of PSTs. More than one LTC per phase may have to be utilized for very large ratings.

Furthermore three-pole LTCs can be used. For high switching-capacity ratings, three single-pole LTCs may be used. The LTC insulation level to ground is independent of the system voltage and can generally be kept low. The potential connection of the regulating winding has to be checked (see 4.6.1), but often it is not critical and the values are comparable with those of a regulating winding at the neutral end of a common network transformer.

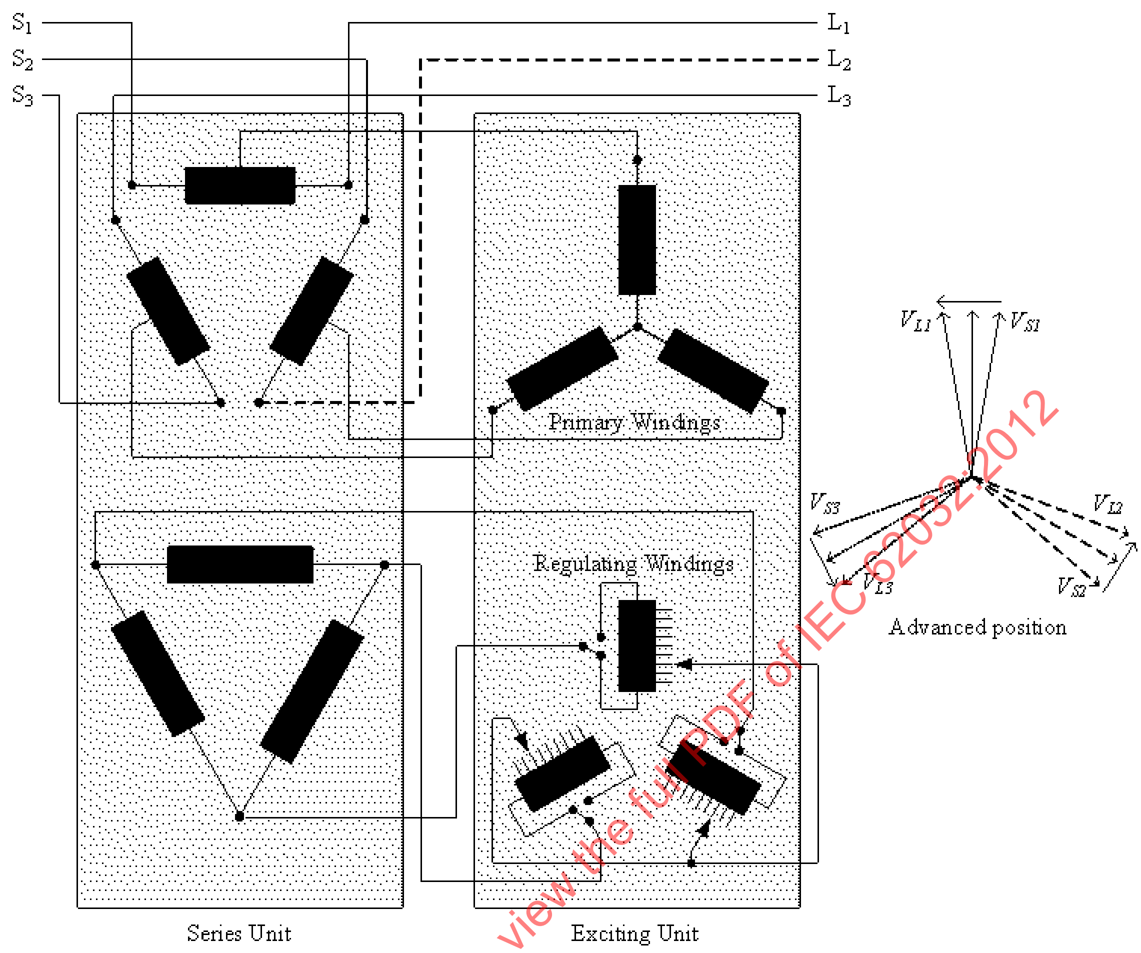

Figure 11 —Commonly used circuit for two-core designs

4.6 Special on-load tap changer (OLTC) features

4.6.1 Potential connection of the regulating winding

During the operation of the reversing changeover selector, the regulating winding is temporarily disconnected from the main winding. Its potential at this moment is determined by the voltages of the adjacent windings as well as by the coupling capacitances to these windings and to the grounded parts. The resulting differential voltage exerts stress across the switching distance of the opening changeover selector contacts. In the case of PSTs having regulation at the line end, high recovery voltages can occur because of the winding arrangement. The changeover operation takes place in the midposition of the LTC, i.e., when the tap selectors are in position “K” (see Figure 9).

Figure 12 shows a typical winding arrangement and the resulting phasor diagram. It can be seen that the recovery voltages are higher than the system line-to-ground voltages of the source and load side. The limit of the recovery voltages is in the range of 15 kV to 35 kV. This condition has to be taken into account during design of a PST. One possibility to decrease the recovery voltage is to install shields between the windings. Each shield must be connected to the “K” point of the corresponding phase.

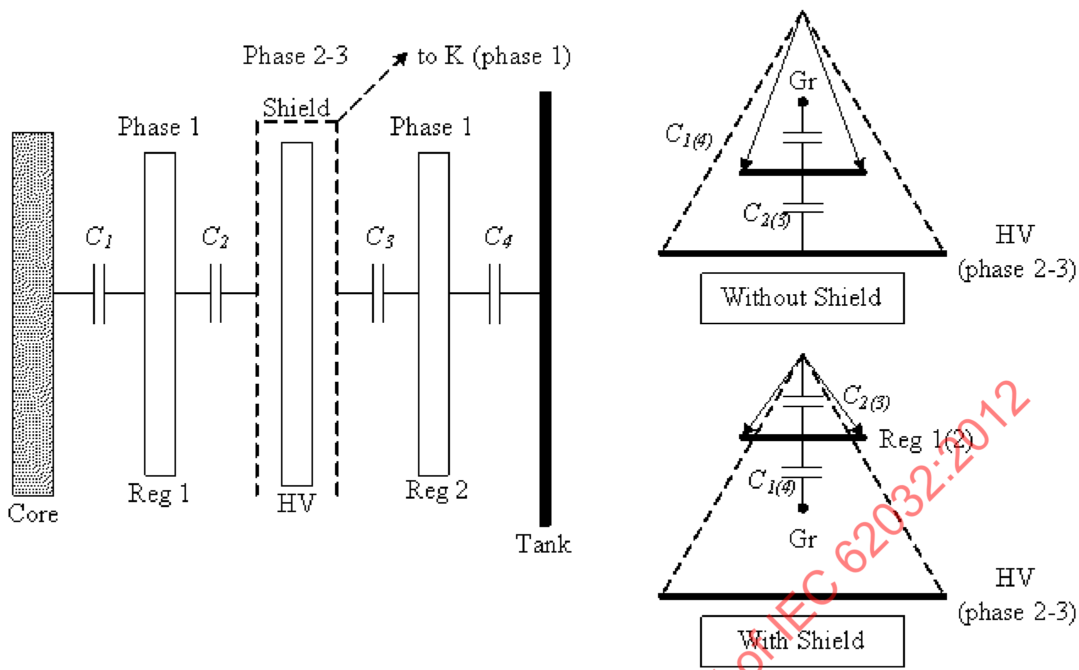

Figure 12—Impact of shields on recovery voltage

Both recovery voltages occurring during reversing changeover selector operation and switched current resulting from capacitances have limitations. The limit of the magnitude of this current is in the range of a few hundred milliamps.

Only in special cases, when a third winding with a low voltage level is specified, it may be possible to use this winding instead of the shields. Shielding has in addition the advantage that it protects the regulating winding from capacitively transferred transients. If shielding is not possible, then one of the following solutions must be used to solve the problem:

a) The first way is to connect the tap winding to a fixed potential during the reversing changeover operation by a fixed ohmic resistor or capacitor, which is usually connected to the middle of the regulating winding and to the current take-off terminal of the LTC. This solution is not applicable in every case (especially with arrangements according to Figure 12, when no shields are used). The connection of resistors or capacitors increases the amount of switched current because of the small resistance compared with that of the capacitances.

b) The second possibility is to use an ARS as shown in Figure 13. This switch allows the reversing changeover operation to be carried out in two steps without interruption. The regulating winding remains connected to a fixed potential during the whole operation. The limiting parameter for the ARS is the process of commutation, which has to be controlled by the ARS. It is determined by the commutation of the through current from a small inductive loop to a larger one.

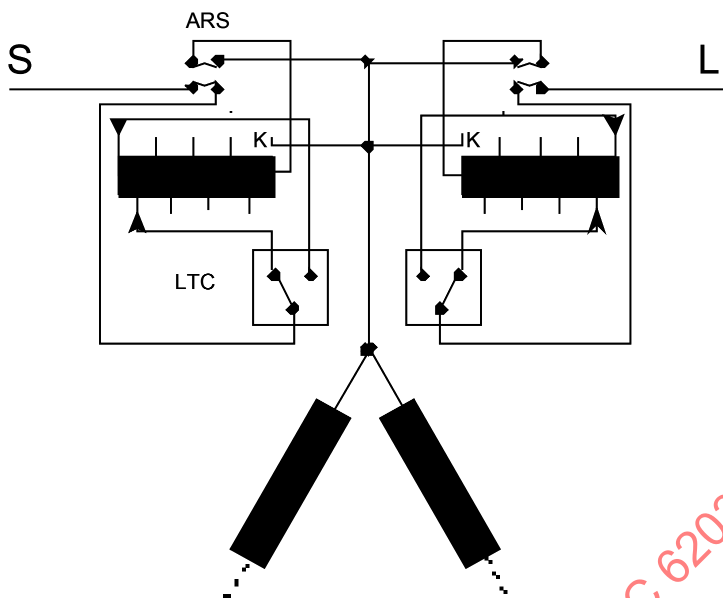

Figure 13—Use of ARS

4.6.2 LTC with coarse ARS

By using the ARS for inserting a coarse-regulating winding, the achievable phase angle in one direction can be enlarged. If a change from advanced to retard position is required, then an additional switching device is necessary, which has to be designed like an ARS so that the switching can be performed without interruption of the load current. The ARS has to control the process of commutation that, in this case, is determined not only by the loop formed by the connecting leads but also by the impedance of the winding itself. If the reversing operation can be carried out with a deenergized transformer, then an off-circuit tap changer is sufficient. Figure 14 shows different arrangements with coarse changeover selectors [Figure 14(a) and Figure 14(b)] and, in addition, the use of two LTCs [Figure 14(c)]. Also, the arrangement of an ARS for the exciting winding of the series transformer is shown in Figure 14(b).

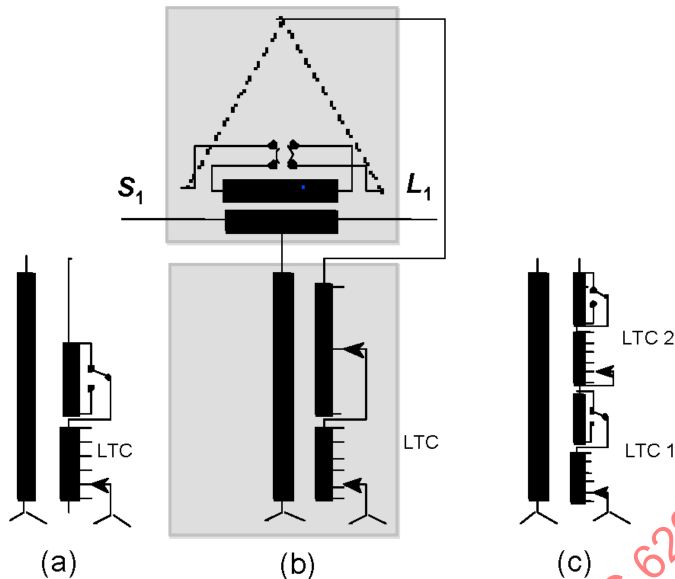

Figure 14—Different arrangements with coarse ARSs

4.6.3 Number of OLTCs required

Table 1 lists the minimum number of LTCs required.

Table 1—Minimum number of LTCs required

Type	Figure	Regulation	Number of LTCs	Number of ARSs
Single core	Figure 7 Figure 5 Figure 8	LTC with reversing changeover selector[a]	3 two-phase units or 6 single-phase units[b] or 3 single-phase units[c]	None
	Figure 13	LTC plus ARS acting as a reversing changeover selector	6 single-phase units	3–6 units[d]
	Figure 10	LTC without changeover selector (linear regulation)	6 single-phase units	None
Two core	Figure 11	LTC with reversing changeover selector	1 three-phase unit (wye-connected) or 3 single-phase units[b]	None
	Figure 14(a)	LTC with one coarse winding	1 three-phase unit (wye-connected) or 3 single-phase units[b]	1–3 units[d]
	Figure 14(b)	LTC with several coarse windings	1 three-phase unit (wye-connected) or 3 single-phase units[b]	1–3 units[d]
	Figure 14(c)	With two LTCs in series with coarse changeover selector	1 three-phase unit (wye-connected) or 3 single-phase units[b]	1–3 units[d]

[a]The reversing changeover selector is not shown in Figure 7 and Figure 8.
[b]Depending on rated switching capacity and through current. The two-phase LTCs have to be connected according to Figure 9.
[c]Asymmetric regulation.
[d]Depending on voltage level and through current.

4.7 Arrangement of more than one PST

4.7.1 Series connection of PSTs

If two or more (n) 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. For example, two 100 MVA PSTs, each with a 5° phase shift and 10% impedance connected in series will be equivalent to one 100 MVA PST with a 10° phase shift and 20% impedance. In case of an outage of one unit, the full current can be maintained with $(n – 1)/n$ maximum phase angle shift, but possible short-circuit problems have to be considered because of the diminished impedance.

4.7.2 Parallel connection of PSTs

If two or more (n) 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. For example, two 100 MVA PSTs, each with a 5° phase shift and 10% impedance connected in parallel, will be equivalent to one 200 MVA PST with a 5° phase shift and 5% impedance.

Consideration should also be given to circulating currents that may occur during tap changes when operating two PSTs in parallel.

4.8 Design criteria

4.8.1 Phase angle

The rated phase angle is defined under no-load conditions. However, it should be noted that the unit is unlikely to operate at this phase angle under load in the advanced position because of the effect of the voltage drop in the unit. In the retard position, the no-load phase angle should not be exceeded (unless the unit has been designed for that), as overexcitation will occur in parts of the PST (see also 4.8.4).

4.8.2 Dielectric design of the two-core type

The transmission of transient voltages in the two-core design is rather complex. When applying impulse tests to either the S or the L terminals of the series transformer, the connected exciting winding of the main transformer will also be exposed to a high voltage. There may be high-voltage oscillations of the connecting leads depending on the capacitive voltage control of the series winding. High voltages may be transferred to other windings coupled to the series winding or to the excitation winding. Therefore, rather complex computer models may be required to compute the transient voltages for this configuration.

4.8.3 Special considerations for a multiple-tank design

When the two-core design is used with multiple tanks, special precautions must be taken to design connections between the tanks. As illustrated in Figure 11, the connection operates at the system voltage level so that the leads must be insulated for the overvoltages that may occur under both transients and power frequency conditions. A short circuit between the connections of the two units has to be considered as an internal fault, which would cause severe damage or even destroy the PST. A short-circuit proof design for this special case would result, if it were possible at all, in a significant increase in cost. Therefore, it is strongly recommended to use metal enclosures to protect the connections against lightning strokes and possible sources of short circuit.

4.8.4 Overload conditions (loading above nameplate rating)

Overloading of a PST increases the internal phase angle β [see Equation (2)] and consequently also the load phase angle $\alpha^*_{(r)}$ in the retard position [see Equation (4)]. This may result in a load phase 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. Furthermore, in a two-core design, the main transformer will experience a certain degree of overexcitation with the same consequences for the regulating winding. The degree depends on the ratio of the impedances of series and main transformer.

It must—besides the effect that parts of the core(s) may be overfluxed—therefore also be checked whether the parameters voltage per step, current, and switching capability are still within the limits of the LTC design. See Jarman et al. [B19].[8]

5. Service conditions

PSTs conforming to this guide will be suitable for operation at rated voltage and rated kVA as shown in 5.1 through 5.4.

5.1 Usual service conditions

These conditions shall be as stated in 4.1.1 through 4.1.7 and 4.1.9 in IEEE Std C57.12.00™-2006, or IEC 60076-1. In item a) of 4.1.6.1 in IEEE Std C57.12.00-2006, the word "secondary" shall mean the L terminals of the PST.

a) The purchaser of the PST shall specify the switching arrangements that will be used to place the PST in and out of service. This shall include breaker or switch operations resulting from faults external and internal to the PST.

b) The PST shall be suitable for energization from either the S or L terminals.

c) The PST shall be capable of transferring rated kVA with the electrical source of power connected to the S or L terminals. Limited power transfer in the *retard* position has to be considered.

d) Seismic requirements shall be as specified in IEEE Std 693™. The purchaser's specifications shall include the seismic zone and the foundation. The manufacturer shall provide for differential motion between the two tanks, if used, and for remotely mounted radiators as applicable.

e) The manufacturer of the PST shall make provisions for differential alignments that will occur when two tanks are connected. The foundation tolerance shall be defined by agreement between the purchaser and the manufacturer.

f) Unless specified otherwise, the PST shall be manufactured for operation in the bypassed state with the source and load bushing connected through bus work. This shall require special consideration in designing for lightning and switching impulses. This condition will require

[8] The numbers in brackets correspond to those of the bibliography in Annex A.

additional testing with the terminals connected, as in service, to demonstrate that the insulation level meets the specified BIL.

5.2 Loading at other than rated conditions

This subclause shall be the same as 4.2 of IEEE Std C57.12.00 or IEC 60076-7 with the exception that additional limits must be observed for retard operation under overload. These limits must be defined by the manufacturer and agreed on by the purchaser prior to completion of the PST design.

5.3 Unusual service conditions

The unusual conditions shall be the same as those listed in 4.3 and 4.3.1 through 4.3.3 of IEEE Std C57.12.00 or IEC 60076-1. Additional unusual service conditions that may apply to PSTs are discussed in the subsequent sections.

5.3.1 Operation with two or more PSTs in parallel or in series

The purchaser must provide the manufacturer with all nameplate and test data of the existing PSTs and applicable system information necessary to design the PSTs for proper load sharing. The purchaser must specify in detail to the manufacturer the LTC's controls that will be provided by the purchaser. If the manufacturer provides the LTC's controls, the purchaser shall provide the control scheme used with any existing PSTs to the manufacturer to enable the manufacture to supply a compatible system.

5.3.2 Operation of PSTs in series with series capacitor banks

If the PST is to be operated in series with a series capacitor bank, this operating condition shall be specified in the purchaser's specification. The operating conditions and the protection scheme used shall also be included in the specifications for consideration in design to prevent series resonance.

5.3.3 Unbalanced current flow through the PST

The purchaser must provide the details of operating conditions that will subject the PSTs to unbalanced phase currents and voltages that may exceed allowable standard limits for design consideration of the PSTs. The following are examples of operating conditions that could produce such problems:

a) Unbalances resulting from operation of parallel transmission lines in close proximity to the PST connected lines. Unequal line transpositions cause unbalanced voltage at the PSTs and unequal current flow through the series windings.

b) Single-pole operation of the circuit breakers following line faults where single pole reclosing is utilized.

5.3.4 Transient recovery voltages

Transient voltage may exist when circuit breakers are operated. These conditions may occur between the PST and the circuit breaker.

5.3.5 Surge protection

Any condition where the PST may operate without surge protection applied at all S and L terminals.

5.4 Protection

The protection scheme recommended for PSTs is similar to that for power transformers with one notable exception: differential relaying. In general, transformer differential relays are designed to allow for a difference between the primary and secondary currents of the transformer of at least 10% because of the voltage taps. This is done by means of restraint windings (or logic) that desensitize the relay during high through fault currents. For a PST with a phase-angle difference of 25° between the source and load currents, the current difference would be approximately 43%, so a special differential scheme is required. In 5.4.1, differential schemes for PSTs will be briefly discussed with emphasis on the PST requirements. Ground protection is also included because of its close association with differential protection. For a more detailed discussion of differential and ground protection, see Applied Protective Relaying [B3], Ibrahim and Stacosm [B11], Sen and Craig [B32], Li [B22], Ibrahim et al. [B10], Plumptre [B31], and Brown et al. [B6]. Other types of protection are discussed in 5.4.2.

5.4.1 Differential and ground protection

The complete current transformer (CT) requirements must be determined and the purchaser must agree to the locations before the design can be finalized because internal "buried" CTs are often required. Protection schemes are different for single-core and two-core type constructions.

5.4.1.1 Single-core arrangement

A differential scheme for the single-core arrangements shown in Figure 7 and Figure 8 should provide primary differential protection that will not misoperate because of PST core saturation. A three-phase transformer differential relay is required with three restraint elements per phase. It is preferable that the CT's have the same ratings and ratios, although the relay can typically compensate for some mismatch.

5.4.1.2 Two-core arrangement

The most common differential scheme for the two-core arrangement shown in Figure 11 is shown in Figure 15 and Figure 16. There are two sets of differential protection. Figure 15 shows the primary set and Figure 16 the secondary set. The two sets provide differential protection with redundancy.

The primary differential relay (Figure 15, 87P) requires a set of CTs toward the neutral end of the primary winding of the exciting unit. These will probably be inside the tank. It is preferable that these CTs have the same rating and ratio as the high-side CTs, although the differential relay can compensate for some mismatch. This scheme is not affected by PST core saturation. A ground relay (51N1) is usually installed in the neutral of the primary winding of the exciting unit to provide sensitive protection for ground faults near the neutral. It will see current during ground faults on the system. The amount of current will depend on the sequence network impedance. If the exciting unit is of shell form construction, the zero sequence current will be relatively high. However, if it is of core form construction or if the secondary circuits provide a path for zero sequence currents because of voltage regulating windings on the exciting unit (see Applied Protective Relaying [B3], and Sen and Craig, p. 7 [B32]), then the zero sequence impedance will be much lower and 51N1 must coordinate with line side ground relays. The 51N1 relay is also subject to false operation because of the inrush current when the exciting unit is energized. To prevent this from happening, the relay must be desensitized or a relay with a second harmonic restraint used (see Plumptre, p. 5 [B31]). The associated CT may be external to the tank.

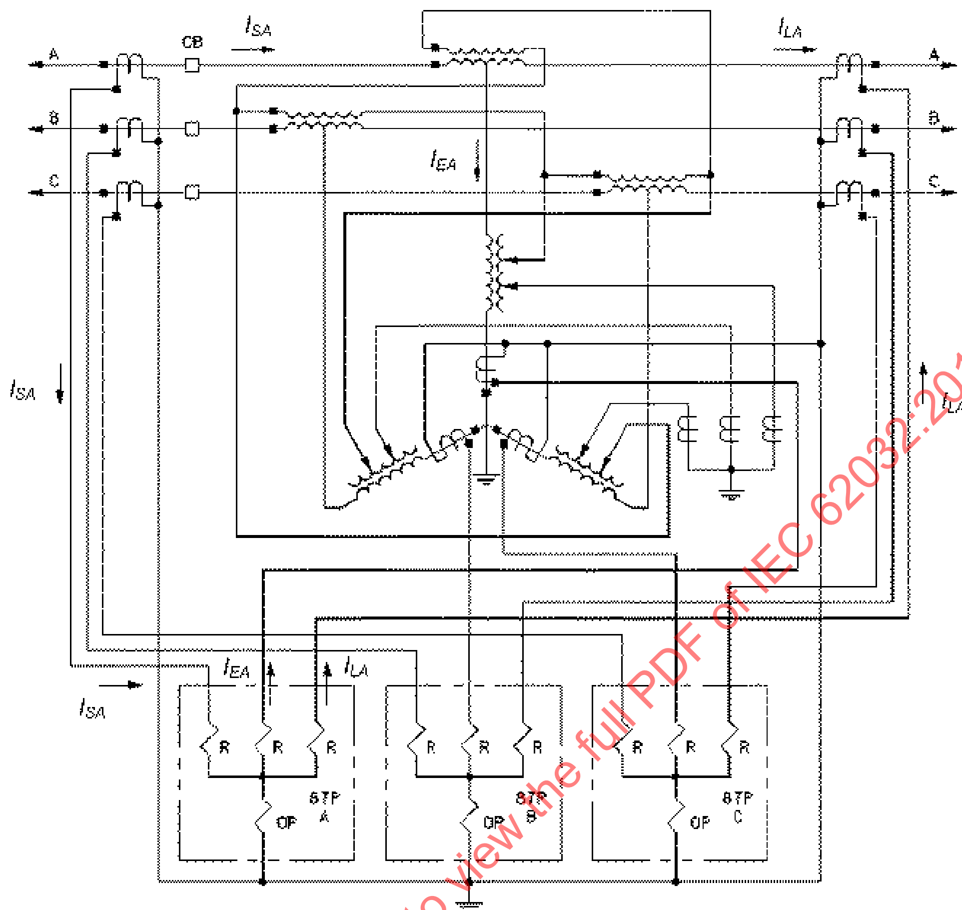

Figure 15—Primary differential relay

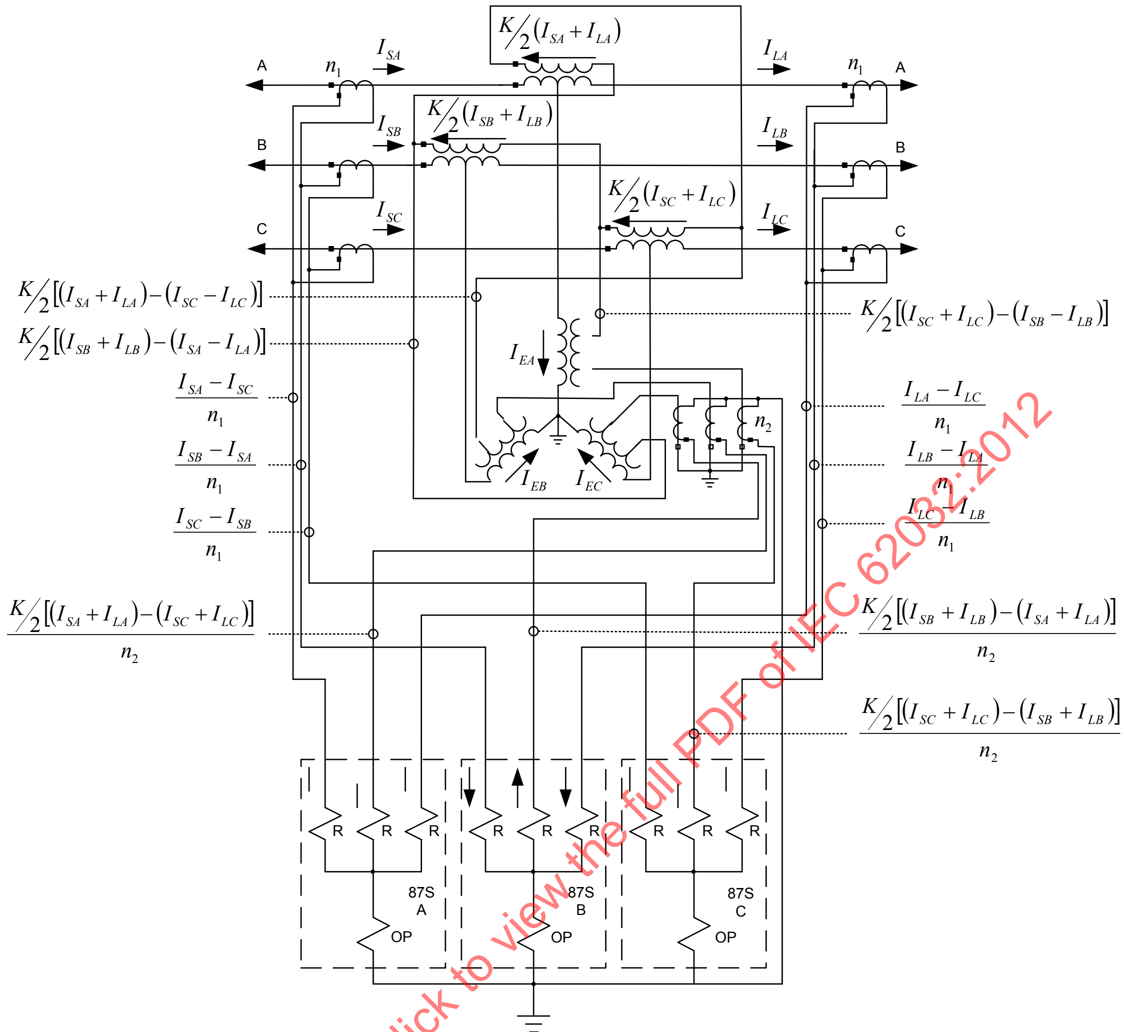

Figure 16 —Secondary differential relay

The secondary differential relay (Figure 16, 87S) requires a set of CTs in the neutral of the secondary of the exciting unit. They will also most likely be inside the tank. The ratio of these CTs will be determined by the ratio (K) of the series unit, as shown in Figure 16. The differential relay can compensate for some CT mismatch. The rating of the CTs should closely match the high-side CTs. A three-phase transformer differential relay is required with three restraint elements per phase. The integrity of this scheme depends on the value of "K" remaining constant ~(the series unit not saturating). Because the voltage rating of the series unit is considerably smaller than rated phase-to-ground voltage, it is possible that it might saturate during high through faults (see p. 397 of Ibrahim and Stacom [B10]). If series unit saturation is a problem, then desensitizing the secondary relay system is required. A ground relay (50N2) is usually installed in the neutral of the exciting unit secondary winding. This relay can be set sensitive because there should be current in it only during a fault in the exciting unit secondary circuit. The associated CT may be external to the tank.

5.4.2 Other types of protection

5.4.2.1 Sudden-pressure (rapid rate of rise) relaying

Sudden-pressure relays protect for arcing faults. It is common practice to have one or more sudden-pressure relays for each oil-filled tank and separate compartments; the number of relays depends on the oil volume. The PST manufacturer should recommend the quantity, location, and type of sudden-pressure relays and the settings if not specified by the purchaser. Also, Buchholz relays will protect for oil displacement.

5.4.2.2 Pressure-relief device

Each oil-filled tank and separate oil-filled compartment shall be provided with a pressure-relief device. It is common practice to have more than one pressure-relief device on large tanks. The number of pressure-relief devices should be determined by the manufacturer.

5.4.2.3 Gas accumulation relay

Gas bubbles generated in the oil will migrate toward the top of the oil compartment. The use of a device to accumulate the gas and cause an alarm or trip is recommended for each compartment.

6. Rating data

In general, the rating data for PSTs should be in accordance with the requirements for power transformers as covered in IEEE Std C57.12.00 or IEC 60076-1 with the following exceptions or additions.

6.1 Polarity, angular displacement, and terminal markings

6.1.1 Terminal markings unique to PSTs

The designations H and X shall not be used and shall be replaced by S and L to indicate the Source and Load. The S terminals shall be marked S_1, S_2, S_3, and (if applicable) S_0. The L terminals shall be marked L_1, L_2, L_3, and (if applicable) L_0. Y and Z designations shall be used for additional windings that are brought out of the tank.

6.1.2 Enclosed throat connection terminal markings

Enclosed throat winding terminal connections shall be marked in any manner that will permit convenient reference and shall not be confused with the markings of the external transformer terminals.

6.2 Impedance

Impedance shall be in accordance with IEEE Std C57.12.00 or IEC 60076-1 with the following additions.

6.2.1 General

Rated impedance shall be at zero phase-shift connections.

6.2.2 Change in impedance with phase-angle regulation

The impedance of a PST can vary substantially over its range of phase-angle regulation. The user must specify the acceptable ranges of impedances, and the manufacturer shall calculate and provide a matrix of impedances as required by the user. The extent of test verification of impedance values other than rated impedance should be specified and agreed upon by the purchaser and the manufacturer.

6.3 Name plates

Nameplates shall be in accordance with IEEE Std C57.12.00 or IEC 60076-1 with the following addition.

The nameplate of the PST shall show the phase shift in degrees from the S to the L terminals starting at the zero phase-shift tap and for each tap position in the advance and retard direction while operating at no load. The nameplate shall also show the phase shift in degrees from the S to the L terminals while operating at maximum rated KVA output at unity power factor at the S terminal for all tap positions, which result in acceptable service conditions. Intermediary phase shifts at varying loads may be specified by the purchaser for inclusion on the nameplate.

The user may request impedance changes be indicated on the nameplate for any tap position.

7. Construction

In general, construction requirements for PSTs should be in accordance with the requirements for power transformers, as covered in IEEE Std C57.12.00 or IEC 60076-1 and other applicable ANSI/IEEE or IEC standards based on kV and kVA ratings, with the following exceptions or additions.

7.1 Enclosed throat connections

Enclosed throat connections in fully assembled condition must meet the pressure and vacuum requirements of PST tanks for all designs that subject the enclosed throat connection to the same operating pressures and vacuum levels as the transformer tank.

7.2 Liquid insulation and preservation system

Liquid insulation and preservation systems shall be in accordance with IEEE Std C57.12.00 or IEC 60076-1 with the following addition.

7.2.1 Two tank designs with enclosed liquid-filled throat connection

Enclosed liquid-filled throat connections may be either sealed from each tank or opened to the insulating liquid from one or both tanks. Enclosed throat connections shall be designed for installation or removal without the need of jacking or moving the transformer tanks, and it shall accommodate thermal expansion and contraction of the throat assembly and both tanks.

For a sealed throat system that isolates the insulating liquid, the throat connections require a separate conservator system.

For a system where the throats are not directly connected to a main tank and the isolation of the insulating liquid in different compartments is not important, the throats may be connected to the conservator system of the main tank. If this approach is used, then the user should be aware that the use of oil and gas analysis to isolate problems will be complicated.

For throat connections that place barriers between both the tanks and the throat, the throat shall be equipped with the following accessories:

- Gas accumulation relay
- Pressure relief device/relay
- Liquid filling and draining valves
- Sudden pressure relay
- Liquid level gauge

8. Short-circuit characteristics

8.1 Short-circuit requirements

8.1.1 General

PSTs shall comply with the short-circuit requirements of IEEE Std C57.12.00 or IEC 60076-5, unless otherwise agreed on by the purchaser and the manufacturer.

8.1.2 Transformer categories

The kVA rating to be considered for determining the category should be the equivalent to the rating according to IEEE Std C57.12.00 or IEC 60076-1.

8.1.3 Short-circuit current magnitude

The manufacturer shall determine the most onerous conditions for short circuit on every winding or active part in accordance with IEEE Std C57.12.00 or IEC 60076-5. These conditions should take into account the large impedance swings that can occur as the tap position is changed from the extreme positions to the mid position. Since the system short-circuit levels are critical to the design of PSTs, the user shall specify the maximum system short-circuit fault levels expected throughout the life of the unit.

If a short-circuit test is performed, it shall be done in accordance with IEEE Std C57.12.90™ or IEC 60076-5. The test shall be carried out on the tap position that produces the most severe stresses in each winding. This may require more than a single test depending on the type of construction.

For two-core PSTs, this usually requires a test on the zero phase-shift position, as this position involves only the series transformer and a second test on a position to be agreed on between the customer and the manufacturer.

9. Control system

9.1 Control equipment and accessories

Control devices to facilitate manual and automatic control of the load tap changing equipment shall be provided.

The control system of a PST includes a sensing apparatus to provide a signal proportioned to the system real power flow through the transformer. For this purpose, positive (+) values of power flow relate to an exchange defined as forward power flow, i.e., power from normal S terminals to normal L terminals. Similarly, negative (–) values of power flow relate to an exchange defined as reverse power flow, i.e., power from normal L terminals to normal S terminals.

The control system also includes a control device to interpret the input of the sensing apparatus, relate the input to conditions desired by the operator, and command the tap changer of the PST automatically to function to hold the power flow thereby required.

The total control system is usually furnished as a complete package with the transformer; however, the “stand-alone” nature of the control system makes it appropriate to consider the control system in a unified context.

9.1.1 Enclosure

A weather-resistant cabinet shall be provided for housing the automatic control and related devices. The cabinet shall be specified by the user.

9.2 Requirements

9.2.1 Environmental

The control must withstand –40 °C to 80 °C control enclosure temperature, relative humidity from 0% to 100%, and altitude of up to 3000 m (9900 ft) without loss of control.

9.2.2 Set point adjustment ranges

The default device shall accommodate parameter set point adjustment as follows:

NOTE—The base power (1.0 pu power) will be scaled as required based on the transformer rating.

a) Power flow adjustable from at least –2.0 pu to 2.0 pu

b) Power flow bandwidth adjustable from at least 0.025 pu to 0.25 pu

c) Fixed time delay adjustable from 0 s to at least 120 s

9.2.3 Accuracy

The control system error shall be 1% or less. The accuracy is based on the combined performance of the sensing apparatus (including instrument transformers, transducers, or other means of sensing as required) and the control device.

For determining the accuracy of the control system, the percent error is based on the following reference conditions: ambient temperature of 25 °C, rated system frequency, no harmonics present on the line, and the PST delivering rated kVA at rated voltage.

9.2.3.1 Accuracy determination criteria

The errors to be included in the determination of the accuracy of the control system are the maximum plus (+) error and the maximum minus (–) error for each of the following. The greater magnitude of the sum of the positive percent errors or the sum of the negative percent errors shall constitute the stated accuracy of the control system:

a) Error of the control system due to the ambient temperature. The control system is operated in its intended configuration and environment as pertains to the control enclosure. The use of supplemental control enclosure heaters must be reported, if used. The enclosure temperature is varied in the range of –40 °C to +65 °C while holding the transformer kVA and power system frequency at the reference conditions.

b) Error in the control system due to the system frequency. The power system frequency to which the control system sensing apparatus is connected is varied in the range of rated power system frequency ±0.25% while holding the transformer kVA and the ambient temperature at reference conditions.

c) Error in the control system due to the power throughput of the PST. The power throughput of the PST to which the sensing apparatus is connected is varied in the range of –2.0 pu to +2.0 pu (where 1.0 pu is the rated kVA of the PST), while holding the ambient temperature and the power system frequency at the reference conditions.

9.2.3.2 Errors for set point marking deviation of control device

The accuracy determination criteria allow for no error in the display of the control device set points.

9.2.4 Ancillary requirements

The following ancillary components, accessories, or functionality will be provided as part of the control system:

a) Means for display of particular parameters of interest:

- Phase angle of power system voltage, S terminals relative to L terminals
- System kVA throughput
- Power throughput, including direction as forward flow or reverse flow
- Reactive throughput, including direction as forward flow or reverse flow
- Tap changer operations counter
- Tap changer tap position

b) Status alarms:

— Control self-check—discrepancy detected

— Tap changer at end of Advance tap range

— Tap changer at end of Retard tap range

— Control system unable to accomplish desired (set point) system power flow

c) Mode selection

— Off/local manual control/automatic control selector switch

— Local manual control—advance/retard control switch

9.3 Test code for control systems

9.3.1 Design tests

9.3.1.1 Determination of accuracy of control system

9.3.1.1.1 Test for error in power due to control system inaccuracy

This design test is made at rated power system frequency ±0.01 Hz and at 25 ºC ± 1 ºC. Record the difference in control system power flow recognition to the actual system power flow in range of –1.5 pu to +1.5 pu in steps of 0.25 pu.

9.3.1.1.2 Test for error in power due to ambient temperature

This test is made at 1.0 pu forward power flow ±0.01 pu and rated system frequency ±0.01 Hz. Record the difference in system power flow recognition to actual system power flow at ambient temperature of –40 °C to +60 °C in steps of 20 °C.

9.3.1.1.3 Test for error in power due to power system frequency

This test is made at 1.0 pu forward power flow ±0.01 pu and at 25 ºC ± 1 ºC. Record the difference in control system power flow recognition to actual system power flow at system frequency of rated frequency –0.25%, at rated frequency and at rated frequency +0.25%.

9.3.1.1.4 Total control system error

For each of the three tests above, note the greatest positive error recorded and the greatest negative error recorded. (Note that the greatest positive error or greatest negative error for a given test may be zero.) Sum the three positive errors and sum the three negative errors. The error of the control system is taken to be the greater of the magnitudes of the two errors summed in this manner.

9.3.1.2 Surge withstand capability (SWC) test

The SWC test is a design test for the control device in its operating environment. To pass this test, the control device shall continue to operate properly after the test.

Refer to IEEE Std C37.90.1™-1989.

9.3.2 Routine tests

9.3.2.1 Applied voltage test

The control device shall withstand a voltage of 1500 V at rated system frequency from all terminals to case for 1 min. The test shall be performed with the control device disconnected from the system. After the test, it shall be determined that no change in calibration or performance has occurred.

9.3.2.2 Operational test

All features of the control device and its peripherals will be operated and checked for verification of proper functioning. The control is also calibrated at this point.

10. Testing of PSTs

10.1 General

Unless otherwise specified, all tests carried out at the factory should be made in accordance with IEEE Std C57.12.90 or IEC 60076-3. Additional tests, particular to PSTs, are defined in 10.2. Because the method of testing PSTs is dependent on the design, the testing methods will be mutually agreed on by the user and manufacturer.

10.1.1 Test setup for PSTs

10.1.1.1 Resonant frequency and transient voltage tests

These tests are normally performed on the core and coil assembly in air. However, they can also be performed inside the tank filled with oil and fitted with temporary bushings to give access to required test points. For a two-core design in one or more tanks, the windings must be interconnected as for impulse testing.

These tests are intended to verify the transient voltages and natural frequencies at various points in the windings, at all tap combinations, and at connections that can be compared and evaluated with studies.

10.1.1.2 Temperature tests and loss distribution

In most cases, temporary bushings must be installed for connections to windings, which are not normally accessible, to determine the various resistances for the temperature tests and to determine the losses and the distribution of these losses.

The location of these temporary bushings depends on the design and winding configuration and is subject to agreement between user and manufacturer.

For two-tank designs, the tanks may be separate to determine the losses in the various cores and windings and the temperature test. This information will be provided by the manufacturer to the user during preliminary discussions.

10.1.1.3 Dielectric test

For dielectric tests, each tank with its corresponding core and windings should be connected electrically and mechanically together as for the service condition. In most cases, temporary bushings must be installed on lower voltage windings to perform the ANSI/IEEE-standard induced test on the higher source and load side windings.

10.1.1.4 Test windings

In very high voltage PSTs, it is sometimes necessary to install an auxiliary winding next to the core for shielding purposes. This auxiliary winding can then be used for performing the induced test through the use of temporary bushings. The presence of these windings should be shown on the nameplate.

10.2 Special tests for PSTs

10.2.1 Special dielectric test

When a bypass switch is installed, the following two special dielectric tests should be specified by the user.

10.2.1.1 Special lightning impulse test

A special lightning impulse test shall be applied individually to each phase with the L and S side terminals connected together. The untested terminals should be grounded separately through resistors. The neutral terminal(s) shall be grounded through shunts for current monitoring. In some cases, it is desirable to perform the tests with the S or L terminals floating. The test shall be performed on tap positions mutually agreed on by the user and the manufacturer.

10.2.1.2 Special switching impulse test

A special switching impulse test shall be applied to each phase with the L and S side terminals under test being tied together. The other untested terminals are connected together, floating and connected to a voltage divider. The neutral terminal(s) shall be solidly grounded through a shunt for current monitoring. This test only applies to PSTs rated 345 kV and above, or as required by the user.