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Guide for the application, specification, and testing of phase-shifting transformers

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

GUIDE FOR THE APPLICATION, SPECIFICATION, AND TESTING OF PHASE-SHIFTING TRANSFORMERS

FOREWORD

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International Standard IEC/IEEE 62032 has been processed through IEC Technical Committee 14: Power transformers.

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

IEEE Std	FDIS	Report on voting
C57.135 (2001)	14/491/FDIS	14/494/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.

Attention is drawn to the fact that a certain number of graphical symbols used in this IEEE publication differ from the IEC graphical symbols laid down in IEC 60617.

Consequently, an Annex B has been created outlining the differences in the graphical symbols for diagrams between IEEE C57.135:2001 and IEC 60617. This annex is not exhaustive and only mentions the equivalences of the most important symbols used.

Once the IEC/IEEE publication has been revised, Annex B will be deleted and the graphical symbols will be put in line with IEC 60617.

The committee has decided that the contents of this publication will remain unchanged until 2006.

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

Sponsor

Transformers Committee
of the
IEEE Power Engineering Society

Approved 1 August 2002
American National Standards Institute

Approved 6 December 2001
IEEE-SA Standards Board

Abstract: Theory, application of phase-shifting transformers, and the difference of specification and testing to standard system transformers are described. 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 specifical to phase-shifting transformers is provided.
Keywords: advance phase angle, dual-core design, main transformer, power transfer, phase-shifting transformer, retard phase angle, series transformer, single-core design, special tests

IEEE Introduction

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.

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. References

This standard shall be used in conjunction with the following publications. When the following standards are superseded by an approved revision, the revision shall apply.

NOTE The user's attention is drawn to the fact that the publications referenced below have no precise equivalent among publications issued by IEC. Normally, it is the practice of the IEC to include equivalent IEC standards for standards published by other organizations at the regional or national levels. However, following comments made by national committees on 14/491/FDIS, it has been determined that as no IEC publications exist that are exactly equivalent to IEEE standards, it would be misleading to provide references to similar IEC publications. This standard therefore includes references in this clause to IEEE standards only.

IEEE Std 693™-1997, IEEE Recommended Practices for Seismic Design of Substations.[1, 2]

IEEE Std 1313.1™-1996, IEEE Standard for Insulation Coordination—Definitions, Principles, and Rules.

IEEE Std C37.90.1™-2002, IEEE Standard Surge Withstand Capability (SWC) Tests for Protective Relays and Relay Systems.

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IEEE Std C57.12.00™-2000, IEEE Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers.

IEEE Std C57.12.10™-1988, American National Standard for Transformers 230 kV and Below 833/958 through 8333/10 417 kVA, Single-Phase, and 750/862 through 60 000/80 000/100 000 kVA, Three-Phase without Load Tap Changing; and 3750/4687 Through 60 000/80 000/100 000 kVA with Load Tap Changing—Safety Requirements.

IEEE Std C57.12.70™-2000, IEEE Standard Terminal Markings and Connections for Distribution and Power Transformers.

IEEE Std C57.12.80™-2002, IEEE Standard Terminology for Power and Distribution Transformers.

IEEE Std C57.12.90™-1993, IEEE Standard Test Code for Liquid-Immersed Distribution, Power, and Regulating Transformers, and IEEE Guide for Short Circuit Testing of Distribution and Power Transformers.

IEEE Std C57.19.00™-1991 (Reaff 1997), IEEE Standard General Requirements and Test Procedures for Outdoor Power Apparatus Bushings.

IEEE Std C57.19.01™-1991 (Reaff 1997), IEEE Standard Performance Characteristics and Dimensions for Outdoor Apparatus Bushings.

IEEE Std C57.19.100™-1995 (Reaff 1997), IEEE Guide for Application of Power Apparatus Bushings.

IEEE Std C57.91™-1995, IEEE Guide for Loading Mineral-Oil-Immersed Overhead and Pad-Mounted Distribution Transformers Rated 500 kVA and Less with 65 °C or 55 C° Average Winding Rise.

IEEE Std C57.93™-1995 (Reaff 2001), IEEE Guide for Installation of Liquid-Immersed Transformers.

IEEE Std C57.131™-1995, IEEE Standard Requirements for Load Tap Changers.

3. Definitions

All definitions, except as specifically covered in this guide shall be in accordance with IEEE C57.12.80-1978 and *The Authoritative Dictionary of IEEE Standards Terms*, Seventh Edition [B10].[3]

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

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

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

3.4 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 main unit.

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

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

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

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

3.8 primary circuit of a phase-shifting transformer (PST): The circuit on the input side of a single-core PST or of the main unit of a two-core PST. This circuit is composed of the excitation winding.

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

3.10 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.

3.11 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.

3.12 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, or 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.

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

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

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

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

3.17 single-core design: A single-core phase-shifting transformer (PST) consists of a single unit in which all windings are mounted on a single core.

3.18 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).

3.19 two-core design: A two-core phase-shifting transformer (PST) consists of a series unit and a main unit. The series and the main 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. While 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, 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 (VL) leads the S terminal voltage (VS); retard means that the L terminal voltage (VL) lags the S terminal voltage (VS).

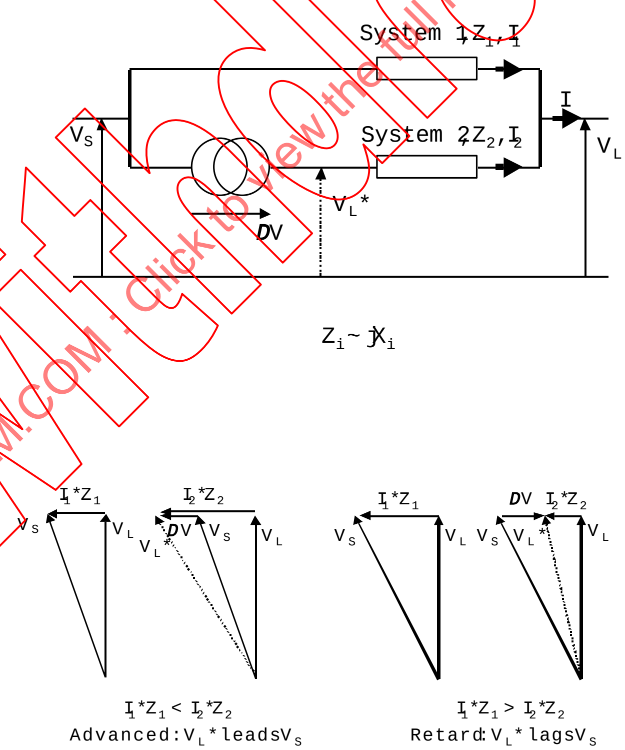

Figure 1—Load-side power factor of 1

$$I_2 \times Z_2 - \Delta V = I_1 \times I_1 \Rightarrow \Delta V = I_2 \times Z_2 - I_1 \times Z_1 \quad (1)$$

A numerical example should illustrate this. If it is required that both systems are loaded with 50% of the total transferred power 2S, and the impedances are assumed to be z_1 = 0.02 and z_2 = .30, related to S, the necessary additional voltage becomes ΔV = .30 – 0.02 = .28. Hence, a load phase angle (advanced) of about 15.6° is necessary. The total angle between source and load becomes 1.1°. In the case of 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, 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).

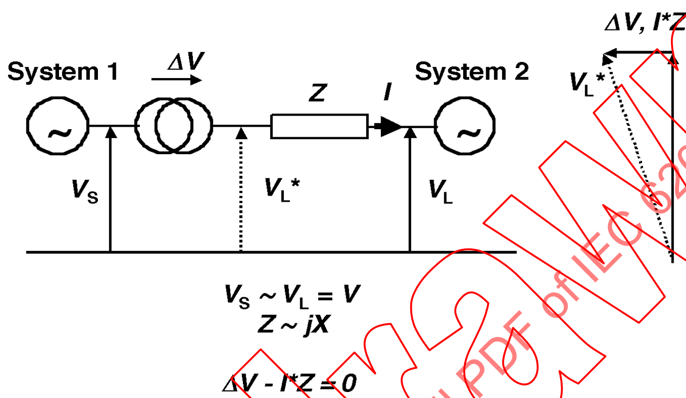

Figure 2—Advanced phase-shifting angle

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

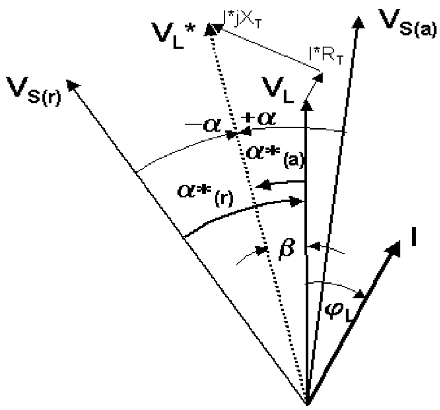

Figure 3—Demonstration of load conditions

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^* at its primary side can be obtained. The load phase angle β can be calculated by using Equation (2).

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

The phase-shifting unit adds ±α and so, finally, the load phase angles of the transformer $\alpha^*_{(a)}$ and $\alpha^*_{(r)}$ respectively are obtained.

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

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

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 β 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 dealt with 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, by the PST, an 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 zero degree phase shift).

With the denotations used in Figure 3 and

P_0	is power transferred when α = 0	(preload)
Q_0	is reactive power transferred when α = 0	(preload)

the power components at the source side become

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

$$Q(\alpha) \;=\; P_0{*}\sin\alpha + Q_0{*}\cos\alpha + \frac{V_S^{\;2}}{X_T}(1 - \cos\alpha_o) \qquad (6)$$

Figure 4 explains the effect of the introduction of the phase-shift angle α. In the equation, the first two terms reflect the effect of the phase angle on the original power flow as easily as 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 $\Delta V(-\Delta V\ cos(\alpha/2)$ drives a current with a positive imaginary component, and the imaginary component of $\Delta V(\Delta V^{*}\sin(\alpha/2))$ a current with a positive real component and that $\Delta V = 2^{*}V_s^{\;*}\sin(\alpha/2)$, the last terms in Equation (3) and Equation (4) respectively can be confirmed without difficulties.

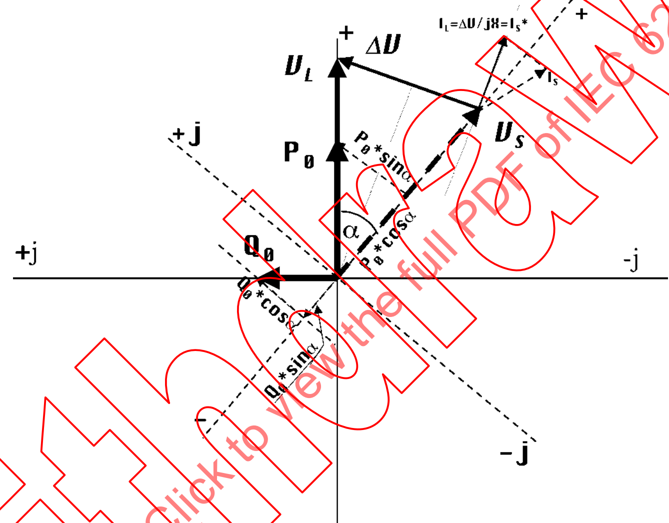

Figure 4—Effect of phase-shift angle α

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 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 transferred power 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 the major impact on the influence of the PST angle.

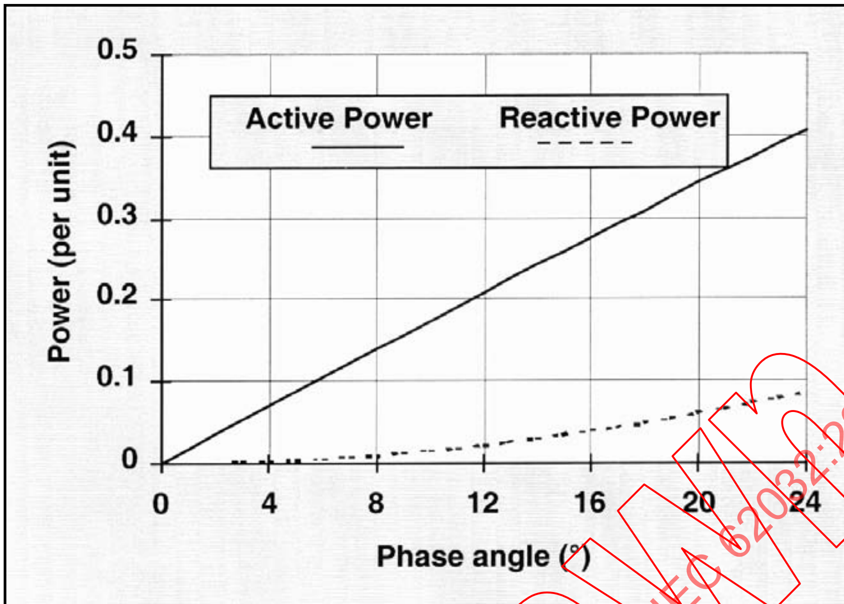

Figure 5—Variation of additional power flow with the PST angle α

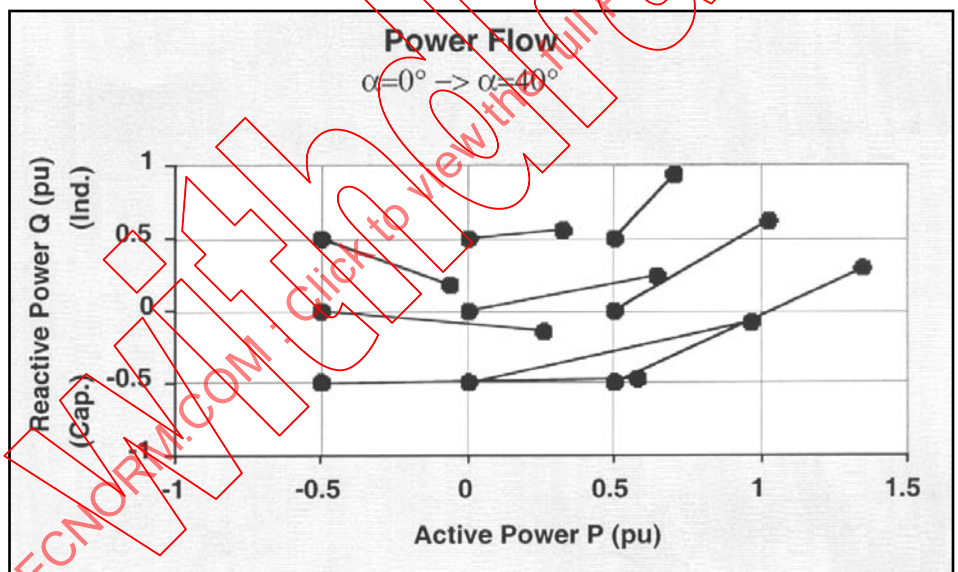

Figure 6—Variation of power flow with the phase-shift angle α depending on different preload conditions

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 7a shows an elementary arrangement; the phasor diagrams are drawn for 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 no-load condition the regulation is symmetrical, i.e., the absolute values of source and load voltage are the same.

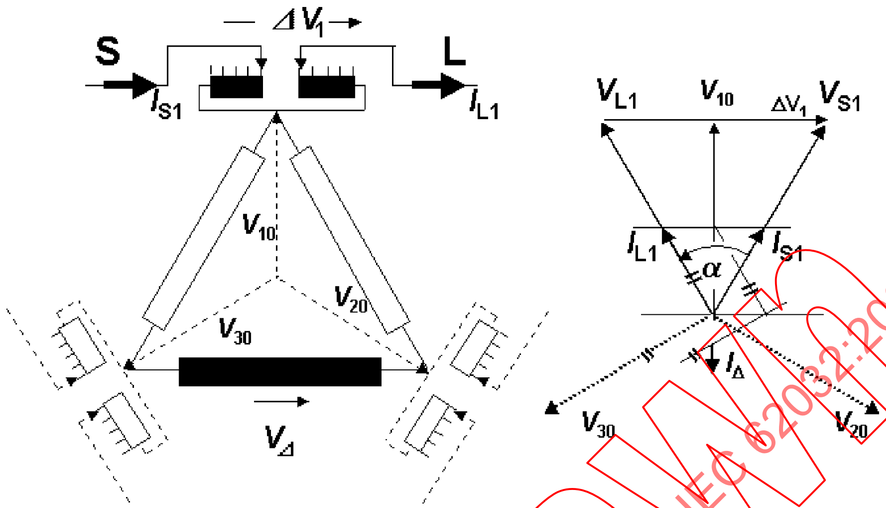

Figure 7a—Phasor diagrams for no-load condition

$$V_{S1} = V_{10} + \frac{\Delta V_1}{2} \quad (7)$$

$$V_{L1} = V_{10} - \frac{\Delta V_1}{2} \quad (8)$$

$$V_{\Delta} = V_{20} - V_{30} \quad (9)$$

With consideration of these equations, the phasor diagram can be drawn and absolute values can be determined.

$$V_{S1} = V_{L1} = V_1 \quad (10)$$

$$V_{10} = V_1 * \cos\frac{\alpha}{2} \quad (11)$$

$$\Delta V_1 = V_1 * 2 * \sin\frac{\alpha}{2} \quad (12)$$

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

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

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

The rated throughput power of the PST is shown in Equation (7).

$$P_s = 3 * V_1 * \underline{I}_{L1} \tag{16}$$

whereas the rated design power which determines the size of the unit becomes:

$$P_T = 3 * \Delta \underline{V}_1 * \underline{I}_{L1} = P_s * 2 * \sin\frac{\alpha}{2} \tag{17}$$

In practice many solutions are possible to the design of 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 given below:

Performance factors

— The power rating and phase-shift angle requirements
— The voltages
— The connected system's short-circuit capability

Design factors

— Type of construction (core form or shell form)
— Layer or disc winding design
— Shipping limitations
— Load tap changer (LTC) performance specification

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 the following clauses.

4.5.2 Single-core design

With the design outlined in Figure 7a, symmetrical conditions are obtained. The LTC can also be equipped with a reversing change-over 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 that case the load voltage increases with respect to the source voltage with increasing phase angle (Figure 7b).

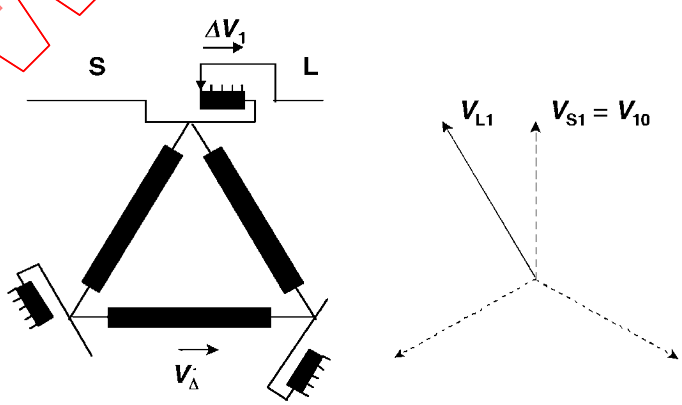

Figure 7b—PST with half tap winding

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 8.

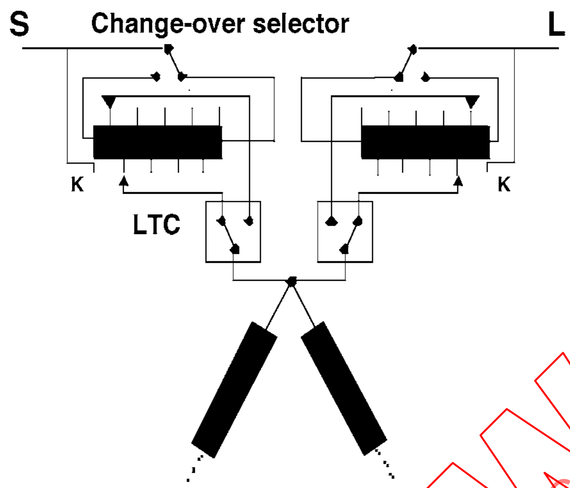

Figure 8—PST with small switching capacity

As a further example, Figure 9 shows the connection diagram and the phasor diagram of a *delta-hexagonal* PST. These transformers have LTCs with linear regulation, i.e., without a change-over selector.[4]

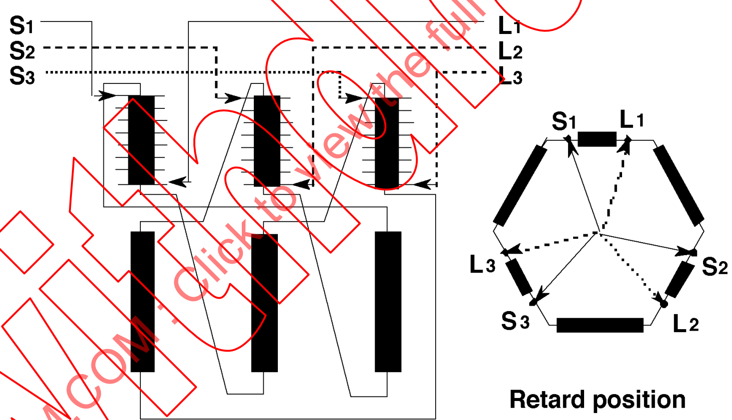

Figure 9—Connection diagram and the phasor diagram of a *delta-hexagonal* PST

The single-core design is less complex and has fewer kVA parts 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 short-circuit currents and overvoltages.
— Voltage per tap and current are determined by the phase angle requirement and rating of the PST and cannot be adjusted to obtain optimum switching conditions. If one of these parameters exceeds its limit, the solution would not be possible although the required switching capability may still be given.

[4]There are numerous other possibilities, e.g., designs with de-energized operation.

4.5.3 Two-core design

The most commonly used circuit for two-core designs is shown in Figure 10. This configuration consists of a series unit and a main unit. For smaller ratings and lower voltages, two-core PSTs may be built into one single tank, while 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. Since LTCs have limited current ratings and step voltages per phase as well as limited 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. If the rated switching capacity is too high, three single-pole LTCs have to 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.

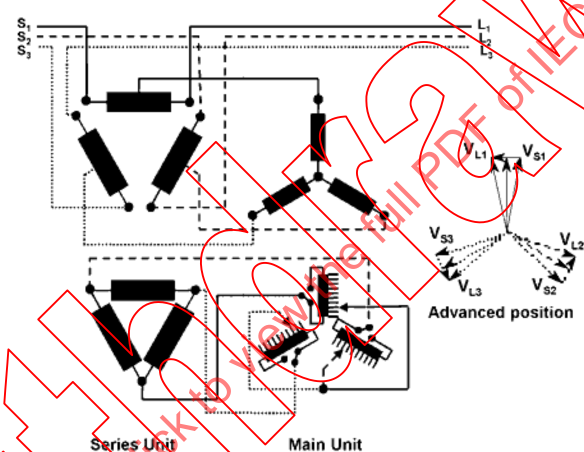

Figure 10—Commonly used circuit for two-core designs

4.6 Special on load tap changer (OLTC) features

4.6.1 Potential connection of the regulating winding

During the operation of the reversing change-over 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 grounded parts. The resulting differential voltage exerts stress across the switching distance of the opening change-over selector contacts. In the case of PSTs having regulation at the line end, high recovery voltages can occur due to the winding arrangement. The change-over operation takes place in the mid-position of the LTC, i.e., when the tap selectors are in position “K” (see Figure 8).

Figure 11 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 15–35 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.

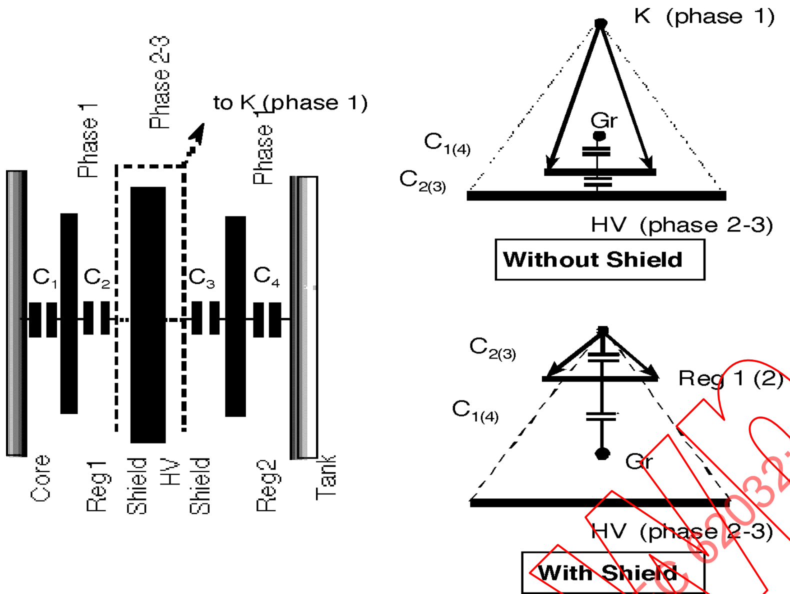

Figure 11—Impact of shields on recovery voltage

Both recovery voltages occurring during reversing change-over 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 milliamperes.

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, one of the following solutions has to be used to solve the problem:

a) The first way is to connect the tap winding to a fixed potential during the reversing change-over operation by a fixed ohmic resistor or capacitor that 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 11, when no shields are used). The connection of resistors or capacitors increases the amount of switched current due to the small resistance compared to that of the capacitances.

b) The second possibility is to use an advance-retard switch (ARS) as shown in Figure 12. This switch allows the reversing change-over 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.

4.6.2 LTC with coarse change-over selector

By using the change-over selector 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, an additional switching device, which has to be designed like an ARS, is necessary so that the switching can be performed without interruption of the load current. The ARS has to control the process of commutation which, in this case, is not only determined 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 de-energized transformer, an off-circuit tap changer is sufficient. Figure 13 shows different arrangements with coarse change-over selectors (a, b) and, in addition, the use of two LTCs (c). Also the arrangement of an ARS for the exciting winding of the series transformer is shown in (b).

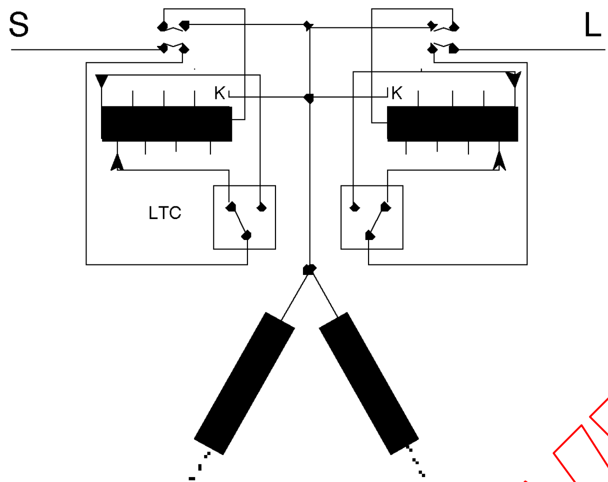

Figure 12—Use of ARS

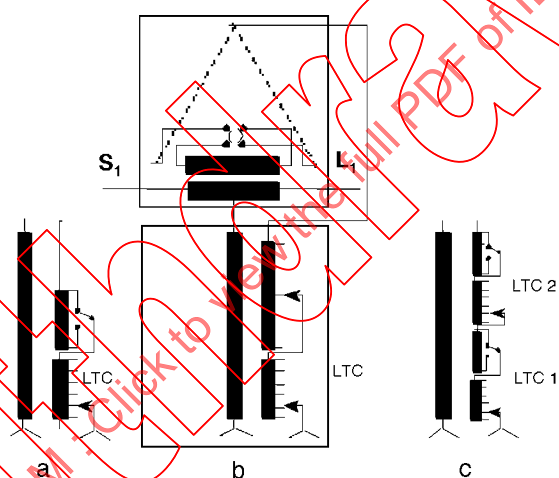

Figure 13—Different arrangements with coarse change-over selectors

4.6.3 Number of OLTCs required

See Table 1.

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.

Table 1—Minimum number of LTCs required

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

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

4.7.2 Parallel connection of PSTs

If two or more (n) identical PSTs are connected in parallel, the impedance 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.

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 due to 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). In the retard position the power that can be transferred is usually lower than the rated power in the advanced position.

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 two-tank design

When the two-core design is used with two tanks, special precautions must be taken to design connections between the two tanks. As illustrated in Figure 10, 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 possible at all, in a significant increase in cost. Therefore, it is strongly recommended to use metal enclosures to protect the connections against lightning strikes and other possible sources of a short circuit.

4.8.4 Overload conditions (loading above nameplate rating)

Overloading of a PST in the sense of operating it with a current beyond the name-plate rating increases the internal phase angle β [see Equation (2)] and consequently also the load phase-shift 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, in this case, exceed the rated voltage. Furthermore, in a two-core design, the main transformer also 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—beside 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.

5. Service conditions

PSTs conforming to this guide will be suitable for operation at rated voltage and rated kVA as follows:

5.1 Usual service conditions

These conditions shall be as stated in IEEE Std C57.12.00-2000, 4.1.1 through 4.1.7, and 4.1.9; 4.1.8 shall not apply. In 4.1.6.1 (a), 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 by voltage applied to 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 693-1997. The seismic zone shall be provided by the purchaser. The foundation design shall be provided to the PST manufacturer by the

purchaser. The manufacturer shall provide for differential motion between the two tanks, if used, and in the case of remotely mounted radiators provide for their differential motion.

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 purchaser and 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 design for lightning impulse and switching surges. This condition will require additional testing with the terminals connected, as in operation, 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 IEEE Std C57.12.00-2000, 4.2, with the exception that additional limits must be observed for retard operation under overload. These limits must be defined by the manufacturer and agreed upon 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 IEEE Std C57.12.00-2000, 4.3.1 through 4.3.3. Additional unusual service conditions that may apply to PSTs are as follows:

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

The purchaser shall ensure the manufacturer has all nameplate data, test data, 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 ensure a compatible system.

5.3.2 Operation of PSTs in series with series capacitor banks

If the PST is, or may be, operated in series with a series capacitor bank, this operating condition shall be pointed out to the manufacturer by the purchaser. The operating conditions shall be specified and the protection scheme used by the purchaser to prevent series resonance shall be provided to the PST manufacturer for review and for considerations in design.

5.3.3 Unbalanced current flow through the PST

The purchaser must provide details of operating conditions that will subject the PSTs to unbalanced phase currents and voltages that may exceed allowable standard limits. The manufacturer will provide for these conditions during the design 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, where line transpositions are unequal resulting in 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 circuit breakers are operated. These conditions may be 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 heavy through fault currents. For a PST with a phase angle difference of 25° between the source and load currents, the current difference would be about 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”[B1], Brown, et al. [B4], Ibrahim, Stacom [B8], [B9], Li [B13], Plumptre [B22], and Sen, Craig [B23]. 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 since internal *buried* CTs are often required. Protection schemes are different for the two types of PST core construction: single- and two-core arrangements.

5.4.1.1 Single-core arrangement

A differential scheme for the single-core arrangements shown in Figure 7a and Figure 7b 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 CTs 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 (see Figure 10) is shown in Figure 14 and Figure 15. There are two sets of differential protection. Figure 14 shows the primary set and Figure 15, the secondary set. The two sets provide differential protection with redundancy.

The primary differential relay (Figure 14, 87P) requires a set of CTs in the neutral of the primary winding of the main 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 of the main 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 main 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 main unit (see “Applied Protective Relaying” [B1], and Sen, Craig [B23]), 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 due to inrush current when the main unit is energized. To prevent this from happening, the relay must be desensitized or a relay with second harmonic restraint used (see Plumptre [B22]). The associated CT may be external to the tank.

The secondary differential relay (Figure 15, 87S) requires a set of CTs in the neutral of the secondary of the main 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 15. 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. Since the voltage rating of the series unit is considerably smaller than rated phase-to-ground voltage, it is possible that it might saturate during heavy through faults (see Ibrahim, Stacom [B8]). If series unit saturation is a problem, desensitizing the secondary relay system is required. A ground relay (50N2) is usually installed in the neutral of the main unit secondary winding. This relay can be set quite sensitive since there should be current in it only during a fault in the main 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 compartment, the number of relays depending 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. Buchholz relays also 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.

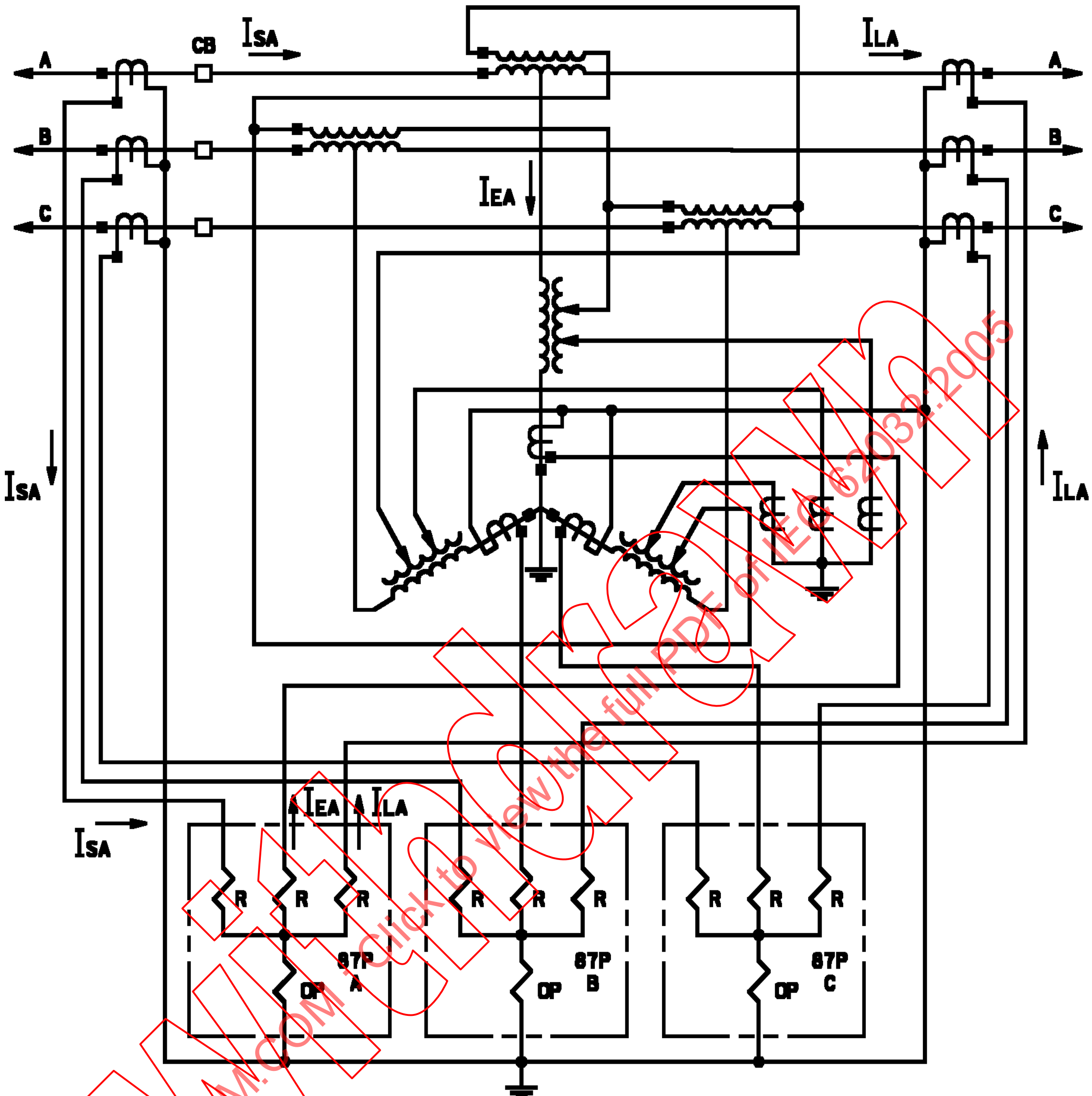

Figure 14—Primary differential relay

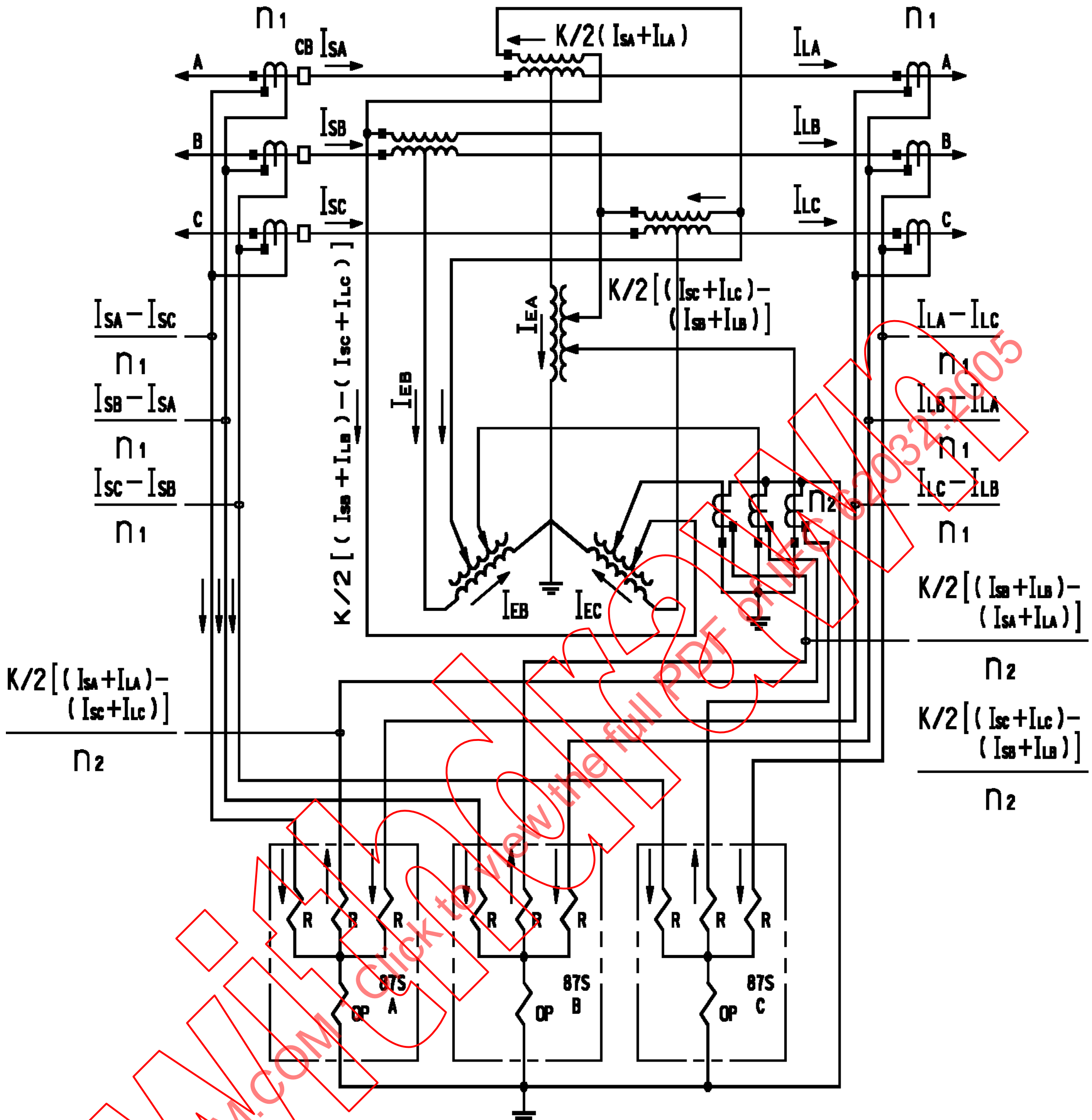

Figure 15—Secondary differential relay

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, rating data for PSTs should be in accordance with the requirements for power transformers as covered in IEEE Std C57.12.00-2000™ 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 cannot be confused with the markings of the external transformer terminals.

6.2 Impedance

Impedance shall be in accordance with IEEE Std C57.12.00-2000™ 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 PSTs 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 manufacturer.

6.3 Nameplates

Nameplates shall be in accordance with IEEE Std C57.12.00-2000 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 C57.12.00-2000 and other applicable IEEE 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 C57.12.00-2000 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 fluid from one or both tanks. Enclosed throat connections shall be designed for installation or removal without the need to jack or move either or both of the transformer tanks and shall accommodate thermal expansion and contraction of the throat assembly and both tanks.

For a sealed throat system that isolates the insulating fluid, 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 fluid in different compartments is not important, the throats may be connected to the conservator system of the main tank. If this approach is used, 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
- Rapid rate of rise 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 C57.12.00-2000, unless otherwise agreed upon by the purchaser and 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 C57.12.00-2000.

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 C57.12.00-2000. 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 C57.12.90-1993. 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 upon between customer and 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 (FPF), 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 (RPF), 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 to automatically command the tap changer of the PST 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.

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–80 °C control enclosure temperature, relative humidity from 0–100% and altitude of up to 3000 m without loss of control.

9.2.2 Set point adjustment ranges

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

a) Power flow adjustable from at least –2.0 pu–2.0 pu
b) Power flow bandwidth adjustable from at least 0.025 pu–0.25 pu
c) Fixed time delay adjustable from 0 s to at least 120 s

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

9.2.3 Accuracy

The control system error shall be 1.0% or less. The accuracy is based upon 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–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–2.0 pu (where 1.0 pu is taken as 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:
    1) Phase angle of power system voltage, S terminals relative to L terminals
    2) System kVA throughput
    3) Power throughput, including direction as forward flow or reverse flow
    4) Reactive throughput, including direction as forward flow or reverse flow
    5) Tap-changer operations counter
    6) Tap-changer tap position
b) Status alarms:
    1) Control self-check—discrepancy detected

2) Tap changer at end of advance tap range
3) Tap changer at end of retard tap range
4) Control system unable to accomplish desired (set point) system power flow

c) Mode selection
1) Off/local manual control/automatic control selector switch
2) 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 actual system power flow in range of –1.5 pu–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–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 magnitude of the summed errors.

9.3.1.2 Surge withstand capability (SWC) test

The SWC test is a design test for the control device in its operating environment. In order 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 minute. 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 C57.12.90-1993. Additional tests, particular to PSTs, are defined in 11.2, Special tests for PSTs. Since the method of testing PSTs is dependent on the design, the testing methods will be mutually agreed upon by the user and manufacturer.

10.1.1 Test set-up 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 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, in order 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 in order to perform the IEEE standard low frequency induced test on the higher source and load side 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 low-frequency induced test through the use of temporary bushings.