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

IEEE Power Engineering Society

Sponsored by the
Transformers Committee



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**Transformers Committee
of the
IEEE Power Engineering Society**

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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 specific 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

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Introduction

(This introduction is not part of IEEE Std C57.135-2001, 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.

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IEEE 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.

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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²IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (<http://standards.ieee.org/>).

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.

³The 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 (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).

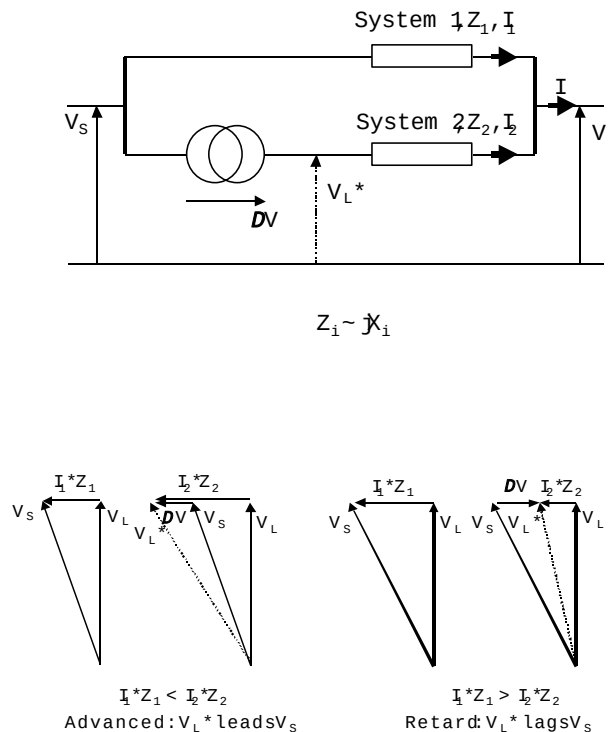


Figure 1—Load-side power factor of 1

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

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 $\Delta V = .30 - 0.02 = .28$. 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).

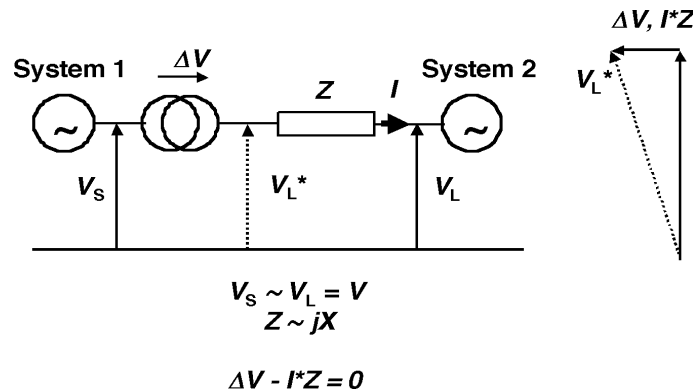


Figure 2—Advanced phase-shifting angle

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,
- $\cos \phi_L$ is load power factor,
- z_T is transformer impedance,
- β is transformer load angle,
- α is phase-shift angle,
 - + advanced
 - retard.