

Recognized as an
American National Standard (ANSI)

IEEE Std C57.12.90-1993
(Revision of IEEE C57.12.90-1987)

IEEE Standard Test Code for Liquid-Immersed Distribution, Power, and Regulating Transformers and IEEE Guide for Short-Circuit Testing of Distribution and Power Transformers

Sponsor

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

Approved March 18, 1993

IEEE Standards Board

Approved August 18, 1993

American National Standards Institute

Abstract: Methods for performing tests specified in IEEE Std C57.12.00-1993, IEEE Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers, and other standards applicable to liquid-immersed distribution, power, and regulating transformers are described. Instrument transformers, step-voltage and induction voltage regulators, arc furnace transformers, rectifier transformers, specialty transformers, grounding transformers, and mine transformers are excluded. This standard covers resistance measurement, polarity and phase-relation tests, ratio tests, no-load-loss and excitation current measurements, impedance and load-loss measurements, dielectric tests, temperature tests, short-circuit tests, and audible-sound-level measurements.

Keywords: transformers, transformer tests, tests

The Institute of Electrical and Electronics Engineers, Inc.
345 East 47th Street, New York, NY 10017-2394, USA

Copyright © 1993 by the Institute of Electrical and Electronics Engineers, Inc.
All rights reserved. Published 1993. Printed in the United States of America

ISBN 1-55937-295-8

No part of this publication may be reproduced in any form, in an electronic retrieval system or otherwise, without the prior written permission of the publisher.

IEEE Standards documents are developed within the Technical Committees of the IEEE Societies and the Standards Coordinating Committees of the IEEE Standards Board. Members of the committees serve voluntarily and without compensation. They are not necessarily members of the Institute. The standards developed within IEEE represent a consensus of the broad expertise on the subject within the Institute as well as those activities outside of IEEE that have expressed an interest in participating in the development of the standard.

Use of an IEEE Standard is wholly voluntary. The existence of an IEEE Standard does not imply that there are no other ways to produce, test, measure, purchase, market, or provide other goods and services related to the scope of the IEEE Standard. Furthermore, the viewpoint expressed at the time a standard is approved and issued is subject to change brought about through developments in the state of the art and comments received from users of the standard. Every IEEE Standard is subjected to review at least every five years for revision or reaffirmation. When a document is more than five years old and has not been reaffirmed, it is reasonable to conclude that its contents, although still of some value, do not wholly reflect the present state of the art. Users are cautioned to check to determine that they have the latest edition of any IEEE Standard.

Comments for revision of IEEE Standards are welcome from any interested party, regardless of membership affiliation with IEEE. Suggestions for changes in documents should be in the form of a proposed change of text, together with appropriate supporting comments.

Interpretations: Occasionally questions may arise regarding the meaning of portions of standards as they relate to specific applications. When the need for interpretations is brought to the attention of IEEE, the Institute will initiate action to prepare appropriate responses. Since IEEE Standards represent a consensus of all concerned interests, it is important to ensure that any interpretation has also received the concurrence of a balance of interests. For this reason IEEE and the members of its technical committees are not able to provide an instant response to interpretation requests except in those cases where the matter has previously received formal consideration.

Comments on standards and requests for interpretations should be addressed to:

Secretary, IEEE Standards Board
445 Hoes Lane
P.O. Box 1331
Piscataway, NJ 08855-1331
USA

IEEE Standards documents are adopted by the Institute of Electrical and Electronics Engineers without regard to whether their adoption may involve patents on articles, materials, or processes. Such adoption does not assume any liability to any patent owner, nor does it assume any obligation whatever to parties adopting the standards documents.

Introduction

(This introduction is not a part of 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.)

This document is a voluntary consensus standard. Its use may become mandatory only when required by a duly constituted legal authority, or when specified in a contractual relationship. To meet specialized needs and to allow innovation, specific changes are permissible when mutually determined by the user and the producer, provided such changes do not violate existing laws, and are considered technically adequate for the function intended.

When this standard is used on a mandatory basis, the words *shall* and *must* indicate mandatory requirements, and the words *should* or *may* refer to matters that are recommended or permissive, but not mandatory.

This revision of IEEE Std C57.12.90 covers only some clauses of Part I. The clauses that have been extensively revised are: a) clause 8, which covers measurement of no-load losses and excitation current; b) clause 9, which covers measurement of load losses and impedance voltage; and c) clause 13, which covers measurement of audible sound emissions. Also, a new subclause 10.4 titled “Routine impulse test for distribution transformers” has been added to clause 10.

However, in the rest of Part I, only editorial changes have been made. These include a revision of the references in clause 3, renumbering of all figures after figure 13, and renumbering of all tables and equations. Also, two tables that were mistakenly put in the wrong clauses in the 1987 revision, are now placed where they belong. These are: a) Table 2 (now Table 6) which has been moved from clause 10 to clause 11; and b) the temperature correction factor table (now Table 5) that was at the end of clause 12, is now placed where it should be, in clause 10. The table of contents has also been revised to reflect all changes made.

This revision does not affect Part II of IEEE Std C57.12.90 except for suitable corrections when references are made to documents listed in clause 3 of Part I.

Revision of the individual clauses that have been modified were prepared by separate groups within the IEEE Transformers Committee and were balloted independently according to the applicable rules and procedures of IEEE and ANSI for the preparation and approval of voluntary consensus standards. It was approved by the IEEE Transformers Committee, the IEEE Standards Board, and the ANSI C57 Committee for Distribution and Power Transformers and Regulators. The applicable rules and procedures were followed. These specify procedures for voting, review and attempted reconciliation of dissenting viewpoints, a 60-day public review period, and final review and approval by the ANSI Board of Standards Review. A special task force was also appointed to coordinate all the approved changes into one complete document and link them together in a logical manner.

The task force that coordinated the consolidation of this standard had the following membership:

Georges H. Vaillancourt, Chair

O. R. Compton

W. R. Henning
J. R. Rossetti

A. M. Teplitzky

At the time clauses 8 and 9 of this standard were approved by the IEEE Transformers Committee, the Working Group on Loss Tolerance and Measurement that developed the revision of clauses 8 and 9 had the following membership:

William R. Henning, *Chair*

D. J. Allan	Philip J. Hopkinson	C. R. Murray
B. F. Allen	O. W. Iwanusiw	R. J. Musil
J. Antweiler	C. P. Kappeler	L. M. Nicholas
D. E. Ballard	S. P. Kennedy	J. Puri
D. A. Barnard	R. L. Lane	G. J. Reitter
D. L. Basel	R. E. Lee	J. R. Rossetti
W. B. Binder, Jr.	L. A. Lowdermilk	H. J. Sim
J. D. Borst	K. Tito Massouda	E. So
John Bosiger	J. W. Matthews	James A. Tingen
R. H. Frazer	C. J. McMillen	D. E. Truax
R. S. Girgis	S. P. Mehta	B. H. Ward
George E. Henry, III	S. P. Moore	Alan. Wilks

At the time clause 10.4 of this standard was approved by the IEEE Transformers Committee, the Working Group on Revision of Dielectric Test for Distribution Transformer that developed clause 10.4 had the following membership:

John R. Rossetti, *Chair*

J. L. Akers	W. R. Henning	J. Puri
J. C. Arnold	G. E. Henry	H. J. Sim
T. Brennan	P. J. Hopkinson	J. E. Smith
C. V. Brown	C. P. Kappeler	S. D. Smith
J. L. Corkran	R. E. Lee	E. G. Strangas
D. A. Duckett	L. Lowdermilk	V. Thenappan
R. L. Ensign	T. Massouda	A. L. Wilks
M. Frydman	C. J. McMillen	W. E. Wrenn
	L. Miller	

At the time clause 13 of this standard was approved by the IEEE Transformers Committee, the Subcommittee on Audible Sound and Vibration that developed the revision of clause 13 had the following membership:

Allan M. Teplitzky, *Chair*
L. A. Swenson, *Secretary*

P. Bancroft	L. Jump	L. M. Nicholas
J. A. Ebert	J. G. Lackey	D. E. Parr
R. S. Girgis	D. Marlow	B. K. Patel
R. L. Grubb	J. W. McGill	L. W. Pierce
R. Hayes	W. J. McNutt	J. M. Pollitt
J. Hupp	C. H. Millian	R. J. Ringlee
	J. A. Molino	

The following persons were on the balloting committee:

E. J. Adolphson
Louis C. Aicher
D. J. Allan
B. F. Allen
Raymond Allustiarti
M. S. Altman
J. C. Arnold
J. Aubin
R. Bancroft
D. A. Barnard
D. L. Basel
P. L. Bellaschi
S. Bennon
Wallace B. Binder
J. V. Bonucchi
J. D. Borst
C. V. Brown
M. Cambre
Olin R. Compton
J. L. Corkran
D. W. Crofts
V. Dahinden
John N. Davis
T. Diamantis
David H. Douglas
R. F. Dudley
John C. Dutton
John A. Ebert
K. Edwards
F. E. Elliott
D. J. Fallon
H. G. Fischer
Jeffrey A. Fleeman
S. L. Foster
M. Frydman
Herman E. Gabel
Robert E. Gearhart
Dennis W. Gerlach
A. A. Ghafourian
Donald A. Gillies
R. S. Girgis
Robert L. Grubb
F. J. Gryszkiewicz
G. Hall
Kenneth Hanus
Jim H. Harlow
F. W. Heinrichs
William R. Henning

K. R. Highton
Peter J. Hoefler
R. H. Hollister
C. C. Honey
Philip J. Hopkinson
J. W. Howard
Edgar Howells
J. Hunt
Y. Peter Iijima
George W. Iliff
Anthony J. Jonnatti
R. D. Jordan
C. P. Kappeler
Richard B. Kaufman
J. J. Kelly
Sheldon P. Kennedy
William N. Kennedy
James P. Kinney
Alexander D. Kline
Egon Koenig
J. G. Lackey
J. P. Lazar
Robert E. Lee
Harold Light
S. R. Lindgren
Leonard W. Long
L. Lowdermilk
Richard I. Lowe
H. B. Margolis
Tito Massouda
John W. Matthews
J. W. McGill
Charles J. McMillen
W. J. McNutt
S. P. Mehta
C. Kent Miller
C. H. Millian
Matthew C. Mingoia
Russell E. Minkwitz
Michael I. Mitelman
Harold R. Moore
R. J. Musil
William H. Mutschler
E. T. Norton
R. A. Olsson
P. E. Orehek
Gerald A. Paiva

Bipin K. Patel
Wesley F. Patterson
J. M. Patton
P. A. Payne
Henry A. Pearce
D. Perco
D. A. Peters
Linden W. Pierce
Donald W. Platts
J. M. Pollitt
C. T. Raymond
C. A. Robbins
R. B. Robertson
M. P. Sampat
L. J. Savio
William E. Saxon
Robert W. Scheu
Devka N. Sharma
V. Shenoy
H. J. Sim
Stephen D. Smith
Leonard R. Smith
Steven L. Snyder
R. J. Stahara
W. W. Stein
L. R. Stensland
F. Stevens
D. Sundin
L. A. Swenson
David S. Takach
Louis A. Tauber
Allan M. Teplitzky
V. Thenappan
R. C. Thomas
Jerry C. Thompson
James A. Thompson
Thomas P. Traub
David E. Truax
W. Bruce Uhl
Georges H. Vaillancourt
R. A. Veitch
Loren B. Wagenaar
B. H. Ward
R. J. Whearty
D. W. Whitley
Alan L. Wilks
John Wood
W. E. Wrenn

The IEEE Standards Board approved this standard on March 18, 1993, with the following membership:

Wallace S. Read, *Chair*

Donald C. Loughry, *Vice Chair*

Andrew G. Salem, *Secretary*

Gilles A. Baril
José A. Berrios de la Paz
Clyde R. Camp
Donald C. Fleckenstein
Jay Forster*
David F. Franklin
Ramiro Garcia
Donald N. Heirman

Jim Isaak
Ben C. Johnson
Walter J. Karplus
Lorraine C. Kevra
E. G. "Al" Kiener
Ivor N. Knight
Joseph L. Koepfinger*
D. N. "Jim" Logothetis

Don T. Michael*
Marco W. Migliaro
L. John Rankine
Arthur K. Reilly
Ronald H. Reimer
Gary S. Robinson
Leonard L. Tripp
Donald W. Zipse

*Member Emeritus

Also included are the following nonvoting IEEE Standards Board liaisons:

Satish K. Aggarwal
James Beall
Richard B. Engelman
David E. Soffrin
Stanley I. Warshaw

Christopher J. Booth
IEEE Standards Project Editor

Contents

Part I

CLAUSE	PAGE
1. Scope.....	1
2. References.....	1
3. Terminology.....	3
4. General.....	4
4.1 Types of tests	4
4.2 Test requirements.....	4
4.3 Purpose.....	4
4.4 Test sequence	4
4.5 Instrumentation	5
5. Resistance measurements.....	5
5.1 Determination of cold temperature	5
5.2 Conversion of resistance measurements	5
5.3 Resistance measurement methods.....	6
6. Polarity and phase-relation tests	7
6.1 Subtractive and additive polarity	7
6.2 Polarity tests: Single-phase transformers.....	7
6.3 Polarity and phase-relation tests: Polyphase transformers.....	9
7. Ratio tests.....	13
7.1 General.....	13
7.2 Tolerances for ratio	13
7.3 Ratio test methods.....	13
8. No-load losses and excitation current	15
8.1 General.....	15
8.2 No-load loss test.....	16
8.3 Waveform correction of no-load losses	18
8.4 Temperature correction of no-load losses.....	19
8.5 Determination of excitation (no-load) current	19
9. Load losses and impedance voltage.....	20
9.1 General.....	20
9.2 Factors affecting the values of load losses and impedance voltage.....	20
9.3 Tests for measuring load losses and impedance voltage	21
9.4 Calculation of load losses and impedance voltage from test data	27
9.5 Zero-phase-sequence impedance	30

CLAUSE	PAGE
10. Dielectric tests.....	33
10.1 General.....	33
10.2 Switching impulse test procedures.....	35
10.3 Lightning impulse test procedures.....	36
10.4 Routine impulse test for distribution transformers.....	40
10.5 Low-frequency tests.....	42
10.6 Applied voltage tests.....	43
10.7 Induced voltage tests for distribution and Class I power transformers.....	43
10.8 Induced voltage test for Class II power transformers.....	44
10.9 Partial discharge measurement.....	45
10.10 Insulation power-factor tests.....	46
10.11 Insulation resistance tests.....	49
11. Temperature rise	50
11.1 Ambient temperature measurement.....	50
11.2 Liquid rise measurement.....	51
11.3 Average winding temperature-rise measurement	51
11.4 Other temperature measurements	53
11.5 Test methods	53
11.6 Correction of temperature rises for differences in altitude	56
12. Short circuit tests.....	56
12.1 Scope.....	56
12.2 Test connections.....	57
12.3 Test requirements.....	58
12.4 Test procedure.....	59
12.5 Proof of satisfactory performance.....	60
13. Audible sound emissions	61
13.1 General.....	61
13.2 Instrumentation	62
13.3 Test conditions.....	63
13.4 Microphone positions.....	65
13.5 Sound power rating	65
13.6 Presentation of results.....	68
14. Calculated data.....	70
14.1 Reference temperature	70
14.2 Losses and excitation current.....	70
14.3 Efficiency	70
14.4 Voltage regulation of a constant-voltage transformer	70
15. Bibliography	77
Annex Minimum information to be included in certified test data.....	79

Part II

CLAUSE	PAGE
1. Scope.....	81
2. Short-circuit testing techniques.....	81
2.1 Fault application.....	81
2.2 Test connections.....	82
2.3 Duration of test	82
2.4 Number of tests	84
2.5 Calibration tests	84
2.6 Voltage and current measurements	86
3. Failure-detection techniques	88
3.1 Voltage and current waveshapes.....	88
3.2 Leakage impedance.....	89
3.3 Excitation current.....	89
3.4 Low-voltage impulse (LVI) testing	89
3.5 Visual inspection.....	96
3.6 Dielectric tests.....	96
4. Analysis of test results	96
4.1 Terminal measurements	96
4.2 Visual inspection.....	98
4.3 Dielectric tests.....	106
5. Bibliography	106
Annex Essential information for inclusion in transformer short-circuit test reports	107

IEEE Standard Test Code for Liquid-Immersed Distribution, Power, and Regulating Transformers and IEEE Guide for Short-Circuit Testing of Distribution and Power Transformers

Part I: IEEE Standard Test Code for Liquid-Immersed Distribution, Power, and Regulating Transformers

1. Scope

This standard describes methods for performing tests specified in IEEE Std C57.12.00-1993¹ and other standards applicable to liquid-immersed distribution, power, and regulating transformers. It is intended for use as a basis for performance, safety, and the proper testing of such transformers.

This standard applies to all liquid-immersed transformers except instrument transformers, step-voltage and induction voltage regulators, arc furnace transformers, rectifier transformers, specialty transformers, grounding transformers, and mine transformers.

When this standard is used on a mandatory basis, the words *shall* and *must* indicate mandatory requirements; and the words *should* or *may* refer to matters that are recommended or permitted, but not mandatory.

2. References

This standard shall be used in conjunction with the following publications:

ANSI Std C57.12.10-1987, Requirements 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.²

ANSI Std C57.12.20-1988, American National Standard for Transformers—Overhead-Type Distribution Transformers, 500 kVA and Smaller: High Voltage 34 500 Volts and Below; Low Voltage 7970/13 800Y and Below.

¹Information on references can be found in clause 2.

²ANSI publications are available from the Sales Department, American National Standards Institute, 1430 Broadway, New York, NY 10018-8002, USA.

ANSI Std C57.12.21-1980, American National Standard Requirements for Pad-Mounted, Compartmental-Type, Self-Cooled, Single-Phase Distribution Transformers with High-Voltage Bushings; High-Voltage, 34 500 GrdY/19 920 Volts and Below; Low-Voltage 240/120 Volts; 167 kVA and Smaller.

ANSI Std C57.12.22-1989, American National Standard for Transformers—Pad-Mounted, Compartmental-Type, Self-Cooled, Three-Phase Distribution Transformers with High-Voltage Bushings, 2500 kVA and Smaller; High-Voltage, 34 500 GrdY/19 920 Volts and Below; Low Voltage, 480 Volts and Below.

ANSI Std C57.12.24-1988, American National Standard for Transformers—Requirements for Underground-Type Three-Phase Distribution Transformers, 2500 kVA and Smaller: High-Voltage, 34 500 GrdY/19 920 Volts and Below; Low Voltage, 480 Volts and Below.

ANSI Std C57.12.25-1990, American National Standard for Transformers—Requirements for Pad-Mounted Compartmental-Type, Self-Cooled, Single-Phase Distribution Transformers with Separable Insulated High-Voltage Connectors; High-Voltage, 34 500 GrdY/19 920 Volts and Below; Low-Voltage, 240/120; 167 kVA and Smaller.

ANSI Std C57.12.30-1977, American National Standard Requirements for Load-Tap-Changing Transformers, 230 000 Volts and Below, 3750/4687 through 60 000/80 000/100 000 kVA, Three-Phase.

ANSI Std C57.12.40-1990, American National Standard Requirements for Secondary Network Transformers—Subway and Vault Types (Liquid-Immersed).

ANSI Std C57.12.70-1978 (Reaff 1987), American National Standard Terminal Markings and Connections for Distribution and Power Transformers.

ANSI Std C63.2-1987, American National Standard Specifications for Electromagnetic Noise and Field Strength, 10 kHz to 40 GHz.

ANSI C84.1-1989, American National Standard Voltage Ratings (60 Hz) for Electric Power Systems and Equipment.

ANSI SI.4-1983, American National Standard Specification for Sound Level Meters.

ANSI Std S1.11-1986, American National Standard Specifications for Octave-Band and Fractional Octave-Band Analog and Digital Filters.

IEEE Std 4-1978, IEEE Standard Techniques for High Voltage Testing (ANSI).³

IEEE Std 100-1992, The New IEEE Standard Dictionary of Electrical and Electronics Terms (ANSI).

IEEE Std 454-1973 (Reaff 1979) (w1988), IEEE Recommended Practice for the Detection and Measurement of Partial Discharges (Corona) During Dielectric Tests.⁴

IEEE Std C57.12.00-1993, IEEE Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers (ANSI).

³IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

⁴IEEE Std 454-1973 (Reaff 1979) has been withdrawn; however, copies can be obtained from the IEEE Standards Department, IEEE, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

IEEE Std C57.12.23-1985, IEEE Standard for Transformers—Underground-Type Single-Phase Distribution Transformers, With Separable, Insulated, High-Voltage Connectors; High-Voltage (24 940 GrdY/14 400 V and Below); Low-Voltage 240/120V; 167 kVA and Smaller (ANSI).

IEEE Std C57.12.26-1992, IEEE Standard for Transformers—Pad-Mounted, Compartmental-Type, Self-Cooled, Three-Phase Distribution Transformers for Use with Separable Insulated High-Voltage Connectors (34 500 GrdY/19 920 Volts and Below; 2500 kVA and Smaller).

IEEE Std C57.12.80-1978 (Reaff 1986), IEEE Standard Terminology for Power and Distribution Transformers (ANSI).

IEEE Std C57.19.00-1991, IEEE General Requirements and Test Procedures for Outdoor Apparatus Bushings (ANSI).

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

IEEE Std C57.92-1981 (Reaff 1991), IEEE Guide for Loading Mineral-Oil-Immersed Power Transformers Up To and Including 100 MVA with 55 °C or 65 °C Winding Rise (ANSI).

IEEE Std C57.98-1986 (Reaff 1992), IEEE Guide for Transformer Impulse Tests (ANSI).

IEEE Std C57.106-1991, IEEE Guide for Acceptance and Maintenance of Insulating Oil in Equipment.

IEEE Std C57.113-1991, IEEE Guide for Partial Discharge Measurement in Liquid-Filled Power Transformers and Shunt Reactors.

3. Terminology

Standard transformer terminology available in IEEE Std C57.12.80-1978 shall apply. Other electrical terms are defined in IEEE Std 100-1992. Terms unique to this document are defined below:

3.1 actual time to crest: The time interval from the start of the transient to the time when the maximum amplitude is reached.

3.2 ambient sound pressure level: The sound pressure level measured at the test facility or at the substation without the transformer energized.

3.3 A-weighted sound level: Loudness that is measured with a sound-level meter using the A-weighted response filter that is built into the meter circuitry. The A-weighting filter is commonly used to measure community noise, and it simulates the frequency response of the human ear.

3.4 efficiency (of a transformer): The ratio of a transformer's useful power output to its total power input.

3.5 guard: One or more conducting elements arranged and connected on an electrical instrument or measuring circuit so as to divert unwanted currents from the measuring means.

3.6 C-weighted sound level: Loudness that is measured with a sound level meter using the C-weighted filter that is built into the sound level meter. The C-weighting has only little dependence on frequency over the greater part of the audible frequency range.

3.7 sound pressure level, L_p [in decibels (dB)]: Twenty times the logarithm to the base ten of the ratio of the measured sound pressure (p) to a reference pressure (p_o) of 20 micro-pascal (μPa), or

$$L_p = (20 \cdot \log_{10}) \frac{p}{p_o}$$

3.8 sound power level, L_w [in decibels (dB)]: Ten times the logarithm to the base ten of the emitted sound power (w) to a reference power of 10^{-12} watt (w_o).

$$L_w = 10 \cdot \log_{10} \left(\frac{w}{w_o} \right)$$

3.9 semi-reverberant facility: A room with a solid floor and an undetermined amount of sound-absorbing materials on the walls and ceiling.

3.10 time to first voltage zero on the tail of the wave: The time interval from the start of the transient to the time when the first voltage zero occurs on the tail of the wave.

3.11 total losses. The sum of the no-load losses and the load losses.

4. General

4.1 Types of tests

Various types of tests (routine, design, conformance, and other tests) are defined in IEEE Std C57.12.80-1978 (Reaff 1986).

4.2 Test requirements

A general summary of test requirements is included in IEEE Std C57.12.00-1993, table 17, which indicates by size which tests are normally considered routine, design, or other.

4.3 Purpose

The purpose of this standard is to provide test procedure information. Transformer requirements and specific test criteria are not a part of this standard but are contained in appropriate standards, such as IEEE Std C57.12.00-1993, ANSI Std C57.12.10-1987, ANSI Std C57.12.20-1988, ANSI Std C57.12.40-1990, or in user specifications.

4.4 Test sequence

See 10.1.5.1 for the sequence of dielectric tests when lightning impulse or switching impulse tests are specified.

NOTE—To minimize potential damage to the transformer during testing, the resistance, polarity, phase relation, ratio, no-load loss and excitation current, impedance, and load loss tests (and temperature-rise tests, when applicable) should precede dielectric tests. Using this sequence, the beginning tests involve voltages and currents, which are usually reduced as compared to rated values, thus tending to minimize damaging effects to the transformer.

4.5 Instrumentation

Although the figures in this standard show conventional meters, adequate digital readout measuring devices and digital sampling techniques with computer calculations are considered to be satisfactory alternatives.

5. Resistance measurements

Resistance measurements are of fundamental importance for the following purposes:

- a) Calculation of the I^2R component of conductor losses
- b) Calculation of winding temperatures at the end of a temperature test
- c) As a base for assessing possible damage in the field

5.1 Determination of cold temperature

The cold temperature of the winding shall be determined as accurately as possible when measuring the cold resistance. The following precautions shall be observed.

5.1.1 General

Cold resistance measurements shall not be made on a transformer when it is located in drafts or when it is located in a room in which the temperature is fluctuating rapidly.

5.1.2 Transformer windings immersed in insulating liquid

The temperature of the windings shall be assumed to be the same as the temperature of the insulating liquid, provided:

- a) The windings have been under insulating liquid with no excitation and with no current in the windings from three hours to eight hours (depending upon the size of the transformer) before the cold resistance is measured.
- b) The temperature of the insulating liquid has stabilized, and the difference between top and bottom temperature does not exceed 5 °C.

5.1.3 Transformer windings out of insulating liquid

The temperature of the windings shall be recorded as the average of several thermometers or thermocouples inserted between the coils, with care used to see that their measuring points are as nearly as possible in actual contact with the winding conductors. It should not be assumed that the windings are at the same temperature as the surrounding air.

5.2 Conversion of resistance measurements

Cold winding resistance measurements are normally converted to a standard reference temperature equal to the rated average winding temperature rise plus 20 °C. In addition, it may be necessary to convert the resistance measurements to the temperature at which the impedance loss measurements were made. The conversions are accomplished by the following formula:

$$R_s = R_m \left(\frac{T_s + T_k}{T_m + T_k} \right) \quad (1)$$

where

- R_s is resistance at desired temperature T_s
- R_m is measured resistance
- T_s is desired reference temperature °C
- T_m is the temperature at which resistance was measured °C
- T_k is 234.5 °C (copper)
- is 225 °C (aluminum)

NOTE—The value of T_k may be as high as 230 °C for alloyed aluminum.

5.3 Resistance measurement methods

5.3.1 Bridge method

Bridge methods or high-accuracy digital instrumentation are generally preferred because of their accuracy and convenience, since they may be employed for the measurement of resistances up to 10 000 Ω . They should be used in cases where the rated current of the transformer winding to be measured is less than one ampere.

NOTE—For resistance values of one ohm or more, a Wheatstone Bridge (or equivalent) is commonly used; for values less than one ohm, a Kelvin Bridge (or equivalent) is commonly used. Some modern resistance bridges have capability in both ranges.

5.3.2 Voltmeter-ammeter method

The voltmeter-ammeter method is sometimes more convenient than the bridge method. It should be employed only if the rated current of the transformer winding is one ampere or more. Digital voltmeters and digital ammeters of appropriate accuracy are commonly used in connection with temperature-rise determinations. To use this method, please perform the following steps:

- a) Measurement is made with direct current, and simultaneous readings of current and voltage are taken using the connections of figure 1. The required resistance is calculated from the readings in accordance with Ohm's Law. A battery or filtered rectifier will generally be found to be more satisfactory as a dc source than will a commutating machine. The latter may cause the voltmeter pointer to vibrate because of voltage ripple.

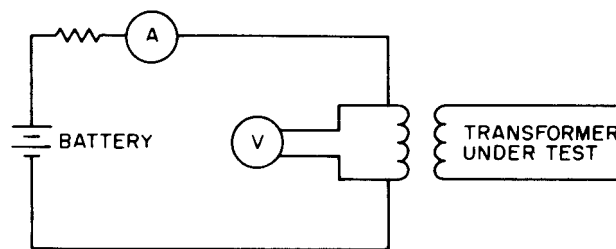


Figure 1—Connections for voltmeter-ammeter method of resistance measurement

- b) To minimize errors of observation:
 - 1) The measuring instruments shall have such ranges as will give reasonably large deflection.
 - 2) The polarity of the core magnetization shall be kept constant during all resistance readings.

NOTE—A reversal in magnetization of the core can change the time constant and result in erroneous readings.

- c) The voltmeter leads shall be independent of the current leads and shall be connected as closely as possible to the terminals of the winding to be measured. This is to avoid including in the reading the resistances of current-carrying leads and their contacts and of extra lengths of leads.

To protect the voltmeter from injury by off-scale deflections, the voltmeter should be disconnected from the circuit before switching the current on or off. To protect test personnel from inductive kick, the current should be switched off by a suitably insulated switch.

If the drop of voltage is less than one volt, a potentiometer or millivoltmeter shall be used.

- d) Readings shall not be taken until after the current and voltage have reached steady-state values.

When measuring the cold resistance, preparatory to making a heat run, note the time required for the readings to become constant. The period thereby determined should be allowed to elapse before taking the first reading when final winding hot resistance measurements are being made.

In general, the winding will exhibit a long dc time constant. To reduce the time required for the current to reach its steady-state value, a noninductive external resistor should be added in series with the dc source. The resistance should be large compared to the inductance of the winding. It will then be necessary to increase the source voltage to compensate for the voltage drop in the series resistor. The time will also be reduced by operating all other transformer windings open-circuited during these tests.

- e) Readings shall be taken with not less than four values of current when deflecting instruments are used. The average of the resistances calculated from these measurements shall be considered to be the resistance of the circuit.

The current used shall not exceed 15% of the rated current of the winding whose resistance is to be measured. Larger values may cause inaccuracy by heating the winding and thereby changing its temperature and resistance.

When the current is too low to be read on a deflecting ammeter, a shunt and digital millivoltmeter or potentiometer shall be used.

6. Polarity and phase-relation tests

Polarity and phase-relation tests are of interest primarily because of their bearing on paralleling or banking two or more transformers. Phase-relation tests are made to determine angular displacement and relative phase sequence.

6.1 Subtractive and additive polarity

Windings arranged for subtractive polarity and additive polarity are shown in figures 2 and 3.

Leads and polarity marks arranged for subtractive polarity and additive polarity are shown in figures 4 and 5.

6.2 Polarity tests: Single-phase transformers

Polarity tests on single-phase transformers shall be made in accordance with one of the following methods:

- a) Inductive kick
- b) Alternating voltage
- c) Comparison
- d) Ratio bridge

6.2.1 Polarity by inductive kick

The polarity of transformers with leads arranged as shown in figures 2, 3, 4, and 5 may be determined at the time of making the resistance measurements as follows:

- a) With direct current passing through the high-voltage winding, connect a high-voltage direct-current voltmeter across the high-voltage winding terminals so as to obtain a small deflection of the pointer.
- b) Transfer the two voltmeter leads directly across the transformer to the adjacent low-voltage leads, respectively.
- c) NOTE—For example, in figure 5, the voltmeter lead connected to H_1 will be transferred to X_2 as the adjacent lead, and that connected to H_2 to X_1 .
- d) Break direct-current excitation, thereby inducing a voltage in the low-voltage winding (inductive kick), which will cause a deflection in the voltmeter, which is interpreted in items d) and e) below.
- e) When the pointer swings in the opposite direction (negative), the polarity is subtractive.
- f) When the pointer swings in the same direction as before (positive), the polarity is additive.

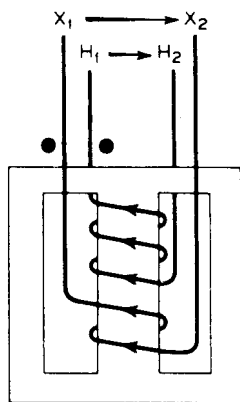


**Figure 2—
Windings: Subtractive
polarity**

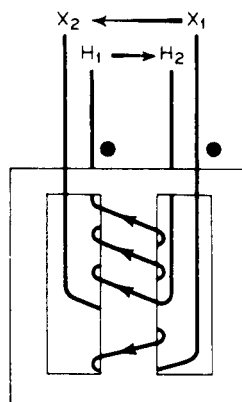


**Figure 3—Windings:
Additive
polarity**

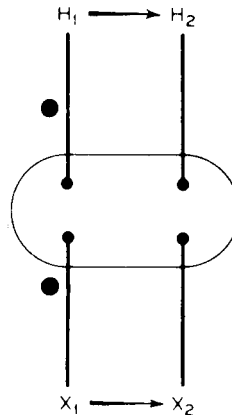


**Figure 4—Leads and
polarity marks:
Subtractive polarity**

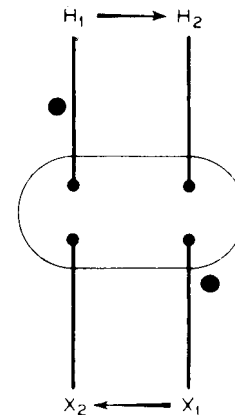


**Figure 5—Leads and
polarity marks:
Additive polarity**

6.2.2 Polarity by alternating-voltage test

For transformers having a ratio of transformation of 30 to 1 or less, the H_1 lead shall be connected to the adjacent low-voltage lead (X_1 in figure 6).

Any convenient value of alternating voltage shall be applied to the full high-voltage winding and readings taken of the applied voltage and the voltage between the right-hand adjacent high-voltage and low-voltage leads.

When the latter reading is greater than the former, the polarity is additive.

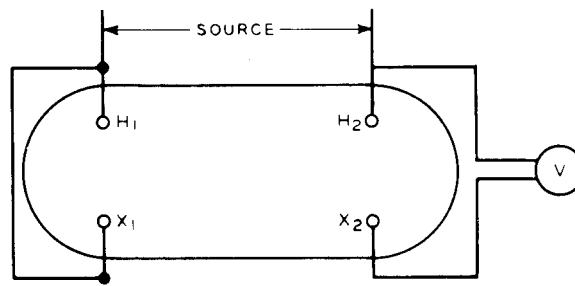


Figure 6—Polarity by alternating-voltage test

When the latter voltage reading is less than the former (indicating the approximate difference in voltage between that of the high-voltage and low-voltage windings), the polarity is subtractive.

6.2.3 Polarity by comparison

When a transformer of known polarity and of the same ratio as the unit under test is available, the polarity can be checked by comparison, as follows, similar to the comparison method used for the ratio test (see figures 9 and 10).

- Connect the high-voltage windings of both transformers in parallel by connecting similarly marked leads together.
- Connect the low-voltage leads, X_2 , of both transformers together, leaving the X_1 leads free.
- With these connections, apply a reduced value of voltage to the high-voltage windings and measure the voltage between the two free leads.

A zero or negligible reading of the voltmeter will indicate that the relative polarities of both transformers are identical.

An alternative method of checking the polarity is to substitute a low-rated fuse or suitable lamps for the voltmeter. This procedure is recommended as a precautionary measure before connecting the voltmeter.

6.2.4 Polarity by ratio bridge

The ratio bridge described in clause 7 can also be used to test polarity.

6.3 Polarity and phase-relation tests: Polyphase transformers

6.3.1 Polarity of polyphase transformers

Each phase of a polyphase transformer shall have the same relative polarity when tested in accordance with one of the methods described for single-phase transformers.

6.3.2 Phase-relation tests

6.3.2.1 Test for phasor diagram for transformers with a ratio of transformation of 30:1 or less

The phasor diagram of any three-phase transformer that defines the angular displacement and phase sequence can be verified by connecting the H_1 and X_1 leads together to excite the unit at a suitably low three-phase voltage, taking voltage measurements between the various pairs of leads and then either plotting these values or comparing them for their relative order of magnitude with the help of the corresponding diagram in figure 7 or figure 8. Typical check measurements are to be taken and their relative magnitudes are also indicated.

6.3.2.2 Zigzag windings

Equal zig and zag windings are usually necessary for zigzag transformers, although unequal windings may be used for special applications.

No required test is proposed to determine the phase relationships between the line end and neutral end sections of a zigzag winding. However, it is recommended that a test connection be made to the junction of the two winding sections and tests be made during manufacture to prove the desired phase relationships. For the purpose of designation in figure 7, zigzag windings are arbitrarily defined as windings whose line end section is rotated 60° counterclockwise with respect to the neutral end section.

6.3.2.3 Six-phase windings

Six-phase windings with no neutral connection shall be temporarily connected in delta (Δ) or wye (Y) for the test for phasor diagram.

6.3.2.4 Test of phase-relation with ratio bridge

The ratio bridge described in clause 7 can also be used to test phase relationships.

6.3.3 Phase-sequence test

The phase-sequence indicator may incorporate either a three-phase induction motor or a split-phase circuit.

It should be connected first to the higher voltage leads, the transformer excited three-phase at a low voltage suitable for the indicator, and the direction of rotation or the indication of the instrument noted.

The indicator is then transferred to the low-voltage side of the transformer by connecting the lead that was connected to H_1 to X_1 , connecting the lead that was connected to H_2 to X_2 , and connecting the lead that was connected to H_3 to X_3 .

The transformer is again excited at a suitable voltage (without changing the excitation connections) and the indication again noted.

The phase sequence of the transformer is correct when the indication is the same in both cases.

Six-phase secondaries with no neutral connection also have to be connected temporarily in Δ or Y for this test. When a six-phase neutral is available, the phase-sequence indicator leads should be transferred from H_1 to X_1 , from H_2 to X_3 , from H_3 to X_5 , respectively, and the direction of rotation should be noted. The test should then be repeated by transferring the leads from H_1 to X_2 , from H_2 to X_4 , and from H_3 to X_6 , respectively, and noting the indication, which should be the same as before.

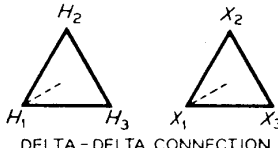
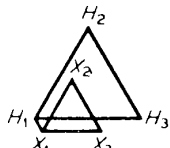
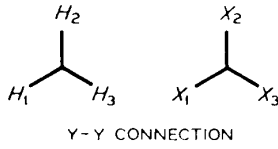
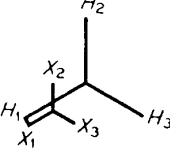
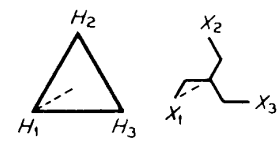
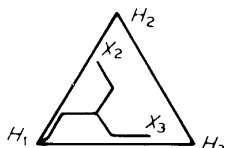
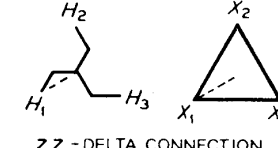
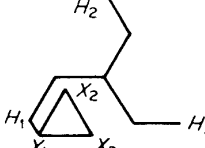
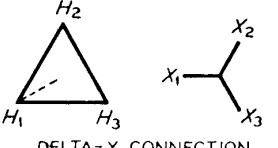
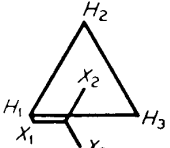
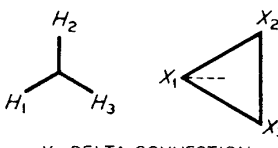
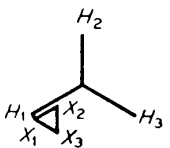
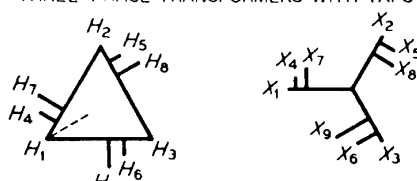
	ANGULAR DISPLACEMENT	DIAGRAM FOR CHECK MEASUREMENT	CHECK MEASUREMENTS
GROUP 1 ANGULAR DISPLACEMENT 0 DEGREES	 DELTA-DELTA CONNECTION		CONNECT H_1 TO X_1 MEASURE $H_2-X_2, H_3-X_3,$ $H_1-H_2, H_2-X_3, H_3-X_3$
	 Y-Y CONNECTION		VOLTAGE RELATIONS (1) $H_2-X_3 = H_3-X_2$ (2) $H_2-X_2 < H_1-H_2$ (3) $H_2-X_2 < H_2-X_3$ (4) $H_2-X_2 = H_3-X_3$
	 DELTA-ZZ CONNECTION		
	 ZZ-DELTA CONNECTION		
GROUP 2 ANGULAR DISPLACEMENT 30 DEGREES	 DELTA-Y CONNECTION		CONNECT H_1 TO X_1 MEASURE $H_3-X_2, H_3-X_3,$ $H_1-H_3, H_2-X_2, H_2-X_3$
	 Y-DELTA CONNECTION		VOLTAGE RELATIONS (1) $H_3-X_2 = H_3-X_3$ (2) $H_3-X_2 < H_1-H_3$ (3) $H_2-X_2 < H_2-X_3$ (4) $H_2-X_2 < H_1-H_3$
	THREE-PHASE TRANSFORMERS WITH TAPS 		

Figure 7—Transformer lead markings and voltage-phasor diagrams for three-phase transformer connections

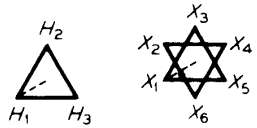
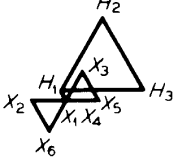
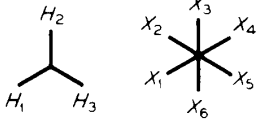
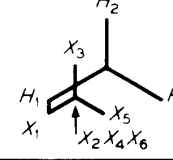
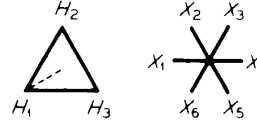
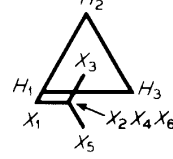
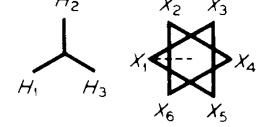
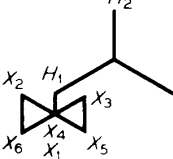
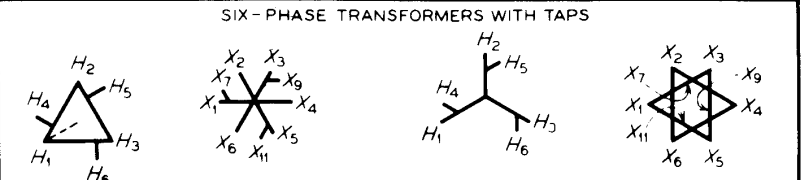
	ANGULAR DISPLACEMENT	DIAGRAM FOR CHECK MEASUREMENT	CHECK MEASUREMENTS
GROUP 1 ANGULAR DISPLACEMENT 0 DEGREES	 DELTA-DOUBLE DELTA		CONNECT H_1 TO X_1 TO X_4 MEASURE $H_2-X_3, H_1-H_2, H_2-X_5, H_2-X_6,$ $H_3-X_2, H_2-X_2, H_3-X_3$ VOLTAGE RELATIONS (1) $H_2-X_5 = H_3-X_3$ (4) $H_2-X_6 = H_3-X_2$ (2) $H_2-X_3 < H_1-H_2$ (5) $H_2-X_6 > H_1-H_2$ (3) $H_2-X_3 < H_2-X_5$ (6) $H_2-X_2 < H_2-X_6$
	 Y-DIAM		CONNECT X_2 TO X_4 TO X_6 H_1 TO X_1 MEASURE $H_2-X_3, H_3-X_5, H_1-H_2, H_2-X_5$ VOLTAGE RELATIONS (1) $H_2-X_5 = H_3-X_3$ (2) $H_2-X_3 < H_1-H_2$ (3) $H_2-X_3 < H_2-X_5$
GROUP 2 ANGULAR DISPLACEMENT 30 DEGREES	 DELTA DIAM		CONNECT X_2 TO X_4 TO X_6 H_1 TO X_1 MEASURE $H_3-X_3, H_3-X_5, H_1-H_3, H_2-X_3,$ H_2-X_5 VOLTAGE RELATIONS (1) $H_3-X_3 = H_3-X_5$ (2) $H_3-X_3 < H_1-H_3$ (3) $H_2-X_3 < H_2-X_5$
	 Y-DOUBLE DELTA		CONNECT H_1 TO X_1 TO X_4 MEASURE $H_3-X_3, H_3-X_5, H_1-H_3, H_2-X_3,$ $H_2-X_5, H_3-X_2, H_3-X_6, H_2-X_2, H_2-X_6$ VOLTAGE RELATIONS (1) $H_3-X_3 = H_3-X_5$ (2) $H_3-X_3 < H_1-H_3$ (3) $H_2-X_3 < H_2-X_5$ (4) $H_3-X_2 = H_3-X_6$ (5) $H_3-X_2 > H_1-H_3$ (6) $H_2-X_2 < H_2-X_6$
SIX-PHASE TRANSFORMERS WITH TAPS 			

Figure 8—Transformer lead markings and voltage-phasor diagrams for six-phase transformer connections

6.3.3.1 Limitation of the phase-sequence test

The preceding method (phase-sequence test) does not disclose the angular displacement of the transformer.

6.3.3.2 Test of phase sequence with ratio bridge

The ratio bridge described in clause 7 can also be used to test phase sequence.

7. Ratio tests

7.1 General

The turn ratio of a transformer is the ratio of the number of turns in the high-voltage winding to that in the low-voltage winding.

7.1.1

When a transformer has taps for changing its voltage ratio, the turn ratio is based on the number of turns corresponding to the normal rated voltage of the respective windings to which operating and performance characteristics are referred.

When the transformer has taps, the turn ratio shall be determined for all taps and for the full winding.

7.1.2

The ratio test shall be made at rated or lower voltage and rated or higher frequency.

7.1.3

In the case of three-phase transformers, when each phase is independent and accessible, single-phase power should be used; although, when convenient, three-phase power may be used.

7.1.4

Transformers that have Y connections but do not have the neutral of the Y brought out shall be tested for ratio with three-phase power. Any inequality in the magnetizing characteristics of the three phases will then result in a shift of the neutral and thereby cause unequal phase voltages. When such inequality is found, the connection should be changed, either to a Δ or to a Y connection, and the line voltages measured. When these are found to be equal to each other and of proper value (1.73 times the phase voltages when connected in Y), the ratio is correct.

7.2 Tolerances for ratio

See IEEE Std C57.12.00-1993, clause 9.

7.3 Ratio test methods

7.3.1 Voltmeter method

Two voltmeters shall be used (with voltage transformers when necessary), one to read the voltage of the high-voltage winding, the other that of the low-voltage winding.

The two voltmeters shall be read simultaneously.

A second set of readings shall be taken with the instruments interchanged, and the average of the two sets of readings taken to compensate for instrument errors.

Voltage transformer ratios should be such as to yield approximately the same readings on the two voltmeters. Compensation for instrument errors by an interchange of instruments will otherwise not be satisfactory, and it will be necessary to apply appropriate corrections to the voltmeter readings.

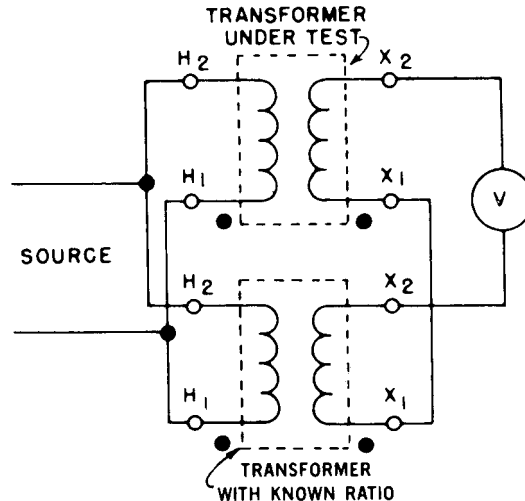


Figure 9—Voltmeter arranged to read the difference between the two secondary voltages

Tests shall be made at not less than four voltages in approximately 10% steps, and the average result shall be taken as the true value. These several values should check within one percent. The tests shall otherwise be repeated with other voltmeters.

When appropriate corrections are applied to the voltmeter readings, tests may be made at only one voltage.

When several transformers of duplicate rating are to be tested, work may be expedited by applying the foregoing tests to only one unit, and then comparing the other units with this one as a standard, in accordance with the comparison transformer method discussed in 7.3.2.

7.3.2 Comparison method

A convenient method of measuring the ratio of a transformer is by comparison with a transformer of known ratio.

The transformer to be tested is excited in parallel with a transformer of the same nominal ratio, and the two secondaries connected in parallel but with a voltmeter or detector in the connection between two terminals of similar polarity (see figure 9). This is the more accurate method because the voltmeter or detector indicates the difference in voltage.

For an alternate method, the transformer to be tested is excited in parallel with a transformer of known ratio, and the voltmeters are arranged to measure the two secondary voltages (see figure 10).

The voltmeters shall be interchanged and the test repeated. The averages of the results are the correct voltages.

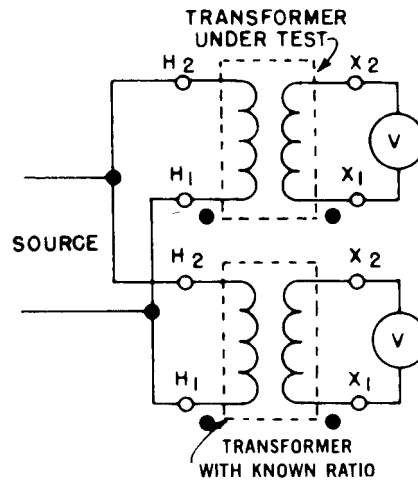
7.3.3 Ratio bridge

A bridge using the basic circuit of figure 11 may be used to measure ratio.

When detector DET is in balance, the transformer ratio is equal to R/R_1 .

NOTES

- 1—Measurement of ratio using circuits of this type has in the past also been described as ratio by resistance potentiometer.
- 2—More accurate results can be obtained using a ratio bridge that provides phase-angle correction.
- 3—The ratio bridge can also be used to test polarity, phase relation, and phase sequence.



NOTE—Readings are repeated after interchanging voltmeters.

Figure 10—Voltmeters arranged to read the two secondary voltages

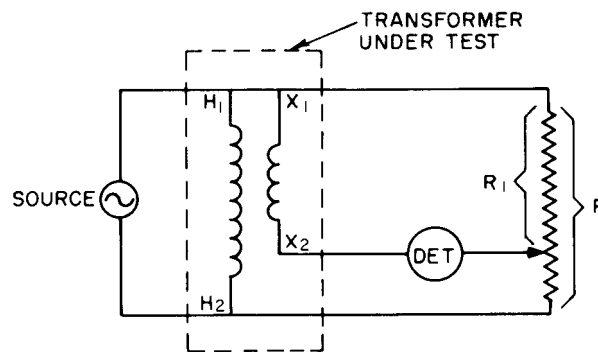


Figure 11—Basic circuit of ratio bridge

8. No-load losses and excitation current

8.1 General

No-load (excitation) losses are those losses that are incident to the excitation of the transformer. No-load (excitation) losses include core loss, dielectric loss, conductor loss in the winding due to excitation current, and conductor loss due to circulating current in parallel windings. These losses change with the excitation voltage.

Excitation current (no-load current) is the current that flows in any winding used to excite the transformer when all other windings are open-circuited. It is generally expressed in percent of the rated current of the winding in which it is measured.

The no-load losses consist primarily of the core loss in the transformer core, which is a function of the magnitude, frequency, and waveform of the impressed voltage. No-load losses also vary with temperature and are particularly sensitive to differences in waveform; therefore, no-load loss measurements will vary markedly with the waveform of the test voltage.

In addition, several other factors affect the no-load losses and current of a transformer. The design-related factors include the type and thickness of core steel, the core configuration, the geometry of core joints, and the core flux density.

Factors that cause differences in the no-load losses of transformers of the same design include variability in characteristics of the core steel, mechanical stresses induced in manufacturing, variation in gap structure, core joints, etc.

8.2 No-load loss test

The purpose of the no-load loss test is to measure no-load losses at a specified excitation voltage and a specified frequency. The no-load loss determination shall be based on a sine-wave voltage, unless a different waveform is inherent in the operation of the transformer. The average-voltage voltmeter method is the most accurate method for correcting the measured no-load losses to a sine-wave basis and is recommended. This method employs two-parallel-connected voltmeters; one is an average-responding (but rms calibrated) voltmeter; the other is a true rms-responding voltmeter. The test voltage is adjusted to the specified value as read by the average-responding voltmeter. The readings of both voltmeters are employed to correct the no-load losses to a sine-wave basis, using equation 2 in accordance with 8.3.

8.2.1 Connection diagrams

Tests for the no-load loss determination of a single-phase transformer are carried out using the schemes depicted in figure 12 and figure 13. Figure 12 shows the necessary equipment and connections for the case where instrument transformers are not required. When instrument transformers are required, which is the general case, the equipment and connections shown in figure 13 apply. If necessary, correction for losses in connected measurement instruments may be made by disconnecting the transformer under test and noting the wattmeter reading at the specified test circuit voltage. These losses represent the losses of the connected instruments (and voltage transformer, if used). They may be subtracted from the earlier wattmeter reading to obtain the no-load loss of the transformer under test.

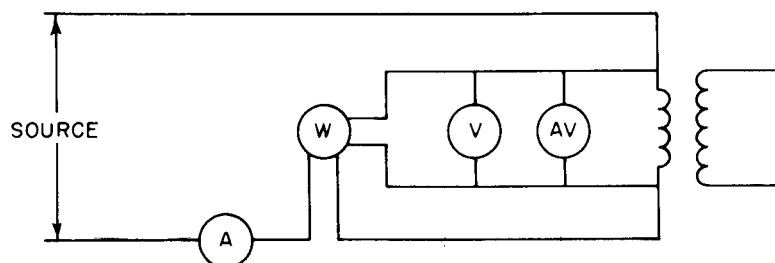


Figure 12—Connections for no-load loss test of a single-phase transformer without instrument transformers

Tests for the no-load loss determination of a three-phase transformer shall be carried out by using the three wattmeter method. Figure 14 is a schematic representation of the equipment and connections necessary for conducting no-load loss measurements of a three-phase transformer when instrument transformers are necessary.

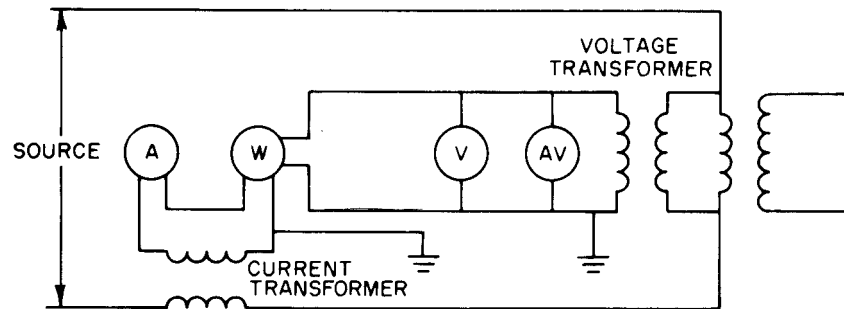


Figure 13—Connections for no-load loss test of a single-phase transformer with instrument transformers

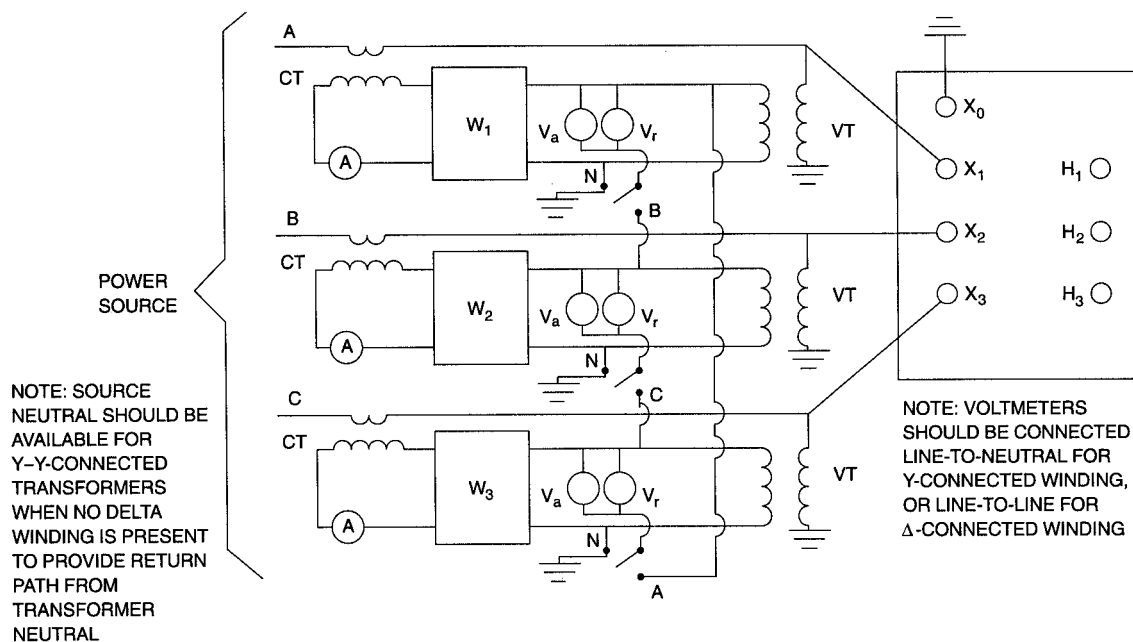


Figure 14—Three-phase transformer connections for no-load loss and excitation current tests using three-wattmeter method

8.2.2 Voltmeter connections

When correcting to a sine-wave basis using the average-voltage voltmeter method, attention must be paid to the voltmeter connections, because the line-to-line voltage waveform may differ from line-to-neutral voltage waveform. Therefore, depending upon whether the transformer windings energized during the test are connected Δ or Y, the voltmeter connections must be such that the waveform applied to the voltmeters is the same as the waveform across the energized windings.

8.2.3 Energized windings

Either the high or the low voltage winding of the transformer under test may be energized, but it is generally more convenient to make this test using the low voltage winding. In any case, the full winding (not merely a portion of the winding) should be used whenever possible. If for some unusual reason, only a portion of a winding is excited, this portion shall not be less than 25% of the winding.

8.2.4 Voltage and frequency

The operating and performance characteristics of a transformer are based upon rated voltage and rated frequency, unless otherwise specified. Therefore, the no-load loss test is conducted with rated voltage impressed across the transformer terminals, using a voltage source at a frequency equal to the rated frequency of the transformer under test, unless otherwise specified.

For the determination of the no-load losses of a single-phase transformer or a three-phase transformer, the frequency of the test source should be within $\pm 0.5\%$ of the rated frequency of the transformer under test. The voltage shall be adjusted to the specified value as indicated by the average-voltage voltmeter. Simultaneous values of rms voltage, rms current, electrical power, and the average-voltage voltmeter readings shall be recorded. For a three-phase transformer the average of the three voltmeter readings shall be the desired nominal value.

8.3 Waveform correction of no-load losses

The eddy-current component of the no-load loss varies with the square of the rms value of excitation voltage and is substantially independent of the voltage waveform. When the test voltage is held at the specified value as read on the average-voltage voltmeter, the actual rms value of the test voltage may not be equal to the specified value. The no-load losses of the transformer corrected to a sine-wave basis shall be determined from the measured value by means of the following equation:

$$P_c(T_m) = \frac{P_m}{P_1 + kP_2} \quad (2)$$

where

T_m is the top oil temperature at the time of test in $^{\circ}\text{C}$

$P_c(T_m)$ is the no-load losses, corrected for waveform, at temperature T_m

P_m is measured no-load losses at temperature T_m

P_1 is per unit hysteresis loss

P_2 is per unit eddy-current loss

$$k = \left(\frac{E_r}{E_a} \right)^2$$

E_r is the test voltage measured by rms voltmeter

E_a is the test voltage measured by average-voltage voltmeter

The actual per unit values of hysteresis and eddy-current losses should be used if available. If actual values are not available, it is suggested that the two loss components be assumed equal in value, assigning each a value of 0.5 per unit.

Equation 2 above is valid only for test voltages with moderate waveform distortion. If waveform distortion in the test voltage causes the magnitude of the correction to be greater than 5%, then the test voltage waveform must be improved for an adequate determination of the no-load losses and currents.

8.4 Temperature correction of no-load losses

A reference temperature is required when stating no-load losses because the no-load losses vary with core temperature. The standard reference temperature, T_r , for transformer no-load losses is specified in 5.9 of IEEE Std C57.12.00-1993.

The observed decrease in no-load losses for an increase in temperature results from several mechanisms acting together. Changes in the core steel resistivity, changes in mechanical stress in the core structure, and variations in the temperature gradients in the core cause the no-load loss to change with temperature. Because these factors vary from design to design and also between transformers of the same design, it is not practical to specify an exact formula to account for temperature variation throughout the operating temperature range of transformers.

However, ordinary variations of temperature encountered when performing the no-load loss test will not affect no-load losses materially, and no correction for temperature need be made, so long as the following conditions are met:

- a) The top oil temperature is within $\pm 10^\circ\text{C}$ of the reference temperature, T_r .
- b) The difference between the top and bottom oil temperatures does not exceed 5°C .

If it is necessary to conduct the test with temperatures outside the specified ranges, the following empirical formula may be used to correct the measured no-load losses to the reference temperature:

$$P_r(T_r) = P_c(T_m)(1 + (T_m - T_r)K_T) \quad (3)$$

where

$P_r(T_r)$ is the no-load losses corrected to the standard reference temperature, T_r

$P_c(T_m)$ is the no-load losses, corrected for waveform, at temperature T_m

T_r is the standard reference temperature, in $^\circ\text{C}$

K_T is an empirically derived per unit change in no-load loss per $^\circ\text{C}$

If the actual value of K_T is not available, a value of 0.00065 per unit change per $^\circ\text{C}$ should be used. This value is typical for cores constructed of grain-oriented silicon steel and is satisfactory as a correction for no-load losses in cases where the transformer must be tested outside the specified temperature range.

8.5 Determination of excitation (no-load) current

The excitation (no-load) current of a transformer is the current that maintains the rated magnetic flux excitation in the core of the transformer. The excitation current is usually expressed in per unit or in percent of the rated line current of the winding in which it is measured. (Where the cooling class of the transformer involves more than one kVA rating, the lowest kVA rating is used to determine the base current.) Measurement of excitation current is usually carried out in conjunction with the tests for no-load losses. Rms current is recorded simultaneously during the test for no-load losses using the average-voltage voltmeter method. This value is used in calculating the per unit or percent excitation current. For a three-phase transformer, the excitation current is calculated by taking the average of the magnitudes of the three line currents.

9. Load losses and impedance voltage

9.1 General

The load losses of a transformer are those losses incident to a specified load carried by the transformer. Load losses include I^2R loss in the windings due to load current and stray losses due to eddy currents induced by leakage flux in the windings, core clamps, magnetic shields, tank walls, and other conducting parts. Stray losses may also be caused by circulating currents in parallel windings or strands. Load losses are measured by applying a short circuit across either the high-voltage winding or the low-voltage winding, and applying sufficient voltage across the other winding to cause a specified current to flow in the windings. The power loss within the transformer under these conditions equals the load losses of the transformer at the temperature of test for the specified load current.

The impedance voltage of a transformer is the voltage required to circulate rated current through one of two specified windings when the other winding is short-circuited, with the windings connected as for rated voltage operation. Impedance voltage is usually expressed in per unit, or percent, of the rated voltage of the winding across which the voltage is applied and measured. The impedance voltage comprises a resistive component and a reactive component. The resistive component of the impedance voltage, called the resistance drop, is in phase with the current and corresponds to the load losses. The reactive component of the impedance voltage, called the reactance drop, is in quadrature with the current and corresponds to the leakage-flux linkages of the windings. The impedance voltage is the phasor sum of the two components. The impedance voltage is measured during the load loss test by measuring the voltage required to circulate rated current in the windings. The measured voltage is the impedance voltage at the temperature of test, and the power loss dissipated within the transformer is equal to the load losses at the temperature of test and at rated load. The impedance voltage and the load losses are corrected to a reference temperature using the formulas specified in this standard.

The impedance kVA is the product of the impedance voltage across the energized winding in kV times the winding current in amperes. The ratio of the load losses in kW at the temperature of test to the impedance kVA at the temperature of test is the load loss power factor of the transformer during the test, and is used in correction for phase-angle error as specified in this standard.

9.2 Factors affecting the values of load losses and impedance voltage

The magnitudes of the load losses and the impedance voltage will vary depending on the positions of tap changers, if any, in various windings. These changes are due to the changes in the magnitudes of load currents and associated leakage-flux linkages as well as being due to changes in stray flux and accompanying stray losses. In addition, several other factors affect the values of load losses and impedance voltage of a transformer. Considerations of these factors, in part, explain variations in values of load losses and impedance voltage for the same transformer under different test conditions as well as variations between the values of load losses and impedance voltage of different transformers of the same design. These factors are discussed below.

9.2.1 Design

The design-related factors include: conductor material, conductor dimensions, winding design, winding arrangement, shielding design, and selection of structural materials.

9.2.2 Process

The process-related factors that impact the values of load losses and impedance voltage are the dimensional tolerances of conductor materials, the final dimensions of completed windings, phase assemblies, metallic parts exposed to stray flux, and variations in properties of conductor material and other metallic parts.

9.2.3 Temperature

Load losses are also a function of temperature. The I^2R component of the load losses increases with temperature, while the stray loss component decreases with temperature. Procedures for correcting the load losses and impedance voltage to the standard reference temperature are described in 9.4.2.

9.2.4 Measurements

At low power factors, such as those encountered while measuring the load losses and impedance voltage of power transformers, judicious selection of measurement method and test system components is essential for accurate and repeatable test results. The phase-angle errors in the instrument transformers, measuring instruments, bridge networks, and accessories affect the load loss test results. Procedures for correcting the load losses for metering phase-angle errors are described in 9.4.1.

9.3 Tests for measuring load losses and impedance voltage

Regardless of the test method selected, the following preparatory requirements shall be satisfied for accurate test results:

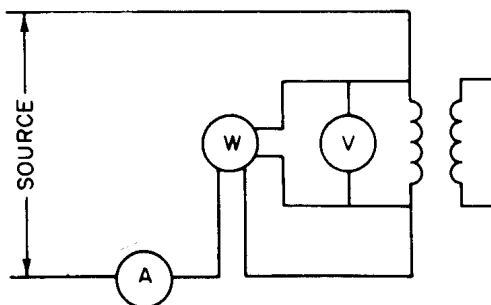
- a) To determine the temperature of the windings with sufficient accuracy, the following conditions shall be met. Except as noted below, the three following conditions are necessary:
 - 1) The temperature of the insulating liquid has stabilized and the difference between top and bottom oil temperatures does not exceed 5 °C.
 - 2) The temperature of the windings shall be taken immediately before and after the load losses and impedance voltage test in a manner similar to that described in 5.1. The average shall be taken as the true temperature.
 - 3) The difference in winding temperature before and after the test shall not exceed 5 °C.

NOTE—For distribution and pad-mounted-type transformers up to 2500 kVA, where it may not be practical to wait for thermal equilibrium, the method used to determine the winding temperature shall take into consideration the lack of thermal equilibrium and the effect of ohmic heating of the winding conductors by load current during the test. The method used can be verified by staging a repeated measurement of the load losses and impedance voltage at a later time when conditions 1), 2), and 3) above are met.

- b) The conductors used to short-circuit the low-voltage, high-current winding of a transformer shall have a cross-sectional area equal to or greater than the corresponding transformer leads.
- c) The frequency of the test source used for measuring load losses and impedance voltage shall be within $\pm 0.5\%$ of the nominal value.
- d) The maximum value of correction to the measured load losses due to the test system phase-angle error is limited to $\pm 5\%$ of measured losses. If more than 5% correction is required, test methods and/or test apparatus should be improved for an adequate determination of load losses.

9.3.1 Wattmeter-voltmeter-ammeter method

The connections and apparatus needed for the determination of the load losses and impedance voltage of a single-phase transformer are shown in figures 15 and 16. Figure 15 applies when instrument transformers are not required. If instrument transformers are required, which is the general case, then figure 16 applies.



NOTE—Instrument transformers to be added when necessary.

Figure 15—Single-phase transformer connections for load loss and impedance voltage tests without instrument transformers

For three-phase transformers, three-phase power measurement utilizing two wattmeters is possible but can result in very large errors at low power factors encountered in load loss tests of transformers. The two-wattmeter method should not be used for loss tests on three-phase transformers.

For three-phase transformers, figure 17 shows the apparatus and connections using the three-wattmeter method.

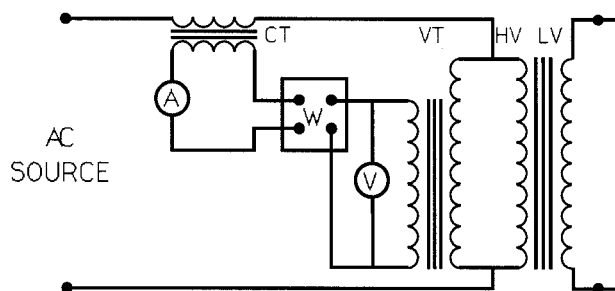


Figure 16—Single-phase transformer connections for load loss and impedance voltage tests with instrument transformers

The selection of test method and test system components should be such that the accuracy requirements as specified in 9.4 of IEEE Std C57.12.00-1993 are satisfied.

9.3.2 Impedance bridge methods

Impedance bridge methods may be used as an alternate to the wattmeter-volmeter-ammeter method for measurement of load losses and impedance voltage.

While many configuration of impedance bridge networks are possible, the choice of a particular network is determined by considerations of the measurement environment and available test facility. The general form of the impedance bridge as shown in figure 18 is an electrical network so arranged that a voltage proportional to the current through the transformer under test is compared with a reference voltage that is a function of the applied voltage E_t . The voltage comparison is made by adjusting one or more of the bridge arms (Z_1 , Z_2 , and Z_3) until the voltage across Z_2 and Z_3 are exactly equal in magnitude and phase. Voltage balance is indicated by a null reading of the detector (DET). The impedance characteristics of the transformer under test can then be calculated from the values of Z_1 , Z_2 , and Z_3 .

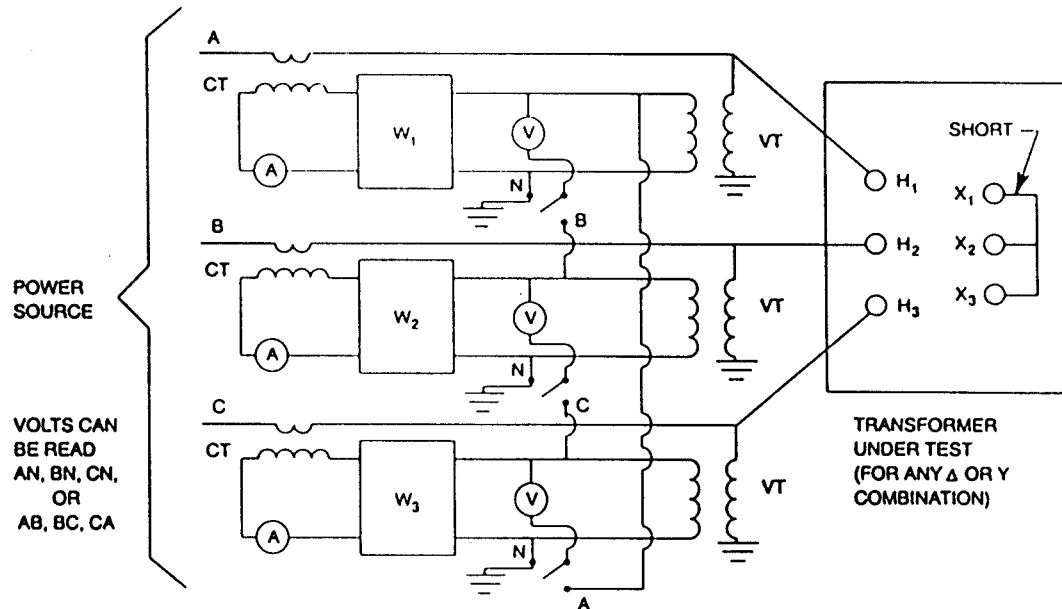


Figure 17—Three-phase transformer connections for load loss and impedance voltage tests using three-wattmeter method

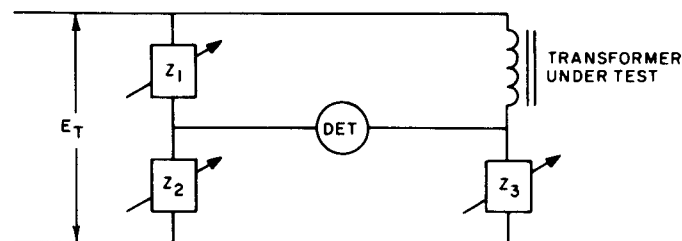
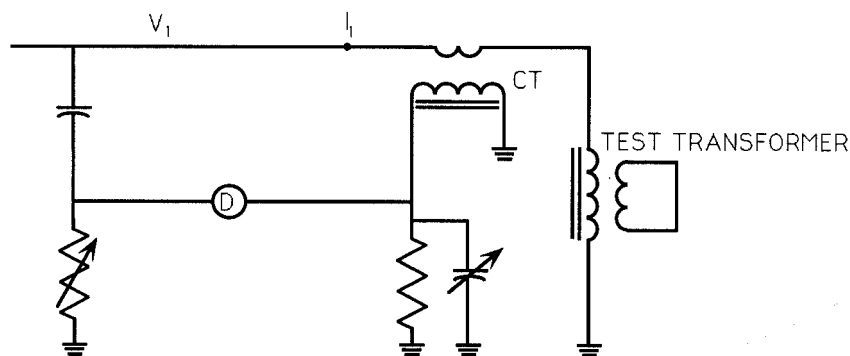
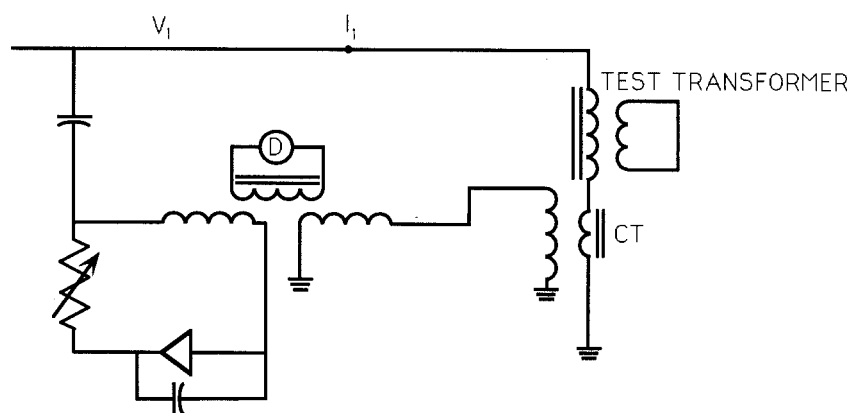


Figure 18—General impedance bridge network

Two of the most commonly used bridge networks for transformer testing are shown in figure 19 and figure 20. In figure 19, a bridge technique is illustrated that employs a precision, low loss high-voltage capacitor and precision current transformer. It has some similarities to the classical Schering and Maxwell bridges. In figure 20, another bridge technique employing an HV capacitor, precision current transformer and a transformer ratio arm bridge is shown.

In general, the bridge network adjustments for voltage balance are frequency-dependent; therefore, excitation of the bridge must be made with a power source that has low harmonic distortion and excellent frequency stability.

The factors that impact overall accuracy of test results by the wattmeter-voltmeter-ammeter method also impact the accuracy of test result by impedance bridge methods.

**Figure 19—RC-type impedance bridge****Figure 20—Transformer-ratio-arm bridge**

Loss measurements on three-phase transformers using a three-phase source are made by connecting the bridge network to each phase in turn and calculating the total losses from the three single-phase measurements. This is analogous to the three-wattmeter method of measuring losses by switching a single wattmeter from phase to phase. To verify that switching the bridge from phase to phase does not affect the result on the remaining phases, and to demonstrate that the time involved in switching the bridge does not result in undue heating of the transformer windings during the test, the losses can be monitored for stable readings by wattmeters in all phases.

9.3.3 Transformer test procedures

9.3.3.1 Two-winding transformers and autotransformers

Load loss and impedance voltage tests are carried out using the connections and apparatus shown in figure 16 for single-phase transformers and figure 17 for three-phase transformers.

With one winding short-circuited, a voltage of sufficient magnitude at rated frequency is applied to the other winding and adjusted to circulate rated current in the excited winding. Simultaneous readings of wattmeter, voltmeter, and ammeter are taken. If necessary, the corrections for the losses in external connections and connected measuring instruments should be made.

The procedure for testing three-phase transformers is very similar, except that all connections and measurements are three-phase instead of single-phase, and a balanced three-phase source of power is used for the tests. If the three line currents cannot be balanced, their average rms value should correspond to the desired value, at which time simultaneous readings of wattmeters, voltmeters, and ammeter should be recorded.

Single-phase and three-phase autotransformers may be tested with internal connections unchanged. The test is made using the autotransformer connection. The input (or output) terminals are shorted, and voltage (at rated frequency) is applied to the other terminals. The voltage is adjusted to cause rated line current to flow in the test circuit as shown in figure 21. Simultaneous readings of wattmeters, voltmeters, and ammeter are recorded for determinations of load losses and impedance voltage.

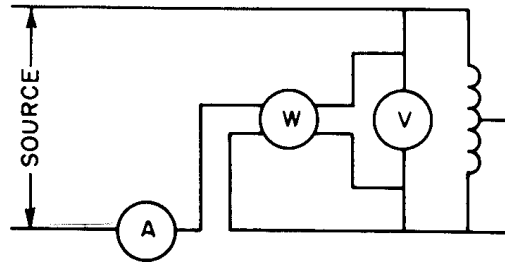


Figure 21—Connections for impedance loss and impedance-voltage tests of an autotransformer

For the purpose of measuring load losses and impedance voltage, the series and common windings of autotransformers may be treated as separate windings, one short-circuited, the other excited. In this situation, where the transformer is connected in the two-winding connection for the test, the current held must be the rated current of the excited winding, which may or may not be the same as rated line current. The load loss watts and applied voltamperes will be the same, whether series and common windings are treated as separate windings in the two-winding connection or are connected in the autotransformer connection—so long as rated winding current is held in the first case and rated line current in the second case.

9.3.3.2 Three-winding transformer

For a three-winding transformer, which may be either single-phase or three-phase, three sets of impedance measurements are made between pairs of windings, following the same procedure as for two-winding transformers. Measurements of the impedances Z_{12} , Z_{23} , and Z_{31} are obtained between windings 1, 2, and 3.

If the kVA capacities of the different windings are not alike, the current held for the impedance test should correspond to the capacity of the lower-rated winding of the pair of windings under test. However, all of these data when converted into percentage form should be based on the same output kVA, preferably that of the primary winding. An equivalent three-winding impedance network as shown in figure 22 can be derived from the following equations:

$$Z_1 = \frac{Z_{12} - Z_{23} + Z_{31}}{2} \quad (4)$$

$$Z_2 = \frac{Z_{23} - Z_{31} + Z_{12}}{2} = Z_{12} - Z_1 \quad (5)$$

$$Z_3 = \frac{Z_{31} - Z_{12} + Z_{23}}{2} = Z_{31} - Z_1 \quad (6)$$

where

Z_{12} , Z_{23} , and Z_{31} are the measured impedance values between pairs of windings, as indicated, all expressed on the same kVA base.

These equations involve complex numbers, but they may be used for the resistance (in-phase) component or the reactance (quadrature) component of the impedance voltage or of the impedance voltamperes.

The treatment of the individual load losses and impedance voltages for temperature corrections, etc., is the same as for two-winding, single-phase transformers.

The total load losses of a three-winding transformer is the sum of the losses in the branches of the equivalent circuit of figure 22 for any specific terminal load conditions.

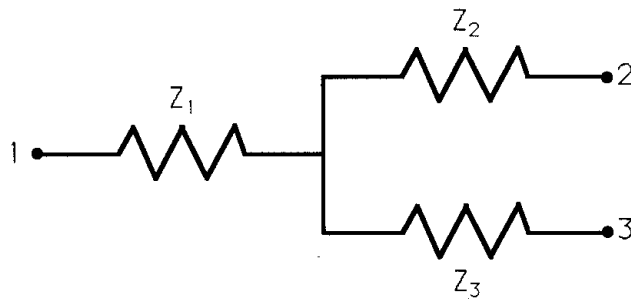


Figure 22—Equivalent three-winding impedance network

9.3.3.3 Interlacing impedance voltage of a Scott-connected transformer

The interlacing impedance voltage of Scott-connected transformers is the single-phase voltage applied from the midtap of the main transformer winding to both ends, connected together. The voltage is sufficient to circulate, in the supply lines, a current equal to the rated three-phase line current. The current in each half of the winding is 50% of this value.

The percent interlacing impedance is the measured voltage expressed as a percent of the teaser voltage. The percent resistance is the measured losses expressed as a percentage of the rated kVA of the teaser winding.

9.3.3.4 Test of three-phase transformer with single-phase voltage

To determine the load losses and impedance voltage of a three-phase transformer with single-phase voltage, the setup as schematically shown in figure 23 is recommended.

The three line leads of one winding are short-circuited, and single-phase voltage at rated frequency is applied to two terminals of the other winding. The applied voltage is adjusted to circulate rated line current.

Three successive readings are taken on the three pairs of leads; for example, H_1 and H_2 , H_2 and H_3 , H_3 and H_1 . Then:

$$\text{Measured load losses (watts)} = 1.5 \left(\frac{P_{12} + P_{23} + P_{31}}{3} \right) \quad (7)$$