

IEEE Guide for Diagnostic Field Testing of Electric Power Apparatus- Part 1: Oil Filled Power Transformers, Regulators, and Reactors

Sponsor

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Abstract: Diagnostic tests and measurements that are performed in the field on oil-immersed power transformers and regulators are described. Whenever possible, shunt reactors are treated in a similar manner to transformers. Tests are presented systematically in categories depending on the subsystem of the unit being examined. A diagnostic chart is included as an aid to identify the various subsystems. Additional information is provided regarding specialized test and measuring techniques.

Keywords: Oil filled transformers, regulators, reactors, diagnostic evaluation, off-line testing, field testing, windings, bushings, insulating fluids, tapchangers, core, tanks, safety.

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Introduction

(This introduction is not a part of IEEE Std 62-1995, IEEE Guide for Diagnostic Field Testing of Electric Power Apparatus.)

The condition of power apparatus is of prime importance for the successful operation of a power system. During transportation, installation, and service operation, the apparatus may be exposed to conditions that adversely affect its reliability and useful life. One of the principal aims of the maintenance engineer is to detect defects at an early stage and take appropriate corrective measures. The detection is usually achieved by means of diagnostic evaluation in the field that is performed at regular intervals as necessary. This guide describes most of the diagnostic procedures and measurements that are common practice and provides additional information in the case of more specialized techniques. Each test has an interpretation section that is provided, not to establish a standard, but merely to guide the user. There is not necessarily any direct relationship between these field tests and factory tests. For tests performed within the warranty period, the measurements should agree with the manufacturer's data when performed under similar conditions. When measurements are performed outside the warranty period on service-aged equipment, there may be some deviation between field and factory data. Interpretation of measured results is usually based on a comparison with data obtained previously on the same unit or by comparison with similar units. Many of the levels specified in this guide are not standardized; however, the values quoted have been found to be practical and are commonly used. The frequency of the tests will vary depending upon the type, size, age, and operating history of the unit. It is recommended that the user of the power apparatus establish a maintenance schedule based on these conditions and on original equipment manufacturer recommendations. The test results obtained during the periodic checks should be systematically filed in order to provide a diagnostic data base.

This guide was first published as IEE Std 62-1958, Recommended Guide for Making Dielectric Measurements in the Field. It was revised and republished as IEEE Std 62-1978, Guide for Field Testing Power Apparatus Insulation. This present revision contains more detailed descriptions of test procedures than the previous editions and also includes guidance covering visual inspection. It will therefore be published in different parts with each part covering a specific type of power apparatus.

This revision was prepared by the Diagnostic Testing Working Group under the sponsorship of the IEEE Power System Instrumentation and Measurements Committee with significant contributions from the IEEE Transformers Committee. The information in annex B is copyrighted by the Doble Engineering Company and used with permission.

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1. Overview

1.1 Scope

This guide describes diagnostic tests and measurements that are performed in the field on oil-immersed power transformers and regulators. Whenever possible, shunt reactors are treated in a similar manner to transformers. The tests are presented systematically in categories depending on the subsystem of the unit being examined. A diagnostic chart is included as an aid to identifying the various subsystems. Additional information is provided regarding specialized test and measuring techniques.

Interpretive discussions are also included in several areas to provide additional insight on the particular test, or to provide guidance on acceptance criteria. These discussions are based on the authors' judgement of accepted practice. It should be noted that sometimes the results of several types of tests should be interpreted together to diagnose a problem. Manufacturer's acceptance criteria should also be consulted as it may take precedence over the criteria in this guide.

2. References

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

ASTM D 117-89, Guide to Test Methods and Specifications for Electrical Insulating Oils of Petroleum Origin.¹

ASTM D 877-87, Test Method for Dielectric Breakdown Voltage of Insulating Liquids Using Disk Electrodes.

ASTM D 923-91, Test Method for Sampling Electrical Insulating Liquids.

ASTM D 924-92(b), Test Method for Dissipation Factor (or Power Factor) and Relative Permittivity (Dielectric Constant) of Electrical Insulating Liquids.

¹ASTM publications are available from the Customer Service Department, American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103, USA.

ASTM D 971-91, Test Method for Interfacial Tension of Oil Against Water by the Ring Method.

ASTM D 974-92, Test Method for Neutralization Number by Color-Indicator Titration.

ASTM D 1298-85 (Reaff 1990), Practice for Density, Relative Density (Specific Gravity), or API Gravity of Crude Petroleum and Liquid Petroleum Products by Hydrometer Method.

ASTM D 1500-91, Test Method for ASTM Color of Petroleum Products (ASTM Color Scale).

ASTM D 1524-84 (Reaff 1990), Method for Visual Examination of Used Electrical Insulating Oils of Petroleum Origin in the Field.

ASTM D 1533-88, Test Method for Water in Insulating Liquids (Karl Fischer Method).

ASTM D 1698-84 (Reaff 1990), Sediment and Soluble Sludge in Service-Aged Insulating Oils.

ASTM D 1816-84a (Reaff 1990), Standard Test Method for Dielectric Breakdown Voltage of Insulating Oils of Petroleum Origin Using VDE Electrodes.

ASTM D 2285-85 (Reaff 1990), Test Method for Interfacial Tension of Electrical Insulating Oils of Petroleum Origin Against Water by the Drop-Weight Method.

ASTM D 3487-88 (Reaff 1993), Specification for Mineral Insulating Oil Used in Electrical Apparatus.

ASTM D 3612-93, Test Method for Analysis of Gases Dissolved in Electrical Insulating Oil by Gas Chromatography.

ASTM D 3613-92, Test Methods of Sampling Electrical Insulating Oils for Gas Analysis and Determination of Water Content.

ASTM D 4059-91, Test Method for Analysis of Polychlorinated Biphenyls in Insulating Liquids by Gas Chromatography.

ASTM F 855-90, Specification for Temporary Grounding Systems to be Used on De-Energized Power Lines and Equipment.

IEEE Std 4-1995, IEEE Standard Techniques for High-Voltage Testing.²

IEEE Std 510-1983 (Reaff 1992), IEEE Recommended Practices for Safety in High-Voltage and High-Power Testing (ANSI).³

IEEE Std 637-1985 (Reaff 1992), IEEE Guide for the Reclamation of Insulating Oil and Criteria for Its Use (ANSI).

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

²As this standard goes to press, IEEE Std 4-1995 is approved but not yet published. The draft standard is, however, available from the IEEE. Anticipated publication date is September 1995. Contact the IEEE Standards Department at 1 (908) 562-3800 for status information.

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

IEEE Std C57.12.80-1978 (Reaff 1992), IEEE Standard Terminology for Power and Distribution Transformers (ANSI).

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 (ANSI).

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

IEEE Std C57.19.100-1995, IEEE Guide for Application of Power Apparatus Bushings.⁴

IEEE Std C57.104-1991, IEEE Guide for the Interpretation of Gases Generated in Oil-Immersed Transformers (ANSI).

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

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

3. Definitions

3.1 apparent charge (terminal charge): That charge that, if it could be injected instantaneously between the terminals of the test object, would momentarily change the voltage between its terminals by the same amount as the partial discharge itself. The apparent charge should not be confused with the charge transferred across the discharging cavity in the dielectric medium. Apparent charge, within the terms of this guide, is expressed in coulombs (C). One pC is equal to 10^{-12} C.

3.2 bushing (power and distribution transformer): An insulating structure including a central conductor, or providing a central passage for a conductor, with provision for mounting on a barrier, conducting or otherwise, for the purpose of insulating the conductor from the barrier and conducting current from one side of the barrier to the other.

3.3 diagnostic field tests and measurements (power apparatus): Procedures that are performed on site on the complete apparatus or parts thereof in order to determine its suitability for service.

NOTE—The parameters measured differ from apparatus to apparatus and may include electrical, mechanical, chemical, thermal, etc., quantities. Interpretation of the results is usually based on a change in the measured characteristics and/or by comparison with pre-established criteria. The tests are normally carried out at regular intervals based on users' experience and/or manufacturers' recommendations. These tests may also be performed on defective apparatus in order to determine the location and/or cause of failure.

3.4 dissipation factor (dielectric): The cotangent of the phase angle between a sinusoidal voltage applied across a dielectric (or combinations of dielectrics) and the resulting current through the dielectric system.

3.5 partial discharge (PD): Electric discharge that only partially bridges the insulation between conductors.

3.6 power factor (dielectric): The cosine of the phase angle between a sinusoidal voltage applied across a dielectric (or combinations of dielectrics) and the resulting current through the dielectric system.

For definitions of other terms concerning transformers see IEEE Std C57.12.80-1978.⁵

⁴As this standard goes to press, IEEE Std C57.19.100-1995 is approved but not yet published. The draft standard is, however, available from the IEEE. Anticipated publication date is September 1995. Contact the IEEE Standards Department at 1 (908) 562-3800 for status information.

⁵Information on references can be found in clause 2.

4. Diagnostic chart

For the purpose of this guide, the diagnostic tests are described with reference to principle categories of systems that constitute the transformer (e.g., windings, bushings, insulating fluids, tap changers, core, tanks, and associated devices). For each category, the quantities measured are shown in the diagnostic test chart (figure 1) for ease of reference. In some cases further subdivision is necessary.

Not all the tests are necessarily performed by any single user. In addition, the specific tests carried out vary according to the regular practice of the user and may depend on the history of the apparatus.

The establishment of benchmark values on a new piece of electrical equipment is very important when considering evaluation of future test results. Benchmark values are the first measurements taken on a piece of new or used equipment. Subsequent test results from tests on the same unit or from similar tests on similar equipment, when compared to these initial values and similar tests on similar equipment, may indicate a trend.

5. Safety

5.1 General

Considerations of safety in electrical testing apply not only to personnel but also to the test equipment and apparatus being tested. The following guidelines cover many of the fundamentally important procedures that have been found to be practical. Since it is impossible to cover all aspects in this guide, test personnel should also consult IEEE Std 510-1983, manufacturers' instruction manuals, union, company, or government regulations.

Prior to performing any test of power apparatus, there should be a meeting of all people who will be involved or affected by the test. The test procedure should be discussed so there is a clear understanding of all aspects of the work to be performed. Particular emphasis should be placed on personnel hazards and the safety precautions associated with these hazards. In addition, procedures and precautions should be discussed to ensure the production of meaningful test results without subjecting the test specimen to unnecessary risks.

Responsibilities for the various duties involved in performing the test should be assigned.

5.2 Personnel

5.2.1 Hazards

Insulation tests in the field present a hazard to personnel unless suitable precautions are taken. Apparatus or circuits to be tested shall be disconnected from the power system. Typical safety procedures call for a visual check of the disconnection or, when this is not possible, a check with a voltage indicator. Grounds are then applied. Personnel shall be instructed to treat all ungrounded apparatus as energized.

5.2.2 Ground connection

Use of working grounds should comply with established company guidelines. For further information see ASTM F 855-90.

		TRANSFORMERS REACTORS REGULATORS		
		TRANSFORMERS	REACTORS	REGULATORS
POWER TRANSFORMER REGULATORS, REACTORS	WINDINGS	RESISTANCE	X	X
		RATIO/POLARITY/PHASE	X	X
		EXCITATION CURRENT	X	X
		SHORT CIRCUIT IMPEDANCE	X	X
		INSULATION RESISTANCE	X	X
		CAPACITANCE	X	X
		POWER FACTOR/DISSIPATION FACTOR	X	X
		INDUCED VOLTAGE/PARTIAL DISCHARGE/RIV	X	X
		CAPACITANCE	X	X
		DIELECTRIC LOSS	X	X
	BUSHINGS	POWER FACTOR/DISSIPATION FACTOR	X	X
		PARTIAL DISCHARGE	X	X
		TEMPERATURE (INFRARED)	X	X
		OIL LEVEL	X	X
		VISUAL INSPECTION	X	X
	INSULATING OIL	WATER CONTENT	X	X
		DISSOLVED GAS	X	X
		DIELECTRIC STRENGTH	X	X
		PARTICLE COUNT	X	X
		DIELECTRIC LOSS	X	X
		POWER FACTOR/DISSIPATION FACTOR	X	X
		INTERFACIAL TENSION	X	X
		ACIDITY	X	X
		VISUAL	X	X
		COLOR	X	X
		OXIDATION STABILITY	X	X
	TAP CHANGERS	CONTACT CONTINUITY	X	
		TEMPERATURE (INFRARED)	X	
		RATIO	X	
		TIMING	X	
		MOTOR CURRENTS	X	
		LIMIT SWITCH	X	
		CONTACT PRESSURE	X	
		CENTERING	X	
		RATIO	X	
		VISUAL INSPECTION	X	
	CORE	INSULATION RESISTANCE	X	X
		GROUND TEST	X	X
	TANKS AND ASSOCIATED DEVICES	CONSERVATOR	X	X
		INERT AIR SYSTEM	X	X
		GAUGES	X	X
		FAULT PRESSURE RELAY	X	X
		HEAT EXCHANGER	X	X
		FANS	X	X
		PUMPS	X	X
		PRESSURE	X	X
		TEMPERATURE (INFRARED)	X	X
		VISUAL INSPECTION	X	X

Figure 1—Diagnostic test chart

5.2.3 Precautions

When testing, precautions shall be taken to prevent personnel from contacting energized circuits. An observer may be stationed to warn approaching personnel and may be supplied with means to de-energize the circuit. The means may include a switch to shut off the power source and ground the circuit until all stored charges are dissipated.

5.2.4 Warning signs and barriers

The test area may be marked off with signs and easily visible tape. Warning signs shall conform to the requirements of governing bodies such as the Occupational Safety and Health Administration (OSHA) in the United States.

5.2.5 Atmosphere inside tank

Prior to entry, confirmation should be made that the atmosphere inside the tank is adequate to support life. This should be checked according to company guidelines and procedures or manufacturer's instructions.

5.3 Apparatus

5.3.1 Consequences of failure

Certain test procedures could result in fire; therefore, noncontaminating fire-fighting equipment should be available before beginning tests that apply dielectric stress to the transformer insulation system.

5.3.2 Overvoltage

The voltage may accidentally exceed the desired maximum during the conduction of high-voltage tests. A sphere gap, adjusted to spark over at a voltage slightly above the desired maximum, may be connected across the voltage source (refer to IEEE Std 4-1995). By selecting the proper value of series resistor, the gap may be used to provide a warning signal, to inhibit further rise in the test voltage, or to activate an overcurrent circuit breaker in the power supply circuit.

5.3.3 Graded insulation

When the insulation level of the winding is graded from one end to the other, the magnitude of the applied test voltage should correspond to the lowest insulation level.

5.3.4 Testing under vacuum

Under no condition shall tests be performed on the transformer while the equipment is under vacuum. The dielectric strength of the system is significantly reduced under these conditions.

5.3.5 Surge arresters

If the test voltage is expected to approach or exceed the operating voltage of any transformer-mounted surge arresters the arresters should be disconnected before energizing the transformer. This avoids arrester damage and limitation of the test voltage due to arrester operation.

6. Tests and test techniques

6.1 Windings

In general, the windings are checked for evidence of physical displacement or distortion, broken connections or strands, short circuited turns, or defects in insulation. The parameters that are usually checked are described in this clause together with an indication, where possible, of acceptable limits for the quantities being measured. For the tests and measurements on windings, the oil pumps should be switched off.

6.1.1 Winding resistance

Transformer winding resistances are measured in the field in order to check for abnormalities due to loose connections, broken strands, and high-contact resistance in tapchangers. Interpretation of results is usually based on a comparison of measurements made separately on each phase in the case of a wye-connected winding or between pairs of terminals on a delta-connected winding. Comparison may also be made with original data measured in the factory. Agreement to within 5% for any of the above comparisons is usually considered satisfactory. It may be necessary to convert the resistance measurements to values corresponding to the reference temperature in the transformer test report. The conversions are accomplished by the following formula:

$$R_s = R_m \frac{T_s + T_k}{T_m + T_k}$$

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 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.

Determination of the transformer winding temperature is important in making a resistance measurement. However, it is very difficult to measure the temperature of the winding accurately under field conditions. Some methods commonly used include the following:

- a) Place a thermometer in contact with the tank wall. This will not give an accurate indication of the real winding temperature if the transformer has been recently removed from service.
- b) Use values obtained from the permanently installed temperature indicators. If the transformer has recently been removed from service, this may be the only means available for estimating the winding temperature.
- c) For nitrogen blanketed transformers a thermometer may be placed in the main tank by inserting it in openings in the top of the tank or in the wells for the permanent temperature indicators. Inserting a thermometer into the main tank usually requires breaking the hermetic seal on the transformer and relieving a positive nitrogen pressure. This may introduce moisture into the transformer and carries the risk that a conductive object could accidentally be dropped into the winding. Mercury thermometers should not be used inside a transformer tank due to the results of breakage. Use of the wells for the permanent temperature indicators requires removal of the permanent sensor from the wells.

Normally there will be some variation in the values indicated by the different sensors. If the transformer has been out of service for long enough to have a uniform temperature throughout its mass, averaging of values from all the indicators may yield better results than using a single indicator.

6.1.1.1 Conductor resistance measurement techniques

Transformer winding resistance is usually measured using either bridge techniques, the voltmeter-ammeter method, or a micro-ohmmeter. When bridges are used, a Wheatstone bridge is preferred for resistance values of $\geq 1 \Omega$. A Kelvin bridge or a micro-ohmmeter is preferable for resistance values of $< 1 \Omega$.

Temperature correction of winding resistance is not normally required on site because measurement comparison is made between phases.

6.1.1.1.1 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 > 1 A. Digital voltmeters and digital ammeters of appropriate accuracy are commonly used. Measurement is made with direct current, and simultaneous readings of current and voltage are taken using the connections of figure 2. The required resistance is calculated from the readings in accordance with Ohm's law.

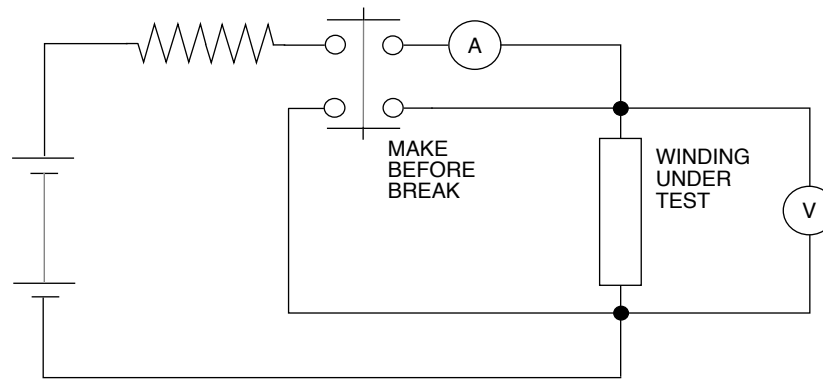


Figure 2—Resistance measurement using voltmeter-ammeter method

A 12 V battery is normally used as the power supply. However, a regulated electronic power supply may also be used providing its ripple content is $< 1\%$ of mean voltage.

In order to minimize measuring errors the following precautions should be taken:

- The measuring instruments should have such ranges that the readings may be made as near full scale as possible and in any case above 70% of full scale.
- The polarity of the core magnetization should be kept constant during all resistance measurements.
NOTE—A reversal in magnetization of the core can change the time constant and result in erroneous readings.
- The voltmeter leads should be independent of the current leads and should be connected as closely as possible to the terminals of the winding to be measured. This avoids including the resistances of current-carrying leads and their contacts and the resistances of extra lengths of leads in the reading.

In general, the winding will exhibit a long dc time constant.

Readings should not be taken until after the current and voltage have reached steady-state values. 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 resistance 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 ensuring that all other transformer windings are open circuited during these tests.

The currents used for these measurements normally do not exceed 15% of the rated current. This avoids heating the winding and thereby changing its resistance. Resistance variation should not exceed 5% from phase to phase.

Precautions: If the current is suddenly switched off, a high voltage will be generated across the winding. The current should be switched off by a suitably insulated switch before personnel contact the test circuit. Alternatively, the transformer winding should be short-circuited before switching the current off providing this does not result in damage to the power supply or any series connected resistor.

To prevent the voltmeter from damage it should be disconnected from the circuit before switching the current on or off.

6.1.1.1.2 Bridge or micro-ohmmeter method

Connection of both the bridge and the micro-ohmmeter to the circuit under test is basically the same. Using the instruction manual as a guide, the four leads should be connected to the circuit being measured. Two leads, one potential and one current, should be connected to each end of the circuit to be measured. Care should be taken to ensure good contact of all lead connections and to ensure that all test leads are the same (i.e., length, gauge, and material).

Care should be taken to connect the current leads outside of the voltage leads at the points of connection to the test circuit (see figure 3).

When using a bridge, it should be balanced, starting with the most significant digit setting followed by the next most significant etc., until the bridge null meter is balanced. The measured conductor resistance is read directly from the bridge settings. When using the micro-ohmmeter, only a “range” selection needs to be made and the measured reading is displayed directly on the instrument. After obtaining the “measured” resistance, R_m , from the bridge settings or the micro-ohmmeter, that value should be corrected for temperature using the procedure given in 6.1.1.

This “corrected” resistance value can now be compared with previous values that were corrected to the same standard conditions.

Interpretation: The interpretation of results is very dependent on the type of conductor being measured. Some conductors consist of several parallel paths of stranded wires and detecting a problem with only one strand may be beyond the resolution of the bridge or micro-ohmmeter. If more than one strand is broken or there is a high-resistance internal connection, the Kelvin bridge or micro-ohmmeter should detect the resulting higher resistance circuit.

Comparison of readings with other phases, duplicate transformers, or previous measurements under field conditions are recommended. Variations under field conditions should not exceed 5%.

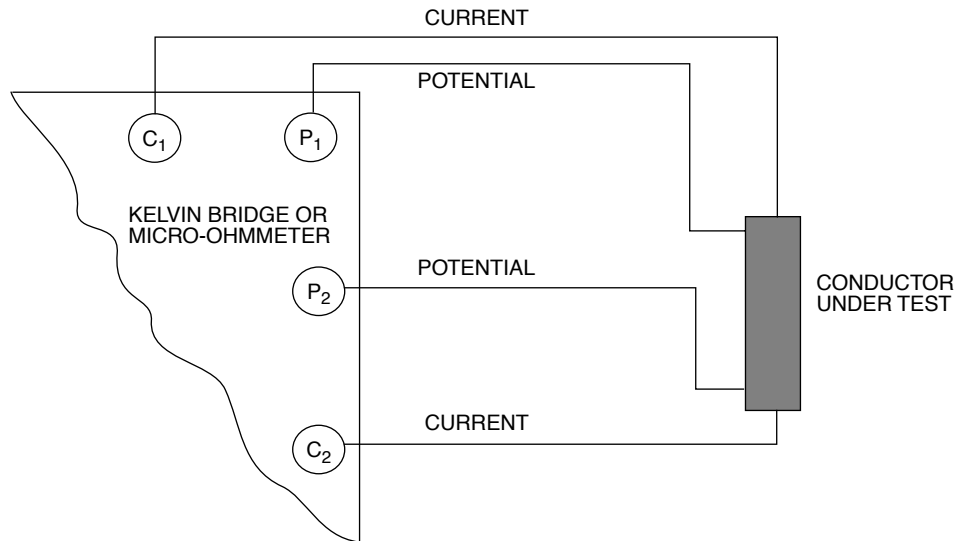


Figure 3—Typical low-resistance measurement connection

6.1.2 Ratio/polarity/phase

6.1.2.1 General

The turns ratio of a transformer is the ratio of the number of turns in a higher voltage winding to that in a lower voltage winding. The voltage ratio of a transformer is the ratio of the rms terminal voltage of a higher voltage winding to the rms terminal voltage of a lower voltage winding under specified conditions of load. For all practical purposes, when the transformer is on open circuit, its voltage and turns ratios may be considered equal.

The polarity of a transformer is determined by the internal connections and is indicated by the nameplate markings. Polarity is of interest if the transformer is to be connected in a parallel manner with one or more other transformers.

Results of the polarity and transformation ratio tests are absolute, and may be compared with the manufacturer's nameplate specifications.

Transformer winding ratios, polarity, and phase connections should be checked before energizing the transformer for the first time on site. The ratio in particular is checked during regular (e.g., annual) inspections and it is recommended that it also be checked before returning the transformer to service if the unit has been subjected to a through-fault.

6.1.2.2 Measurement of transformer polarity

There are a number of commercial transformer turns ratio test sets available from manufacturers serving the power industry. These instruments, when operated in accordance with the manufacturer's instructions, provide convenient and accurate readings of ratio and polarity of power transformers.

If a commercial test set is not available, then transformer polarity may be measured and interpreted using the procedures in 6.1.2.2.1 and 6.1.2.2.2.

6.1.2.2.1 Measurement of transformer polarity by inductive kick

Polarity by inductive kick may be measured using two dc voltmeters and a source of dc current. For safety reasons it is preferable to apply the dc source across the high-voltage winding. Figure 4 illustrates the technique.

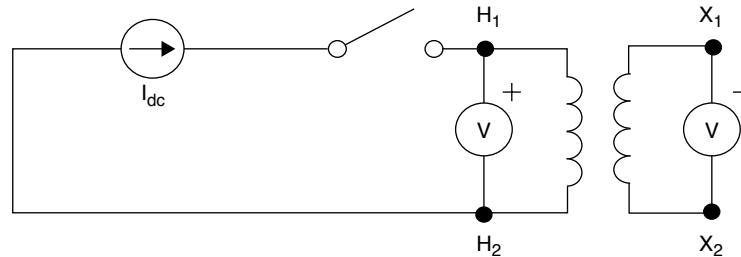


Figure 4—Polarity by inductive kick

A dc voltmeter should be placed across the H_1 – H_2 leads, with the positive lead connected to the H_1 terminal.

A dc voltmeter should be placed across the X_1 – X_2 leads, with the positive lead connected to the X_1 terminal.

A low-voltage source, such as a battery, should be connected to the H_1 – H_2 terminals, thus causing a small but noticeable deflection of the dc voltmeter connected across the H_1 – H_2 terminals. The connection of the dc source should be such that the dc voltmeter indication is positive. The magnitude of the deflection is not of concern.

The direction of the deflection of the dc voltmeter connected across terminals X_1 – X_2 should be observed as the excitation is broken. If the deflection is positive then the transformer is additive. If the deflection is negative then the transformer is subtractive. The polarity, not the magnitude of deflection, is of concern.

This test should be repeated for each phase of a polyphase transformer.

6.1.2.2.2 Measurement of transformer polarity by alternating voltage

If the transformer ratio is <30 then polarity may be measured by using a convenient source of ac with an ac voltmeter, as shown in figure 5.

The transformer should be connected as shown in figure 5.

A small alternating voltage (as measured in the tens of volts), supplied by a fused variable transformer, should be applied to the H_1 – H_2 leads.

If the ac voltmeter indicates a value less than the source voltage then the polarity is subtractive. If the voltmeter indicates a value greater than the source voltage then the polarity of the transformer is additive.

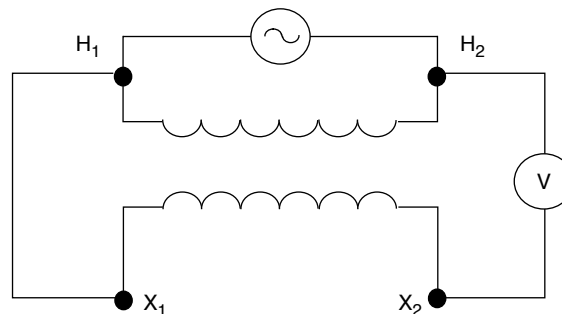


Figure 5—Polarity by ac method

6.1.2.2.3 Polarity of polyphase transformers

Each phase of a polyphase transformer should have the same relative polarity when tested in accordance with either of the methods described in 6.1.2.2.1 and 6.1.2.2.2 or with a commercial instrument.

6.1.2.3 Transformer turns ratio test set

There are a number of commercial transformer turns ratio test sets available from manufacturers serving the power industry. These instruments, when operated in accordance with the manufacturer's instructions, provide convenient and accurate readings of ratio and polarity of power transformers.

If the transformer has load taps, the turns ratio should be determined for all of these taps with the tap changer for de-energized operation in one specific position such as the nominal or the maximum turns position. In addition, with the load tap changer (LTC) in the neutral position, the turns ratio should be determined for all positions of the tap changer for de-energized operation.

If a commercial test set is not available, then transformation ratio may be measured and interpreted using the procedures in 6.1.2.3.1 and 6.1.2.3.2.

6.1.2.3.1 Voltmeter method

Two ac voltmeters are used, one connected to the high-voltage winding and the other connected to the low voltage winding. The high-voltage winding is excited to a voltage not exceeding the rating of the voltmeter. Both voltmeters are read simultaneously. A second set of readings should be taken with the instruments interchanged. The values indicated should be averaged to calculate the ratio.

A meaningful ratio measurement may be made using only a few volts of excitation. The transformer should be excited from the highest voltage winding in order to avoid possibly unsafe high voltages. Care should be taken during the application of voltage and during the measurement. It is important that simultaneous readings of both voltmeters be made.

The voltmeters used should have accuracies commensurate with the requirements of a 0.5% ratio calculation.

6.1.2.3.2 Ratio measurement using a capacitance and power factor bridge

Transformation ratio may be measured with a capacitance and power factor bridge (sometimes called a dissipation factor bridge). This method will provide good results with power transformers as well as with potential transformers where the phase angle error can also be measured. In addition, higher voltage tests may be performed, up to the rating of the instrument, which is frequently 10 kV or 12 kV.

There are several excellent instruments available for this purpose. The manufacturer's instructions should be consulted for the exact procedure for the bridge used.

6.1.2.4 Interpretation of the transformer ratio test

The turns ratio tolerance should be within 0.5% of the nameplate specifications for all windings. For three-phase, Y-connected windings, this tolerance applies to the phase-to-neutral voltage. If the phase-to-neutral voltage is not explicitly indicated on the nameplate, then the rated phase-to-neutral voltage should be calculated by dividing the phase-to-phase voltage by $\sqrt{3}$.

From time to time it may be observed that the measured ratios of the outer phases of a three-phase transformer will be slightly different. Unless the differences are >0.5% there is no cause for rejection of this transformer.

Infrequently, it will be found that the ratio will be different from that specified on the transformer nameplate. This condition may occur when a very large transformer is equipped with a low-voltage winding having a relatively small number of turns. In this case, the turns ratio should be expressed to the nearest complete turn. This error is one of resolution, since the number of turns may be less than 200 turns (200 turns being required to provide 0.5% resolution). For further information see IEEE Std C57.12.00-1993.

It should also be noted that transformers with load taps in the low-voltage winding, may not have an equal number of turns between taps due to the overall low number of turns in the low-voltage winding. In such cases, the voltage variation with tap changer operation will not be uniform. All three phases should have the same measured ratio, although it may not be in exact agreement with the nameplate.

6.1.3 Exciting current

6.1.3.1 General

The single-phase exciting-current test is very useful in locating problems such as defects in the magnetic core structure, shifting of the windings, failures in the turn-to-turn insulation, or problems in the tap changing devices. These conditions result in a change in the effective reluctance of the magnetic circuit, which affects the current required to force a given flux through the core.

6.1.3.2 Test methods

The test comprises a simple measurement of single-phase current on one side of the transformer, usually the high-voltage side, with the other side left floating (with the exception of a grounded neutral). Three-phase transformers are tested by applying a single-phase voltage to one phase at a time. The tests should be performed at the highest possible test voltage without exceeding the voltage rating of the excited winding. The instrumentation should, whenever possible, exclude from the measurement the capacitive currents between the excited winding and the other windings, the core, or the tank. For purposes of comparison, the subsequent tests should be performed at the same value of test voltage and use the same test connections.

6.1.3.3 Analysis of test results

The usual approach to the analysis of the exciting-current test results is to compare the results with the previous tests, or with similar single-phase transformers, or with phases of a given three-phase transformer. For the great majority of three-phase transformers, the pattern is two similar high readings on the outer phases and one lower reading on the center phase. The recommended initial tests include measurements at half of the LTC positions, the neutral position, and one step in the opposite direction. The results may differ for various LTC positions, but the relationship between the phases is expected to remain unchanged. The understanding of how the LTC affects the current magnitude of individual phases is essential for developing proper analysis.

6.1.3.4 Effect of residual magnetism

The transformer core may have residual magnetism present as a result of being disconnected from the power line, or as is frequently the case, as a result of dc measurements of winding resistance. The residual magnetism results in the measurement of higher than normal exciting current.

There is no widely accepted field method for distinguishing between the effect of residual magnetism and the effect of a problem present in the transformer. However, experience shows that although some residual magnetism is almost always present in the core, in most cases it has no significant effect on test results.

In most of the problems detected by using this procedure, the difference between the individual phase currents in the case of three single-phase transformers or between the currents of the outer phases of a three-phase transformer has exceeded 10%. This also applies when comparing with previous measurements.

However, smaller changes in relative currents may also be indicative of problems associated with the core and should be investigated.

If a significant change in the test results is observed, the only known reliable method of excluding the effect of residual magnetism is to demagnetize the transformer core.

It is recommended that the dc measurements of the winding resistance be performed after the exciting current tests.

6.1.3.5 Methods for demagnetization

There are two techniques that can be used to demagnetize the transformer core. The first method is to apply a diminishing alternating current to one of the windings. For most transformers, due to high voltage ratings involved, this method is impractical and involves safety hazards.

A more convenient method is to use a direct current. The principle of this method is to neutralize the magnetic alignment of the core iron by applying a direct voltage of alternate polarities to the transformer winding for decreasing intervals. The interval is usually determined when the demagnetizing current reaches a level slightly lower than the previous level, at which time the polarity of the voltage is reversed. The process is continued until the current level is zero. On three-phase transformers the usual practice is to perform the procedure on the phase with the highest exciting current reading. In most cases, experience has demonstrated that this procedure is sufficient to demagnetize the whole core.

6.1.4 Short-circuit impedance

6.1.4.1 General

The short-circuit impedance (%Z) of power transformers is sometimes measured on site and it can be compared to the nameplate or factory test values. It is used to detect winding movement that may have occurred since the factory tests were performed. Winding movement usually occurs due to heavy fault current or mechanical damage during transportation or installation.

The measurements are usually performed on one phase at a time. Changes of more than $\pm 3\%$ of the short-circuit impedance should be considered significant.

6.1.4.2 Test methods and procedures

Method: A convenient method to measure the short-circuit impedance of a transformer is the voltmeter-ammeter method. This method is applicable to testing either single-phase or three-phase transformers. A power source is used to drive a current through the impedance. The current and the voltage across the impedance are measured simultaneously. The impedance is then given by the ratio of the measured voltage and current.

Preparation: Conductors used for short circuiting the transformer windings should be low-impedance conductors having a cross-section equal to, or greater than No. 1 AWG. They should be as short as possible and be kept away from magnetic masses. Contacts should be clean and tight. These precautions are of importance in avoiding extraneous impedance voltages and losses that might otherwise be introduced into the measurements.

True rms responding meters (voltmeter and ammeter) with accuracies of at least 0.5% and a sinusoidal 60 Hz (rated frequency) adjustable power source should be used for the measurements. The adjustable power source could be derived from the station service transformer through a variable autotransformer rated 0–280 V and at least 10 A. Alternatively a completely isolated power amplifier with an internal 60 Hz oscillator rated at least 250 VA may be used. The adjustable power source should not be obtained directly from a portable gasoline engine generator since the output waveform is usually distorted and its frequency is not sufficiently stable.

6.1.4.3 Impedance test of a single-phase transformer

One of the two windings of the transformer (usually the low-voltage winding) is short-circuited with a low-impedance conductor, and voltage at rated frequency is applied to the other winding. The energizing voltage is adjusted to circulate current in the order of 0.5–1.0% of rated current in the windings or 2–10 A depending on the rating of the transformer under test. Care should be taken to limit the test current so that it will not cause the energizing voltage waveform to become distorted due to overloading the power source. An oscilloscope should be used to observe the voltage waveform during testing. The energizing voltage can be extremely small in comparison with the rated voltage of the winding without introducing significant errors. A typical arrangement is shown in figure 6.

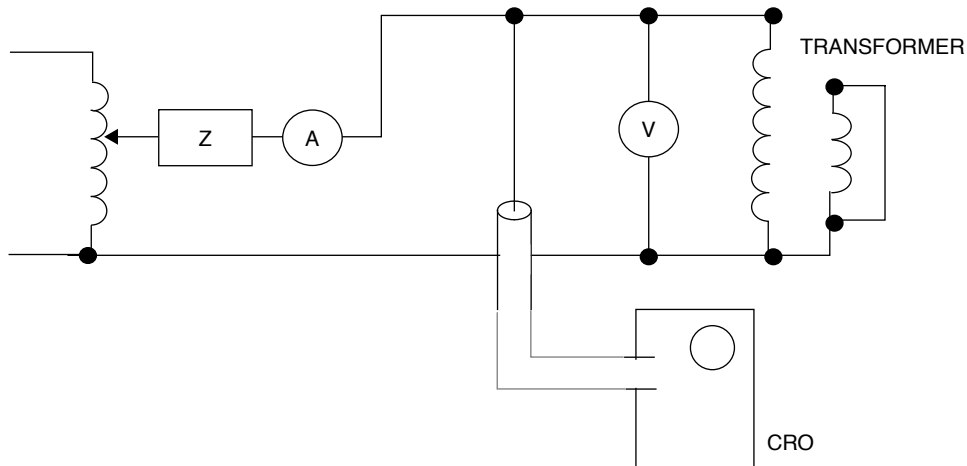


Figure 6—Short-circuit impedance measurement on single-phase transformer

For accurate measurements, the voltmeter should be connected directly to the transformer terminals to avoid voltage drop in the current carrying leads. Meter ranges should be chosen so that their readings are in the upper half of full scale. The current and voltage readings should be read simultaneously.

The %Z of the single-phase transformer can be calculated using the following formula:

$$\%Z \text{ single-phase} = (1/10) \cdot [(E_m/I_m) \cdot kVA_r / (kV_r)^2]$$

where

E_m is measured test voltage

I_m is the current

kVA_r is the rating of the transformer in kilovoltamperes

kV_r is the rating of the winding being energized in kilovolts

6.1.4.4 Impedance test of an autotransformer

An autotransformer may be tested for impedance with its internal connections unchanged. The test is made by short-circuiting its low-voltage terminals and applying voltage at rated frequency to the high-voltage terminals. The same procedure is followed as that used for a single-phase transformer.

6.1.4.5 Impedance test of a three-phase, two-winding transformer

A three-phase transformer may be tested for impedance using a single-phase power source regardless of winding connection. The neutral terminals, if any, are not used. The test is made by short-circuiting the three