



IEEE Guide for Test Procedures for Synchronous Machines Including Acceptance and Performance Testing and Parameter Determination for Dynamic Analysis

IEEE Power and Energy Society

Developed by the
Electric Machinery Committee

IEEE Std 115™-2019
(Revision of IEEE Std 115-2009)



STANDARDS

IEEE Guide for Test Procedures for Synchronous Machines Including Acceptance and Performance Testing and Parameter Determination for Dynamic Analysis

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Electric Machinery Committee
of the
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Approved 7 November 2019

IEEE SA Standards Board

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Abstract: Instructions for conducting generally applicable and accepted tests to determine the performance characteristics of synchronous machines are contained in this guide. Although the tests described are applicable in general to synchronous generators, synchronous motors (larger than fractional horsepower), synchronous condensers, and synchronous frequency changers, the descriptions make reference primarily to synchronous generators and synchronous motors.

Keywords: acceptance and performance testing, dynamic analysis, IEEE 115™, parameter determination, synchronous machines

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Introduction

This introduction is not part of IEEE Std 115-2019, IEEE Guide for Test Procedures for Synchronous Machines Including Acceptance and Performance Testing and Parameter Determination for Dynamic Analysis

IEEE Std 115-2019 incorporates and updates the contents of the 2009 edition.

The first AIEE “Test Code” for Synchronous Machines (#503) was issued in 1945 and formed the basis for the subsequent IEEE Std 115, which was first published in 1965.

The Generator Subcommittee’s Working Group (WG) #7, which produced this guide, was formed in July 2015 at the IEEE PES General Meeting, and the Project Authorization Request (PAR) was approved by the IEEE SA Standards Board in December 2015. This PAR included a proposal by the WG to update the entire document to reflect the state-of-the-art practices and technology. All corrections sent by users of the standard to IEEE SA were reviewed by the WG and implemented as needed.

The WG decided to keep the format and titles of the guide the same as in the previous edition.

During editorial review, it was recommended that the working group discontinue the title in two parts and make one title including the previous separate titles.

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Including ~~Part I~~—Acceptance and Performance Testing

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1. Overview

1.1 Scope

This guide contains instructions for conducting generally applicable and accepted tests to determine the performance characteristics of synchronous machines. Although the tests described are applicable in general to synchronous generators, synchronous motors (larger than fractional horsepower), synchronous condensers, and synchronous frequency changers, the descriptions make reference primarily to synchronous generators and synchronous motors. The tests described may be applied to motors and generators, as needed, and no attempt is made to partition this guide into clauses applying to motors and clauses applying to generators. It is not intended that this guide shall cover all possible tests or tests of a research nature, but only general methods that may be used to obtain performance data. The schedule of factory and field tests, which may be required on new equipment, is normally specified by applicable standards or by contract specifications. This guide should not be interpreted as requiring any specific test in a given transaction or implying any guarantee about specific performance indices or operating conditions.

The term *specified conditions* for tests as used in this guide will be considered as rated conditions unless otherwise agreed upon. Rated conditions apply usually to the quantities listed on the machine nameplate.

1.2 Organization of the guide

The guide consists of 12 clauses. ~~is broken down into 12 clauses. Part I contains Clause 1 through Clause 8, and part II contains Clause 9 through Clause 12.~~ Each clause is organized into subclauses.

Alternative methods of making many of the tests covered in this guide are described and are suitable for different sizes and types of machines and different conditions. In some cases, the preferred method is indicated. The manufacturer's choice of method for factory or field tests on new equipment will govern in the absence of prior agreement or contract specification.

This guide is intended to provide sufficient instructions for performing normally required tests. Throughout this guide, cross-references to subclauses have been used frequently to call attention to pertinent related material. When reference is made to a subclause, it is intended that the reference [includes](#) ~~include~~ not only the specific subclause but any immediately following subclauses that apply to the same general subject.

1.3 Miscellaneous notes

This guide is a revision of ~~the~~ IEEE Std 115-[2009](#) ~~1995 (Reaff 2002)~~ and contains the following updates:

- ~~— Added a new subclause (3.16) on vibration testing to recommend procedures for performing vibration tests according to current industry practices.~~
- ~~— Revised 7.3.6 to correct errors in the previous edition.~~
- Updated [the](#) procedures to reflect state-of-the-art practices and technology.
- [Redrawn some figures to make them more legible and clear.](#)
- Updated references and ~~the~~ bibliography.
- [Added a definitions clause \(see Clause 3\) to define the significant terms used in this guide.](#)
- [Deleted Clause 8 of the 2009 version and included the contents in Clause 11.](#)
- [The testing methods for telephone-influence factor \(TIF\) have been moved from the main body to Annex C.](#)
- ~~— Reedited all equations to make them flexible to further changes and corrections.~~
- ~~— Added an annex (Annex F) on the load rejection test procedure in Clause 11.~~

~~At the time of revision of this document, a separate IEEE working group was working to develop a guide for superconducting machines. Although some test procedures described in this revision of IEEE Std 115 might be applicable to superconducting machines, the working group decided that insufficient experience with commercially available machines existed to make it feasible to cover testing procedures for this emerging technology. The decision to include superconducting machines to the scope of future revisions of IEEE Std 115 will depend on the advancement of the technology and the emergence of consensus concerning testing procedures.~~

It is anticipated that the development of improved practices and new equipment such as electronic and automatic devices will result in new or improved methods of carrying out the ~~tests~~ ~~purposes~~ of this ~~guide~~ ~~standard~~. New or modified methods may be used as substitutes when their results have been shown to be reliable and consistent with the results obtained by methods ~~described~~ ~~given~~ in this guide.

The tests listed ~~in both Part I and Part II~~ basically relate to three-phase machines. The need for addressing tests for machines with more than three phases was recognized. Procedures may be developed for tests on, for example, six-phase, twelve-phase, or much higher phase synchronous machines. When such practices ~~are~~ ~~have been~~ reviewed and found to be acceptable, they will be considered for incorporation into future revisions of this guide.

The International System of Units (SI) or metric system of units has been used in this [guide document](#). Annex A lists a bibliography, in which [the non-normative references cited in the guide](#) are [listed](#) ~~noted particularly for Clause 5 and for Clause 9 through Clause 12.~~ Annex B lists [the nomenclature of main symbols](#) ~~used particularly in Clause 5 and in Clause 9 through Clause 12.~~ Annex C [discusses the telephone influence factor \(TIF\).](#) Annex D includes [the same](#) discussions on leakage and Potier reactance ~~as in~~ Annex [C of the 2009 version.](#) Annex E [updates the](#) ~~D gives an~~ example of calculation of per unit (p.u.) field current ~~of~~ Annex [D of the 2009 version.](#) ~~E describes the test procedures for quadrature axis transient and subtransient reactances and time constants.~~ Annex F includes [the details](#) ~~descriptions~~ on [mathematical background for the equations in Clause 11.](#) ~~generator load rejection test procedure.~~ Annex G includes [same](#) discussions on magnetic nonlinearity [as in the 2009 version.](#) Annex H [includes a new example of standstill frequency response \(SSFR\) test data analysis for a large synchronous machine.](#) Clause 12 has been updated ~~describes an alternative approach~~ to [include an example of SSFR testing on a large salient-pole machine](#) ~~model development.~~

1.4 Instrumentation

The tests described in this guide usually require considerable care to obtain the desired accuracy. It is important that instruments of proper type and range be used.

Information relating to the proper use of instrument transformers and instruments for obtaining the measurements described in this guide is contained in IEEE Std 120™.¹ Consequently, the measurement circuits shown in the figures of this guide are often only schematic, and IEEE Std 120 should be consulted for accurately detailed circuits. However, for some special tests and for purposes of improved clarity, more detailed figures of instrument connections have been included in this guide.

Calibrated high-accuracy instrumentation and accessory equipment should be used. When suitable automatic data acquisition systems or high-speed recorders are available, they [should](#) ~~may~~ be used. Where appropriate, special methods that may be required to obtain accurate data have been indicated.

¹ Information on references can be found in Clause 2.

WARNING

Many tests described in this guide subject the machine to excessive thermal, dielectric, or mechanical stresses that could occur beyond normal operating limits. To [help](#) minimize the risk of damage to the machine or operators, it is recommended that all tests be performed either under the manufacturer's supervision or in accordance with the manufacturer's recommendations.

Because of the dangerous currents, voltages, and forces encountered, adequate safety precautions must be taken for all tests. No attempt is made here to list or review the numerous general safety precautions that are well established throughout the industry. However, this guide recommends special safety precautions applicable to the particular tests described. Knowledgeable and experienced personnel should perform all tests.

2. Normative references

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

ASME PTC 18, Hydraulic Turbines and Pump-Turbines.²

IEC 60034-14, [Rotating electrical machines—Part 14: Mechanical vibrations of certain machines with shaft heights 56 mm and higher—Measurement, evaluation and limits of vibration severity](#).³

² ASME publications are available from the American Society of Mechanical Engineers, ~~22 Law Drive, Fairfield, NJ 07007, USA~~ (<http://www.asme.org/>).

³ IEC publications are available from the International Electrotechnical Commission, ~~Case Postale 131, 3, rue de Varembe, CH 1211, Genève 20, Switzerland/Suisse~~ (<http://www.iec.ch/>). IEC publications are also available in the United States from the American National Standards Institute, ~~25 West 43rd Street, 4th Floor, New York, NY 10036, USA~~ (<http://www.ansi.org/>).

IEEE Std C50.13™, IEEE Standard for Cylindrical-Rotor 50 Hz and 60 Hz Synchronous Generators Rated 10 MVA and Above.^{4, 5}

IEEE Std 4™, IEEE Standard ~~Techniques~~ for High-Voltage Testing Techniques.

IEEE Std 43™, IEEE Recommended Practice for Testing Insulation Resistance of Electric ~~Rotating~~ Machinery.

IEEE Std 56™, (withdrawn), IEEE Guide for Insulation Maintenance of Large Alternating-Current Rotating Machinery (10 000 VA and Larger).

IEEE Std 62.2™, IEEE Guide for Diagnostic Field Testing of Electric Power Apparatus—Electrical Machinery.

IEEE Std 67™, IEEE Guide for Operation and Maintenance of Turbine Generators.

IEEE Std 85™-1973 (Reaff 1980) (withdrawn), IEEE Test Procedure for Airborne Sound Measurements on Rotating Electric Machinery.

IEEE Std 86™-1987 (withdrawn), IEEE Recommended Practice: Definitions of Basic Per-Unit Quantities for AC Rotating Machines.

IEEE Std 95™, IEEE Recommended Practice for Insulation Testing of ~~Large~~-AC Electric Machinery (2300 V and Above) With High Direct Voltage.

IEEE Std 112™, IEEE Standard Test Procedure for Polyphase Induction Motors and Generators.

IEEE Std 118™-1978 (withdrawn), IEEE Standard Test Code for Resistance Measurement.

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IEEE Std 120™, IEEE Master Test [Guide](#) ~~Code~~ for Electrical Measurements in Power Circuits.

IEEE Std 433™-1974 (withdrawn), IEEE Recommended Practice for Insulation Testing of Large AC Rotating Machinery with High Voltage at Very Low Frequency.

IEEE Std 492™, IEEE Guide for Operation and Maintenance of Hydro-Generators.

IEEE Std 519™, IEEE Recommended [Practice](#) ~~Practices~~ and Requirements for Harmonic Control in Electric Power Systems.

IEEE Std 1095™, IEEE Guide for [the](#) Installation of Vertical Generators and Generator/Motors for Hydroelectric Applications.

IEEE Std 1110™, IEEE Guide for Synchronous Generator Modeling Practices [and Applications](#) in [Power System](#) Stability Analyses.

IEEE Std 1434™, IEEE Guide for the Measurement of Partial Discharges in [AC Electric Machinery Rotating Machines](#).

ISO 3744, [Acoustics—](#)Determination of sound power levels [and sound energy levels](#) of noise sources using sound pressure—[Engineering methods for an essentially free field over a reflecting plane](#).⁶

ISO [20816](#) ~~10816~~-1, Mechanical vibration—[Measurement and](#) evaluation of machine vibration—~~by measurements on non-rotating parts~~—Part 1: General guidelines.

ISO [20816](#) ~~10816~~-2, Mechanical vibration—[Measurement and](#) evaluation of machine vibration—~~by measurements on non-rotating parts~~—Part 2: Land-based [gas turbines](#), steam turbine and generators in excess of [40](#) ~~50~~ MW, with [fluid-film bearings and rated](#) ~~normal operating~~ speeds of 1500 r/min, 1800 r/min, 3000 r/min and 3600 r/min.

⁶ ISO/IEC publications are available from the [International Organization for Standardization](#) ~~ISO Central Secretariat, Case Postale 56, 1 rue de Varembe, CH 1211, Genève 20, Switzerland/Suisse~~ (<http://www.iso.ch/>). ISO/IEC publications are also available in the United States from the American National Standards Institute, ~~25 West 43rd Street, 4th Floor, New York, NY 10036, USA~~ (<http://www.ansi.org/>).

ISO ~~20816~~ ~~10816~~-4, Mechanical vibration—Measurement and evaluation of machine vibration ~~by measurements on non-rotating parts~~—Part 4: Gas turbines in excess of 3 MW, with fluid-film bearings ~~turbine driven sets excluding aircraft derivatives~~.

ISO ~~20816~~ ~~10816~~-5, Mechanical vibration—Measurement and evaluation of machine vibration ~~by measurements on non-rotating parts~~—Part 5: Machine sets in hydraulic power generating and pump-storage pumping plants.

ISO 4871, Acoustics—Declaration and verification of noise emission values of machinery and equipment.

~~ISO 7919-1, Mechanical vibration of non-reciprocating machines—Measurement on rotating shafts and evaluation criteria—Part 1: General Guidelines.~~

~~ISO 7919-2, Mechanical vibration of non-reciprocating machines—Measurement on rotating shafts and evaluation criteria—Part 2: Land-based steam turbine and generators in excess of 50 MW with normal operating speeds of 1500 r/min, and 3600 r/min.~~

~~ISO 7919-4, Mechanical vibration of non-reciprocating machines—Measurement on rotating shafts and evaluation criteria—Part 4: Gas turbine sets.~~

~~ISO 7919-5, Mechanical vibration of non-reciprocating machines—Measurement on rotating shafts and evaluation criteria—Part 5: Machine sets in hydraulic power generating and pumping plants.~~

ISO 9614, Acoustics—Determination of sound power levels of noise sources using sound intensity.

NEMA MG1, Motors and Generators.⁷

⁷ NEMA publications are available from the National Electrical Manufacturers Association, ~~1300 N. 17th St., Ste. 1847, Rosslyn, VA 22209, USA~~ (<http://www.nema.org/>).

3. Definitions

For the purposes of this guide, the following terms and definitions apply. The *IEEE Standards Dictionary Online* may be consulted for terms not defined in this clause.⁸

balanced telephone-influence factor (balanced TIF): The ratio of the square root of the sum of the squares of the weighted root-mean-square values of the fundamental and the nontriple series of harmonics to the root-mean-square value of the normal no-load voltage wave.

direct-axis subtransient open-circuit time constant: A constant that characterizes the initial decay of transients in the direct-axis variables of the synchronous machine with the stator windings open-circuited. The interval characterized is that immediately following a disturbance, during which the effects of all amortisseur windings are considered. A detailed (derived) closed-form expression for the subtransient open-circuit time constant of a machine with a single direct-axis amortisseur winding is obtained by taking the reciprocal of the smallest root of the denominator of the direct-axis operational impedance. An approximate (standard) value is often used, in which it is assumed the field winding resistance is very small and the detailed expression simplified.

direct-axis synchronous impedance: The magnitude obtained by the vector addition of the value for armature resistance and the value for direct-axis synchronous reactance.

direct-axis synchronous reactance: The sum of the stator winding leakage reactance and the direct-axis magnetizing (armature) reactance of a synchronous machine. This sum represents the balanced steady-state value of the direct-axis operational impedance of the synchronous machine and thus characterizes the equivalent reactance of the machine during steady-state operation.

⁸ IEEE Standards Dictionary Online is available at <http://dictionary.ieee.org>.

direct-axis transient open-circuit time constant: A constant that characterizes the decay of transients in the direct-axis variables of the synchronous machine with the stator windings open-circuited. The interval characterized is that following the subtransient interval, but prior to steady state, during which the effects of the amortisseur windings are small (possibly negligible). A detailed (derived) closed-form expression for the transient open-circuit time constant of a machine with a single direct-axis amortisseur winding is obtained by taking the reciprocal of the smallest root of the denominator of the direct-axis operational impedance. An approximate (standard) value is often used, in which it is assumed the amortisseur winding resistance is infinite and the detailed expression simplified.

leakage reactance: The amount of inductive reactance associated with leakage flux. The leakage flux is the flux that traverses in paths farther from the designated paths, such as the magnetic core in transformers and the air gap in electric machines, and constitutes the non-useful flux. The electric circuit symbol of leakage reactance is X_ℓ . It is a function of the leakage inductance and the frequency of operation. Higher values of leakage reactance affect the regulation and efficiency of the system. X_ℓ is expressed in ohms.

negative-sequence impedance: The impedance offered by a circuit when negative-sequence currents alone flow through it, expressed in ohms. The impedance is complex, with its real part being the circuit resistance and imaginary part, which is a function of frequency and inductance referenced as negative-sequence reactance, also expressed in ohms.

negative-sequence reactance: Inductive reactance offered by a circuit for the flow of negative sequence currents alone. Expressed in ohms, the inductive reactance is a function of frequency and the inductance of the circuit to negative-sequence current flow.

negative-sequence resistance: The quotient of the in-phase fundamental component of negative-sequence primary voltage, due to sinusoidal negative-sequence primary current of rated frequency, and the value of this current, when the machine is running at rated speed.

operational impedance: A representation in which the impedance of a system is expressed as a function of the Heaviside operator $p = d/dt$ or the Laplace operator $s = j\omega$. In the modeling of synchronous machines, the Park transformed stator flux linkages per second are often expressed in terms of impedances $X_q(p)$ and $X_d(p)$, termed the quadrature-axis and direct-axis operational impedances, respectively.

Using these expressions, the dynamics of the rotor windings are represented within the operational impedances; therefore, the rotor of a synchronous machine can be considered as either a distributed or lumped parameter system.

positive-sequence resistance: The value of resistance that, when multiplied by the square of the fundamental positive-sequence rated-frequency component of armature current and by the number of phases, is equal to the sum of the copper loss in the armature and the load loss resulting from that current, when the machine is operating at rated speed. Positive-sequence resistance is normally that corresponding to rated armature current. Note that, inasmuch as the load loss may not vary as the square of the current, the positive-sequence resistance applies accurately only near the current for which it was determined.

pull-out torque: The maximum value of torque that a synchronous machine can deliver before pulling out of synchronism and slipping poles.

quadrature-axis subtransient reactance: The high-frequency asymptote of the quadrature-axis operational impedance of a synchronous machine. The reactance characterizes the equivalent reactance of the quadrature-axis windings of the machine during the initial time following a system disturbance. In models in which the rotor windings are represented as lumped parameter circuits, the quadrature-axis subtransient reactance is expressed in closed form as the sum of (a) the stator winding leakage reactance and (b) the parallel combination of the quadrature-axis magnetizing reactance and the quadrature-axis rotor amortisseur leakage reactances.

quadrature-axis synchronous reactance: The sum of the stator winding leakage reactance and the quadrature-axis magnetizing (armature) reactance of a synchronous machine. This reactance represents the balanced steady-state value of the quadrature-axis operational impedance of the synchronous machine.

residual-component telephone-influence factor (residual-component TIF): The ratio of the square root of the sum of the squares of the weighted residual harmonic voltages to three times the root-mean-square no-load phase-to-neutral voltage.

short-circuit time constant of the armature winding: The time required for the direct-current component present in the short-circuit armature current following a sudden change in operating conditions to decrease to 0.368 of its initial value, when the machine is running at rated speed.

zero-sequence reactance: The ratio of the fundamental component of reactive armature voltage, due to the fundamental zero-sequence component of armature current, to this component at rated frequency, when the machine is running at rated speed.

zero-sequence resistance: The ratio of the fundamental in-phase component of armature voltage, resulting from fundamental zero-sequence current, to this component of current at rated frequency.

4. Miscellaneous tests

4.1 Insulation resistance

The recommended methods for testing insulation resistance are given in IEEE Std 43. Polarization index and the effects of temperature, moisture, and duration of application of test voltage are also covered in that standard.

Too low a value of insulation resistance may indicate the presence of moisture in or on the insulation. In this case, the machine should be dried out before dielectric tests are made or before the machine is placed in operation. See IEEE Std 1095 for methods of dry-out.

NOTE—While IEEE Std 1095 is written specifically for vertical hydraulic-turbine-driven generators, the procedure is applicable to other types of machines. ⁹⁸

Any questions regarding the proper methods to be used for drying out a machine should be referred to the manufacturer.

4.2 Dielectric and partial discharge tests

4.2.1 General

The high-potential test is usually, but not necessarily, applied after all other tests have been completed. The magnitude, frequency, wave shape, and duration of the test voltage are given in IEEE Std C50.13 and NEMA MG1.

WARNING

Due to the high voltage used, which could cause serious personal injury or death, high-potential tests should be conducted only by experienced personnel, and adequate safety precautions should ~~must~~ be taken to help minimize the risk of such injury to personnel or damage to property. For the recommended procedures, refer to IEEE Std 4 and IEEE Std 62.2.

The test voltage should be applied to each electric circuit (including each phase of polyphase windings if they are not internally connected) with all other electric circuits and metal parts grounded. The leads of each winding or phase should be connected together, regardless of whether the winding is to be tested or grounded.

All wiring brought out for resistance temperature detectors (RTDs), thermocouples, or other monitoring devices installed in the coils or windings must be connected together and grounded. Voltage transformers must be disconnected from the leads under test.

⁹⁸ Notes ~~to~~ in text, tables, and figures are ~~given~~ for information only and do not contain requirements needed to implement the standard ~~guide~~.

The high-potential test can be performed using the following methods:

- Method 1. Alternating-voltage testing at power frequency (see [4.3.2.3](#))
- Method 2. Direct-voltage testing of stator windings (see [4.3.2.4](#))
- Method 3. Very low frequency testing of stator windings (see [4.3.2.5](#))
- Method 4. Partial discharge testing (see [4.3.2.6](#))

4.2.2 Preparation

During testing of the field windings of large machines, the brushes normally should be lifted and isolated electrically from the collector rings so that no excessive voltage stress will be imposed on the field winding if some part of the brush rigging or the leads fails. The brush rigging and station leads should be tested separately from the field. If it is desired to test the brush rigging of a machine at the same time the field is being tested, the exciter leads should be disconnected unless it is intended that the exciter be tested simultaneously. In any case, the permanent instrumentation leads should be disconnected. They may be tested separately if desired.

During testing of the field windings of brushless machines, the dc excitation leads should be completely disconnected from the exciter unless it is intended that the exciter and associated components be tested simultaneously. In either case, the brushless circuit components (e.g., diodes, thyristors) should be short-circuited (not grounded) during the test.

Additional methods, procedures, and precautions are given in IEEE Std C50.13 and NEMA MG1.

4.2.3 Method 1. Alternating-voltage testing at power frequency

An alternating voltage of power frequency is applied to the winding being tested. The following two standard methods of measuring alternating voltage are recognized:

- Transformer-voltmeter
- Sphere gap

These methods are fundamentally different in kind, and each can readily be checked against the other.

The transformer-voltmeter method is based upon the use of voltage transformers designed for instrument use and having accurately determined voltage ratios.

The sphere-gap method is based on an extensive calibration of the breakdown of air as a dielectric between spheres of specified sizes and spacings. Every precaution must be taken against the occurrence of overvoltage oscillations due to sphere-gap discharges. The sphere gap is frequently used only for overvoltage protection.

Resistance voltage divider methods are also available and should be considered where applicable.

During application, the test voltage should be increased smoothly and promptly, held for the test period (normally one minute), and then promptly and smoothly reduced to zero.

Because this testing can be destructive to the winding, some precautions are advised. It should be noted that the test voltage applied during manufacture testing of new windings is a one-time value. For purposes of maintenance testing in subsequent years, it is advisable to apply only a lesser percentage of the original test value. For suggested values, see EPRI EL-5036 [[B19](#) [B20](#)]. [10⁹](#)

4.2.4 Method 2. Direct-voltage testing of stator windings

A direct voltage equal to 1.7 times the root-mean-square (rms) value of the specified power frequency test voltage (effective value) is applied to the winding being tested. For the method of test, see IEEE Std 4 and IEEE Std 95.

The resistor-ammeter method is the standard method for direct-voltage measurements.

[10⁹](#) The numbers in brackets correspond to the numbers of the bibliography in Annex A.

WARNING

Following a direct-voltage high-potential test, the tested winding should be thoroughly grounded. The insulation rating of the winding and the test level of the voltage applied determine the period of time required to dissipate the charge. In many cases, the ground must be maintained for several hours to dissipate the charge to [help reduce](#) ~~minimize~~ the hazard to personnel.

The same precautionary advisory regarding lesser percentages of test values also applies to the direct-voltage testing.

4.2.5 Method 3. Very low frequency testing of stator windings

A [very low frequency](#) ~~VLF~~ voltage (frequency around 0.1 Hz) with crest equal to 1.63 times the rms value of the specified power-frequency test voltage (effective value) is applied to the winding being tested. [Very low frequency](#) ~~VLF~~ testing is advantageous on large machines with high winding capacitance where the test may result in reduced size and rating of the required test equipment. For the method of test, see IEEE Std 433-1974.

4.2.6 Method 4. Partial discharge testing

Insulation maintenance, slot-discharge testing, and corona-probe testing are described in IEEE Std 56. In addition, IEEE Std 1434 and IEEE Std 62.2 describe partial discharge measurements on rotating machines. There has been a large increase in the research and application of partial discharge techniques using permanently and temporarily mounted detectors. Application of such techniques to machines covered by this guide is increasingly common and yields valuable information for both maintenance and diagnosis of winding problems. Partial discharge analysis states abilities to distinguish between problems in the ground-wall insulation and surface discharges due to degraded voltage stress control materials in high-voltage windings. ~~It should be noted that~~ The tests referenced in this subclause are off-line partial discharge tests that cannot detect loose stator windings in the slots. Neither on-nor off-line partial discharge tests will detect end-winding vibration problems. Partial discharge can be measured when the machine is off line or on line when the machine is fully energized, loaded, and running continuously.

4.3 Resistance measurements

4.3.1 General

To obtain dc resistance measurements of armature and field windings, the procedures given in IEEE Std 118-1978 should be used. The following subclauses give special considerations pertaining to the measurement of winding resistance. Where generator field leads are inaccessible such as when brushless exciters are used, it may not be possible to measure the field resistance unless provision is available through special instrumentation and procedures. The manufacturer should be consulted.

4.3.2 Correction to specified temperature

When the resistance, R_{t_1} , of a winding has been determined by test at a winding temperature t_{t_1} , the resistance may be corrected to a specified temperature t_s by ~~using the following~~ Equation (1):

$$R_s = R_{t_1} \left(\frac{t_s + k}{t_{t_1} + k} \right) \quad (1)$$

where

R_s is the winding resistance, corrected to specified temperature, t_s , in ohms

t_s is the specified temperature, in ~~°C degrees Celsius~~

R_{t_1} is the test value of winding resistance, in ohms

t_{t_1} is the temperature of winding when resistance was measured, in ~~°C degrees Celsius~~

k is the characteristic constant for the winding material (see ~~7~~ 6.4.4)

4.3.3 Reference field resistance

The resistance [of the field winding](#) is commonly measured at standstill in order to obtain a reference value (R_b) from which to determine field temperature during running tests by the method of [Z 6.4.4](#). For this purpose, the rotor is allowed to be exposed to an essentially constant ambient temperature long enough for the entire rotor to reach the ambient temperature. It is important that the method of measurement does not alter the temperature of the winding. When a double bridge is used, the current through the winding is not sufficient enough to produce a change in temperature.

When the field resistance is measured by drop of potential, a relatively low value of current should be used so that the resulting $I^2 R$ loss will not cause a significant change in temperature during the time of application. The application of current should be no longer than necessary for the electric transient due to field inductance to die out and the instruments to come to rest.

Also, when the field resistance is measured by drop of potential, the current should be applied through clamping rings or other equivalent devices to avoid damage to the active surface of the collector. The field temperature can be measured by thermometers or thermocouples.

4.3.4 Reference field resistance from a running test

Although it is preferable to obtain the reference value of field resistance at standstill because both the resistance and temperature can be determined more accurately, it is often advantageous to obtain or verify the reference value by a test made at or near normal speed using the drop-of-potential method. For conductor-cooled rotors, winding temperature may change too rapidly to make this method practicable. The making or relieving of turn-to-turn short circuits in the field winding may cause the measured resistance of the field circuit to differ substantially from the standstill value and thus provide a possible incidental check for short-circuited turns (see [4 3.4](#)).

Immediately after the machine has been brought up to speed, starting with the rotor at a known uniform temperature, a dc voltage is applied to the field in as small a value as will permit accurate current and voltage measurements. As soon as the current has become constant, the voltage drop across the collector rings should be measured. Since the voltage drop of the normal brushes may be a substantial fraction of the impressed voltage in this test, it is essential that the brush voltage drop be eliminated from the voltage measurement or [reduced](#) ~~minimized~~ by special methods of voltage measurement or special test procedures (see [4 3.3.6](#)).

4.3.5 Field resistance for running temperature tests

To determine the field temperature under specified or desired load conditions, the field resistance should be measured by the drop-of-potential method after the machine has been operated at the required field current and as near as practicable to the required loading conditions long enough for a uniform temperature to be reached. The temperature of the field winding is then determined in accordance with [7 6.4.4](#). The resistance obtained from this test is called R_f in Equation ([59 6-11](#)).

Including brush voltage drop in the measured field voltage may introduce a substantial error in the temperature determination; therefore, it is highly desirable to eliminate or [reduce](#) ~~minimize~~ its effect in this test (see [4 3.3.6](#)).

When measuring the resistance of the field with the machine loaded, the voltage regulator should be disconnected, and a number of armature voltage, power, and current readings should be taken simultaneously with field current and voltage readings to [help](#) ensure that the resistance is measured under uniform conditions.

4.3.6 Effect of brush voltage drop

To determine the field resistance of a running machine accurately, it is necessary to obtain the voltage drop across the field winding without including the voltage drop of the brushes supplying the field current. This step is especially important when the field current is very small, e.g., when determining the reference resistance value (see [4.3.3.4](#)). For this purpose, it is desirable to measure the voltage drop directly across the collector rings, using special brushes that are in contact with the collector rings only during voltage measurement. For this purpose, it is possible to use [the following](#):

- a) Special copper or bronze leaf brushes bearing directly on the collector rings.
- b) Insulated brushes that have not developed a glazed surface.
- c) Insulated special carbon or graphite brushes compounded with highly conducting materials to reduce their resistance.

Unless a very small voltage drop occurs across these measurement brushes, a significant error may be introduced.

When these special methods of voltage measurement are not available, the voltage measurement necessarily includes the voltage drop across the brushes. In such cases, efforts to reduce its effect should be made. Since the voltage drop across the brushes remains reasonably constant with varying current, the effective brush resistance is reduced by increasing the current density. This step may be accomplished by reducing the number or cross section of brushes used during the test, particularly for low field currents. When information is available regarding the expected voltage drop across the brushes, more accurate results can be obtained by subtracting the brush drop from the measured voltage before calculating the resistance, but the results thus obtained should be used with caution.

On machines whose collectors have high peripheral speed, care must be exercised to avoid damaging the surface condition of the collector by voltage-measuring devices.

4.4 Tests for short-circuited field turns

4.4.1 General

The object of these tests is to detect field coils that have short-circuited turns, an incorrect number of turns, or incorrect conductor size. Not all short-circuited field turns are apparent at standstill, and a test at rated speed may be required. Short-circuited field turns can be tested using the following methods:

- Method 1. Voltage drop, dc ([see 4.4.2](#))
- Method 2. Voltage drop, ac ([see 4.4.3](#))
- Method 3. DC resistance ([see 4.4.4](#))
- Method 4. Exciting coil for cylindrical rotors ([see 4.4.5](#))
- Method 5. Rotor waveform detection for cylindrical rotors ([see 4.4.6](#))

4.4.2 Method 1. Voltage drop, dc

This method can be used to detect short-circuited turns only when connections between coils are accessible. The test is made, with the rotor at standstill, by passing a constant dc through the entire field winding. The drop in voltage of each coil or pair of coils is measured by means of a voltmeter. If these readings vary more than $\pm 2\%$ from the average, it is an indication that there may be short-circuited turns in the coil or that part of the winding may be wound with the wrong number of turns or size of conductor.

4.4.3 Method 2. Voltage drop, ac

A more sensitive test for short-circuited turns is made by passing constant-amplitude ac through the entire field winding. If there is access to connections between coils, with the rotor at standstill, the voltage across each coil or pair of coils should be measured. The voltage across a coil having a short-circuited turn will be substantially less than the voltage across a sound coil. The voltage across a sound coil adjacent to the coil with a short-circuited turn will be somewhat less than the voltage across other sound coils because of the reduced flux in the short-circuited coil. Comparison of the measured voltages will readily locate any coils that are defective.

If the connections between coils are not accessible, the current and voltage drop (across the entire winding) should be measured. The impedance of a one-circuit winding in which one coil has a short-circuited turn will be reduced to approximately $(m - 1)/m$ times the value across a sound winding, where m is the number of turns in the winding. This test is useful for detecting a machine that has a short-circuited turn only when running. If the speed is varied while the ac is applied, a discontinuity in the current or voltage readings should indicate the occurrence or removal of a short circuit.

The sensitivity of this method of test is much lower for cylindrical rotors in which the field winding lies in slots, especially for solid-steel rotors. The sensitivity varies depending on which coil has a short-circuited turn. Factory trials in which temporary short circuits are applied can be made to serve as the basis for future analysis when short-circuited turns are suspected. For cylindrical-rotor machines, Method 3, Method 4, or Method 5 may be preferred.

4.4.4 Method 3. DC resistance

In this method, a comparison is made between the field resistance and a value previously obtained by test or calculation.

After the rotor has been exposed to an ambient temperature long enough for the entire rotor winding to be at ambient temperature, the field resistance is measured by double bridge, and the temperature of the rotor is measured by several thermometers or thermocouples located at suitable points. The resistance is then corrected to a temperature at which the resistance has previously been determined by a similar test (or by calculation in the case of a new machine). If the corrected value of the newly obtained resistance is significantly lower than the reference value, short-circuited turns may be present.

4.4.5 Method 4. Exciting coil for cylindrical rotors

This method uses a testing device having a U-shaped core capable of bridging one coil slot of a cylindrical rotor and having an exciting coil wound on the core. The test is made by placing the device successively across each field coil slot and passing ac (normally at power frequency) through the exciting coil. The voltage across the field winding or the impedance of the exciting coil should be determined for each slot. When the device spans a coil side with a short-circuited turn, the voltage of the field winding or the impedance of the coil will be lower than the corresponding value for a slot containing a sound coil.

4.4.6 Method 5. Rotor waveform detection for cylindrical rotors

This method utilizes a transducer or coil pickup to determine the rotor magnetic field waveform. The magnetic pick-up should be mounted from the stator in the air gap in close proximity to the rotor, according to the manufacturer's recommendations, and connected to an oscilloscope or other suitable recording device. With the rotor rotating at speed and the field winding excited, the occurrence of short-circuited turns can often be detected as discontinuity or dissymmetry in the recorded trace (see IEEE Std 67).

4.5 Polarity test for field poles

The polarity of the field poles may be checked by means of a small permanent magnet mounted so that it can turn and reverse its direction freely. The field winding should be energized by 5% to 10% of rated current. The magnet indicates [alternating](#) ~~proper~~ polarity by reversing direction as it is passed from pole to pole. The magnet should be checked to [help](#) ensure that its magnetism has not been lost or its polarity reversed by the field flux.

4.6 Shaft current and bearing insulation

4.6.1 General

Irregularities in the magnetic circuit may cause a small amount of flux to link the shaft, with the result that an electromotive force is generated between the shaft ends. This electromotive force may cause a current through the shaft, bearings, bearing supports, and machine framework and back to the other end of the shaft, unless the circuit is interrupted by insulation.

NOTE—While other causes may produce a shaft voltage not involving a difference in potential from one end of the shaft to the other, special tests are not provided for the resulting effects because each of these sources requires specially adapted methods of tests, essentially of an investigative research nature.

Shaft current and bearing insulation can be tested using the following methods:

- Method 1. Across end shafts [\(see 4.6.2\)](#)
- Method 2. Across bearing oil film, uninsulated bearings [\(see 4.6.3\)](#)
- Method 3. Across bearing insulation [\(see 4.6.4\)](#)
- Method 4. Bearing insulation—Running test [\(see 4.6.5\)](#)
- Method 5. Bearing insulation—Static test [\(see 4.6.6\)](#)
- Method 6. Double insulation [\(see 4.6.7\)](#)

For Method 1 through Method 4, the machine should be run at rated speed and excited at rated armature voltage open circuit, unless other operating conditions are specified.

4.6.2 Method 1. Across end shafts

The presence of shaft voltage may be determined by measuring the voltage from end to end of the shaft with a high-impedance voltmeter.

4.6.3 Method 2. Across bearing oil film, uninsulated bearings

This method requires that the insulating properties of the bearing oil film be adequate to withstand the shaft voltage without breaking down. The presence of shaft voltage or current may be determined by running the machine at rated speed and voltage and connecting a low-resistance conductor from the shaft to the frame of the machine at one bearing and a low-range ac voltmeter (or a high-range ac ammeter) with low-resistance leads from the shaft to the frame at another bearing. Deflection of the instrument indicates the presence of a voltage that may produce shaft currents. If the instrument does not deflect, there is either insufficient voltage present or the bearing oil film is not acting as an adequate insulator.

4.6.4 Method 3. Across bearing insulation

Many machines have one or more bearings insulated to eliminate shaft currents. For these methods as described in this subclause as well as 4.3.6.5 through 4.3.6.7, it is assumed that insulation is located between the bearing and the frame of the machine. To determine the presence of a voltage that will produce shaft currents in such a machine, a low-resistance conductor is connected from the shaft to the uninsulated bearing in order to short-circuit the oil film, and a low-range ac voltmeter (or a high-range ac ammeter) is connected between the shaft and the frame successively at each insulated bearing. Deflection of the instrument indicates the presence of a voltage that will produce shaft currents if the bearing insulation is not present.

4.6.5 Method 4. Bearing insulation—running test

The insulation can be tested by connecting a low-range ac voltmeter (or a high-range ac ammeter) across the insulation. A low-resistance conductor may be applied from the shaft to each bearing to short-circuit the oil film. Deflection of the instrument, in this case, is evidence that the insulation is at least partially effective. If there is no deflection of the instrument, either the insulation is defective or there is no shaft voltage present.

4.6.6 Method 5. Bearing insulation—static test

A layer of heavy paper is placed around the shaft to insulate the journals of the uninsulated bearings. The coupling of the driving or driven units should be disengaged if it is not insulated. Then, from a 110 [V to](#) 125 V source, with either a filament lamp suitable for the circuit voltage or a voltmeter of approximately 150 V full scale with a resistance in the range of 100 Ω/V to 300 Ω/V placed in a series with the voltage source, two leads should be run, one to the insulated bearing and the other to the frame (across the insulation). If the lamp filament does not glow (or if the reading of the voltmeter does not exceed 60 V), the insulation may be considered satisfactory.

A 500 V mega-ohm-meter may also be used. This method is much more sensitive than the above method and may tend to reject insulation that is adequate to [reduce](#) ~~prevent~~ the small shaft voltage from causing injurious current.

4.6.7 Method 6. Double insulation

On some machines, bearings are provided with two layers of insulation with a metallic separator between them. The test of Method 5 is applied between the metallic separator and the frame of the machine. This test should be carried out on each of the various multiple paths between the shaft and the frame where insulated bearings are used (e.g., thermometer tubes, control pipes for a hydraulic turbine, hydrogen seals, insulated couplings).

This test may be made with the machine stationary or running. The test should be supplemented by careful visual inspection to verify that there are no possible parallel paths that are not provided with insulation.

4.7 Phase sequence

4.7.1 General

The phase-sequence test is made to check the agreement of the machine with the terminal markings and phase rotation that have been specified or with the requirements of NEMA MG1. The results are used when connecting line leads to the armature terminals to obtain correct phasing of a generator to the bus or the correct direction of rotation for motors.

The phase sequence on three-phase machines can be reversed by interchanging the line connections to any two armature terminals. The phase sequence on two-phase machines can be reversed by interchanging the two leads of either phase.

Phase sequence can be tested using the following methods:

- Method 1. Phase-sequence indicators [\(see 4.7.2\)](#)
- Method 2. Indication of differential voltage [\(see 4.7.3\)](#)
- Method 3. Direction of rotation for machines that can be started on a power source [\(see 4.7.4\)](#)

4.7.2 Method 1. Phase-sequence indicators

Phase sequence is determined by running the machine as a generator in the direction of rotation for which it was designed and by connecting to the terminals a phase-sequence indicator or an induction motor whose direction of rotation is known when a given phase sequence is applied to its terminals.

Figure 1 is a diagram of one type of phase-sequence indicator that consists of windings placed on a laminated iron core, with a steel bar mounted in the center. The terminals of the machine under test, whether three-phase or two-phase, should be connected to the corresponding terminals of the indicator. The indicator shown in Figure 1 will operate clockwise if the phase sequence is 1, 2, 3, and counterclockwise if the phase sequence is 1, 3, 2.

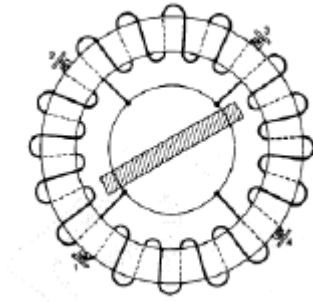


Figure 1—Phase-sequence instrument

A type of phase-sequence indicator without moving parts is also available for three-phase machines and is shown schematically in Figure 2. The indicator makes use of a small capacitor and two neon lamps connected in [wye](#) ∇ across the three-phase circuit to be tested. For phase sequence 1, 2, 3, the lamp connected to terminal 1 will glow. For phase sequence 1, 3, 2, the lamp connected to terminal 3 will glow. To check the indicator, the switch shown in Figure 2 should be closed. If operating correctly, both lamps will glow with equal intensity.

When it is necessary to connect a phase-sequence indicator to the machine terminals through voltage transformers, extreme care should be exercised in observing the conventions for polarity markings of the voltage transformers. (See 4.8.1 in IEEE Std C57.13.)

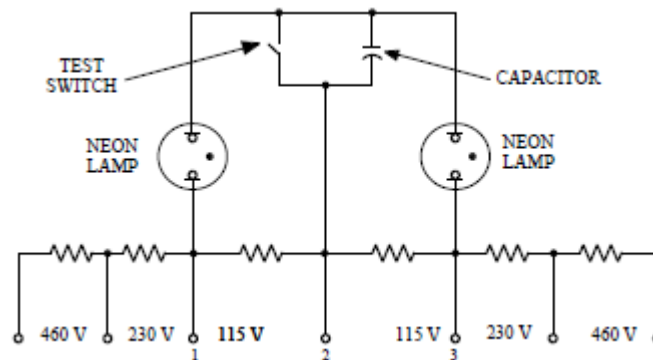


Figure 2—Neon-lamp phase-sequence indicator

4.7.3 Method 2. Indication of differential voltage

A convenient check of the phase sequence of a synchronous generator compared to the system to which it is to be connected can be obtained as described below.

Four voltage transformers are connected as shown in Figure 3 for three-phase machines. Great care is necessary to maintain the correct polarity of the transformer connections. The asterisks show the corresponding terminals of the primary and secondary windings. This connection effectively places indicating lamps across open disconnecting switches between the generator and the system. The generator should be brought up to speed and excitation applied corresponding to normal voltage. When it is near synchronous speed, lamps connected to the voltage transformer secondaries will brighten or dim simultaneously if the generator has the same phase sequence as the system, whereas they will brighten or dim one after the other if the phase sequences are opposite.

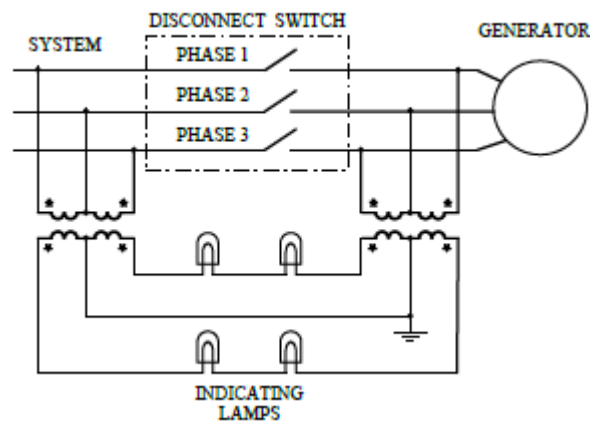


Figure 3—Connection diagram for comparing phase sequence of a generator with that of a system by indicating voltage across an open disconnect switch

4.7.4 Method 3. Direction of rotation for machines that can be started on a power source

The phase sequence can be checked by starting the machine from its normal source of power with a known phase sequence and observing its direction of rotation. If damage can result from improper rotation, the motor should be disconnected from the apparatus that could be damaged. In some cases, apparatus such as a nonreverse ratchet cannot be disconnected. In this case, a sufficiently low voltage should be used so that the apparatus is not damaged, or another procedure such as Method 1 or an adaptation of Method 2 should be used.

3.8 Telephone-influence factor (TIF)

3.8.1 General

TIF for the synchronous machine alone is normally measured when its rectified excitation has been replaced by a ripple-free supply and power transformers have been removed from the line. It is obtained as the quotient of a weighted rms value of the fundamental and harmonics of a voltage wave and the rms of the wave. This calculation can be done analytically from data taken by harmonic analysis in conjunction with the weighting factors using the following equations:

$$TIF = \frac{E_{TIF}}{E_{RMS}} \quad (3-2)$$

$$E_{TIF} = \sqrt{\sum (T_N E_N)^2} \quad (3-3)$$

(Deleted)

where

E_{TIF} is the weighted rms value of the voltage wave, using the weighting factors T_N

T_N is the TIF weighting factor for the n^{th} harmonic

E_N is the rms value of the n^{th} harmonic component of voltage (including the fundamental components of voltage) in the same units as E_{TIF}

E_{RMS} is the rms value of the voltage wave, in the same units as E_{TIF}

The weighting factor, T_N , used above is equal to the single frequency TIF.

3.8.2 Weighting factors

For the weighting factors to be used in calculating TIF, see IEEE Std C50.13 or NEMA MG1.

3.8.3 Voltage transformer considerations

If a voltage transformer is connected between the machine and the instrument, it should be established that the harmonic content of the machine voltage is not affected by the presence of the transformer. To perform such a check, a resistance voltage divider (having approximately 300 Ω/V and designed to produce the desired voltage for a harmonic analyzer) should be placed across the terminals of the machine with the voltage transformer disconnected, and the harmonic content of the machine voltage should be obtained. The voltage transformer should then be placed across the machine terminals and the harmonic analysis repeated, using the voltage divider. A second check can be made by making a harmonic analysis using the secondary of the voltage transformer.

If the three analyses of machine voltage harmonic content agree, the transformer can be considered satisfactory for use on other similar machines.

3.9 Balanced TIF

3.9.1 General

For the definition of *balanced telephone influence factor (TIF)*, see *The IEEE Standards Dictionary: Glossary of Terms & Definitions* [B29]. Balanced TIF can be measured using the following test methods:

— Method 1. Line-to-line voltage

— Method 2. Phase voltage

3.9.2 Method 1. Line-to-line voltage

For a three-phase wye-connected machine, Equation (3-2) can be used, based on line-to-line voltage. The value of E_{TIF} for a wye-connected machine can be measured by means of a TIF meter or can be obtained from a harmonic analysis of the line-to-line voltage using Equation (3-3). Readings are taken with the machine operating at rated voltage and speed, without load.

3.9.3 Method 2. Phase voltage

The balanced TIF of a three-phase wye-connected machine can be obtained using Equation (3-2) and Equation (3-3) based on a harmonic analysis of line-to-neutral voltage, but omitting the third harmonic and multiples thereof from the computation of E_{TIF} . Readings are taken with the machine operating at rated voltage and speed, without load.

3.10 Residual-component TIF

3.10.1 General

For the definition of *residual-component telephone-influence factor (TIF)*, see *The IEEE Standards*

Dictionary [B29]. The residual-component TIF can be determined by the following test methods:

- Method 1. Machines that can be connected in delta
- Method 2. Machines that cannot be connected in delta
- Method 3. Line-to-neutral test

3.10.2 Method 1. Machines that can be connected in delta

The residual-component TIF of a three-phase machine can be obtained by connecting the machine in delta with one corner open and with the machine operating at normal speed and no load, with excitation corresponding to rated open-circuit voltage. A TIF instrument or harmonic analyzer is placed across the open corner of the delta. Equation (3-4) should be used to evaluate residual TIF from this method.

$$\text{Residual TIF} = \frac{E_{TIF}}{3E_{RMS}} \quad (3-4)$$

(Deleted)

where

E_{TIF} is the weighted rms voltage taken across the open corner of the delta. It can be obtained from reading a TIF instrument or calculated from harmonic analyzer data using Equation (3-3).

E_{RMS} is the voltage across one phase of the delta, in the same units as E_{TIF} . This value can be taken as the average of the voltages of the three phases.

For other nomenclature, see Equation (3-2).

Caution should be used in making the open delta test on high voltage machines. The voltage to be measured is a very small fraction of the voltage of one side of the delta. Hence, a low ratio voltage transformer (from 1:1 to 10:1) might be used even on high voltage machines. However, should one side of the delta accidentally become completely or partially short-circuited during the test, the voltage across the TIF instrument or harmonic analyzer would jump to many times (from 10 to 100 times) the instrument voltage before the accidental short circuit. This new voltage would equal approximately the voltage that existed between the two points that were short-circuited divided by the ratio of the voltage transformer. For a 1:1 transformer, this voltage could equal full normal line-to-neutral voltage of the machine.

To minimize the hazard associated with such an accidental short circuit, it is necessary on high voltage machines to isolate the instrument and circuits from all personnel or to use protective gaps and fuses to ground the instrument and isolate it from the machine in case of overvoltage. The duration of excitation during the test should be kept to a minimum.

3.10.3 Method 2. Machines that cannot be connected in delta

In cases where the machine cannot be conveniently connected in delta, the residual component TIF may be obtained by connecting three identical voltage transformers in wye to the terminals of the machine and connecting the secondaries in delta with one corner open. The neutral of the voltage transformer primaries should be connected to the neutral of the machine.