



IEEE Guide for Test Procedures for Synchronous Machines

Part I—Acceptance and Performance Testing

Part II—Test Procedures and Parameter Determination for Dynamic Analysis

IEEE Power & Energy Society

Sponsored by the
Electric Machinery Committee

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IEEE Guide for Test Procedures for Synchronous Machines

Part I—Acceptance and Performance Testing

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**Electric Machinery Committee
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IEEE Power & Energy Society**

Approved 9 December 2009

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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, parameter determination, synchronous machines

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Introduction

This introduction is not part of IEEE Std 115-2009, IEEE Guide for Test Procedures for Synchronous Machines: Part I—Acceptance and Performance Testing and Part II—Test Procedures and Parameter Determination for Dynamic Analysis.

IEEE Std 115-2009 incorporates and updates virtually all of the 1995 edition (reaffirmed in 2002).

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 #7, which produced this guide, was formed in June 2005, and the Project Authorization Request (PAR) was approved by the IEEE-SA Standards Board in March 2005 and again in March 2009. This PAR included a proposal by the working group to revise the procedure of 7.3.6 to correct errors in the previous edition, to add a new subclause about vibration testing procedure, and to update the entire document to reflect state-of-the-art practices and technology.

The working group decided to keep the format and titles of the guide the same as the previous edition, i.e., in two parts with the overall title of “Test Procedures for Synchronous Machines” and the following titles for the parts:

- Part I, Acceptance and Performance Testing
- Part II, Test Procedures and Parameter Determination for Dynamic Analysis

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Contents

Part I—Acceptance and Performance Testing

1. Overview	1
1.1 Scope	1
1.2 Organization of the guide	1
1.3 Miscellaneous notes	2
1.4 Instrumentation	3
2. Normative references	4
3. Miscellaneous tests	6
3.1 Insulation resistance	6
3.2 Dielectric and partial discharge tests	6
3.3 Resistance measurements	8
3.4 Tests for short-circuited field turns	10
3.5 Polarity test for field poles	12
3.6 Shaft current and bearing insulation	12
3.7 Phase sequence	14
3.8 Telephone-influence factor (TIF)	16
3.9 Balanced TIF	17
3.10 Residual-component TIF	18
3.11 Line-to-neutral TIF	19
3.12 Stator terminal voltage—waveform deviation and distortion factors	19
3.13 Overspeed tests	24
3.14 Line-charging capacity	25
3.15 Acoustic noise	26
3.16 Vibration testing	26
4. Saturation curves, segregated losses, and efficiency	28
4.1 General	28
4.2 Method 1. Separate drive	31
4.3 Method 2. Electric input	36
4.4 Method 3. Retardation	42
4.5 Method 4. Heat transfer	50
4.6 Efficiency	51
5. Load excitation	53
5.1 General	53
5.2 Test methods	53
5.3 Load excitation calculation methods for specified machine terminal conditions	56
5.4 Excitation calculation methods used in stability computer programs	62
6. Temperature tests	65
6.1 General	65
6.2 Methods of loading	65
6.3 Duration of test	71
6.4 Methods to measure temperature	72
6.5 Preparation for test	73

6.6 Determination of coolant temperature	74
6.7 Temperature readings	76
6.8 Shutdown temperatures.....	77
6.9 Temperature rise	78
7. Torque tests	79
7.1 General.....	79
7.2 Locked-rotor current and torque	79
7.3 Speed-torque tests	82
7.4 Pull-out torque	87
8. Sudden short-circuit tests.....	89
8.1 Mechanical integrity of machine	89
8.2 Electrical integrity of machine.....	89
Part II—Test Procedures and Parameter Determination for Dynamic Analysis	
9. Applications of machine electrical parameters.....	90
9.1 General.....	90
9.2 P.U. quantities.....	91
10. Tests for determining parameter values for steady-state conditions.....	97
10.1 Purpose	97
10.2 Instrumentation	97
10.3 Direct-axis synchronous reactance, X_d	98
10.4 Quadrature-axis synchronous reactance, X_q	99
10.5 Negative-sequence quantities (steady state).....	102
10.6 Zero-sequence quantities	108
10.7 Testing procedures and parameter determination for positive-sequence resistance for a synchronous machine	113
10.8 Additional miscellaneous steady-state tests for synchronous machines	114
11. Tests for evaluating transient or subtransient characteristic values	117
11.1 General.....	117
11.2 Reasons for tests with sudden changes to armature or field electrical circuits	117
11.3 Methodology for conducting short-circuit current tests	117
11.4 Procedural details and instrumentation for short-circuit test data extraction	118
11.5 Precautions required in conducting short-circuit tests	119
11.6 Theoretical background for determining short-circuit reactance and time constant values	120
11.7 Tests for transient and subtransient direct-axis parameters (reactance values).....	121
11.8 Determination of transient and subtransient reactance values based on method 1, method 2, and method 3 in 11.7	125
11.9 Tests for direct-axis transient and subtransient short-circuit time constants.....	129
11.10 Tests for direct-axis transient and subtransient open-circuit time constants	131
11.11 Determining short-circuit armature time constant, τ_a	135
11.12 Computerized implementation of the general procedures noted in 11.7 through 11.11.....	137
11.13 Stationary or unbalanced tests for determining X''_d , X_2 , or X''_q	143

12. Standstill frequency response (SSFR) testing.....	148
12.1 General considerations and basic theory.....	148
12.2 Testing conditions for SSFR procedures and instrumentation requirements	152
12.3 Test procedures.....	157
12.4 Interpretation of test data	165
12.5 Suggested procedure for development of a third-order model.....	168
Annex A (informative) Bibliography	179
Annex B (normative) Nomenclature	183
Annex C (informative) Discussion on leakage and Potier reactances	184
Annex D (informative) Example of calculation of p.u. field current (I_F).....	185
Annex E (informative) Quadrature-axis transient or subtransient tests.....	186
Annex F (informative) Generator load rejection tests	190
Annex G (informative) Magnetic nonlinearity	198
Annex H (informative) Alternative approach to model development	201

IEEE Guide for Test Procedures for Synchronous Machines

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 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 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 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 115-1995 (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 procedures to reflect state-of-the-art practices and technology.
- 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.
- Updated references and the bibliography.

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 purposes of this 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 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 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 document. Annex A lists a bibliography, in which references are noted particularly for Clause 5 and for Clause 9 through Clause 12. Annex B lists nomenclature used particularly in Clause 5 and in Clause 9 through Clause 12. Annex C includes discussions on leakage and Potier reactance. Annex D gives an example of calculation of per unit (p.u.) field current. Annex E describes the test procedures for quadrature-axis transient and subtransient reactances and time constants. Annex F includes descriptions on generator load rejection test procedure. Annex G includes discussions on magnetic nonlinearity. Annex H describes an alternative approach to 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 may be used. Where appropriate, special methods that may be required to obtain accurate data have been indicated.

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 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.

¹ Information on references can be found in Clause 2.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this 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, Mechanical vibrations of certain machines with shaft heights 56 mm and higher—Measurement, evaluation and limits of vibration severity.³

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

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

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

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

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

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

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

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

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

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

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

IEEE Std 119TM-1974 (withdrawn), IEEE Recommended Practice for General Principles of Temperature Measurement as Applied to Electrical Apparatus.

IEEE Std 120TM, IEEE Master Test Code for Electrical Measurements in Power Circuits.

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

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

IEEE Std 519™, IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems.

IEEE Std 1095™, IEEE Guide for Installation of Vertical Generators and Generator/Motors for Hydroelectric Applications.

IEEE Std 1110™, IEEE Guide for Synchronous Generator Modeling Practices in Stability Analyses.

IEEE Std 1434™, IEEE Guide to the Measurement of Partial Discharges in Rotating Machines.

ISO 3744, Determination of sound power levels of noise sources using sound pressure.⁶

ISO 10816-1, Mechanical vibration — Evaluation of machine vibration by measurements on non-rotating parts — Part 1: General guidelines.

ISO 10816-2, Mechanical vibration — Evaluation of machine vibration by measurements on non-rotating parts — Part 2: Land-based steam turbine and generators in excess of 50 MW with normal operating speeds of 1500 r/min, 1800 r/min, 3000 r/min and 3600 r/min.

ISO 10816-4, Mechanical vibration — Evaluation of machine vibration by measurements on non-rotating parts — Part 4: Gas turbine driven sets excluding aircraft derivatives.

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

ISO 4871, 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, Determination of sound power levels of noise sources using sound intensity.

NEMA MG1, Motors and Generators.⁷

⁶ ISO/IEC publications are available from the 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/>).

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. Miscellaneous tests

3.1 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.⁸

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

3.2 Dielectric and partial discharge tests

3.2.1 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 must be taken to 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.

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

- Method 1. Alternating-voltage testing at power frequency (see 3.2.3)
- Method 2. Direct-voltage testing of stator windings (see 3.2.4)
- Method 3. Very low frequency testing of stator windings (see 3.2.5)
- Method 4. Partial discharge testing (see 3.2.6)

⁸ Notes in text, tables, and figures are given for information only and do not contain requirements needed to implement the guide.

3.2.2 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.

3.2.3 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:

- a) Transformer-voltmeter
- b) 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 [B20].⁹

3.2.4 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.

⁹ 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 minimize the hazard to personnel.

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

3.2.5 Method 3. Very low frequency (VLF) testing of stator windings

A 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. 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.

3.2.6 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 groundwall 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 endwinding 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.

3.3 Resistance measurements

3.3.1 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.

3.3.2 Correction to specified temperature

When the resistance, R_t , of a winding has been determined by test at a winding temperature t_t , the resistance may be corrected to a specified temperature t_s by the following equation:

$$R_s = R_t \left(\frac{t_s + k}{t_t + k} \right) \quad (3-1)$$

where

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

- t_s is the specified temperature, in degrees Celsius
 R_t is the test value of winding resistance, in ohms
 t_t is the temperature of winding when resistance was measured, in degrees Celsius
 k is the characteristic constant for the winding material (see 6.4.4)

3.3.3 Reference field resistance

The resistance 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 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^2R 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.

3.3.4 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 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 minimized by special methods of voltage measurement or special test procedures (see 3.3.6).

3.3.5 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 6.4.4. The resistance obtained from this test is called R_t in Equation (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 minimize its effect in this test (see 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 ensure that the resistance is measured under uniform conditions.

3.3.6 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 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

- 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.

3.4 Tests for short-circuited field turns

3.4.1 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
- Method 2. Voltage drop, ac
- Method 3. DC resistance
- Method 4. Exciting coil for cylindrical rotors
- Method 5. Rotor waveform detection for cylindrical rotors

3.4.2 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.

3.4.3 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.

3.4.4 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.

3.4.5 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.

3.4.6 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 pickup 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).

3.5 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 proper polarity by reversing direction as it is passed from pole to pole. The magnet should be checked to ensure that its magnetism has not been lost or its polarity reversed by the field flux.

3.6 Shaft current and bearing insulation

3.6.1 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
- Method 2. Across bearing oil film, uninsulated bearings
- Method 3. Across bearing insulation
- Method 4. Bearing insulation—Running test
- Method 5. Bearing insulation—Static test
- Method 6. Double insulation

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.

3.6.2 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.

3.6.3 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.

3.6.4 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 3.6.5 through 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.

3.6.5 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.

3.6.6 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 110–125 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 prevent the small shaft voltage from causing injurious current.

3.6.7 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.

3.7 Phase sequence

3.7.1 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
- Method 2. Indication of differential voltage
- Method 3. Direction of rotation for machines that can be started on a power source

3.7.2 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 counter-clockwise if the phase sequence is 1, 3, 2.

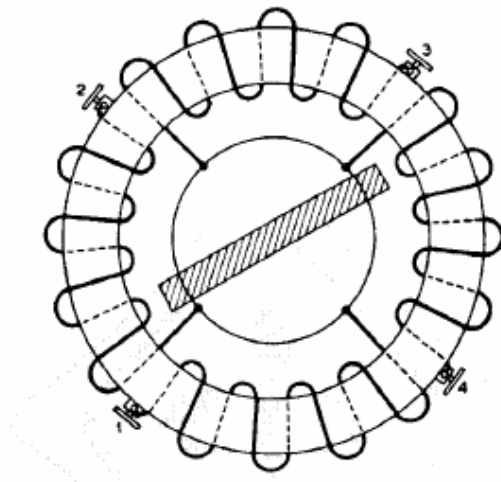


Figure 1—Phase-sequence instrument

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 Y 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.)

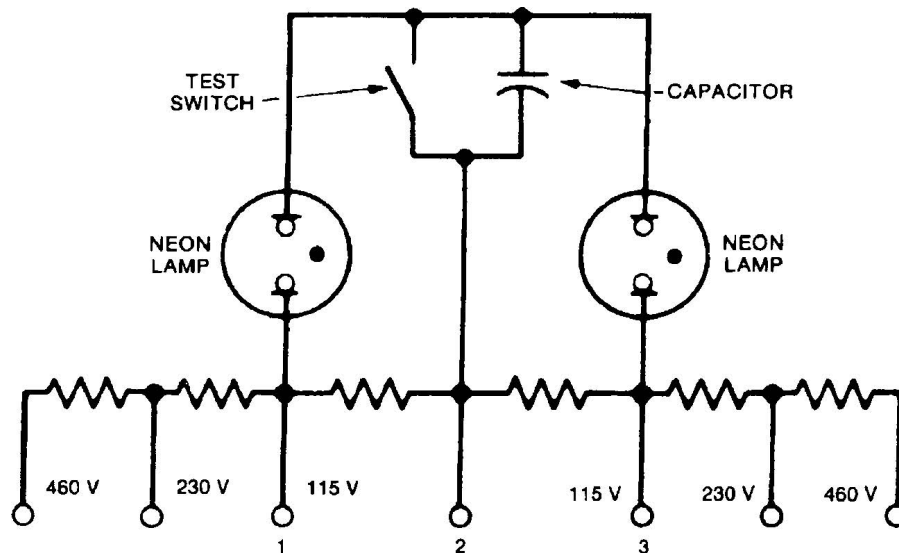


Figure 2—Neon-lamp phase-sequence indicator

3.7.3 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.

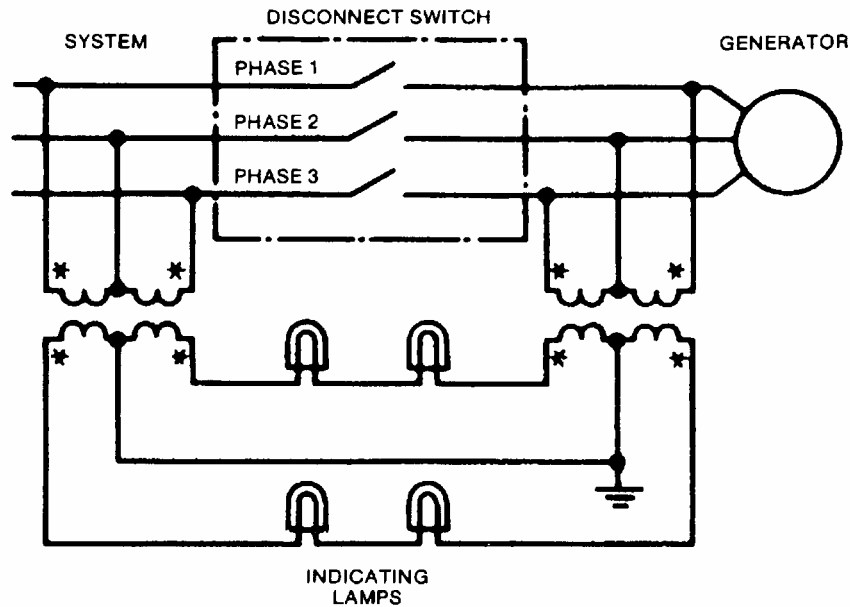


Figure 3—Connection diagram for comparing phase sequence of a generator with that of a system by indicating voltage across an open disconnect switch

3.7.4 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:

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

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

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.

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

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.

The measurements then may be taken in the voltage transformer secondary in the same manner as when taken directly on the machine, as in method 1. When this method is used, it should be recognized that with low values of TIF, the accuracy may be affected by the exaggerated effect of slight variations among the transformers.

3.10.4 Method 3. Line-to-neutral test

In the case of a three-phase machine where the phase voltages are balanced (the usual case), the residual-component TIF can be computed using Equation (3-2) and Equation (3-3) from a harmonic analysis of the line-to-neutral voltage, considering only the third harmonic and multiples thereof. Readings are taken with the machine operating at rated voltage and speed, without load.

3.11 Line-to-neutral TIF

3.11.1 General

The line-to-neutral TIF of a three-phase machine is calculated from Equation (3-2) based on the line-to-neutral no-load voltage of the machine (considering all harmonics). This calculation has significance only for a wye-connected machine and is of value primarily for checking (see 3.11.3).

3.11.2 Method of test

The line-to-neutral TIF can be measured with one voltage transformer connected from line-to-neutral across one phase of the machine when operating at rated voltage and speed, without load. The weighted rms value, E_{TIF} , of the voltage across the secondary of the transformer is obtained by TIF instrument or by harmonic analysis using Equation (3-3). The TIF is obtained from Equation (3-2).

3.11.3 Check of balanced, residual, and line-to-neutral TIF

A useful check of the values of balanced, residual, and line-to-neutral TIFs is obtained from the following relationship:

$$\text{Line-to-neutral TIF} = \sqrt{(\text{balanced TIF})^2 + (\text{residual TIF})^2} \quad (3-5)$$

3.12 Stator terminal voltage—waveform deviation and distortion factors

3.12.1 Procedure for testing

For the definition of *deviation and distortion factor*, see *The IEEE Standards Dictionary* [B29]. The waveform of the test voltage is recorded by using a waveform recorder adjusted to produce a wide deflection and operated at high speed so that the time interval of one-half cycle may be subdivided into a series of equal intervals. To permit adequate analysis, the maximum amplitude of the wave from zero should be at least 3.2 cm, and the distance for one-half cycle at least 4 cm. Figure 4 shows the trace of an exaggerated wave to be analyzed, in rectangular coordinates. Also, the equivalent sine wave has been plotted on the same figure, and it is located so that the maximum deviation of the wave to be analyzed from the sine wave is a minimum. The amplitude of the equivalent sine wave may be determined by the method described below. Plots of the wave in polar coordinates may also be used (also see IEEE Std 519).

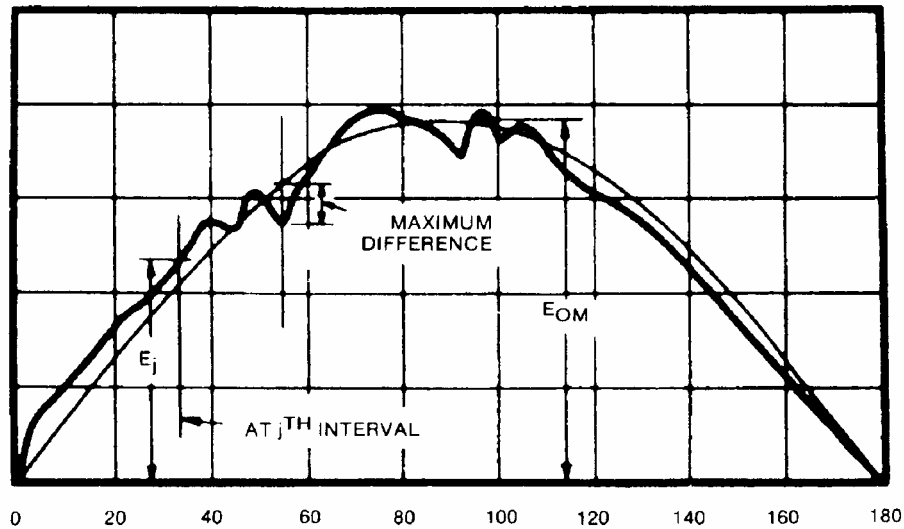


Figure 4—Plot of wave for deviation factor

To obtain the amplitude of the equivalent sine wave, the time interval of one-half cycle of the wave to be analyzed is divided into N (at least 18) equal intervals, beginning at a point where the trace of the wave crosses the axis of abscissas, and a vertical line is erected at the end of each interval, crossing the trace. If the value of the instantaneous voltage, E_j , is measured at each of the N points of intersection with the wave trace, the zero-to-peak amplitude of the equivalent sine wave, E_{OM} , is given by Equation (3-6).

$$E_{OM} = \sqrt{\frac{2}{N} \sum_{j=1}^N E_j^2} \quad (3-6)$$

where

E_j equals an instantaneous value of the voltage wave at the j^{th} point

In certain machines, even harmonics of voltage may be produced and result in alternate half cycles differing from the negative of the intervening ones. For such an unsymmetrical wave, a complete cycle should be analyzed.

As an alternate method, the rms value of the equivalent sine wave, E_o , may be measured by an accurate dynamometer or thermocouple ac instrument that has been calibrated against the same reference standard as the oscillograph. Since differences in calibration cause a magnified relative error in the deviation factor, a voltmeter reading should not be relied upon unless the calibrations of the oscillograph and the voltmeter have been carefully compared. The crest value of the equivalent sine wave, E_{OM} , is the instrument reading E_o multiplied by $\sqrt{2}$.

To adjust the equivalent sine wave so that the deviation between the wave being analyzed and the equivalent sine wave is a minimum, it is convenient to plot the equivalent sine wave on a transparent overlay to the same scales as the oscillogram and slide the overlay over the oscillogram, with the axes of the abscissa coincident, until a location is found where the absolute value of the vertical deviation between the two waves is a minimum. This location will usually occur when the zero values of voltage waveform occur at nearly the same point in time and often occur when the maximum positive deviation is the same or nearly the same as the maximum negative deviation during the half cycle (see Figure 4).

The traditional waveform analysis done by using an oscilloscope, a wave analyzer, and instrument meters requiring manual calculations and operations can be replaced by computer-controlled data acquisition systems for fast, accurate, and automatic data reduction and analysis. To illustrate this method, Figure 5 shows a block diagram of a computer-controlled data acquisition system used for waveform analysis.

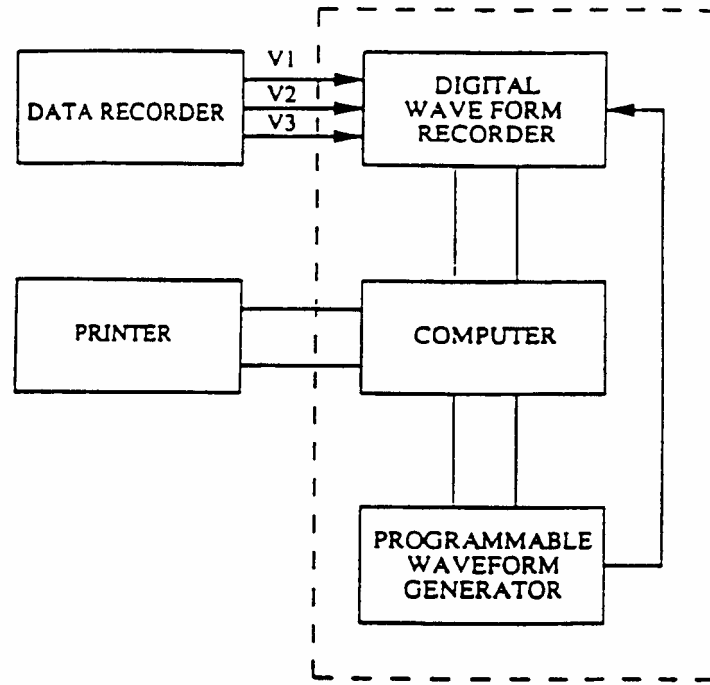


Figure 5—Block diagram of instrumentation used in waveform analysis

The line-to-line or line-to-neutral analog voltage waveforms can be conveniently recorded at site or in the factory at the secondaries of the voltage transformers in a data recorder for off-line processing and data reduction.

The computer controls the programmable waveform generator to generate sampling pulses at a rate of at least 100 times the frequency of the voltage. The sampling pulses are transmitted to the waveform recorder to trigger the data sampling of the input waveform. Data samples are stored in the memory of the waveform recorder for transmission to the computer via the interface bus. Waveform analysis is then carried out by software codes that implement the method described in 3.12.2.

3.12.2 Waveform analysis

The maximum value of the deviation between the two waves, when located as described in 3.12.1, may be designated by ΔE . Then the deviation factor, F_{DEV} , is given by Equation (3-7).

$$F_{DEV} = \frac{\Delta E}{E_{OM}} \quad (3-7)$$

Waveform analysis usually includes the determination of the rms amplitude of the equivalent sine waveform, the maximum deviation between the waveform and the equivalent sine waveform, the deviation factor, the harmonic contents of the waveform, and the distortion factor.

Prior to the analysis, any dc value in the waveform should be removed. This step can be done by calculating the dc value as follows:

$$E_O = \frac{\sum_{i=1}^N E_i}{N} \quad (3-8)$$

where

E_O is the dc value of the waveform
 N is the number of sample data in one period
 E_i is the i^{th} sample data of the waveform

This dc value should be subtracted from the input waveform as follows:

$$E_j = E_i - E_O$$

For $j = 1, 2, \dots, N$

The rms value of the input waveform is given by Equation (3-9).

$$E_{RMS} = \sqrt{\frac{1}{N} \sum_{j=1}^N E_j^2} \quad (3-9)$$

Therefore, the zero-to-peak amplitude of the equivalent sine wave, E_{OM} , is as shown in Equation (3-10).

$$E_{OM} = \sqrt{2} E_{RMS} \quad (3-10)$$

To determine the maximum deviation, designated by ΔE , the location of the sine waveform relative to the input waveform should be found where the absolute value of the vertical deviation between the two waves is a minimum. This location will usually occur when the zero values of voltage occur at nearly the same point in time.

Therefore, the zero voltage points of the two waves are taken as the common points in time, and a comparison is carried out by shifting the input waveform so that it will start from zero point with positive slope. The starting point will then be the point having the smallest absolute value and a positive first derivative. This point can be found by a computer algorithm.

Then the input waveform is shifted, and each sample point is relabeled, i.e., the first point ($j=1$) corresponds to the smallest absolute value with a positive slope. The maximum deviation ΔE is given by Equation (3-11).

$$\Delta E = \text{MAX} \left[\text{ABS} \left(E_j - E_{OM} \sin \left(2\pi \frac{j}{N} \right) \right) \right] \text{ for } j = 1, 2, \dots, N \quad (3-11)$$

3.12.3 Fourier analysis

Fourier analysis is carried out to determine the harmonic contents of the wave by the following equations:

$$a_n = \frac{2}{N} \sum_{j=1}^N E_j \cos\left(\frac{2\pi nj}{N}\right) \quad (3-12)$$

$$b_n = \frac{2}{N} \sum_{j=1}^N E_j \sin\left(\frac{2\pi nj}{N}\right) \quad (3-13)$$

$$E_n = \sqrt{a_n^2 + b_n^2} \quad (3-14)$$

$$\begin{aligned} \phi_n &= \tan^{-1}\left(\frac{b_n}{a_n}\right) \quad a_n > 0 \\ &= \tan^{-1}\left(\frac{b_n}{a_n}\right) + \pi \quad a_n < 0 \end{aligned} \quad (3-15)$$

$$n = 1, 2, 3, \dots$$

where

n is the order of the harmonic
 a_n and b_n are coefficients for cosine and sine terms, respectively
 E_n and ϕ_n are rms magnitudes and corresponding relative phase angles of the various orders of harmonics

The distortion factor, F_{Di} , of a wave is obtained by dividing the rms harmonic content (i.e., the square root of the sum of the squares of the rms amplitudes of all frequency components except the fundamental) by the rms value of the wave including the fundamental as shown in Equation (3-16).

$$F_{Di} = \frac{\sqrt{\sum E_n^2}}{E_{rms}} \quad (3-16)$$

where

$\sum E_n^2$ is the sum of the rms values of all components of the voltage except the fundamental
 E_{rms} is the rms value of the voltage

By digital method, after obtaining the magnitudes of the harmonics, the distortion factor F_{Di} can be calculated as shown in Equation (3-17).

$$F_{Di} = \frac{\sqrt{\sum E_n^2}}{E_{OM}} \quad (3-17)$$

$n = 2, 3, \dots$, where E_n are calculated by Equation (3-14).

In most cases, the amplitudes of the harmonics decrease as the order of the harmonic increases so that determination of the amplitudes of the first few harmonics is all that is needed to obtain a satisfactory value of the distortion factor. However, if the waveform indicates the presence of significant high-frequency ripples, the harmonics of relatively high frequencies may have significant amplitudes; the number of sample points used should be sufficient to provide an accurate determination of the amplitudes of these harmonics.

The rms value of the harmonic content of the wave can be obtained by a notch filter that blocks out only the fundamental, in conjunction with a dynamometer ac voltmeter calibrated with the circuit. A harmonic analyzer can also be used to measure E_n .

3.12.4 Measuring rms value

The rms value of the wave is obtained using a dynamometer or thermocouple ac instrument of suitable accuracy or a true rms digital meter. (Other types of instruments are likely to give incorrect readings because they do not respond to the rms value of distorted waves.)

3.13 Overspeed tests

3.13.1 General

Overspeed tests are made only when specified. They are generally specified for synchronous generators connected to turbines or other mechanical equipment that may be subject to overspeed on loss of load or other causes.

The manufacturer should be consulted prior to conducting any test that is above rated speed.

3.13.2 Procedure

Before making an overspeed test, the machine should be carefully inspected to make sure, in particular, that all holding-down bolts and rotating parts are tight and in good condition. The rotor should be in as good a mechanical balance as possible before starting the test. Every precaution must be made to protect life and property in case of any mishap. The speed should be read with an electric tachometer or other accurate remote speed-indicating device. The tachometer should be calibrated with the leads used in the test, and the reading checked at normal speed before starting the test.

When making the test, the machine should be operated at rated speed long enough to make and stabilize vibration readings and to ascertain that the machine is running satisfactorily. The machine should then be accelerated with reasonable promptness to the specified overspeed. For tests at speeds greater than 115% of rated speed, it is desirable to pause briefly at various speeds during acceleration to check such operating conditions as vibration, runout of the rotor shaft, and behavior of the oil in the bearings. Vibration readings should also be made in accordance with 3.16 at rated speed following the test for comparison and reference.

Normally, the overspeed test is made with the machine unexcited. If the machine is excited, care should be exercised to reduce excitation during the test so that the voltage does not exceed 105% of rated voltage.

Following operation at the specified overspeed for the specified time, the machine should be brought promptly and smoothly back to or below rated speed.

If the overspeed has been applied for any prolonged period, the bearings will be at substantially higher than normal temperatures, and the viscosity of the oil much lower than normal. Therefore, either the machine should be returned to normal speed or below until the bearing temperatures return to normal, or it should be shut down quickly and not restarted until the bearing temperatures cool down to normal conditions. The machine should be carefully inspected after the test.

3.14 Line-charging capacity

3.14.1 General

The line-charging capacity of a synchronous machine is its reactive power in kilovoltamperes when operating synchronously at zero power factor, rated voltage, and with the field current reduced to zero. (This quantity has no inherent relationship to the thermal capability of the machine; therefore, note the caution in 3.14.4.) Line-charging capacity can be measured by the following test methods:

- Method 1. As motor
- Method 2. As generator
- Method 3. As generator

3.14.2 Method 1. As motor

The machine under test is operated as a synchronous motor at no load, preferably uncoupled, and at rated voltage and frequency, with excitation reduced to zero. Because machine losses are now supplied from the electric supply, the line-charging capacity is approximately the reactive power input in kilovoltamperes. If the machine is coupled to a condensing steam turbine, it should be uncoupled to prevent overheating of the turbine.

3.14.3 Method 2. As generator

The machine under test is driven at rated speed and is connected to a load consisting of idle-running overexcited synchronous machines or to a bus that may be considered as an infinite-capacity voltage source, with rated voltage on the generator at rated frequency and with its excitation reduced to zero. The line-charging capacity is approximately the reactive power input in kilovoltamperes.

3.14.4 Method 3. As generator

The machine under test is driven at rated speed and is connected to sections of transmission line, using sufficient sections to give rated voltage when generator excitation is reduced approximately to zero. The line-charging capacity is the reactive power input in kilovoltamperes. Because a transmission line requires at least a small synchronous source of excitation, it is not possible to make the test at zero excitation. Therefore, a series of tests with successively smaller values of excitation can be used as a basis for extrapolating the reactive power to zero excitation.

CAUTION

Note that a limit for reduction of field current of cylindrical-rotor machines at rated voltage may be set by the manufacturer to avoid local heating in the armature. If such a limit exists, the data may be taken at several greater values of field current (at rated voltage and zero power factor) and extrapolated to obtain a value of reactive power at zero excitation (see IEEE Std 67).

If armature current in excess of rated current is expected, the data may be taken at several values of reduced current (and voltage) and extrapolated to obtain a value of reactive power at rated voltage.

3.15 Acoustic noise

3.15.1 General

Test procedures for airborne sound are described in IEEE Std 85-1973, NEMA MG1, and IEEE Std C50.13. The word *noise* refers to any unwanted sound. The duration for the maximum permitted hours of exposure per work day for various noise levels are set in the United States by the Occupational Safety and Health Administration (OSHA).

3.15.2 Procedure

A sound level instrument is an omnidirectional microphone with an amplifier, weighting filters, processing electronics, and an indicating dial. The filters allow the selection of the ANSI “A,” “B,” or “C” frequency response characteristics. More details about tests, relative weightings, and test environments are described in IEEE Std 85-1973 and ISO 3744.

A sound level instrument provides a single number in decibels for all sound within the audio frequency range, but gives no indication of the frequency content. Some indication of the importance of the components below 600 Hz may be obtained by switching from an A- to a C-weighting curve.

An analysis of the sound in the frequency domain, called *spectrum analysis*, can provide valuable information for noise suppression and control.

NEMA MG1 gives A-weighted sound power limits for motors up to 5000 hp. Corrections for background noise can be made by following ISO 3744. Methods of declaring noise emission values are described in ISO 4871. Additional information on sound measurement can also be found in ISO 9614.

3.16 Vibration testing

3.16.1 General

This subclause primarily addresses factory acceptance testing of shaft and bearing housing lateral vibration in synchronous machines. Torsional and axial shaft vibration considerations are excluded.

In-situ testing and evaluation of synchronous machine vibration may also be conducted based on these guidelines, within the practical limitations imposed by the specific installation. Interpretation of field results is more complex due to unknown rotor support considerations.

3.16.2 Motors and small generators

When vibration tests are specified for a synchronous machine, such tests may be performed in accordance with NEMA MG1 or IEC 60034-14, as applicable, based on arrangements between customer and manufacturer and within the machine type and size limits set by those standards. Acceptance criteria will also be per agreement between customer and manufacturer, with typical criteria provided in NEMA MG1 or IEC 60034-14, as applicable.

3.16.3 Large synchronous cylindrical rotor generators—Shaft vibrations

For large synchronous cylindrical rotor generators used in thermal power stations, shaft vibration measurements are made during rotor or machine overspeed testing or may be specified as a separate rated speed test.

Shaft radial and axial vibrations shall be measured at rated speed. As a minimum, the peak-to-peak magnitude of broadband vibration shall be measured and recorded.

Measurements shall be made per ISO 7919-1. Relative or absolute displacements may be measured, based on the judgment and normal practice of the manufacturer.

Unless specified otherwise by the customer, the machine shall be unexcited and at no load during the vibration test.

Acceptance criteria will be per agreement between buyer and seller, with typical criteria provided in ISO 7919-2 for steam turbine applications and ISO 7919-4 for combustion turbine applications.

It is also acceptable for the manufacturer to measure and report filtered vibrations for comparison to expected or type test values.

3.16.4 Large synchronous cylindrical rotor generators—Bearing vibrations

For generators that are fully assembled at the factory, bearing housing lateral vibrations shall be measured in addition to the shaft vibration at rated speed during rotor overspeed testing or may be specified as a separate rated speed test.

For bearing vibrations, measurements shall be made per ISO 10816-1.

Acceptance criteria will be per agreement between customer and manufacturer, with typical criteria provided in ISO 10816-2 for steam turbine applications and ISO 10816-4 for combustion turbine applications.

3.16.5 Synchronous generators in hydroelectric applications

For synchronous generators used in hydroelectric applications, see ISO 7919-5 for shaft vibration testing procedures only. Acceptance criteria will be per agreement between customer and manufacturer.

In-situ testing and evaluation of synchronous generators vibration may also be conducted based on these guidelines, within the practical limitations imposed by the specific installation. Interpretation of field results is more complex due to unknown rotor support considerations.

For bearing vibrations, measurements shall be made per ISO 10816-1.

Acceptance criteria will be per agreement between customer and manufacturer, with typical criteria provided in ISO 10816-5 for hydro generators.

4. Saturation curves, segregated losses, and efficiency

4.1 General

4.1.1 Efficiency

The true efficiency of a machine is the ratio of output power to input power under specified conditions. On small machines, these values can be measured directly. On larger equipment where the mechanical power cannot be measured accurately, a conventional efficiency is used, based on segregated losses (see 4.6.1).

The losses to be used in determining the conventional efficiency of a synchronous machine and their method of evaluation are prescribed in the applicable IEEE C50 standards series and NEMA MG1. Test procedures for determining the following individual losses are given in the subsequent subclauses:

- a) Friction and windage loss
- b) Core loss (on an open circuit)
- c) Stray-load loss (on a short circuit)
- d) Armature I^2R_a loss using the armature current at the specified load and the dc armature resistance corrected to a specified temperature (see 3.3.1 and 3.3.2)
- e) Field I^2R_f loss using the field current (see Clause 5) and the field resistance corrected to a specified temperature (see 3.3)

4.1.2 Methods to measure losses

The following methods are available to measure the losses of a synchronous machine:

- Method 1. Separate drive (see 4.2)
- Method 2. Electric input (see 4.3)
- Method 3. Retardation (see 4.4)
- Method 4. Heat transfer (see 4.5)

It is convenient to obtain data for the open-circuit and short-circuit saturation curves during the tests for determination of losses, if one of the first three methods is used.

Each of the first three methods of loss determination requires the machine to be operated for two series of runs to simulate load conditions, one with the armature terminals open-circuited and another with them short-circuited. For the heat transfer method, the machine may be operated either with load or with simulated load conditions.

If the armature terminals are open-circuited, the total loss includes friction and windage of all mechanically connected apparatus and the open-circuit core loss corresponding to the armature voltage and frequency. If the armature terminals are short-circuited, the total loss includes friction and windage of all mechanically connected apparatus and the armature copper loss and stray-load loss corresponding to the armature current and frequency.

Open-circuit losses can include non-negligible losses associated with circulating currents that are induced in the stator winding, especially at voltages above 105% of rated voltage.

CAUTION

Windage loss varies with air or gas temperature. In the following test procedures for measuring losses, the air or gas temperature should be recorded in order to provide loss correction to rated coolant temperature.

4.1.3 Elimination of exciter input

If a direct-connected or belted exciter is used for excitation during the loss tests, its power input should be deducted from the total input when determining friction and windage loss, core loss, and stray-load loss (see also 4.2.9).

4.1.4 Effect of temperature and pressure

The bearing temperature should be held as constant as possible during the test because it affects the viscosity of the oil and, therefore, the friction loss. Therefore, the machine should be run at rated speed until the bearing temperatures or friction and windage losses become constant before starting the loss measurements.

Coolant temperature, barometric pressure, humidity, and gas purity affect the density of gas and, therefore, the windage loss. For machines in which this loss is of major significance, correction for changes in gas density may be needed to correlate tests made under different conditions. In hydrogen-cooled generators, it is also possible to extract friction losses from friction and windage losses by testing at several different hydrogen pressures and extrapolating the resulting pattern of friction and windage losses to zero hydrogen pressure.

These effects should be considered in establishing conditions of tests for losses for machines where temperature can be adjusted.

4.1.5 Coupled machines

The preferred condition for testing for friction and windage loss is with the machine uncoupled from other apparatus. It is frequently necessary to test a machine coupled to other apparatus for which the friction and windage loss cannot be determined experimentally. The bearings may not be designed to permit running it uncoupled, or circumstances may make it inadvisable to uncouple for test and to recouple and realign after test. In these cases, it is necessary to allocate the total measured friction and windage loss to the various machines. Such a procedure would frequently be required for a hydraulic-turbine-driven generator (see IEEE Std 492). Motor-generator sets and frequency-changer sets are examples of equipment where this allocation may not be necessary since efficiencies are usually provided on an overall basis.

When the tested friction and windage loss are allocated to the various machines, it should be done in proportion to the best available estimates of the expected values for each.

The thrust bearing of a vertical unit is usually included with the generator (or motor). However, only the thrust bearing loss due to the weight of the generator rotor is considered a generator loss. When the machine is tested coupled to other apparatus, there may be an additional thrust bearing loss due to the weight of the connected apparatus. An estimate of this additional loss may be obtained from the generator manufacturer. This loss (as well as other losses of the connected apparatus) should be considered in the allocation described above.

ASME PTC 18 gives formulas for calculating the windage loss of a hydraulic turbine runner. Since these formulas have been found to give inaccurate results in many cases, they should be used with care. Test data on similar runners should be used as a basis for the estimated friction and windage loss when available.

4.1.6 Steam turbine overheating

Occasionally, steam-turbine-driven generators are tested for losses without steam on the turbine blades. During such tests, precautions should be taken to avoid severe overheating of parts of the turbine. Because of the many factors involved and the differences between machines, the turbine manufacturer should be consulted before making the test.

4.1.7 Dewatering hydraulic turbine

A hydraulic-turbine-driven generator must be tested with its turbine completely dewatered and the runner seal cooling water shut off if accurate values of generator losses are to be obtained (see ASME PTC 18). An acceptable alternative term to *dewatering* is the term *unwatering*.

Dewatering the turbine should be done in accordance with instructions from the turbine manufacturer. Impulse turbines generally can be dewatered while motoring at normal speed. Francis and propeller turbines usually must be dewatered at standstill, but there are exceptions. Their scroll cases should be empty to eliminate the effect of even minor leakage through the wicket gates. Unless there is a valve ahead of the scroll case, this step requires the draining of the penstock, which is a time-consuming operation. If the runner is set above tail water, proper venting through the turbine air valve will allow the water to drain out of the draft tube. When the runner is not high enough above tail water, the tail water in the draft tube can be depressed by compressed air or by pumping. The water in the turbine seals produces appreciable loss. For this reason, it is preferable to run loss tests without the seal water. The turbine manufacturer's approval should be obtained to do this step since some types of seals cannot be operated without water. It should be recognized that inaccurate test values may result if tests are run with seal water flowing.

4.1.8 Electric starting

When it is not feasible to bring the machine to speed by mechanical means, it is necessary to start it electrically. Occasionally, the generator (or motor) is suitable for starting from a rated-frequency full-voltage power source. If the power source is adequate, this method of starting is the simplest.

If the inrush current or the heating of the amortisseur winding is excessive with full-voltage starting, it is occasionally feasible to use reduced-voltage starting. This approach requires a power supply whose voltage can be reduced to a suitable value. For large machines, it is usually necessary that a second machine of suitable size be available, to be connected only to the machine under test, for variable-voltage operation.

Most generators do not have amortisseur windings capable of starting the machine at full frequency and accelerating it to full speed. In such cases, it is necessary that another machine of suitable size and capable of operation at variable speed be available for synchronous starting of the machine under test.

For synchronous starting, the armatures of the driving and driven machines are connected together electrically while the machines are at rest. Under certain conditions, synchronous starting can be initiated in accordance with the manufacturer's recommendation while both machines are being driven by their turning gears. Separate sources of excitation for both machines should be available; however, a single source of excitation feeding both fields in series may be used. The exciter of a third synchronous machine is sometimes used.

Approximately normal no-load full-voltage field current is applied to the driving machine, and approximately 80% of normal no-load full-voltage field current is applied to the driven machine.

The prime mover of the driving machine is then started slowly, and the two electrically connected machines are brought up to the desired speed. Unless the bearings of the driving machine are equipped for the supply of high-pressure oil at starting, the sudden reduction of friction torque after breakaway may cause such rapid acceleration that the driven machine will oscillate and will fail to accelerate. A restart immediately after shutdown before the oil film has been squeezed out of the bearing may prove successful. Where the

design of the bearing permits, jacking of the rotor prior to the starting operation may reduce the breakaway torque by introducing a fresh oil film.

Reduced-frequency starting can sometimes be used on successive test runs as a means of saving the time required to slow the driving machine completely to rest. With the driving machine running at a frequency recommended by the manufacturer of the machine under test, sufficient excitation is applied to the driving machine to produce the recommended voltage-frequency ratio at the terminal of the machine under test. The field of the machine under test is short-circuited through a starting resistor. When the driven machine approaches synchronism with the driving machine, approximately 80% of normal no-load full-voltage excitation is applied to the driven machine, and normal no-load full-voltage excitation is applied to the driving machine to pull them into synchronism and to bring them up to the desired speed.

4.2 Method 1. Separate drive

4.2.1 Driving motor

The machine under test is usually driven by a motor, directly or through a belt or gear. The motor should be a shunt dc motor (preferably the commutating-pole type), an induction motor, a synchronous motor, or the direct-connected exciter (if it is large enough). Preferably, the capacity of the driving motor should be such that it will operate at not less than 15% to 20% of its rating when supplying friction and windage losses of the driven machine and not more than 125% of its rating when supplying friction, windage, and rated-voltage core loss or supplying friction, windage, rated-current stator I^2R_a and stray-load loss. This capacity permits the motor to operate on the flat part of its efficiency curve, and often it may not be necessary to correct for change in efficiency. The no-load losses of the driving motor should be known, and where extreme accuracy is required, a curve of losses against input should be available.

The driving motor should be capable of operating the driven machine at its rated speed. When using an induction-motor drive, a source of adjustable frequency is necessary to provide for variations in slip with change of losses of the machine under test. A synchronous motor has a decided advantage where all tests are to be made at rated speed; however, the synchronous motor either should have variable-frequency power for starting or should have sufficient starting torque and thermal capacity to start and accelerate the machine under test. It simplifies the determination of driving-motor losses if the line voltage of a synchronous or induction driving motor is held constant throughout the run. The field of a shunt motor may be excited from a separate source so that the field current may be held constant to simplify the determination of its losses.

When a machine that does not require a belt in service is belt-driven for test, the tension of the belt should be kept as low as possible so that the increased bearing friction is not detrimental to the bearings and will not increase the friction loss appreciably. The belt should be of minimum width and weight to carry the load without dipping. Its losses should be known for the test conditions.

When a gear drive is used, the losses of the gear should be known under the test conditions.

Testing with a driving motor will give erroneous results if the machines are either accelerating or decelerating. Hence, readings should be taken only when the speed is constant at the correct value as measured by a reliable tachometer or a stroboscope.

It is also possible to determine driving power by using an accurate torque sensor between the driving motor and the generator being tested.

4.2.2 Procedure

The usual procedure for the test is to drive the machine at its rated speed until the bearings reach constant temperature and the friction loss becomes constant; this condition can be determined by observing when the input to the driving motor becomes constant. The input to the driving motor minus the losses of the driving motor (and belt or gear, if any) equals the input to or the losses of the tested machine.

4.2.3 Dynamometer as driver

It may be desirable to use a dynamometer as a driving motor, in which case only readings of torque and speed are required to determine the power input to the machine under test. The power input in kilowatts to the machine under test is obtained from Equation (4-1).

$$\text{Power in kilowatts} = \frac{nT}{k} \quad (4-1)$$

where

- n is the rotational speed, in revolutions per minute
- T is the torque
- k is 30 000/ π if T is in Newton-meters

For correction of dynamometer and coupling windage and bearing losses, see IEEE Std 112.

4.2.4 Mechanical driver

The machine can be driven by its prime mover or other mechanical apparatus such as a turbine or engine. Since it is usually not feasible to obtain an accurate measurement of power input to the machine under test, this method can seldom be used to obtain losses but is satisfactory for determining the saturation curves if the speed can be controlled accurately and held constant at the desired value.

4.2.5 Open-circuit saturation curve

The open-circuit saturation curve is obtained by driving the machine under test at rated speed, open-circuited, and recording its armature terminal voltage, field current, and terminal frequency, or shaft speed. In order to obtain useful data for generator model derivation, these readings should be distributed approximately as follows:

- a) Six readings should be taken below 60% of rated voltage (1 at zero excitation).
- b) From 60% to 110%, readings should be taken, at a minimum, at every 5% increment in terminal voltage (minimum of 10 points). This area is a critical range, and an attempt should be made to obtain as many points as the excitation control resolution will allow.
- c) Above 110%, readings should be taken, at a minimum, at two points, including one point at approximately 120% of the rated no-load field current (or at the maximum value recommended by the manufacturer).
- d) At rated voltage, readings should be taken of the terminal voltage (line-to-line) of all three phases to check phase balance. These readings should be made under constant conditions of excitation and speed and with the same voltmeter.

CAUTION

For cylindrical machines, it is recommended that the manufacturer be consulted to determine the maximum voltage, or excitation, that should be used in making the open-circuit saturation curve while recognizing the ability of the machine to operate for the required time at each test point. Operating the generator at voltages above 105% of rated voltage may cause detrimental effects, such as sparking and excessive heating, because of excessive voltage generation in the stator core support structure. Testing should not be made with a transformer on the line unless the transformer manufacturer has approved operation at the intended overvoltages.

Readings for this curve should always be taken with progressively increasing excitation. This method allows for an initial energization of the generator with minimum safety risk. If it ever becomes necessary to decrease the field current, it shall be reduced to zero and then increased carefully to the desired value to remove the effects of hysteresis in the results.

The machines should be allowed to run for several minutes at each voltage point to allow the speed to stabilize at the rated value so there will be no error caused by variation in speed and excitations, except for the 2 points above 110% of rated voltage where the manufacturer's recommendations should be followed.

The results must be corrected for speed and may be plotted as in Figure 6. The voltage of a single phase (line-to-line) or the average of the voltages of the phases at each value of excitation may be used.

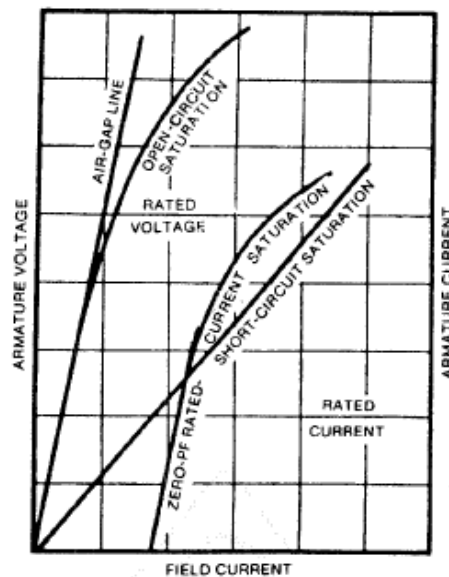


Figure 6—Saturation curves

On hydraulic units, it is possible to have the unit run at a lower speed to obtain high field-current excitation without exceeding the absolute terminal voltage limit. Once corrected for speed, this produces a high open-circuit saturation curve end point. Flux levels must be respected when using this approach.

4.2.6 Air-gap line

The air-gap line is obtained from the open-circuit saturation curve by extending the straight-line lower portion of the curve (see Figure 6). If the lower portion is not linear, the air-gap line is drawn as a straight line of maximum possible slope through the origin, tangent to the saturation curve. The same suggestions can be applied to the lower voltage test points of the zero power factor, rated current saturation curve.

4.2.7 Core loss and friction and windage loss

Core loss and friction and windage loss can be determined from additional readings taken using the same test setup used for the open-circuit saturation curve. At each value of terminal voltage, the power input to the driving motor is measured. If a dc motor is used, this measurement can be accomplished by taking readings of armature current and voltage (the product of which is power input) and field current of the driving motor. If an ac motor is used, power input can be measured directly by a wattmeter. The power input to the machine under test is obtained by subtracting the losses of the driving motor (which should have been determined previously) from the power input to the driving motor (see 4.1.3).

The friction and windage loss is obtained as the power input to the machine under test, with zero excitation (see 4.2.9). The voltage at the machine terminals should be checked, and if any appreciable residual voltage appears, the field should be demagnetized by applying field current in alternate directions with successively smaller magnitude.

The core loss at each value of armature voltage is determined by subtracting the friction and windage loss from the total power input to the machine under test. The core loss may be plotted as in Figure 7 as a function of voltage.

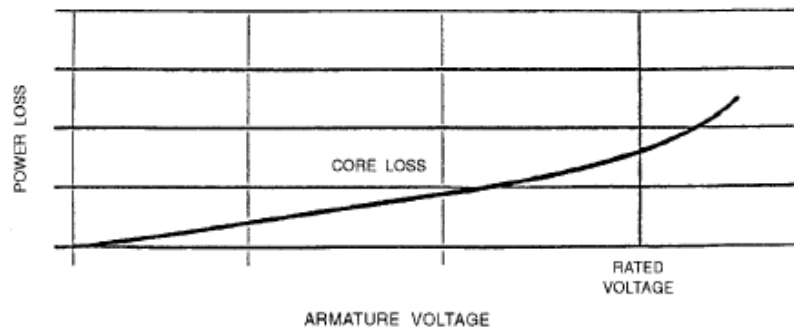


Figure 7—Core loss curve (power loss versus armature voltage)

It is recognized that the core loss described above includes circulating current losses in the stator winding, eddy current losses in the stator core support structure and frame, and rotor surface losses caused by slot passing frequency harmonics in the air-gap flux. These losses may become non-negligible at voltages above 105% of rated voltage, leading to a tip-up in the loss curve as shown in Figure 7.

4.2.8 Short-circuit saturation curve

The short-circuit saturation curve is obtained by driving the machine under test at rated speed, armature short-circuited, and recording its armature and field currents. Normally, readings should be recorded for armature currents of about 125%, 100%, 75%, 50%, and 25% of rated current.

The maximum test current value, traditionally set at 125%, should be obtained from the manufacturer since, for some types of machines, stator cooling will not permit operation in excess of 100% rated current without the risk of damage.

At rated current, readings should be taken of the current in all three phases to check current balance. If there is more than one line or neutral terminal per phase, the current balance between the separate terminals should be checked for each phase.

Current readings should be taken with decreasing excitation starting with the value that will produce an armature current equal to the maximum allowable. The highest current point should be taken first so that

the winding temperature will be as nearly constant as possible during the run. The results may be plotted as in Figure 6.

4.2.9 Short-circuit loss and stray-load loss

Stray-load loss can be determined from additional readings taken at the time the short-circuit saturation curve is made (see 4.2.8). At each value of armature current, the power input to the driving motor is measured as described in 4.2.7. The driving-motor loss should be subtracted from the measured power input to obtain the loss of the machine under test. (See also 4.1.3.) The friction and windage loss, determined as in 4.2.7, is subtracted from the loss of the machine to obtain the short-circuit loss.

The temperature of the armature winding should be taken by thermometers located in several places on the end windings or by embedded detectors in machines so equipped. For machines with a conductor-cooled armature winding, the temperature of the winding may be determined from the average of the temperatures of the coolant at the inlets and outlets of the coils.

Short-circuit loss includes the stray-load loss plus the armature $I^2 R_a$ loss, where R_a is the dc value of the armature resistance. The stray-load loss is obtained by subtracting the armature $I^2 R_a$ loss calculated for the measured current values and with the dc resistance corrected to the average temperature of the winding during the test. For high-voltage hydrogen-cooled machines, there may be an appreciable difference between the temperature of the armature conductors and the measured values. In such cases, a correction to the measured temperature can be used to improve the accuracy of determining the armature $I^2 R_a$ loss. The manufacturer may be consulted for the correction, if any, to be used for the test conditions.

The stray-load loss may be plotted as in Figure 8.

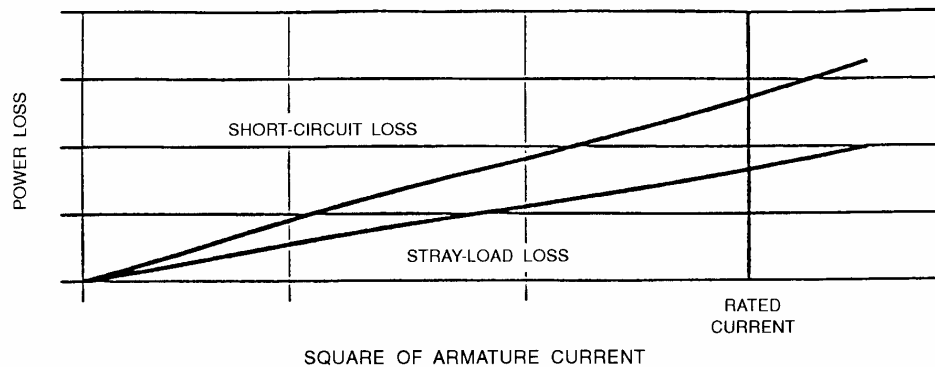


Figure 8—Short-circuit loss and stray-load loss curves

Friction and windage loss should be measured before and after the runs described in 4.2.7 as well as in this subclause. This approach provides a check on the friction and windage loss throughout each run. If there is not over 5% difference between the two readings of friction and windage loss, the average value should be used as the value during each run. When the difference is between 5% and 10%, the change in friction and windage should be prorated uniformly from the beginning to the end of the run. A run should be repeated if the corresponding difference in friction and windage loss is over 10%. An alternative method is to measure the power loss and the coolant temperature of the machine (see 6.6) for each run and to plot the friction and windage losses as in Figure 9. The friction and windage losses for the runs described in 4.2.7 and above in this subclause are then associated with the coolant temperature measured during each run. In some machines, a 10% difference in windage and friction loss may be experienced with a variation in coolant temperature of as little as 4 °C.

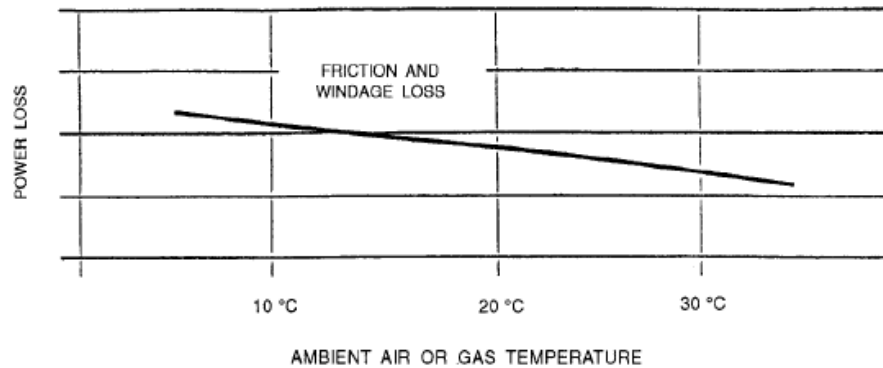


Figure 9—Plot of windage losses against temperature

4.2.10 Zero-power-factor saturation curve

The zero-power-factor saturation curve may be obtained by overexciting the machine under test while it is connected to a load consisting of idle-running, underexcited synchronous machines. By proper adjustment of the excitation of the machine under test and that of its load, the terminal voltage may be varied while the armature current of the machine under test is held constant at the specified value. The zero-power-factor saturation curve for the machine under test is the plot of terminal voltage against field current as shown in Figure 6 for constant armature current. This characteristic is used to obtain Potier reactance (see 5.2.2.2). For this purpose, the point at rated current and rated voltage is often sufficient. In the case of a large machine tested in the power station, the desired test may usually be obtained by redistribution of power and reactive kilovoltampere loading among other machines on the same bus or system and without removing them from productive operation.

4.3 Method 2. Electric input

4.3.1 General

The machine is run as an unloaded synchronous motor from a power supply of adjustable voltage and steady frequency equal to the rated frequency of the machine under test. Power input is measured by wattmeters or wathour meters under various conditions of voltage and current to obtain the losses.

There may be a tendency for the power input to pulsate due to a hunting action between the driving generator and the machine under test. This complication will make obtaining correct readings of the power input difficult. The use of a driving generator that has a damper winding and is appreciably smaller than the driven machine may be helpful.

In testing for the open-circuit losses, the machine under test is operated at approximately unity power factor by adjusting for minimum armature current. If there is a difference in waveform of the driving generator and the machine under test, harmonics will be present in the current input. The harmonics may cause the apparent power input to exceed the active power input at practically all voltages. The importance of this effect can be determined from waveforms of the current and of the terminal voltage of the machine under test.

4.3.2 Instrument transformers

The instrument transformers used should be insulated for the highest voltage applied in the test. The length and size of secondary leads and the ratings of the other secondary burdens should be clearly stated for calibrating purposes.

4.3.2.1 Current transformers

The primary current rating of the current transformers used to test for open-circuit characteristics should be approximately 5% of the rated full-load current of the machine under test. Hence, the current transformers should be connected across a set of disconnecting switches in the machine leads, which are kept closed during the adjusting of the voltages and until the hunting of the machine subsides so that the current remains within the rating of the transformers. The permanent transformers provided for measurement and control purposes can be used for making the rough adjustments.

The current transformers used to test for open-circuit characteristics may also be used for one or two of the low-current points on the stray-load loss curve. The permanent current transformers or special test transformers with current ratings approximately 125% of the machine current rating may be used for the higher current points on this curve.

4.3.2.2 Voltage transformers

The primary voltage rating of the voltage transformers for the open-circuit characteristic test should be sized greater than the rated line-to-line stator voltage. It should be noted that the voltage transformer's accuracy is linear to 10% in excess of its voltage nameplate rating. One alternative is to connect the voltage transformer to neutral.

The voltage transformer should have a standard accuracy class of 0.3 so that the limit of ratio correction is between 0.997 and 1.003. For short-circuit and stray-load loss characteristics, the voltage transformer ratios should be at the lowest possible ratio (see 4.3.9). Since the test is done near zero power factor, high-burden voltage transformers should be used to minimize the phase angle errors to the high-accuracy, low-burden digital instruments.

4.3.3 Voltage on instruments

For low-voltage points and points near normal voltage in the test for open-circuit characteristics, the voltage transformers used should have voltage ratings so that the voltage impressed on the wattmeters or watthour meters is not less than 70% of the voltage rating of the potential coils of the measuring devices. Voltages less than 70% may be used for intermediate points, as these points can be checked by the curve through the points taken at the recommended voltage values of 70% or greater.

4.3.4 Methods to measure power input

The measurement of the power input is an important item in the application of this test method, and the following methods of measurement may be used:

- Method 1. Wattmeters (see 4.3.4.2)
- Method 2. Portable standard watthour meters (see 4.3.4.3)
- Method 3. Ordinary watthour meters (see 4.3.4.4)

The one to be used for any particular test will depend on test conditions. While more difficult to apply, method 1, when used with the proper precautions, is capable of giving the most accurate results. Sometimes method 1 and method 2 or 3 are used simultaneously to obtain checks on the readings.

4.3.4.1 Connections of measuring devices

The connections that are used for reading power input depend on the connections of the machine. If the neutral of the test machine is brought out and is connected to the system during the test, the three-wattmeter connection as in Figure 10 should be used. If the neutral of the test machine is brought out, but not connected to the system during the test, either the three-wattmeter connection, Figure 10, or the

two-wattmeter connection for measuring three-phase power, Figure 11, may be used. The three-wattmeter method affords a simpler and more nearly correct calculation of corrections of ratio and phase-angle errors of the instrument transformers and for scale corrections of the wattmeters or registration errors of the watthour meters if such corrections are required. If the neutral of the test machine is *not* available, it is necessary to use the two-wattmeter method, Figure 11, or three identical wattmeters connected in wye for measuring three-phase power. One point of each secondary circuit should always be connected to a common ground as shown in Figure 10 and Figure 11. A polyphase wattmeter may also be used.

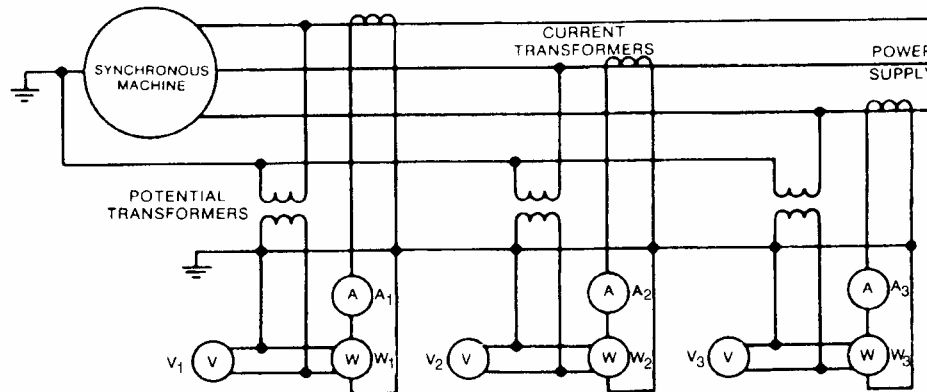


Figure 10—Connection diagram—Three-wattmeter method of measuring power

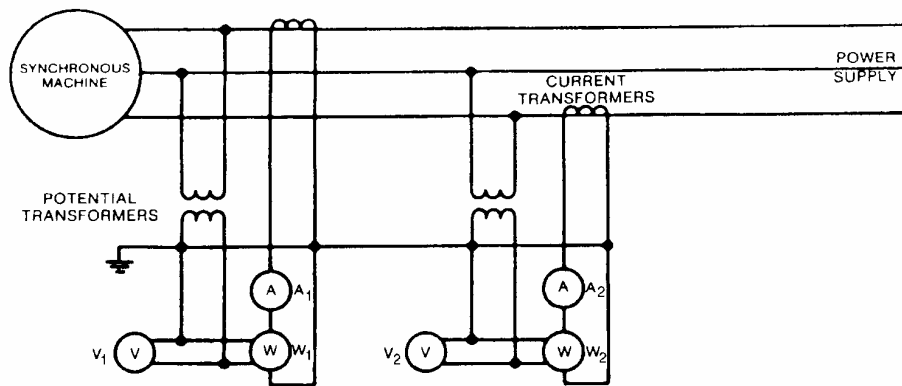


Figure 11—Connection diagram—Two-wattmeter method of measuring power

4.3.4.2 Method 1. Wattmeters

Instruments are connected according to the requirements as given in the preceding subclause. All readings should be taken simultaneously. A number of readings for each point on the curve should be taken, and average values used for plotting the points.

4.3.4.3 Method 2. Portable standard watthour meters

Portable standard watthour meters are connected according to the requirements given in 4.3.4.1. In measuring the energy over a short period of time, it will generally be found preferable to start and stop all instruments together, using a period of at least three minutes for small machines and five minutes for large