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(Revision of IEEE Std 115-1983 and IEEE Std 115A-1987)

IEEE Guide: Test Procedures for Synchronous Machines

Part I Acceptance and Performance Testing

Part II Test Procedures and Parameter Determination for Dynamic Analysis

Sponsor

**Electric Machinery Committee
of the
IEEE Power Engineering Society**

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Abstract: Instructions for conducting the more 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 115-1995, IEEE Guide: Test Procedures for Synchronous Machines.)

IEEE Std 115-1995 incorporates and updates virtually all of the 1983 edition (reaffirmed in 1991), along with IEEE Std 115A-1987.

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 Synchronous Machinery Subcommittee Working Group #12, which produced this present document, was formed in January 1992, and a revised PAR form, dated April 1992, was approved by the Standards Board in June 1992. This approval included a proposal by the Working Group to divide the new document "Test Procedures for Synchronous Machines," into 2 parts, as follows:

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

Part I basically includes all of the sections (1–7) of IEEE Std 115-1983, except section 8. These are now designated sections 1–8.

Part II includes section 8 of IEEE Std 115-1983 plus IEEE Std 115A-1987. These are now designated as sections 9 through 12.

A new feature of this revised and expanded standard is the inclusion of several annexes following sections 5, 11, and 12.

The Working Group believes strongly that the new arrangement will be more convenient to use; the now expanded section 8 from the 1991 document includes three new sections. These are:

- Section 9: Applications of machine electrical parameters
- Section 10: Tests for determining parameter values for steady-state conditions
- Section 11: Tests for evaluating transient or subtransient characteristic values

Section 12 deals with all aspects of standstill frequency response testing of synchronous machines, which was derived from IEEE Std 115A-1987.

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IEEE Guide: Test Procedures for Synchronous Machines

Part I—Acceptance and performance testing

1. Overview

1.1 Scope

This guide contains instructions for conducting the more 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 those more general methods which 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 the making of any specific test in a given transaction or implying a guarantee to meet 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 following quantities listed on the machine nameplate. These include MVA, terminal voltage (or kilovolts), armature current, and power factor.

1.2 Organization of guide

The guide is broken down into 12 sections. Part I contains sections 1 to 8, and part II contains sections 9 to 12. Each section is organized into clauses and subclauses. Certain sections are followed immediately by one or more annexes.

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 should provide sufficient instructions for performing normally required tests. Throughout this guide, cross references to clauses have been used frequently to call attention to pertinent related material. When reference is made to a clause, it is intended that the reference include not only the specific clause but any immediately following subclauses that apply to the same general subject.

1.3 Miscellaneous notes

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 those obtained by methods given in this guide.

The tests listed in both parts I and II basically relate to three-phase machines. The need for addressing tests for machines with more than three phases was recognized. Procedures will probably be developed for tests on for example six, twelve, or much higher phase synchronous machines, and such practices should subsequently be reviewed and found to be acceptable. They will be considered for incorporation into future revisions of this standard.

The SI or metric system of units has been used in this document. To provide continuity with previous issues of this IEEE guide, a conversion table is provided as annex Annex B, which relates metric units to English units. Annex Annex A lists nomenclature used particularly in section 5, and in sections 9 through 12. Annex Annex C lists a bibliography, in which references are noted particularly for section 5 and for sections 9 through 12.

Annexes Annex A, Annex B, and Annex C are situated at the end of Part II.

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 herein is contained in IEEE Std 120-1989¹. Consequently, the measurement circuits shown in the figures of this guide are often only schematic and IEEE Std 120-1989 should be referred to for accurately detailed circuits. However, for some special tests and for purposes of improved clarity, more detailed figures of instrument connections have been included.

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 which may be required to obtain accurate data have been indicated.

CAUTION — Many of the 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, 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 should 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. All tests should be performed by knowledgeable and experienced personnel.

¹The numbers in brackets correspond to those bibliographic items listed in annex Annex C.

2. References

ANSI C50.10-1977, American National Standard General Requirements for Synchronous Machines.²

ANSI C50.12-1982 (R1989), American National Standard Requirements for Salient Pole Synchronous Generators and Generator/Motors for Hydraulic Turbine Applications.

ANSI C50.13-1989, American National Standard Requirements for Rotating Electrical Machinery—Cylindrical Rotor Synchronous Generators.

ANSI C50.14-1977, American National Standard Requirements for Combustion Gas Turbine-Driven Cylindrical Rotor Synchronous Generators.

ASME PTC 18-1949, Hydraulic Prime Movers.³

NEMA MG1-1978, Motors and Generators.⁴

IEEE Std 1-1986 (Reaff 1992), IEEE Standard General Principles for Temperature Limits in the Rating of Electric Equipment and for the Evaluation of Electrical Insulation (ANSI).⁵

IEEE Std 4-1995, IEEE Standard Techniques for High-Voltage Testing (ANSI).

IEEE Std 43-1974 (Reaff 1991), IEEE Recommended Practice for Testing Insulation Resistance of Rotating Machinery (ANSI).

IEEE Std 56-1977 (Reaff 1991), IEEE Guide for Insulation Maintenance of Large Alternating-Current Rotating Machinery (10 000 kVA and Larger) (ANSI).

IEEE Std 62-1978, IEEE Guide for Field Testing Power Apparatus Insulation (ANSI).

IEEE Std 67-1990, IEEE Guide for Operation and Maintenance of Turbine Generators (ANSI).

IEEE Std 85-1973 (Reaff 1986), Test Procedure for Airborne Sound Measurements on Rotating Electric Machinery (ANSI).

IEEE Std 86-1987, IEEE Standard Definitions of Basic Per-Unit Quantities for Alternating-Current Rotating Machines (ANSI).⁶

IEEE Std 95-1977 (Reaff 1991), IEEE Recommended Practice for Insulation Testing of Large AC Rotating Machinery with High Direct Voltage (ANSI).

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

IEEE Std 112-1991, IEEE Standard Test Procedure for Polyphase Induction Motors and Generators (ANSI).

IEEE Std 118-1978 (Reaff 1992), IEEE Standard Test Code for Resistance Measurements (ANSI).

²ANSI publications are available from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA.

³ASME publications are available from the American Society of Mechanical Engineers, 22 Law Drive, Fairfield, NJ 07007, USA.

⁴NEMA publications are available from the National Electrical Manufacturers Association, 1300 N. 17th St., Ste. 1847, Rosslyn, VA 22209, USA.

⁵IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

⁶IEEE standard 86-1987 has been withdrawn; however, copies can be obtained from Global Engineering, 15 Inverness Way East, Englewood, CO 80112-5704, USA, tel. (303) 792-2181.

IEEE Std 119-1974, IEEE Recommended Practice for General Principles of Temperature Measurement as applied to Electrical Apparatus (ANSI).⁷

IEEE Std 120-1989, IEEE Master Test Code for Electrical Measurements in Power Circuits (ANSI).

IEEE Std 433-1974 (Reaff 1991), IEEE Recommended Practice for Insulation Testing of Large AC Rotating Machinery with High Voltage at Very Low Frequency (ANSI).

IEEE Std 492-1974 (Reaff 1986), IEEE Guide for Operation and Maintenance of Hydro-Generators (ANSI).

IEEE Std 810-1987 (Reaff 1994), IEEE Standard for Hydraulic Turbine and Generator Integrally Forged Shaft Couplings and Shaft Runout Tolerances (ANSI).

IEEE Std 1095-1989 (Reaff 1994), IEEE Guide for Installation of Vertical Generators and Generator/Motors for Hydroelectric Applications (ANSI).

IEEE Std 1110-1991, IEEE Guide for Synchronous Generator Modeling Practices in Stability Analyses (ANSI).

3. Miscellaneous tests

3.1 Insulation resistance

The recommended methods for testing insulation resistance are given in IEEE Std 43-1974. Polarization index and the effects of temperature, moisture, and duration of application of test voltage are also covered in IEEE Std 43-1974.

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 43-1974 and IEEE Std 1095-1989 for methods of dry-out.

NOTE — While IEEE Std 1095-1989 is written specifically for vertical hydraulic-turbine-driven generators, the procedure is applicable to other types of machines.

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 ANSI C50.10-1977 and ANSI/NEMA MG1-1978.

CAUTION — Due to the high voltage used, which could cause serious personal injury or death, high-potential tests should be conducted only by experienced personnel, and adequate safety precautions should be taken to avoid such injury to personnel or damage to property. For the procedures recommended, refer to IEEE Std 4-1978 and IEEE Std 62-1978.

⁷IEEE Std 119-1974 has been withdrawn; however, copies can be obtained from Global Engineering, 15 Inverness Way East, Englewood, CO 80112-5704, USA, tel. (303) 792-2181.

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, whether the winding is to be tested or grounded.

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 falls. 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 (diodes, thyristors, etc.) should be short-circuited (not grounded) during the test.

Additional methods, procedures, and precautions are given in ANSI C50.10-1977 and NEMA MG1-1978, parts 3, 21, and 22.

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) The transformer-voltmeter and
- b) The 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 potential 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 should 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.

3.2.4 Method 2. Direct-voltage testing of stator windings

A direct-voltage equal to 1.7 times the 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 4-1995 and IEEE Std 95-1977.

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

CAUTION — 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 avoid hazard to personnel.

3.2.5 Method 3. Very-low-frequency testing of stator windings

A very-low-frequency (VLF) voltage (frequency being in the range of 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 it may result in reduced size and rating of the test equipment required. 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 56-1977. In addition, clause 7.1.2 of IEEE Std 62-1978 describes partial discharge measurements on rotating machines. There has been a very 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 standard is increasingly common and yields valuable information for both maintenance and diagnosis of winding problems.

3.3 Resistance measurements

3.3.1 General

To obtain direct-current 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:

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

where

R_s	is the winding resistance, corrected to specified temperature, t_s (ohms)
t_s	is the specified temperature, °C
R_t	is the test value of winding resistance (ohms)
t_t	is the temperature of winding when resistance was measured, °C
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 for a time sufficiently 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 to be 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.

If 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 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, thus providing 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, direct current 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 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 have been reached. The temperature of the field winding is then determined in accordance with 6.4.4. The resistance obtained from this test should be 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, and 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 is especially important when the field current is very small, as 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 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.

3.4.2 Method 1. Voltage drop, direct-current

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 direct current 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 is wound with the wrong number of turns or size of conductor.

3.4.3 Method 2. Voltage drop, alternating current

A more sensitive test for short-circuited turns is made by passing constant-amplitude alternating current 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 that across a sound coil. The voltage across a sound coil adjacent to the coil with a short-circuited turn will be somewhat less than that 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 which has a short-circuited turn only when running. If the speed is varied while the alternating current 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, 4, or 5 may be preferred.

3.4.4 Method 3. Direct-current 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 for a period sufficient 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 alternating current (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 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 pick-up to determine the rotor magnetic field waveform. The magnetic pick-up should be mounted from the stator, in the air gap in close proximity to the rotor, according to the manufacturer's recommendations, and connected to an oscilloscope or other suitable recording device. With the rotor rotating at speed and the field winding excited, the occurrence of short-circuited turns can often be detected as discontinuity or dissymmetry in the recorded trace (see IEEE Std 67-1990).

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 may 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 to flow 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 test, essentially of an investigative research nature.

For methods 1 through 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

The insulation can be tested by connecting a low range alternating-current voltmeter (or a high range alternating-current 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

A layer of heavy paper is placed around the shaft to insulate the journals of the uninsulated bearings. The coupling of the driving or driven units should be disengaged if it is not insulated. Then, from a 110 V–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–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 megger may also be used. This is much more sensitive than the above method and may tend to reject insulation which 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 (for example, thermometer tubes, control pipes for a hydraulic turbine, hydrogen seals, and insulated couplings). This test may be made with the machine stationary or running. The test should be supplemented by careful visual inspection to assure 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 MG1-1978. 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.

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 3.1 is a diagram of one type of phase sequence indicator which 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 3.1 will operate clockwise if the phase sequence is 1, 2, 3, and counter-clockwise if the phase sequence is 1, 3, 2.

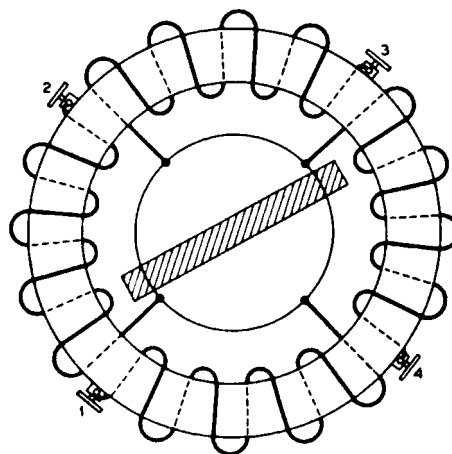


Figure 3.1—Phase-sequence instrument

A type of phase-sequence indicator without moving parts is also available for three-phase machines and is shown schematically in figure 3.2. 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 3.2 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 potential transformers, extreme care should be exercised in observing the conventions for polarity markings of the potential transformers. (See ANSI C57.13-1978, clause 4.8.1.)

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 potential transformers are connected as shown in figure 3.3 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 potential 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.

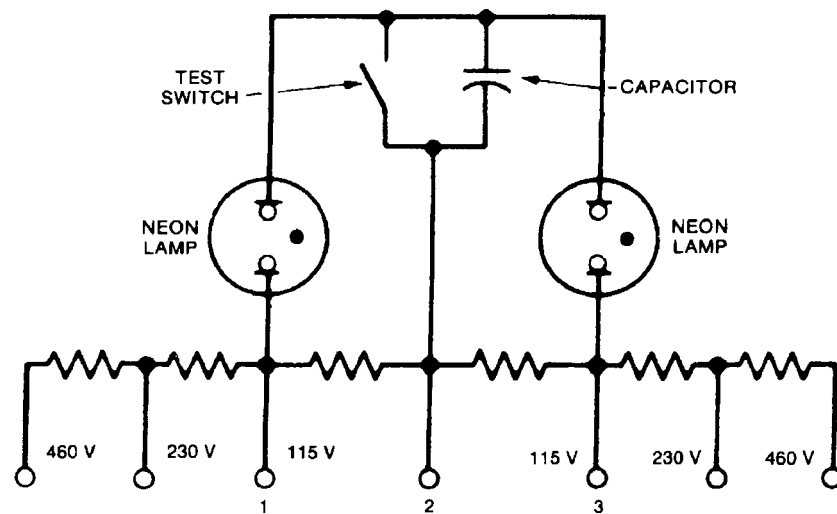


Figure 3.2—Neon-lamp phase-sequence indicator

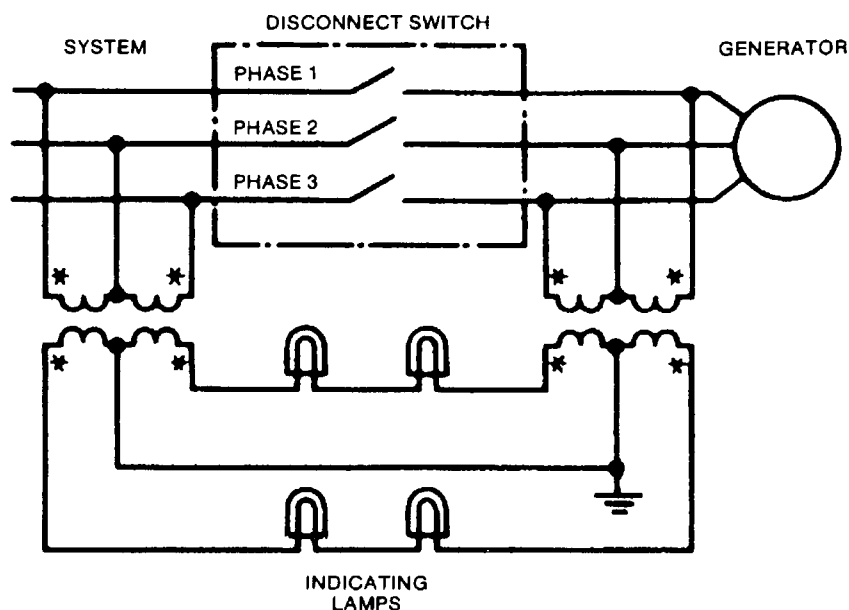


Figure 3.3—Connection diagram for comparing the phase-sequence of a generator with that of a system by indicating the voltage across an open disconnect switch

3.7.4 Method 3. Direction of rotation for motors

In the case of a motor, the phase sequence can be checked by starting it from its normal source of power and observing its direction of rotation. If damage can result from improper rotation, the motor should be disconnected from the apparatus which would be damaged. In some cases, apparatus such as a non-reverse ratchet cannot be disconnected. In this case, a sufficiently low voltage should be used so as not to damage the apparatus, or another procedure such as method 1 or an adaptation of method 2 should be used.

3.8 Telephone-influence factor

3.8.1 Telephone-influence factor

Telephone-influence factor (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 root-mean-square value of the wave. This can be done analytically from data taken by harmonic analysis in conjunction with the weighting factors using the following equations:

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

where

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

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 component 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 telephone influence factor, TIF_f , corresponding to the n th harmonic frequency.

3.8.2 Weighting factors

For the weighting factors to be used in calculating TIF, see ANSI C50.13-1989 or NEMA MG1-1978.

3.8.3 Potential transformer considerations

If a potential 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 potential transformer disconnected, and the harmonic content of the machine voltage should be obtained. The potential 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 potential 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 telephone-influence factor

3.9.1 General

For the definition of *balanced telephone-influence factor*, see IEEE Std 100-1992.

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 telephone-influence factor of a three-phase wye-connected machine can be obtained using equations 3-2 and 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 telephone-influence factor

3.10.1 General

For the definition of residual-component telephone-influence factor, see IEEE Std 100-1992.

3.10.2 Method 1. Machines that can be connected in delta

The residual-component telephone-influence factor 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 root-mean-square voltage taken across the open corner of the delta. It can be obtained from the reading of a TIF instrument or is 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 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 potential 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 potential transformer. For a 1:1 transformer, this could equal full normal line-to-neutral voltage of the machine.

To eliminate 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 over-voltage. 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 those cases where the machine cannot be conveniently connected in delta, the residual-component TIF may be obtained by connecting three identical potential transformers in wye to the terminals of the machine and connecting the secondaries in delta with one corner open. The neutral of the potential transformer primaries should be connected to the neutral of the machine. The measurements then may be taken in the potential 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 telephone-influence factor can be computed using equations 3-2 and 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 telephone-influence factor

3.11.1 General

The line-to-neutral telephone-influence factor 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 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 potential transformer connected from line-to-neutral across one phase of the machine when operating at rated voltage and speed, without load. The weighted root-mean-square 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 telephone-influence factors 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 IEEE Std 100-1992. The waveform of the test voltage is recorded by using an oscillograph 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 3.4 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, so located 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.

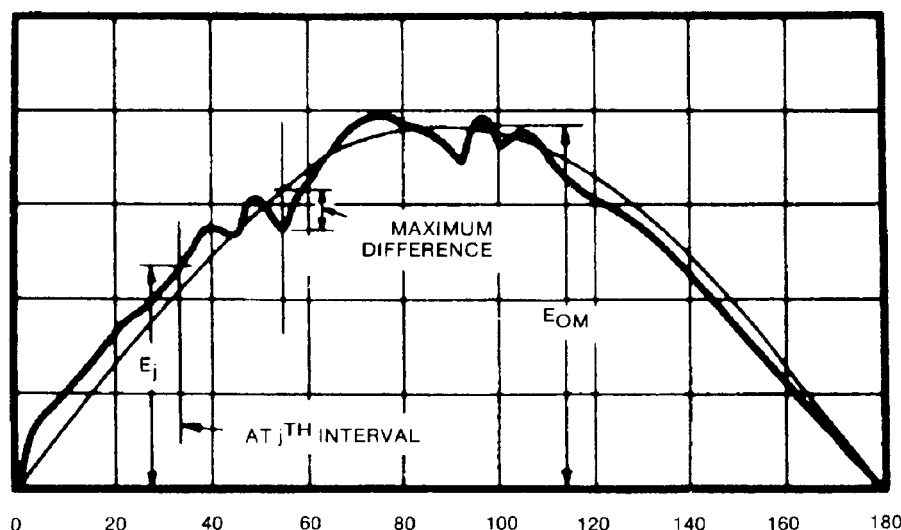


Figure 3.4—Plot of wave for deviation factor

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 J (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 J 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.

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

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, resulting 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 type 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 when the maximum positive deviation is the same or nearly the same as the maximum negative deviation during the half cycle (see figure 3.4).

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 3.5 shows a block diagram of a computer-controlled data acquisition system used for waveform analysis.

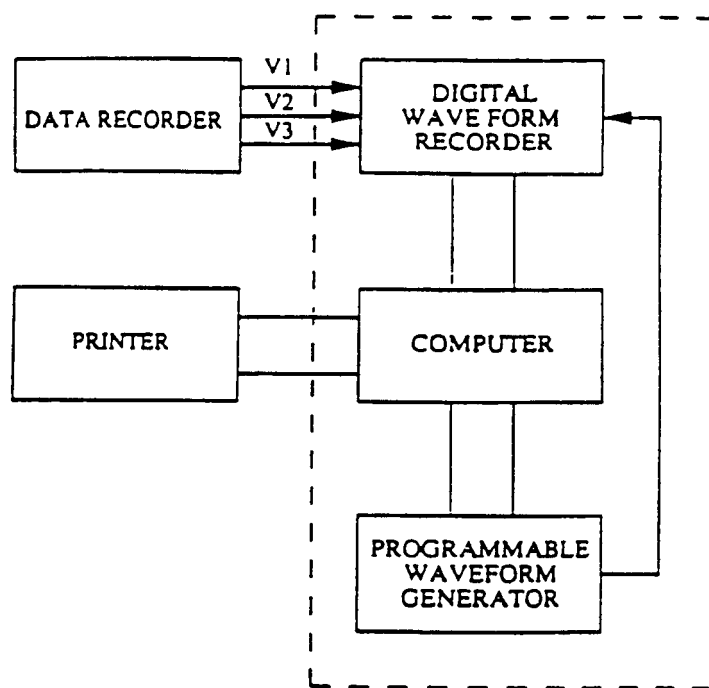


Figure 3.5—Block diagram of the instrumentation used in waveform analysis

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 potential transformers, in a data recorder for off-line processing and data reduction. The recorded waveforms on the video cassette are fed into a multi-channel digital waveform recorder.

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 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

$$E_j = E_i - E_O$$

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

The rms value of the input waveform is given by

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

Therefore, the zero-to-peak amplitude of the equivalent sine wave E_{OM} is

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

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 relabelled, i.e., the first point ($j=1$) corresponds to the smallest absolute value with a positive slope. The maximum deviation ΔE is given by

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

3.12.3 Fourier analysis

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

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

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

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

$$\begin{aligned} \phi_n &= \tan^{-1}(b_n/a_n) & a_n > 0 \\ &= \tan^{-1}(b_n/a_n) + \pi & a_n < 0 \\ n &= 1, 2, 3, \dots \end{aligned} \quad (3-15)$$

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 (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

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

where

$\sum E_n^2$ is the sum of the squares of all components of the voltage except the fundamental
 E_{rms} is the root-mean-square value of the voltage

By digital method, after obtaining the magnitudes of the harmonics, the distortion factor F_{Di} can be calculated as

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

$n = 2, 3, \dots$, 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 type 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 type alternating-current instrument of suitable accuracy or a true rms digital meters. (Other types of instruments are likely to give incorrect readings because they do not respond to the root-mean-square 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 over-speed on loss of load or other causes. The manufacturer should be consulted prior to conducting any test which is above rated speed.

3.13.2 Procedure

Before making an overspeed test, the machine should be carefully inspected, making sure 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 should 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 for a sufficiently long period for vibration readings to be made and stabilized, 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 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.)

3.14.2 Method 1. As motor

The machine 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 supplied from the driving units, 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 normal speed and is connected to a load consisting of idle-running over-excited 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 is driven at normal 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 67-1990).

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 the IEEE Std 85-1973 and ANSI Std C50.12-1982. 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 U.S. 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.

A sound level instrument provides a single number in decibels (dB) 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.

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 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 ANSI C50 standards series and NEMA MG1-1978. 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 using the field current (see section 5) and the field resistance corrected to a specified temperature (see 3.3).

4.1.2 Methods of loss measurement

There are four methods available to measure the losses of a synchronous machine as follows:

- a) Separate-drive method (see 4.2)
- b) Electric-input method (see 4.3)
- c) Retardation method (see 4.4)
- d) Heat transfer method (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 as for the first three methods.

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.

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, 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.

These effects should be considered in establishing conditions of tests for losses for those 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 492-1974). Motor-generator sets and frequency-changer sets are examples of equipment where this allocation may not be necessary, since the efficiencies are usually guaranteed 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 is 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 18-1949 gives formulas for calculating the windage 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 turbines

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 18-1949). An acceptable alternative term to "dewatering" is the use of 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 requires draining the penstock, which is a time-consuming operation. If the runner is set above tailwater, proper venting through the turbine air valve will allow the water to drain out of the draft tube. When the runner is not sufficiently high enough above tailwater, the tailwater 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 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 is the simplest method of starting.

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 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 being tested, 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 to be tested.

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 to be tested, 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 Separate-drive method for saturation curves and losses

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 direct-current 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 friction, windage, rated-current stator I^2R_a , and stray-load loss. This 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 dip with change of losses of the machine being tested. 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 it 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.

The driving-motor method 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.

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 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 (see 4.1.3).

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 being tested. The power input in kilowatts to the machine under test is obtained from the following equation:

$$\text{power in kilowatts} = \frac{n \cdot T}{k} \quad (4-1)$$

where

n	is the rotational speed, r/min
T	is the torque
k	is 9549 if T is in N·m (Newton-meters)
K	is 7043 if T is in lb _f ·ft

For correction of dynamometer and coupling windage and bearing loss, see IEEE Std 112-1991.

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 being tested, 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 being tested 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 below 60% of rated voltage (1 at zero excitation)
- b) From 60% to 110%, at least 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%, at least 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 citation, which should be used in making the open-circuit saturation curve, recognizing the ability of the machine to operate for the required time at each test point. 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 increasing excitation. This method allows for a safe initial energization of the generator. 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 4.1. 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.

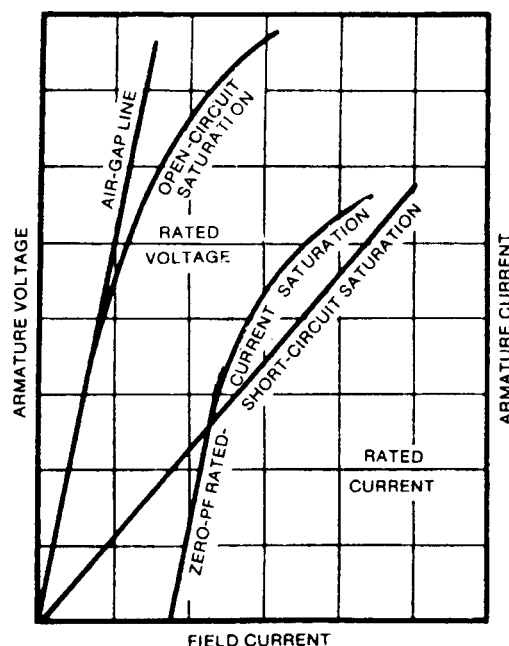


Figure 4.1—Saturation curves

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 thereof (see figure 4.1). 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 set up 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 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 being tested 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 being tested, 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 being tested. The core loss may be plotted as in figure 4.2 as a function of voltage.

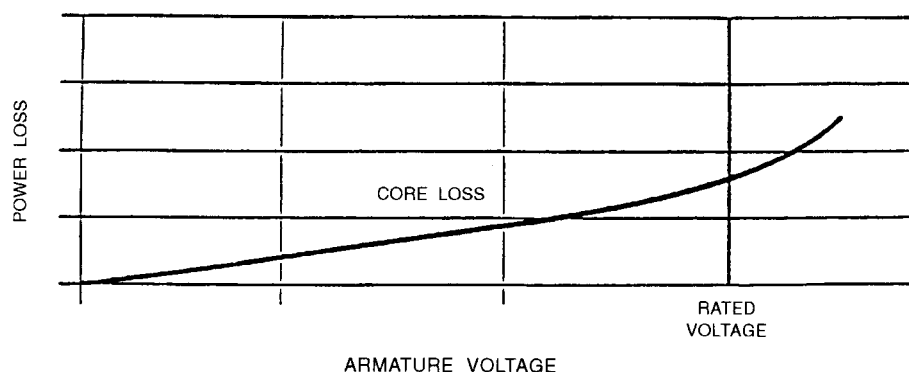


Figure 4.2—Core loss curve (power loss vs. armature voltage)

4.2.8 Short-circuit saturation curve

The short-circuit saturation curve is obtained by driving the machine being tested 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 which 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 4.1.

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 being tested. (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^2R_a loss, where R_a is the dc value of the armature resistance. The stray-load loss is obtained by subtracting the armature I^2R_a loss calculated for the measured current values and with the direct-current 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. If such is the case, a correction to the measured temperature can be used to improve the accuracy of determining the armature I^2R_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 4.3.

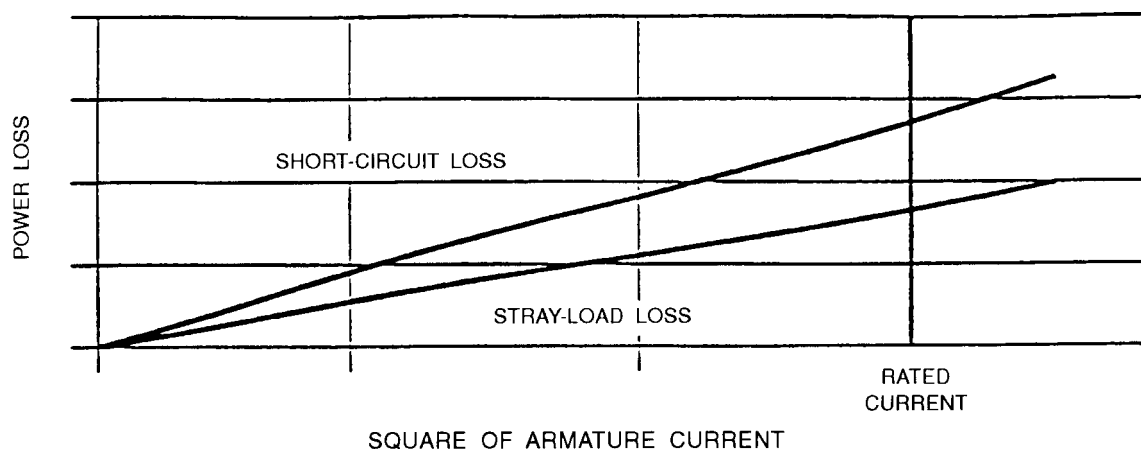


Figure 4.3—Short-circuit loss and stray-load loss curves

Friction and windage loss should be measured before and after the runs described in 4.2.7 as well as in this subclause. This 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 plot the friction and windage losses as in figure 4.4. 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.

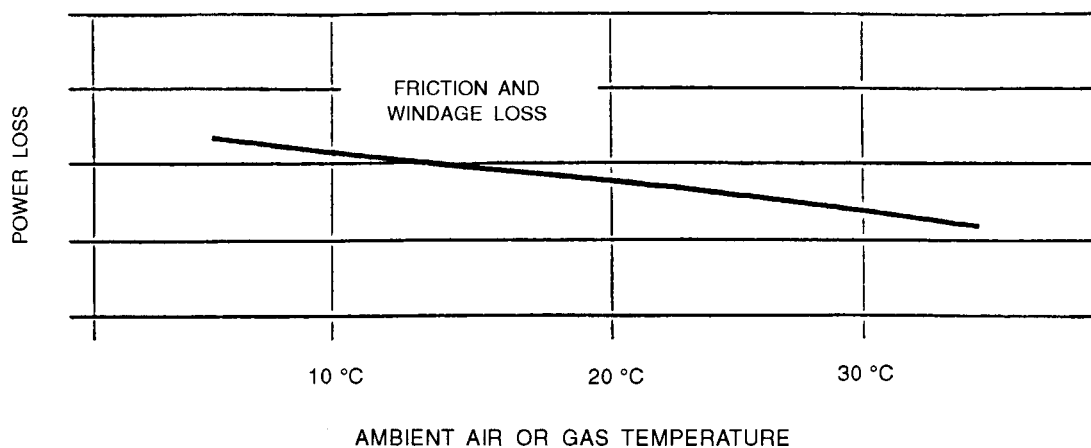


Figure 4.4—Plot of windage losses against temperature

4.2.10 Zero-power-factor saturation curve

The zero-power-factor saturation curve may be obtained by overexciting the machine being tested while it is connected to a load consisting of idle-running, underexcited, synchronous machines. By proper adjustment of the excitation of the machine being tested and that of its load, the terminal voltage may be varied while the armature current of the machine being tested is held constant at the specified value. The zero-power-factor saturation curve, for the machine being tested, is the plot of terminal voltage against field current as shown in figure 4.1 for constant armature current. This characteristic is used to obtain Potier reactance (see 5.2.6). 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 Electric-input method for losses and saturation curves

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 being tested. Power input is measured by wattmeters or watthour 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 will result in difficulty in obtaining correct readings of the power input. The use of a driving generator which has a damper winding and which 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 oscillograms of the current and of the terminal voltage of the machine being tested.

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 for the tests 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 for the 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 Potential transformers

The primary voltage rating of the potential 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 potential transformer's accuracy is linear to 10% over its voltage nameplate rating. One alternative is to connect the potential transformer to neutral.

The potential transformer should have a standard accuracy class of 0.3, so the limit of ratio correction is between 0.997 and 1.003. For short-circuit and stray-load loss characteristics the potential transformer ratios should be at the lowest possible ratio (see 4.3.13). Since the test is done near zero power factor, high burden potential 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 potential transformers used should have voltage ratings such that the voltage impressed on the wattmeters or watt-hour 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 Measurement of power input

The measurement of the power input is a very important item in the application of this test method, and there are three methods of measurement which may be used (see 4.3.6, 4.3.7, and 4.3.8). 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 methods 2 or 3 are used simultaneously to obtain checks on the readings.

4.3.5 Connections of measuring devices

The connections which 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 4.5 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 4.5, or the two-wattmeter connection for measuring three-phase power, figure 4.6, 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 watt-hour 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 4.6, 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 figures 4.5 and 4.6. A polyphase wattmeter may also be used.

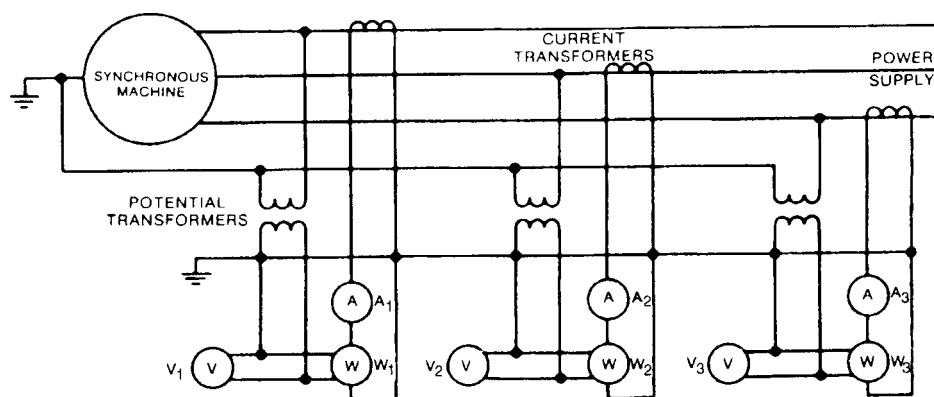


Figure 4.5—Connection diagram—Three-wattmeter method of measuring power

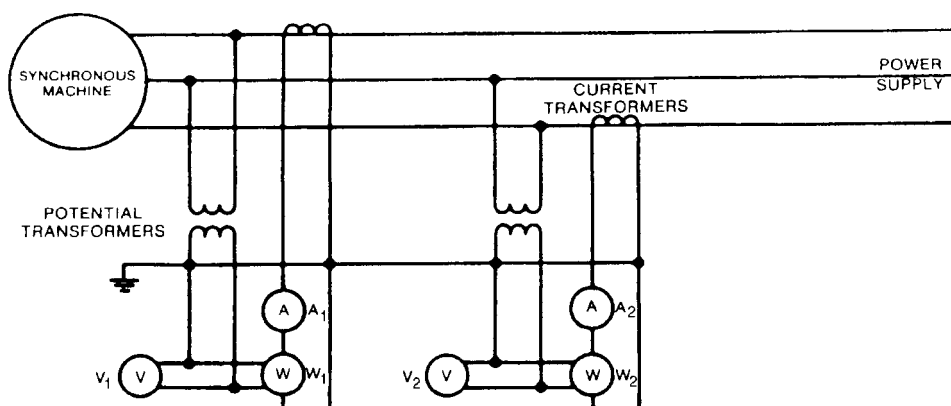


Figure 4.6—Connection diagram—Two-wattmeter method of measuring power

4.3.6 Method 1. Measuring power input

Instruments are connected according to the requirements as given in the preceding clause. All readings should be taken simultaneously. Under some test conditions, there will be relatively wide swings of the instrument pointer. In such cases, the ammeter pointer should remain at a minimum value for one-half of a second, or longer to indicate that stable conditions have been held for sufficient time to permit accurate wattmeter readings to be obtained. The wattmeter should be read simultaneously at a signal from the observer of the ammeter. A number of readings for each point on the curve should be taken, and average values used for plotting the points.

4.3.7 Method 2. Measuring power input

Portable standard watthour meters are connected according to the requirements given in 4.3.5. 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 machines. Suitable precautions should be taken so that errors in the measurement of time are not appreciable. To obtain good results, it is important that variations in operating conditions be minimized.

4.3.8 Method 3. Measuring power input

In some cases, it may be convenient to use ordinary watthour meters instead of portable standard watthour meters (as in method 2). The readings can be taken most satisfactorily by timing a suitable number of complete revolutions of the instrument disks by stop watches.

4.3.9 Accuracy

Normally, corrections are required for scale marking of the instruments. For those tests where the highest order of accuracy is required, corrections should be made for the ratio and phase-angle error of the instrument transformers, the phase-angle error of wattmeters, and errors of watthour meters.

4.3.10 Stray-load loss

The electric-input method can be used to determine open-circuit loss, open-circuit saturation curve, and short-circuit saturation curve with sufficient accuracy using normal instruments and procedures. Special procedures and instruments as described below are necessary to obtain satisfactory measurement of stray-load loss.

Since the power factor in the measurements for stray-load losses is low and measurements also include two relatively large losses (friction and windage plus I^2R losses for both field and armature), it is necessary to make corrections for ratio and phase-angle errors of the instrument transformers and for the scale corrections for the wattmeters or error of the watt-hour meters. These corrections can be more easily applied to the three-wattmeter method of measurement, as the three readings are approximately equal and are at the same power factor. The low power factor also requires the use of wattmeters having power factor ratings agreeing closely with the power factor of the circuits in which they are used.

4.3.11 Open-circuit loss

The test machine is run as a synchronous motor at approximately unity power factor and at as many of the voltages listed in 4.2.4 as possible. Readings should be taken of power input (or energy and time), armature voltage, and field current. Sufficient accuracy will be obtained at any power factor between 0.95 overexcited and 0.95 underexcited. A check for unity power factor may be obtained by the use of a single-phase wattmeter connected with the current coil in one line and the voltage coil connected across the other two phases, and adjusting the field of the test machine to obtain a zero reading of this wattmeter. Unity power factor conditions, when using the two-wattmeter method for measuring three-phase power, may also be checked by obtaining equal readings on the two wattmeters or watthour meters.

Open-circuit core loss at each point is equal to the power input less the friction and windage loss and the armature I^2R_a loss (see 4.1.3). The results may be plotted as shown in figure 4.2.

In general, it will be impossible to use less than 30% voltage without the machine under test dropping out of synchronism. Loss data from a typical test are shown in figure 4.7. If the data could be taken to zero voltage, the intercept at the bottom would be the friction and windage loss. In order to find this intercept, a curve, as shown in figure 4.8, is plotted with the voltage squared as ordinate and power input as abscissa. For low values of saturation, the core loss varies approximately as the square of the voltage. Therefore, the lower part of the curve of voltage squared against power loss is a straight line and can be easily extended to give the intercept on the horizontal axis.

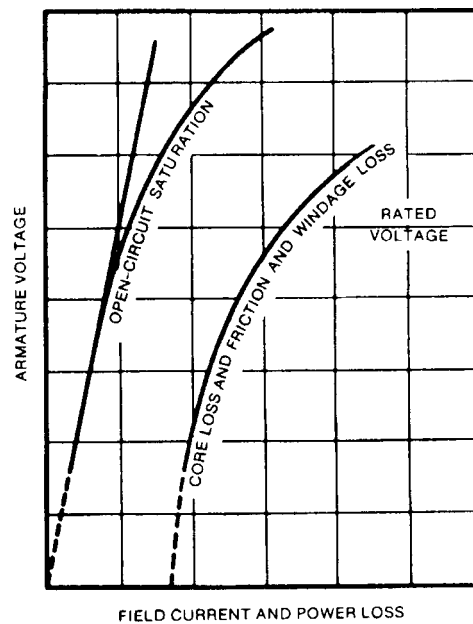


Figure 4.7—Open-circuit saturation and core loss curves by electric-input method

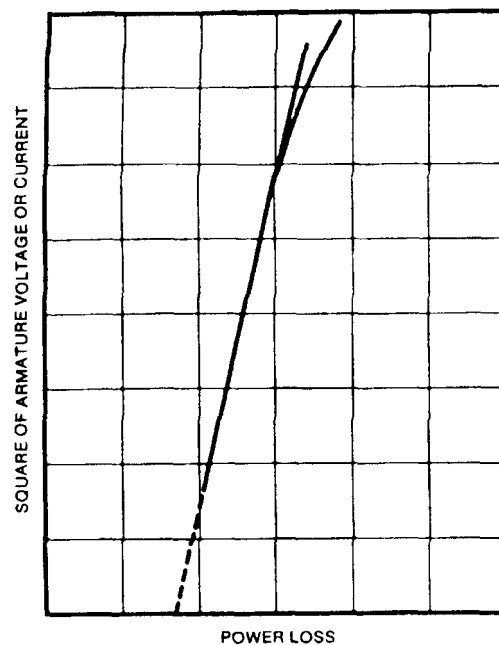


Figure 4.8—Construction curves for extrapolating loss curves from electric-input method

4.3.12 Open-circuit saturation curve

The open-circuit saturation curve can be plotted from the readings of armature voltage and field current taken from the open-circuit loss test. Since the armature voltage cannot drop much below 30% of rated value during this test, the lower portion of the saturation curve will have to be extrapolated to zero voltage as shown in figure 4.7.

4.3.13 Short-circuit loss and stray-load loss

The machine is operated as a synchronous motor at a fixed voltage, preferably about 1/3 normal or at the lowest value for which stable operation can be obtained. The armature current is varied by control of the field current. The armature current should be varied in about six steps between 125% and 25% of rated current and should include one or two points at very low current. The maximum test current value, traditionally set at 125%, should be obtained from the manufacturer since sometimes stator cooling will not permit operation in excess of 100% rated current without damage. The highest readings should be taken first to secure more uniform stator coil temperatures during the test. Readings of power input (or energy and time), armature current, armature voltage, and field current should be taken. The temperature of the stator conductors should be taken by thermometers located in several places on the end windings, or by embedded detectors in machines so equipped (see 4.2.8).

4.3.14 Total loss curve

Figure 4.9 shows data from a typical test using the electric-input method. The curve of total loss is composed of friction and windage, core, and short-circuit losses. This may be extrapolated (dotted line) to zero current by first plotting separately the total loss against the square of the armature current and extrapolating this separate curve to zero current as shown in figure 4.8. The total loss at zero current is the sum of core loss plus friction and windage loss. By subtracting this sum from the total loss at any armature current, the short-circuit loss for that armature current is obtained. The short-circuit loss is the sum of the $I^2 R_a$ and stray-load losses. The stray-load loss is then determined by subtracting the armature $I^2 R_a$ loss calculated for the temperature of the winding during the test.

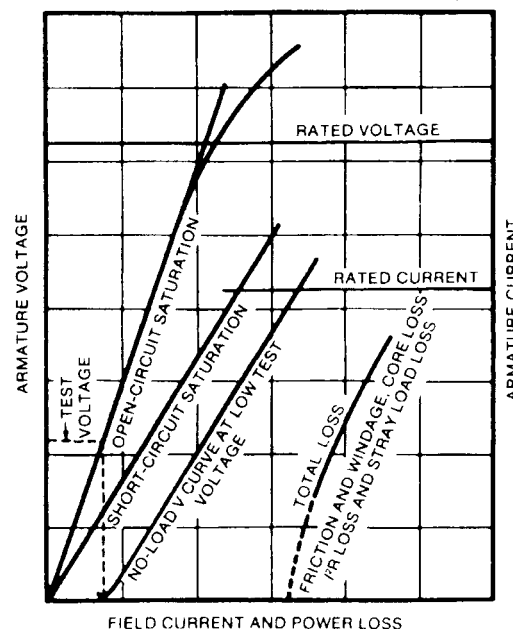


Figure 4.9—Curves from electric-input method

4.3.15 Short-circuit saturation curve

The curve resulting from the plotting of armature current versus field current as obtained in 4.3.13 and 4.3.14 is the overexcited part of a zero-power-factor V curve. This curve, extended to zero armature current, should give the same field current as the no-load saturation curve at the voltage at which the test was made. A straight line passing through the origin, parallel to this part of the V curve, is approximately the same as the short-circuit saturation curve.

4.4 Retardation method for losses and saturation curves

4.4.1 General

The retardation method of loss determination was developed in connection with the testing of large hydraulic-turbine-driven generators after installation (see IEEE Std 492-1974). The availability of electronic counters makes it applicable to other machines. It is also useful in factory tests where use of a separate driving motor is not practical or convenient.

The method is based on the relationship between the rate of deceleration of a rotating mass, its weight and radius of gyration, and the power loss tending to decelerate it.

Machine losses are obtained from retardation tests made under conditions such that the power tending to decelerate the machine is the loss to be determined. Allowances shall be made for any apparatus connected to the machine during these tests.

Knowing the rate of deceleration, the loss can be determined by the following equation:

$$\text{Loss in kilowatts} = \left(\frac{\pi}{30}\right)^2 \cdot \frac{1}{1000} \cdot J \cdot n \cdot \frac{dn}{dt} \quad (4-2)$$

where

$(\pi/30)$ is the conversion from RPM to radian/s

n is the rotational speed, r/min

dn/dt is the rate of deceleration as determined from the slope of speed-time curve at n , (r/min)/s

J is the moment of inertia of rotating parts, $\text{kg} \cdot \text{m}^2$

Procedures will be given for obtaining speed-time curves and determining deceleration rates, and for obtaining the moment of inertia (J) of the rotating parts. Reference should be made to 4.1 for general comments applicable to this method of loss determination.

4.4.2 Friction and windage loss

When a generator (or motor) is permitted to decelerate without any excitation and with its terminals open-circuited, the power tending to decelerate it is the friction and windage loss. The voltage at the machine terminals should first 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.

4.4.3 Open-circuit core loss

The total open-circuit loss is obtained by providing constant excitation during a retardation test with the armature terminals open-circuited. This test should be made at several values of excitation in order to make a plot of open-circuit core loss versus voltage at rated speed. By subtracting the friction and windage loss (see 4.4.2) from the total open-circuit loss for each test, the open-circuit core loss is obtained.

4.4.4 Short-circuit loss and stray-load loss

The short-circuit loss plus friction and windage loss is obtained by providing constant excitation during a retardation test with the armature terminals short-circuited. This test should be made at several values of excitation in order to make a plot of short-circuit loss and stray-load loss versus armature current at rated speed. By subtracting the friction and windage loss (see 4.4.2) the short-circuit loss for each test is obtained. By subtracting the I^2R_a loss (calculated at the temperature of the winding) from the short-circuit loss for each test, the stray-load loss is obtained.

4.4.5 Effect of connected apparatus

Apparatus connected either mechanically or electrically to the machine under test may affect the results, and should be taken into account. Some circumstances encountered commonly are commented on in the following subclauses.

4.4.5.1 Power transformers

The machine should be disconnected from its power transformers during the test, or the transformer losses should be evaluated for the test conditions and taken into account properly when determining the losses of the machine under test. Measuring the transformer losses is difficult because either the current or the voltage is very low, and the power factor is very low. Loss values of the transformer often may be obtained from the manufacturer of the transformer, either from a test of the particular unit or from tests of similar units. The preferred method of test is to disconnect the transformer whenever possible, particularly for short-circuit tests.

4.4.5.2 Exciters

It is preferred that the machine under test be excited from a separate source because this eliminates both the need for correcting the results for exciter loss and the problem of maintaining constant excitation during the deceleration. If a direct-connected exciter must be used, it should be adjusted continuously to maintain constant excitation on the machine under test, and its power input should be deducted in calculating the results.

4.4.5.3 Other mechanically-connected apparatus

The inertia J of the prime mover and any other mechanically-connected apparatus should be added to that of the machine under test when calculating losses. If the apparatus is connected through a gear or belt so that its speed is different from that of the machine under test, its inertia J should be multiplied by the square of the ratio of its speed to the machine speed before adding it to the machine inertia.

4.4.6 Test procedures

Since the loss at rated speed is of principal interest, data are obtained which will enable determination of the rate of deceleration at rated speed. The machine under test is started, and operated at approximately rated speed until its bearing temperatures become constant. If the unit is a hydraulic-turbine-driven generator, its turbine should be uncoupled, but if this is not possible it should be dewatered (see 4.1.7 and 4.1.8). The unit is then brought to approximately 10% overspeed, and disconnected from its power source and allowed to decelerate. During the deceleration period, the conditions of the armature and field windings of the machine under test are established to suit the loss test being conducted. Deceleration rate is measured so that it can be determined at rated speed.

When testing hydraulic-turbine-driven generators, it is common that the machine under test is driven electrically from another unit. Since many test runs must be made to obtain several points on the core-loss and stray-load-loss curves as well as several measurements of friction and windage, much testing time can be saved by developing an efficient operating sequence. As soon as the machine under test is separated from the driving machine, the field on the driving machine is reduced practically to zero and the driving machine is brought down to approximately 75% speed, where it is left idling. When the machine under test approaches the speed of the driving machine, its field is reduced essentially to zero. The two machines are then connected together without excitation, and field is built up gradually on the driving unit. As the machines begin to pull into synchronism, the field on the machine under test should be built up.

Both units can then be brought up to the desired overspeed for another test run. To accomplish this resynchronization, the driving machine should be running at lower frequency than the machine under test when the two machines are connected together again. Modifications of this procedure can be used depending upon machine characteristics and the testing experience of the people involved.

After the test machine is left free to decelerate, a well-planned procedure is desirable, especially for the short-circuited runs where it is necessary to remove excitation from the test machine, close the armature short-circuiting switches, and apply the proper value of field current before the speed has decreased too much.

4.4.7 When overspeed cannot be obtained

If the retardation curves must be taken below rated speed, that is, if the machine is brought up to speed from a normal-frequency alternating-current source, the losses should be calculated at several speeds below normal up to as near normal as possible for each condition of excitation, and curves of loss versus speed should be plotted and extrapolated to normal speed to get an approximate value of the loss at normal speed.

4.4.8 When low-voltage switchgear is omitted

In some station switching arrangements, low-voltage switchgear is omitted and the only possible low-voltage connection between machines is through disconnecting switches on the low-voltage transfer bus. In such a setup, it is possible to make retardation tests as outlined above by bringing the machine up to approximately 15% overspeed, opening both field switches, and after allowing a suitable time (5–10 s) for the field to decay, opening the disconnecting switches and closing the field on the machine under test with the field voltage adjusted to give the required field current. Sufficient overspeed should be allowed to permit the field current to rise to its steady value before the machine drops to 10% overspeed. This time is longer when measuring open-circuit losses than it is when measuring short-circuit losses, due to the effect of the difference between the open-circuit and short-circuit time constant on the time required to build up excitation for the test. However, since additional switching is required to close the short circuit on the machine for the short-circuit losses, the initial overspeed required for both conditions is about the same. The effect of the build-up of the field is quite noticeable in the initial portion of the retardation curve and readings from this part should not be used for determining losses.

4.4.9 Methods of measuring deceleration

Three methods of measuring deceleration are covered in this standard: speed-time, dc generator, and electronic counter.

4.4.9.1 Method 1. Speed-time

The speed-time method consists of obtaining data for a curve of machine speed versus time. The following three procedures can be used for recording speed-time relations.

- a) *Tachometer.* This method is especially applicable to machines of large inertia. Simultaneous readings of an accurate tachometer and a stop watch are recorded. Since the stop watch can be read with greater accuracy than the tachometer, the signal to read the stop watch should be given at convenient full intervals on the tachometer scale.
- b) *Speed recorder.* A pen actuated by a tachometer is used to make an automatic plot of speed versus time on a chart which moves at a known constant speed. A button should be provided to cause *pips* in the r/min trace to indicate starting time, stopping time, and time of any desired intermediate readings.
- c) *Photographic/video.* A continuously running watch and an electric tachometer are simultaneously recorded by a motion-picture or video camera. (See ASME PTC 18-1949, for additional details.)

A series of speed-time curves should be plotted from the test data. Figure 4.10 shows typical retardation curves. For each curve, the loss at any speed may be calculated by means of equation 4-2.

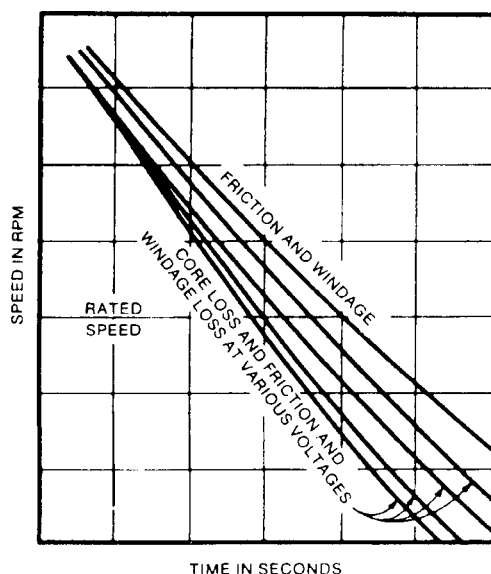


Figure 4.10—Typical retardation curves

The loss may be determined from several points on the speed-time curve and the slope of a tangent at each point using equation 4-2. The values of loss may then be plotted versus speed and a smooth curve drawn through these points. The loss at rated speed is then read directly from this curve.

It may be convenient to determine the slope of the speed-time curve at each of several points spaced along the curve, above and below rated speed. These slopes are then plotted as a function of speed, and the best smooth curve drawn through them. The slope at rated speed is read from this curve and used in equation 4-2 to calculate loss at rated speed.

If the speed-time curve is carefully drawn and if the points lie on a smooth curve, finding the slope at rated speed and using equation 4-2 can give satisfactory results.

Another method for obtaining the loss from a speed-time curve is to choose speeds n_1 and n_2 , which are A revolutions per minute respectively above and below rated speed, n_s (where $n_1 = n_s + A$, and $n_2 = n_s - A$). The speed-time curve should be reasonably straight between speeds n_1 and n_2 . The values of time t_1 and t_2 in seconds, are read from the speed-time curve respectively at n_1 and n_2 . The loss is then calculated using equation 4-3.

$$\text{Loss in kilowatts} = \left(\frac{\pi}{30}\right)^2 \cdot \frac{1}{1000} \cdot J \cdot n_s \cdot \frac{2A}{t_2 - t_1} \quad (4-3)$$

where

- $(\pi/30)$ is the conversion from RPM to radian/s
- n_s is the synchronous speed, r/min
- A is the speed increment above and below n_2 , r/min
- $t_2 - t_1$ is the time in seconds as determined from the speed-time curve to decelerate from $(n_s + A)$ to $(n_s - A)$
- J is the moment of inertia of rotating parts, $\text{kg} \cdot \text{m}^2$

4.4.9.2 Method 2. Direct-current generator

This method is a refinement of method 1, in which a more accurate speed determination is obtained. If the machine under test has a direct-connected exciter, it may be used to provide the speed indication. If there is no direct-connected exciter, a small direct-current generator should be set up and coupled or belted to the generator shaft. Coupling is preferable as it avoids the uncertainty of belt slip. If a belt must be used, checks described later should be used to make sure that no errors are occurring from belt slip. The dc machine should be excited from a constant-voltage battery (No. 1). Suitable wiring connections should be made so that the voltage of the direct-current generator will be opposed to the voltage of a second battery (No. 2). (See figure 4.11 for a typical diagram of connections.)

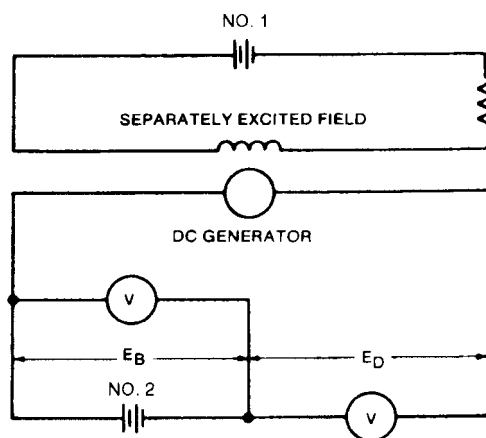


Figure 4.11—Speed measurement by dc generator

Battery number 1 should have an output voltage about 1/10 or less of the rated voltage of the field circuit of the direct-current generator so the I^2R loss in the separately excited field will not materially change the temperature and therefore the resistance thereof.

Two voltmeters should be chosen—one to read the voltage of battery number 2 at approximately full scale and the other, with about 1/5 this range, to read the difference between the voltages of battery number 2 and the direct-current generator. The voltage of battery number 2 should be such that the differential voltage between it and the direct-current generator is approximately zero at 10% under the rated speed of the machine under test. The voltage of the differential voltmeter will hence be approximately full scale at 10% overspeed. The speed is proportional to the sum of the battery and differential voltages. The rate of deceleration is derived as follows:

Let

- K = proportionality factor relating speed to voltage (it is not actually necessary to evaluate K)
- E_B = voltage of battery number 2
- E_D = differential voltage
- n_c = known speed (in r/min) at which losses are to be determined (usually rated speed)
- E_{DC} = differential voltage at speed n_c

$$n_c = K(E_{DC} + E_B) \text{ or } K = \frac{n_c}{E_{DC} + E_B}$$

$$n = K(E_D + E_B) \text{ speed at test point}$$

$$\frac{dn}{dt} = \frac{KdE_D}{dt} = \frac{n_c}{E_{DC} + E_B} \frac{dE_D}{dt}$$

$$\frac{dE_D}{dt} = \text{rate or decrease of differential voltage, V/s}$$

$$\frac{dn}{dt} = \text{rate of deceleration, (r/min)/s}$$

The speed n_c at which the losses are desired (usually rated speed) should be checked under steady conditions by comparison with known system frequency or by an accurate tachometer or frequency meter. The value E_{DC} of the differential voltage at this speed should be recorded. Then the speed should be brought to approximately 10% overspeed, test conditions established in the machine, and reading of E_D taken at equal time intervals during the retardation. The use of uniform time intervals assists in plotting and checking the results. The value of E_D versus time in seconds should be plotted and a smooth curve drawn through the points. The slope of this curve (dE_D/dt) at the point where $E_D = E_{DC}$ is used to determine the loss. The loss is then calculated using equation 4-4 as follows:

$$\text{Loss in kilowatts} = \left(\frac{\pi}{30}\right)^2 \cdot \frac{1}{1000} \cdot J \cdot \frac{n_c^2}{(E_{DC} + E_B)} \cdot \frac{dE_D}{dt} \quad (4-4)$$

where

$$\begin{aligned} \pi/30 & \text{ is the conversion from RPM to radian/s} \\ J & \text{ is the moment of inertia of rotating parts, kg} \cdot \text{m}^2 \end{aligned}$$

The voltage of battery number 2 and the differential voltage E_{DC} at speed n_c should be checked at least once an hour to ensure that a change in ambient temperature or discharge of the battery has not changed their values. A useful check after making the open-circuit core-loss test (see 4.4.3) is to plot E_D against the alternating-current generator voltage. This curve should be a straight line. The value of differential voltage E_D should be $(-E_B)$ when the curve is projected to zero alternating-current generator voltage. This check should always be made if a belted exciter or belted direct-current generator is used, to ensure that the speed of the belted machine is proportional to that of the machine under test. If this is not the case, the projected line will not correspond to $(-E_B)$ at zero alternating-current generator voltage. Likewise, the differential voltmeter should be checked carefully against the battery voltmeter or the same condition will result.

4.4.9.3 Method 3. Electronic counter

High-speed electronic interval counters make it possible to record the time interval required for the rotor to make a predetermined number of revolutions. A variety of counters are available, each of which requires an appropriate procedure for its use and for the analysis of speed and rate of deceleration.

In the following example, it is assumed that a counter measures the time interval t_1 , required for n_r revolutions, then after a second group of n_r revolutions, the counter measures the time interval t_3 required for a third group of n_r revolutions, etc. The counter continues to measure the time duration of alternate groups of n_r revolutions of the rotor of the machine being tested. From a single retardation test, then, a list of intervals, t_1, t_3, t_5, t_7 , etc., would be obtained. The average speed n for time intervals t_1 and t_3 for example, and the average rate of deceleration dn/dt are calculated by equations 4-5 and 4-6.

$$n = \frac{30 n_r (t_1 + t_3)}{t_1 t_3} \quad (4-5)$$

$$\frac{dn}{dt} = \frac{60 n_r (t_3 - t_1)}{t_1 t_3 (t_1 + t_3)} \quad (4-6)$$