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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.

The membership of the working group at the time of approval was as follows:

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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 120-1989 [1]. 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.

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[1] The 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).

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

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

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

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

[6] IEEE 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 .

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[7] IEEE 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 I. 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:

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

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 ±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.

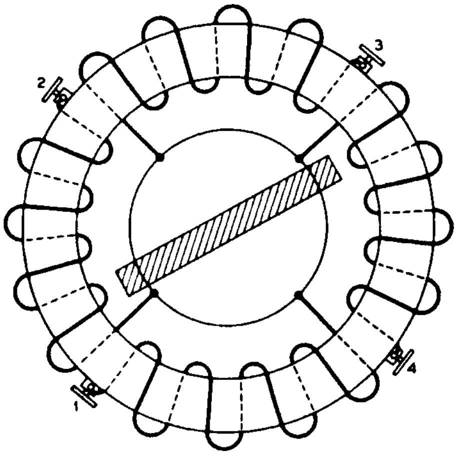


Figure 3.1—Phase-sequence instrument

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.

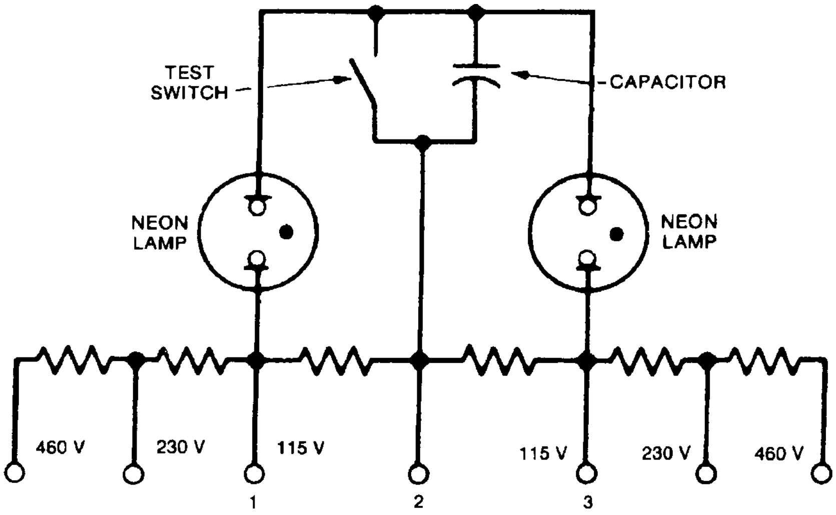


Figure 3.2—Neon-lamp phase-sequence indicator

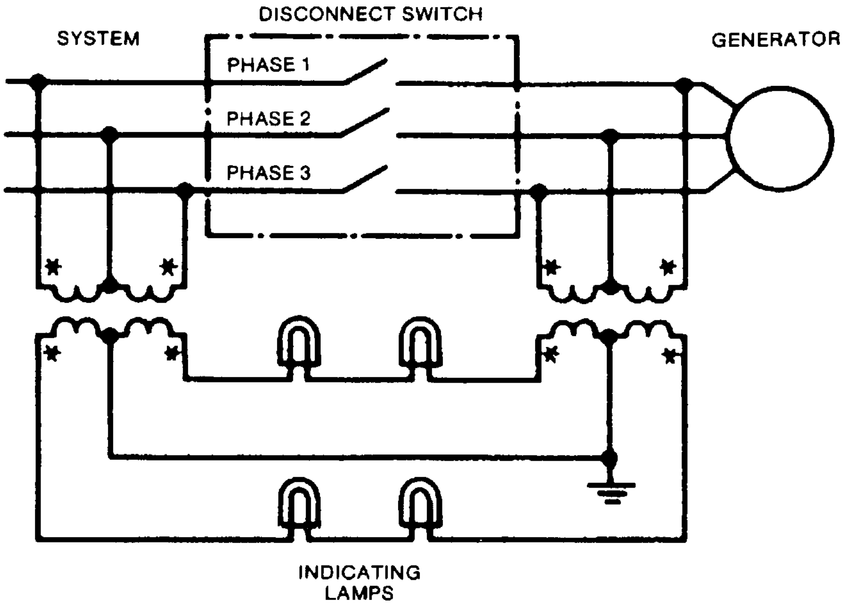


Figure 3.3—Connection diagram for comparing the phase-sequence of a generator with that of a system by indicating the voltage across an open disconnect switch

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:

$$TIF = \frac{E_{TIF}}{E_{rms}} \tag{3-2}$$

where

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

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 nth 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 nth 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.

$$\text{Residual TIF} = \frac{E_{TIF}}{3E_{rms}} \tag{3-4}$$

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:

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

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.

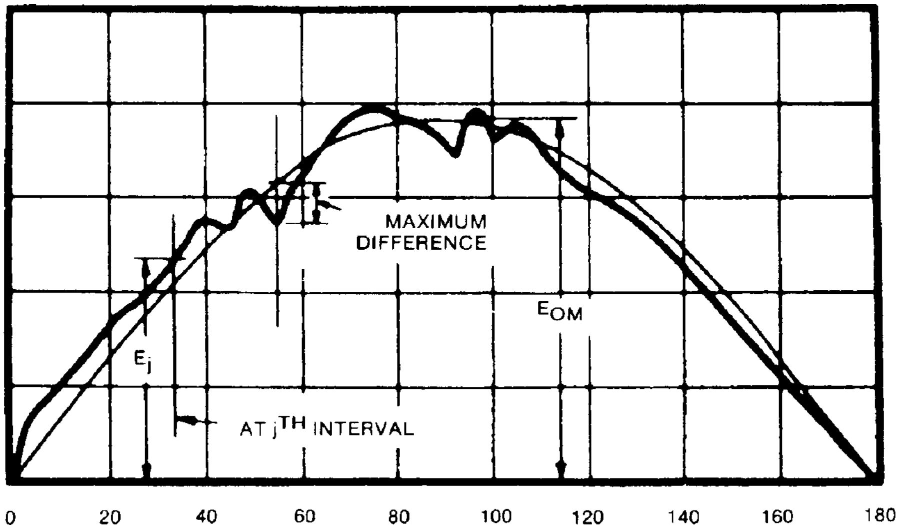


Figure 3.4—Plot of wave for deviation factor

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.

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

where

E_j equals an instantaneous value of the voltage wave at the jth 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.

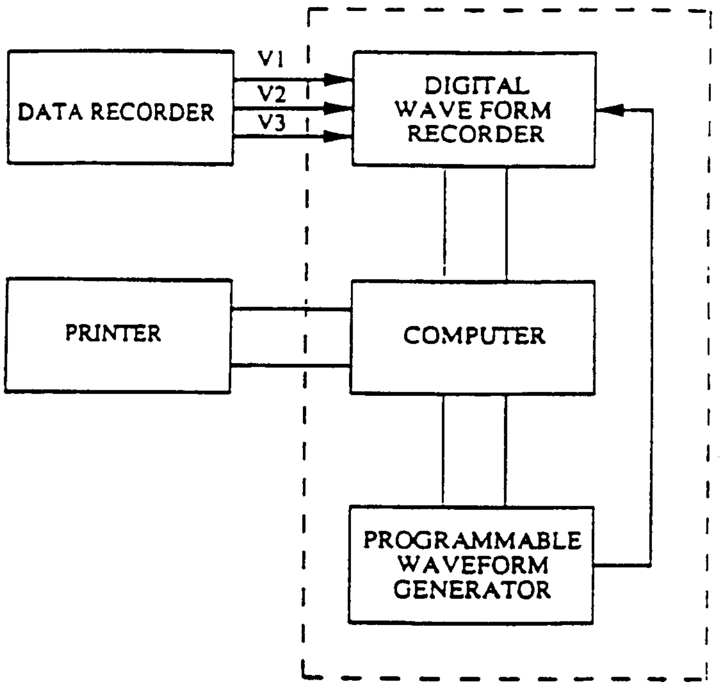


Figure 3.5—Block diagram of the instrumentation used in waveform analysis

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.

$$F_{DEV} = \frac{\Delta E}{E_{OM}} \tag{3-7}$$

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:

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

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 $j = 1, 2,\ldots,N$

The rms value of the input waveform is given by

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

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

$$E_{OM} = \sqrt{2} \cdot E_{rms} \tag{3-10}$$

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

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

3.12.3 Fourier analysis

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

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

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

$$E_n = \sqrt{a_n^2 + b_n^2} \tag{3-14}$$

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

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

$$F_{Di} = \frac{\sqrt{\Sigma E_n^2}}{E_{rms}} \tag{3-16}$$

where

ΣE_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

$$F_{Di} = \frac{\sqrt{\Sigma E_n^2}}{E_{OM}} \tag{3-17}$$

n = 2, 3,…, 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:

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

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 $\mathrm{lb_f \cdot ft}$

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.

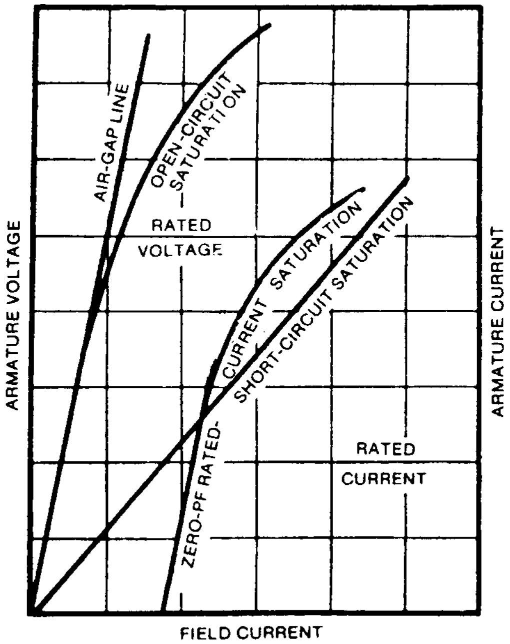


Figure 4.1—Saturation curves

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.

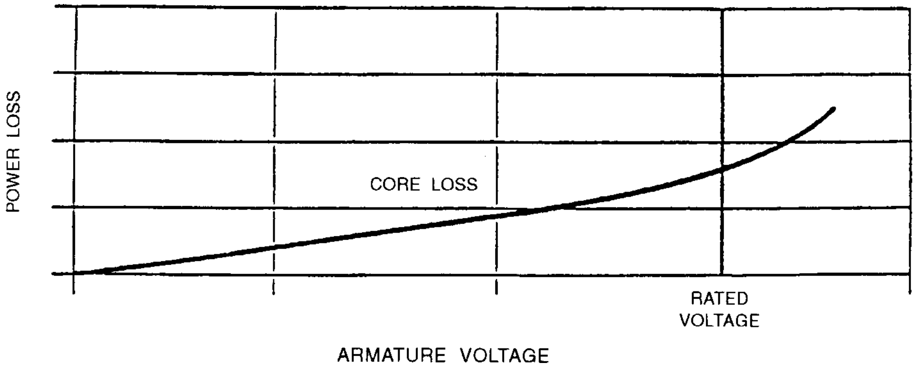


Figure 4.2—Core loss curve (power loss vs. armature voltage)

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.

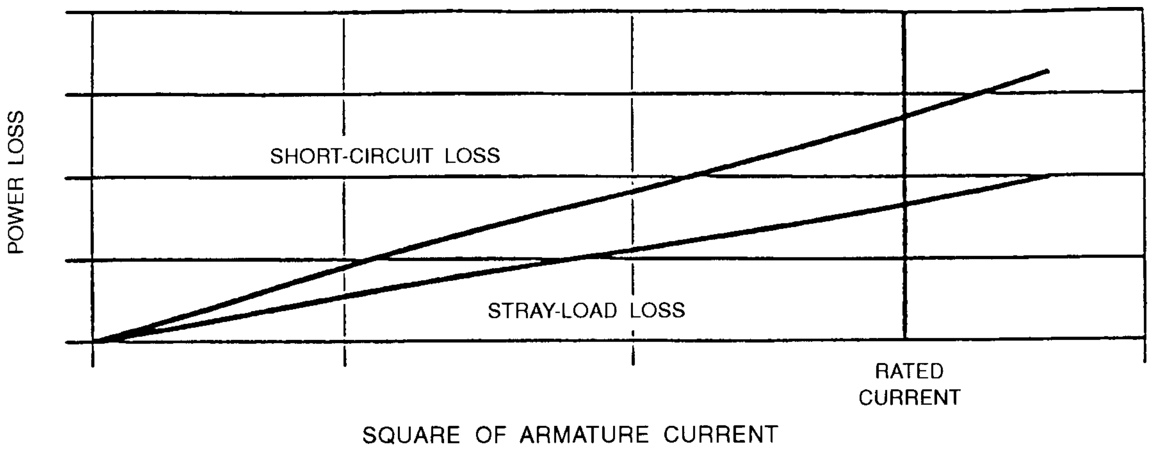


Figure 4.3—Short-circuit loss and stray-load loss curves

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.

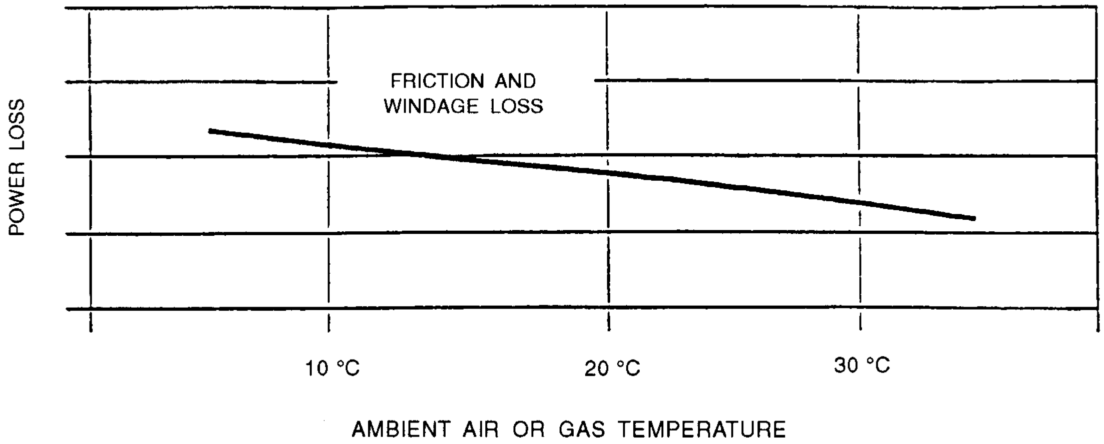


Figure 4.4—Plot of windage losses against temperature

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.

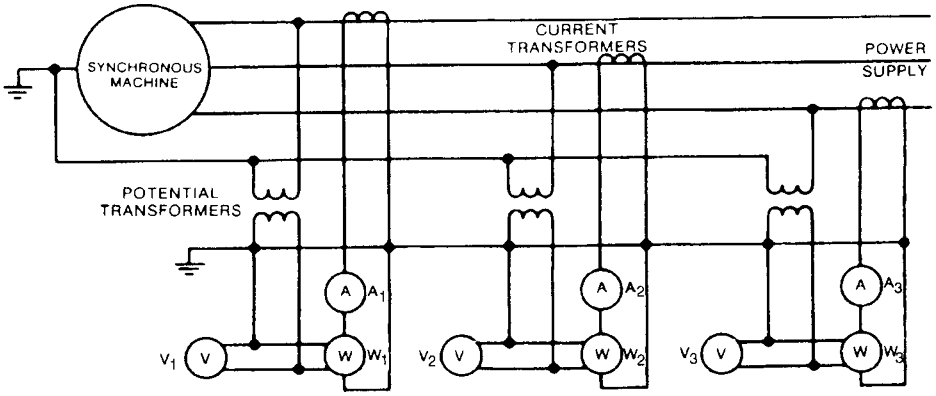


Figure 4.5—Connection diagram—Three-wattmeter method of measuring power

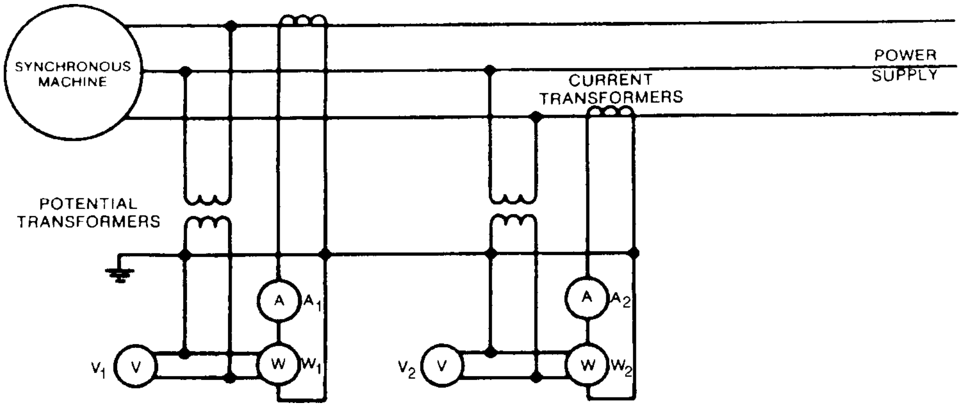


Figure 4.6—Connection diagram—Two-wattmeter method of measuring power

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.

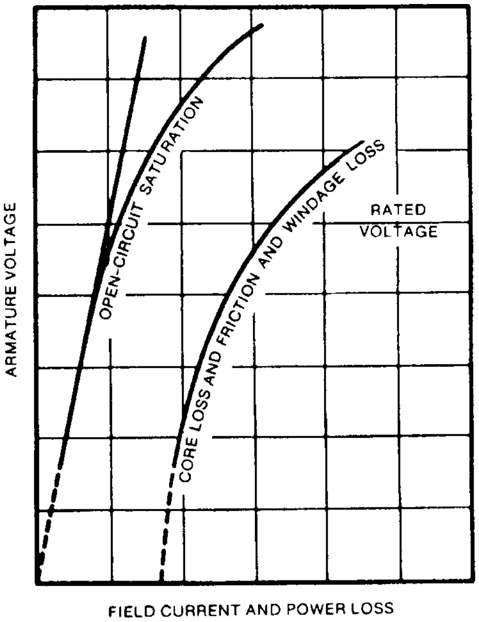


Figure 4.7—Open-circuit saturation and core loss curves by electric-input method

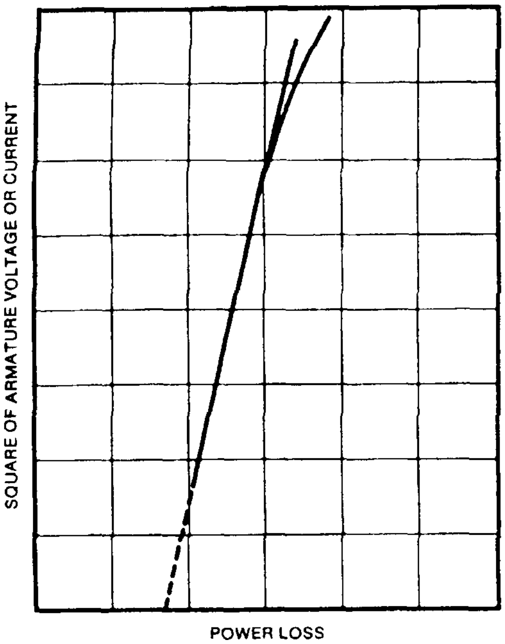


Figure 4.8—Construction curves for extrapolating loss curves from electric-input method

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^2R_a and stray-load losses. The stray-load loss is then determined by subtracting the armature I^2R_a loss calculated for the temperature of the winding during the test.

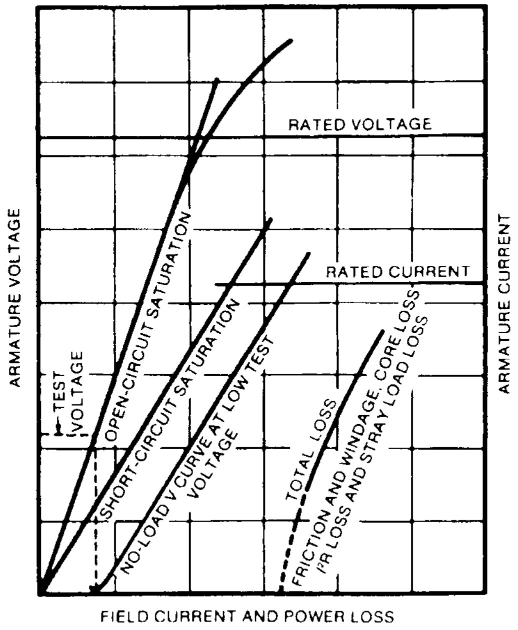


Figure 4.9—Curves from electric-input method

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:

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

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.

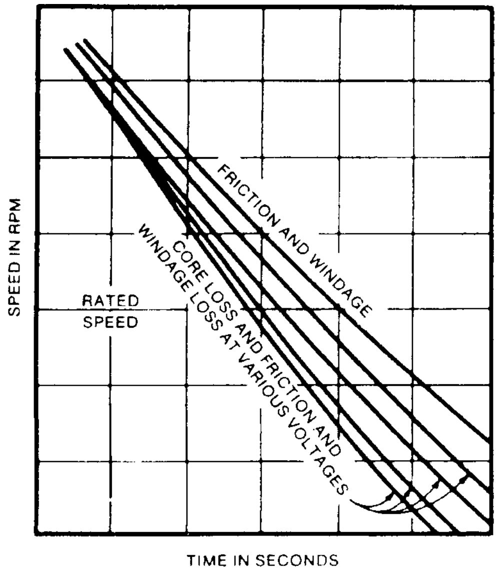


Figure 4.10—Typical retardation curves

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 $n_1 = n_s + \mathrm{A}$, and $n_2 = n_s - \mathrm{A}$). 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.

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

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 $(n_s + \mathrm{A})$ to $(n_s - \mathrm{A})$
J	is the moment of inertia of rotating parts, $\mathrm{kg} \cdot \mathrm{m}^2$

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.)

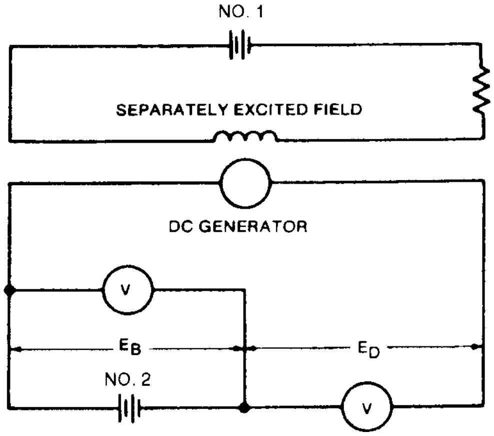


Figure 4.11—Speed measurement by dc generator

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

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

n= $K(E_D + E_B)$ speed at test point

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

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

$\frac{dn}{dt}$ = 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:

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

where

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

J is the moment of inertia of rotating parts, kg · m^2

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.

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

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

where

n	is the speed in r/min
dn/dt	is the angular deceleration, (r/min)/s
t_1	is the time for the first group of n_r revolutions of the rotor, seconds
t_3	is the time for the third group of n_r revolutions of the rotor, seconds
n_r	is the number of revolutions of the rotor in each of the intervals t_1, t_3, and in the intervening interval

The average speed, n, and average rate of deceleration, dn/dt, for any two intervals, such as t_s and t_7, would be obtained by substituting t_s and t_7 for t_1, and t_3 in equations 4-5 and 4-6.

By plotting the deceleration as a function of speed, the value can be obtained by interpolation for any desired speed. Substitution of n and dn/dt in equation 4-2 determines the loss.

4.4.10 Open-circuit and short-circuit saturation curves

Saturation curves should be obtained while driving the unit at rated speed if possible (see 4.2.4, 4.2.7, 4.3.12, and 4.3.13). The open-circuit saturation curve can be checked by data from the open-circuit retardation tests, 4.4.3, using readings of armature voltage, field current, and speed. The voltage readings for each test are plotted vs. speed. The value of voltage at rated speed constitutes a point on the saturation curve when plotted against its corresponding field current.

The short-circuit saturation curve can likewise be checked by data from the short-circuit retardation tests (see 4.4.4); but in these tests it will be found that the armature current is practically constant through a considerable range in speed above and below rated speed, eliminating the need for correcting the armature currents to rated-speed values for use in the saturation curve.

4.4.11 Method 1. Determination of *J*

The value of moment of inertia (J) of the rotor is customarily obtained from the manufacturer, who can calculate the value.

4.4.12 Method 2. Determination of *J*

The friction and windage loss should first be determined by the separate-driving-motor method (see 4.2.7). The value of J is calculated from the retardation curve of the unexcited machine and the known value of friction and windage loss, using equation 4-2.

4.4.13 Method 3. Determination of *J*

The machine is run as an unloaded synchronous motor at normal speed at approximately unity power factor (see 4.3.11). The power input is measured; this includes friction and windage, core, and copper losses. The copper loss should be subtracted to obtain the loss which will be present on an open-circuit retardation test at the same field current. A retardation test at the same field current with the armature open-circuited will then give the necessary date to be substituted in equation 4-1 with the known losses, to obtain the J.

4.4.14 Method 4. Determination of *J*

The value of J may be determined experimentally by taking a retardation run with the machine unexcited, and another run with the machine unexcited, but with the direct-connected exciter loaded on a variable resistor, maintaining constant power output. From the measured load and the known exciter losses, the value of J can be calculated from the two retardation curves.

4.4.15 Method 5. Determination of *J*

When the value of J is to be utilized for the determination of losses (see 4.4) or the determination of torque (see 7.3.3), the physical pendulum method described below should be used for increased accuracy.

It is possible to determine the value of J by the following procedure: the rotor is supported with its journal placed in horizontal bearings with a bore two or three times as large as the diameter of the journals. In case the two journals are not of the same diameter, it is necessary to equip the smaller journal with a close-fitting bushing to build it up to the size of the larger. The rotor should be displaced and allowed to rock freely in the bearings and the time required to make several oscillations should be accurately measured with a stop watch. The radius of gyration (k) in SI units may then be calculated by means of the following equation:

$$k = R_2\sqrt{\frac{gt^2}{4\pi^2(R_1 - R_2)} - 1} \qquad (4\text{-}7)$$

where

k	is the radius of gyration in meters
R_1	is the radius of bearings in meters
R_2	is the radius of journals in meters
t	is the time of one cycle of oscillation, in seconds
g	is the acceleration due to gravity = 9.807 $\mathrm{m/(s)^2}$

then

$$J \quad \text{equals } Mk^2 \qquad (4\text{-}8)$$

where

M	is the mass of the rotor in kg

Alternatively, a balanced rotor of known weight, supported by its shaft resting on two horizontal rails in such a way that its axis is level, becomes a physical (compound) pendulum when an unbalance is rigidly attached to its perimeter. In case the two journals are not the same diameter, it is necessary to equip the small journal with a close-fitting bushing to build it up to the size of the larger. When the geometry, mass, and position of such unbalance are known, the period of oscillation should be accurately measured and the moment of inertia J may then be calculated by means of the following equation:

$$J = \frac{g}{4\pi^2}t^2 \cdot Ub - Ma^2 - U(b - a)^2 \qquad (4\text{-}9)$$

where

J	is the moment of inertia (gravity) of rotating parts, $\mathrm{kg \cdot m^2}$
g	is the acceleration due to gravity, 9.807 $\mathrm{m/s^2}$
a	is the radius of bearing journal, m
b	is the distance from rotor axis to centroid of unbalance, in meters
U	is the mass of added unbalance, kg
M	is the mass of the balanced rotor, kg
t	is the time of one cycle of oscillation, s

4.5 Calorimetric method for losses

4.5.1 Machines with water coolers

This method can be used on machines with water coolers in which the ventilating medium circulates in a closed system. It is based on the fact that the loss is equal to the heat added to the water plus the heat lost by radiation and convection. The equation for the loss absorbed by the water is as follows:

$$\text{Loss in kilowatts} = 0.264(t_h - t_c)Q \qquad (4\text{-}10)$$

where

t_h is the temperature of water leaving cooler, °C
t_c is the temperature of water entering cooler, °C
Q is the rate of water flow in U.S. gallons per minute (1 U.S. gallon = 3.785 liters)

If the bearings are separately cooled, or if they are outside the ventilating medium enclosure, their loss should be determined separately and added to the other losses. The loss in bearings from which heat is removed by circulated water or oil can be calculated from the circulated water quantity and water temperature rise from equation 4-10, or from the quantity of circulated oil and oil temperature rise as follows:

$$\text{Loss in kilowatts} = 0.264c_pGQ(t_h - t_c) \qquad (4\text{-}11)$$

where

c_p is the specific heat of the oil (relative to water)
G is the specific gravity of the oil (relative to water); heat and gravity evaluated at the average temperatures t_h and t_c
t_h is the temperature of oil leaving bearing, °C
t_c is the temperature of oil entering bearing, °C
Q is the rate of oil flow, U.S. gallons per minute

Because the difference between t_h and t_c is usually small, it is very important that all temperature measurements be accurate to within 0.1 °C. Properly constructed thermometer wells should be used (see IEEE Std 119-1974). In temporary piping a hole may be drilled so that the thermometer can be inserted directly into the water. The thermometers should be placed as close to the machine housing as possible to minimize the effect of loss of heat from the pipes by radiation. Also, it is well to run half of the test with the thermometers interchanged so as to cancel any difference in thermometers.

The rate of flow of water can be measured by a calibrated flowmeter, or, if this is not available, the total amount of water used in a given time can be collected and weighed. The conditions of the test should be held as constant as possible.

The heat lost by radiation and convection may be particularly important in small machines or in large machines having a relatively large amount of exposed surface with operating temperatures appreciably above ambient. The heat loss may be estimated by the following approximate equation:

$$\text{Loss} = 0.008(t_r - t_a)\ \text{W/in}^2 \qquad (\ 4\text{-}12)$$

where

t_r is the average temperature of the entire radiating surface, °C
t_a is the ambient temperature, °C

If the calculated radiation and convection loss exceeds 5% of the total full-load losses, it is desirable to use one of the other methods of loss determination for better accuracy.

4.6 Efficiency

4.6.1 Method 1. Segregated losses

The conventional efficiency is related to the sum of the segregated losses as follows:

For a generator:

$$\text{Efficiency (\%)} = 100 - \frac{\text{losses} \cdot 100}{(\text{output} + \text{losses})} \tag{4-13}$$

For a motor:

$$\text{Efficiency (\%)} = 100 - \frac{\text{losses} \cdot 100}{\text{input}} \tag{4-14}$$

In the above equations, power output, input, and losses are in the same units. The losses to be included and how to evaluate them are specified in the applicable ANSI C50 standard series and NEMA MG1-1978.

4.6.2 Method 2. Input-output

The efficiency from the input-output method is determined as follows:

$$\text{Efficiency (\%)} = \frac{\text{output}}{\text{input}} \cdot 100 \tag{4-15}$$

Output and input are in the same units.

The preferable method of measuring either input to a generator or output of a motor is to use a dynamometer. Power input or output is obtained from the following equation:

$$\text{Power in kilowatts} = \frac{n \cdot T}{k} \tag{4-16}$$

where

n is the rotational speed, r/min
T is the torque
k is 9549 if T is in·m
K is 7043 if T is $\text{lb}_f \cdot \text{ft}$

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

The electric input to the motor or output of the generator should be carefully measured. The leads to the potential transformers should be connected to the terminals of the machine under test, thereby eliminating the possibility of including voltage drop in the external cable. The instrument readings should be corrected for scale errors, and for errors in ratio and phase angle of the current and potential transformers.

If a dynamometer is not available, the test machine may either be driven by or loaded by an alternating-current or direct-current motor or generator. The efficiency curve of such a machine should be available and its accuracy proved before the machine can be used in input-output tests.

5. Load excitation and voltage regulation

5.1 General

The field current or excitation required to operate a synchronous machine under various steady-state load conditions of apparent power, power factor, and voltage may be obtained by the methods described below. To make these computations the following machine information is required: open-circuit saturation curve, armature resistance, unsaturated direct axis reactance, unsaturated quadrature axis reactance, and the Potier or leakage reactance. Methods for determining the Potier or leakage reactance are described in the following clauses. In some cases the manufacturer may supply the machine constants and the open-circuit saturation curve.

5.2 Test methods

Some of these following methods are part of the parameter requirements for excitation calculations, and are more fully described in other sections or clauses.

a) Open circuit saturation curve (see 4.2.5)
b) Armature resistance (R_a) (see 3.3.1)
c) Direct-axis unsaturated synchronous reactance (X_{du}) (see 10.3.3)
d) Quadrature-axis unsaturated synchronous reactance (X_{qu}) (see 10.4 and 10.4.1)

5.2.1 Armature leakage reactance (X_l)

There are no specific tests for directly determining X_l. (Subclauses 12.3.1 and 12.5.4 gives methods of determining L_{afdu}, and hence L_{adu}, referred to the stator, and also X_{adu}. Thus, $X_l = X_{du} - X_{adu}$.)

L_{afdu} in henries may be obtained from terminal voltage and field current values read from the air-gap line, at rated speed, on open circuit.

Leakage reactance is derived from the calculation of leakage inductance (see IEEE Std 100-1992). It is composed of several elements:

a) slot leakage
b) end connection leakage
c) air gap leakage.

Air gap leakages are sometimes classified by machine designers as "zig-zag" and "belt" leakage. Since the fluxes associated with the air gap leakages are in air, these inductances and reactances in a machine under load are almost constant. Slot leakage fluxes traverse paths in both iron and air. If the iron surrounding the slot is saturated, the magneto-motive force (mmf) associated with the iron path may become significant. Thus, the leakage reactance may not be constant for the whole range of armature currents, especially for short circuit currents. Because the leakage reactance is determined from geometric and physical details usually only available to the designer, the manufacturer is in the best position to provide the leakage reactance value.

5.2.2 Potier reactance from the zero-power-factor test

The Potier reactance is determined from the open-circuit saturation curve and from the rated current zero-power-factor overexcited saturation curve (see 4.2.4 and 4.2.10). Typical curves are plotted in figure 5.1.

The intersection of the zero-power-factor saturation curve with the rated-voltage ordinate locates the point *d*, as shown in figure 5.1. To the left of *d* on the rated-voltage ordinate, the length *ad* is laid off equal to the field current (I_{FSI}) for zero voltage on the zero-power-factor saturation curve. This value of field current also corresponds to that required for rated armature current under sustained short circuit conditions. This is equal to line a′d′ on figure 5.1.

Through *a* the line *ab* is drawn parallel to the air-gap line. The intersection of this line with the actual no-load saturation curve locates the point *b*. The vertical distance *bc* from the point *b* to the rated-voltage ordinate, expressed in per unit, is equal to the product of the per unit Potier reactance, X_p, and per unit armature current. When the armature current is 1.0 p.u., or rated, then the per unit value of *bc* is equal to X_p in per unit.

If the zero-power-factor saturation curve for a current substantially different from rated current is used, an approximate value of X_p may likewise be found by dividing the voltage *bc* in per unit by the value of the armature current (in per unit of rated current), for which the curve is drawn.

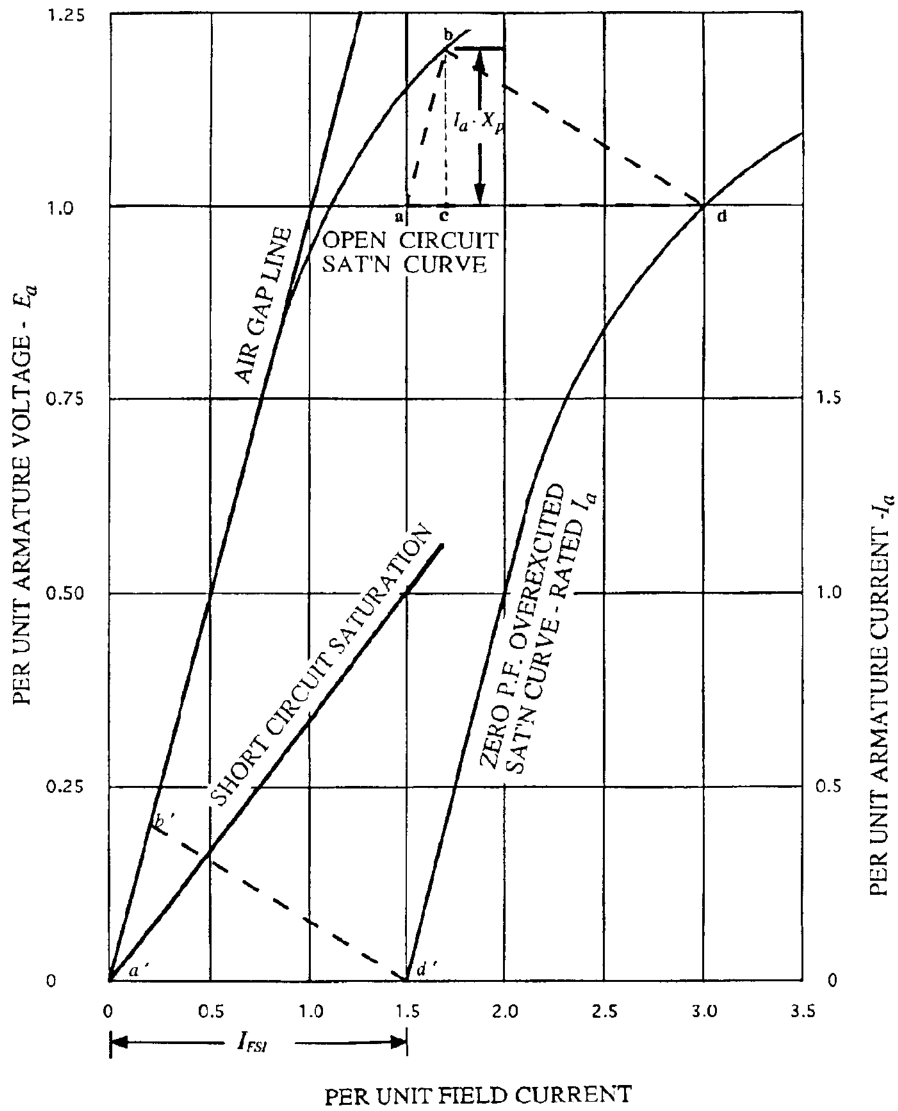


Figure 5.1—Determination of Potier reactance voltage

5.2.3 Potier reactance determination under normal machine operation

This method is most applicable when a test is conducted with the machine operating near full load and with terminal conditions at unity power factor or overexcited.

Readings are taken of armature voltage and current, kilowatts and kilovars (or megawatts and megavars), and field current. The following steps outline the procedure for determining a per unit value of X_p. The unsaturated direct-axis synchronous impedance (X_{du}) must be known, as well as the open circuit saturation curve. For salient pole machines, X_{qu} the quadrature axis synchronous reactance must also be known.

a) Calculate a p.u. value of excitation or p.u. value of field current (I_{FU}) as described in 5.3.3 or 5.3.4.
b) Determine the p.u. value of the *measured* field current I_F by dividing that current by the base value of field current corresponding to 1.0 per unit terminal voltage on the air-gap line of the given open circuit saturation curve. This base value is referred to as I_{FG} (see figure 5.4).

c) Determine $I_{FS} = I_F - I_{FU}$.

d) Using any desired fitting process, determine the p.u. value of E_p (the voltage behind Potier reactance) on the ordinate of, for example, figure 5.4. This shows an open circuit saturation curve and includes the air gap line. By using the difference (I_{FS}) between a voltage value on the open circuit saturation curve and the same voltage value on the air gap line, the actual magnitude of E_p, corresponding to this measured condition for I_{FS}, can be determined. It is represented by a line parallel to the x-axis (or abscissa).

e) The phasor position of E_p relative to E_a is not known; however, figure 5.2 indicates the actual phase relationship between E_a in per unit and I_a in per unit. The power factor angle, ϕ, is also shown. The magnitude of E_p has been determined in step d.

f) The per unit magnitude of the phasor $E_p - E_a$ can now be determined by the following equation:

$$\left|E_p - E_a\right| = \sqrt{E_p^2 - (E_a \cos\phi \pm I_a R_1)^2} - E_a \sin\phi \tag{5-1}$$

NOTE — The phasor $I_a R_1$ is almost always neglected in this calculation. If used, the plus sign is for generator operation, and the minus sign is for motor operation.

Then

$$X_p = \frac{\left|E_p - E_a\right|}{\left|I_a\right|} \tag{5-2}$$

where

I_a is the p.u. value of stator current used in step e).

NOTES:

1 — Strictly speaking, the $I_a X_p$ term in the figure should be an impedance voltage drop. However, in machines larger than 100–200 Kw, the resistance term is usually small enough that it may be neglected. As noted in 4.2.10, the Potier reactance may be determined from one point: the field current required for rated armature current at rated voltage when the machine is in the *over-excited* zero power factor condition. When the field-current exceeds that corresponding to unity power factor at the test voltage, the machine is considered to be *overexcited.* Conversely, when the field current is less than that corresponding to unity power factor, the machine is *underexcited.*

2 — For *overexcited* conditions in a generator the armature current (I_a) lags the terminal voltage (E_a) in phase, and ϕ, the power factor angle, is negative. The opposite is true for an *overexcited* synchronous motor (ϕ is positive), and I_a leads the terminal voltage (E_a) in phase. Refer below to figure 5.3. The convention for positive angle in these phasor diagrams is that phase *rotation* is counter clockwise.

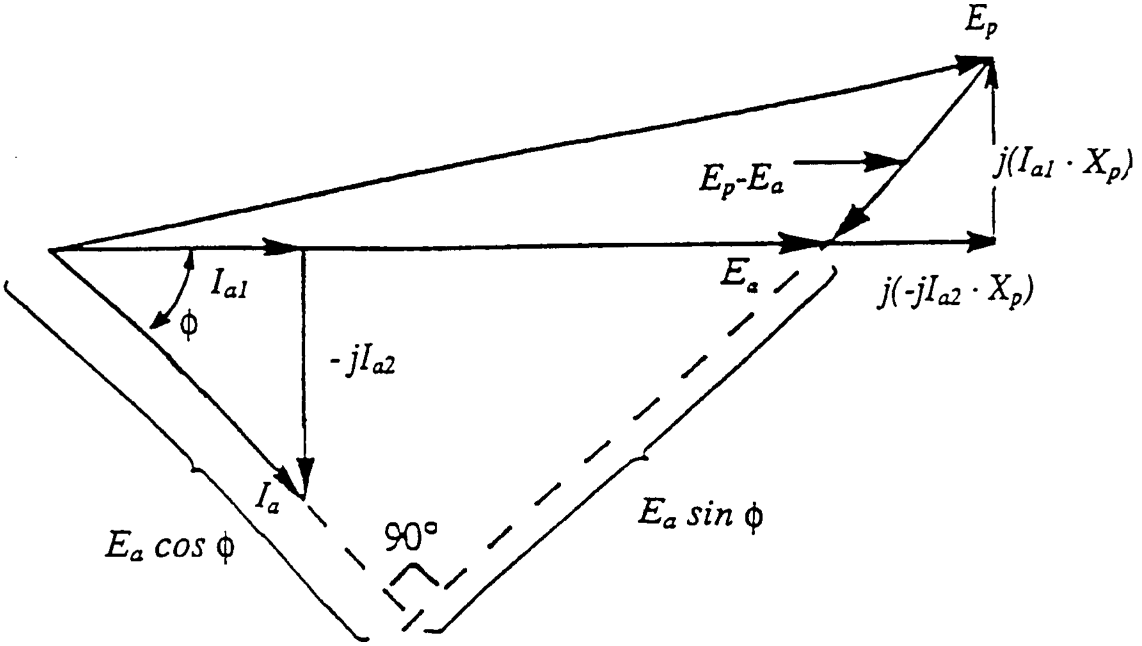


Figure 5.2—Calculation of magnitude of $E_p - E_a$

Theoretically, the leakage and Potier reactances should be the same value. However, because of saturation phenomena, they often differ. Annex 5A provides some background information on the accuracy of using leakage or Potier reactance in the computation of the saturation component of the excitation field current at any load condition.

Since the computation of the efficiency of a synchronous machine may be affected by the method used in computing the field current and, since the efficiency is often a warranty matter, the customer and the manufacturer should agree which reactance (Potier or leakage) will be used to compute the additional field current to compensate for saturation in the machine.

5.3 Load excitation calculation methods for specified machine terminal conditions

The field current for a specified armature current, voltage, and power factor of a synchronous machine may be obtained by any one of several calculation methods. These are all empirical, but seem to give relatively close agreement with measured values of field current.

5.3.1 Load excitation determination at specified operation conditions

The field current for a specified armature current, power factor, and voltage may be obtained directly by loading the machine at the specified conditions and measuring the field current required. This method is not generally applicable to factory tests, particularly on large machines, but may sometimes be employed after installation. When two similar machines are available, the synchronous feedback method of loading can be used in factory testing (see 6.2.2).

5.3.2 Terminology and definitions

The following terminology is used in 5.3.3 and 5.3.4, which describe the steps in the phasor diagram analysis:

E_a	machine terminal voltage (or kilovolts), in per unit.
I_a	machine armature current, in per unit.
E_{QD}	location of a phasor relative to E_a, defining the quadrature magnetic axis of the machine, and hence the phase displacement δ relative to E_a. The symbol, δ is usually calculated in electrical degrees and is positive for a generator and negative for a synchronous motor (E_{QD} is also a fictitious voltage back of X_{qu}).
E_{GU}	generated voltage back of X_{du}, in per unit.
I_{FU}	field current (usually in amperes or sometimes in per unit) required to induce a voltage E_{GU} on the air gap line. (See figure 5.4)
E_p	voltage back of Potier reactance, X_p, in per unit.
R_1	positive sequence resistance. This is generally assumed to be equal to R_a, the stator resistance per phase (see 10.7).
I_{FG}	1.0 per unit field amperes corresponding to 1.0 per unit E_a on the air-gap line.

5.3.3 Phasor diagram analysis—salient-pole machines

The excitation field-current for specified armature voltage, current, and power factor may be computed using one of the phasor diagrams of figure 5.3. The following procedures are used for salient-pole machines

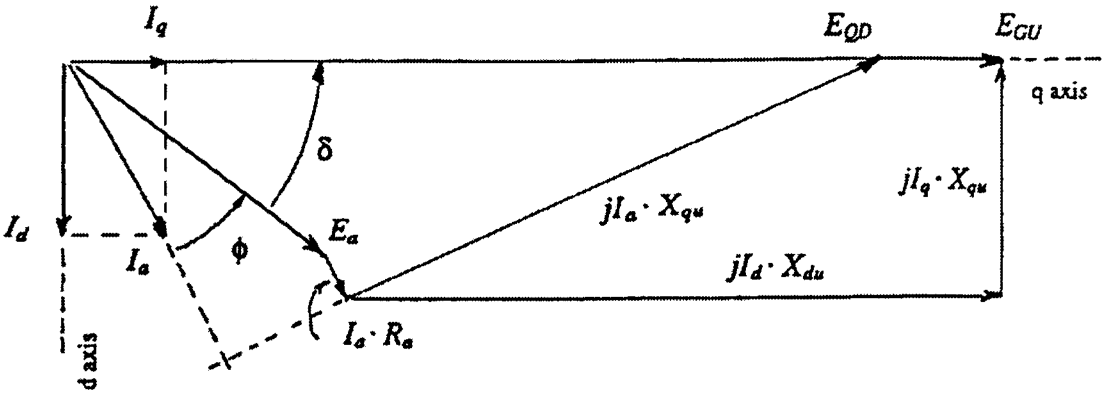
- for generators
- for motors

NOTE — For generator notation the "+" sign should be used when a "±" sign is encountered; conversely the "−" sign should be used for motors).

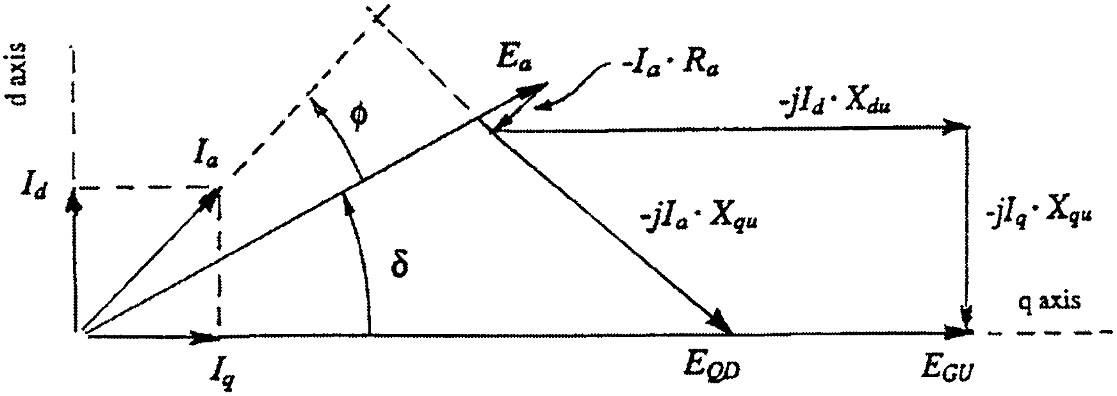
The following steps are indicated for determining the magnitude and phase of E_{GU} and then of I_{FU}. The power factor angle ϕ is positive when I_a leads E_a, and negative when I_a lags E_a. In the following expression, a generator notation is assumed. For the motoring notation, the plus signs become minus signs, and the one minus sign below is changed to a plus sign.

a)
$$\delta = \tan^{-1}\left\{\frac{|I_a|\cdot R_a\cdot\sin\phi + |I_a|\cdot X_{qu}\cdot\cos\phi}{|E_a| + |I_a|\cdot R_a\cdot\cos\phi - |I_a|\cdot X_{qu}\cdot\sin\phi}\right\} \tag{5-3}$$

b)
$$\mathrm{I_d} = |I_a|\sin(\delta-\phi)\,/\underline{\delta - 90} \tag{5-4}$$



a) Generator notation



b) Motor notation

Figure 5.3—Phasor diagrams for calculation of unsaturated generated voltage E_{GU} for salient pole machines

$$I_q = |I_a|\cos(\delta - \phi)\underline{|\delta} \qquad (5\text{-}5)$$

NOTE — The angles of I_d and I_q are shown relative to phasor E_a for a generating mode.

Generator notation is shown for the following phasor equations:

c) $$E_{GU} = E_a + I_a \cdot R_a + jI_q \cdot X_{qu} + jI_d \cdot X_{du} \qquad (5\text{-}6)$$

d) Determine I_{FU} by locating E_{GU} on the air gap line (figure 5.4 is illustrative).

e) Calculate the voltage back of E_p.

$$E_p = E_a + I_a \cdot R_a + jI_a \cdot X_p \qquad (5\text{-}7)$$

For motor notation, all the plus signs in equations 5-6 and 5-7 become minus signs.

f) Find the saturation increment, I_{FS}, the *difference* between the field current value required to induce E_p on the air gap line, and that value of field current corresponding to E_p on the open circuit saturation curve (see figure 5.4).

g) I_F, the total field current, including the effects of saturation, is equal to $I_{FU} + I_{FS}$.

A numerical example is given in annex 5B.

5.3.4 Phasor diagram analysis—cylindrical rotor machines

The procedure is simpler since $X_{qu} = X_{du}$. Generator notation is assumed again.

a) Calculate the unsaturated generated voltage

$$E_{GU} = E_a + I_a \cdot R_a + jI_a \cdot X_{du} \qquad (5\text{-}8)$$

b) Find I_{FU} for E_{GU} from the air gap line of the open-circuit saturation curve.

c) Calculate the voltage back of Potier reactance

$$E_p = E_a + I_a \cdot R_a + jI_aX_p \qquad (5\text{-}9)$$

d) Find the incremental field current, I_{FS} to account for saturation (see figure 5.4).

e) Calculate the overall field current, which, as in 5.3.3, is equal total sum of I_{FU} and I_{FS}.

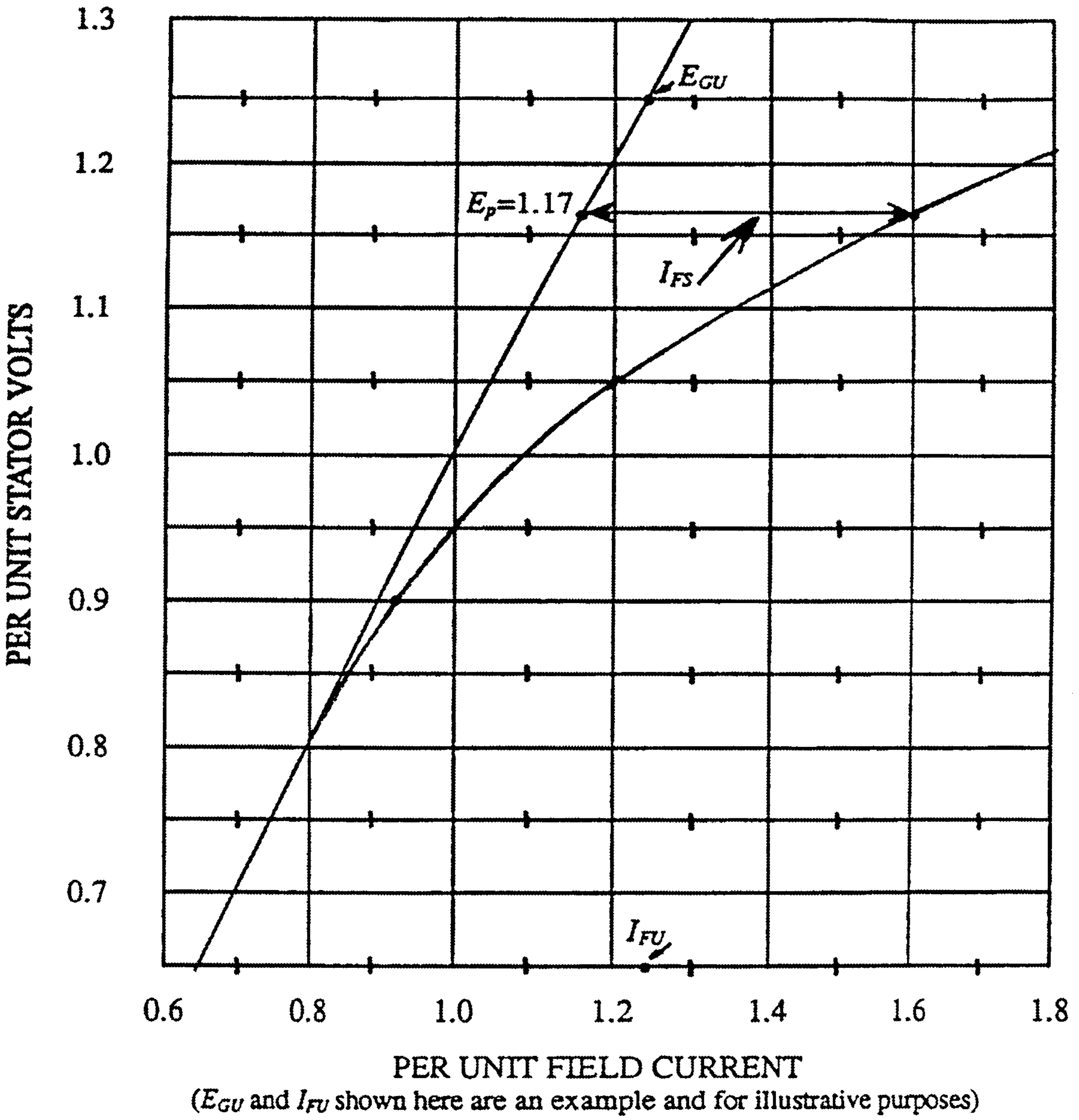


Figure 5.4—Typical open circuit saturation curve for a 2400 kVA generator

5.3.5 Graphical excitation calculations using Potier reactance and without machine saliency

In this subclause, load excitation is first calculated from test data using Potier reactance. This method consists of determining the voltage, E_p, back of Potier reactance as shown in equation 5-10 and figure 5.5

where

E_a is the specified terminal voltage
I_a is the specified armature current
R_1 is the positive-sequence resistance (see 10.7)
X_p is the Potier reactance

The values may be laid out to scale, laying off I_aR_1 to the right for a generator and to the left for a motor, and laying off I_aX_p vertically upward as shown. For an over-excited machine, ϕ, the power-factor angle, is positive and drawn above the horizontal. For an under-excited machine, ϕ is negative and drawn below the horizontal. For this analysis, the armature current and voltage are in per unit while the field current is in amperes or per unit.

E_p may also be calculated from the following equation:

$$E_p = \sqrt{(E_a \cos\phi \pm I_aR_1)^2 + (E_a \sin\phi + I_aX_p)^2} \text{ p.u.} \tag{5-10}$$

where

X_p is the Potier reactance, per unit
E_a is the specified armature terminal voltage, per unit
I_a is the specified armature current, per unit
R_1 is the positive-sequence resistance, per unit. R_a may be used if R_1 data is unavailable.
ϕ is the power-factor angle, positive for overexcited operation, negative for under-excited operation.
I_aR_1 is the positive for a generator and negative for a motor

NOTE — The sign convention for ϕ, the power factor angle, as used in equations 5-10 and 5-11 is *opposite* to that used in the phasor diagram analysis of 5.3.3. The usage in 5.3.3 is common to-day in stability and excitation analysis of synchronous machines. 5.3.5 has been repeated verbatim from IEEE Std 115-1983 and is retained for the purposes of continuity. By implication, the reference phasor for determining the sign of ϕ is I_a, the armature current.

The load field current for a specified armature current, power factor, and voltage may be obtained as shown in figures 5.6 and 5.7. The values should be laid out to a convenient scale with the power factor angle to the right of the vertical for an overexcited machine or to the left of the vertical for an under-excited machine, as shown. The electrical angle between I_{FG} and I_{FL} corresponds to the power angle, δ, of the machine. This is based on the assumption that $X_{qu} = X_{du}$. Both figures 5.6 and 5.7 below are shown for generator operation. The diagrams for motor operation would be mirror images of those shown below, and with a negative electrical angle, δ, between I_{FG} and I_{FL}.

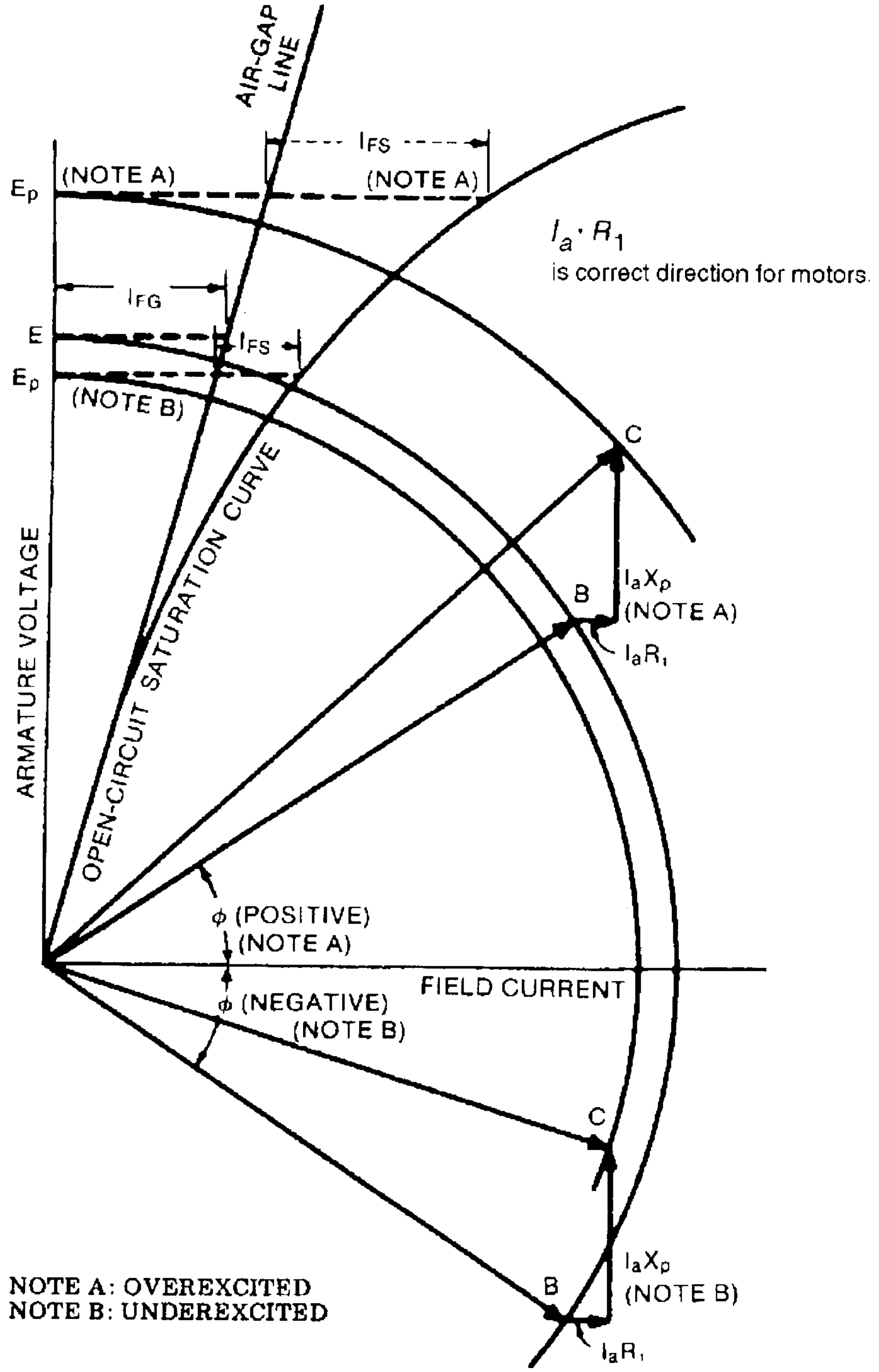


Figure 5.5—Diagram for voltage back of Potier reactance for synchronous generator

See note in 5.35 regarding the atypical convention for the sign of ϕ, the power factor angle.

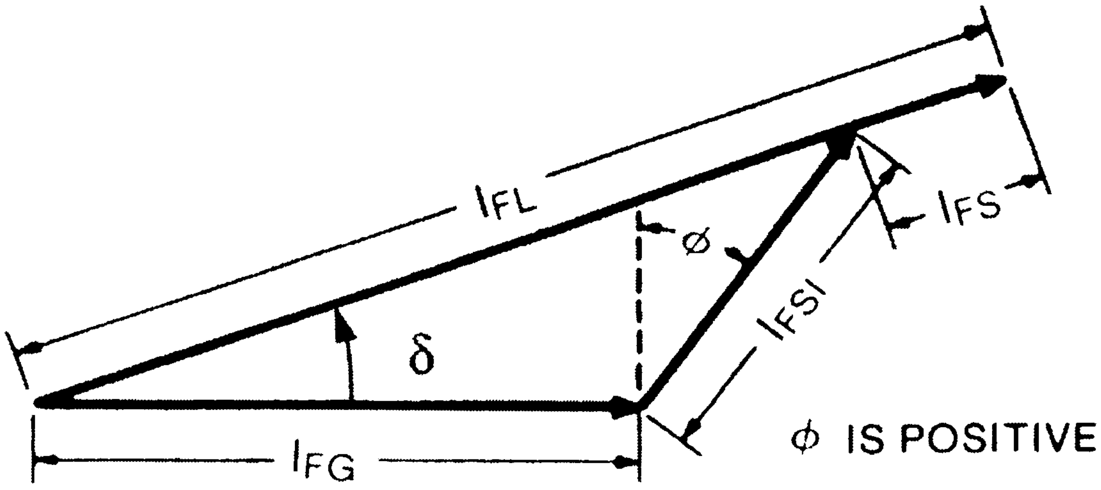


Figure 5.6—Determination of load field current overexcited operation motor or generator

The value of I_{FL} (the load field current) can also be determined by the following equation:

$$I_{FL} = I_{FS} + \sqrt{(I_{FG} + I_{FSI} \cdot \sin\phi)^2 + (I_{FSI}\cos\phi)^2} \qquad (5\text{-}11)$$

where

ϕ	is the power-factor angle, positive for overexcited operation and negative for under-excited operation, with armature current as the reference phasor.
I_{FG}	is the field current for the air-gap line at the specified armature terminal voltage (see 4.2.5 and figure 5.1 or figure 5.4)
I_{FSI}	is the field current corresponding to the specified armature current on the short-circuit saturation curve (see 4.2.7)
I_{FS}	is the difference between the field current on the open-circuit saturation curve and the field current on the air-gap line, both for the voltage E_p (see figure 5.5)

All values of field current should be in amperes, or in per unit on any suitable base.

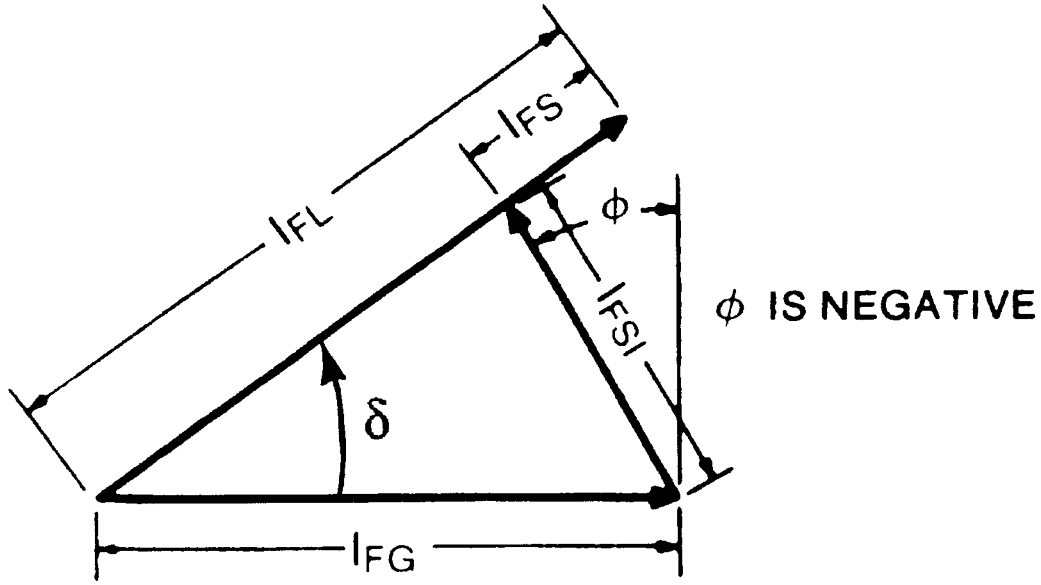


Figure 5.7—Determination of load field current under-excited operation (motor or generator)

5.4 Excitation calculation methods used in stability computer programs

There are many methods available for calculating load excitation (or p.u. field current) in stability computer programs. Two will be briefly discussed in this standard; they are also treated in more detail in section 5 (including annexes 5B and 5C) of IEEE Std 1110-1991.

Inherent in all step-by-step time domain stability calculations is the requirement to simulate excitation system changes due to voltage regulator and stabilizer action. The changes in field flux linkages, as well as stator and rotor body flux linkages, are accounted for, as are changes in field current and stator and machine rotor body currents. All these are used in calculating machine electrical torques (T_e) as shown by the equation

$$T_e = \psi_d \cdot i_q - \psi_q \cdot i_d \tag{5-12}$$

All the quantities in equation 5-12 are assumed to be in per unit. The symbols ψ_d and ψ_q are the direct axis and quadrature axis components of armature flux-linkages. See annex 4A of IEEE Std 1110-1991 for further discussion of synchronous machine electrical torques.

The two-axis concepts of R. H. Park prevail throughout most present-day stability analyses. Establishing the widely accepted direct axis and quadrature axis concepts is, at present, considered basic to stability time-domain methods.

In the first of the two methods considered typical, the equations describing the synchronous machine flux-linkage changes are derived from a given set of time constants and reactances. Characteristically, in this approach, a second order model is considered in both the direct and quadrature axes. Thus, the transient and subtransient flux linkage and current changes are recorded from one time step to the next. The field excitation (in terms of $X_{adu} \cdot I_{fd}$) is calculated at each time step and is compared to an excitation regulating system voltage. This is done to obtain the change in direct-axis field flux linkages from one step to the next.

Figure 5.8 depicts the load excitation calculation process. From this figure, the basic equation for field excitation is, in per unit

$$E_I = X_{adu} \cdot I_{fd} = E'_q + (X_{du} - X'_d)jI_d \tag{5-13}$$

An open circuit saturation curve is used to determine the saturation increment function. In this case, the voltage E'_q (rather than E_p or E_l) is used to calculate an increment $\Delta X_{adu} \cdot I_{fd}$. This is the difference between the value field excitation from the air gap line and another value from the open circuit curve, all at a voltage E'_q. (See figure 5.8 below and annex 5B of IEEE Std 1110-1991 for more detail.) $\Delta X_{adu} \cdot I_{fd}$ is added to E_1 to give a total excitation. Field excitation E_1 in per unit is based on the non-reciprocal system.

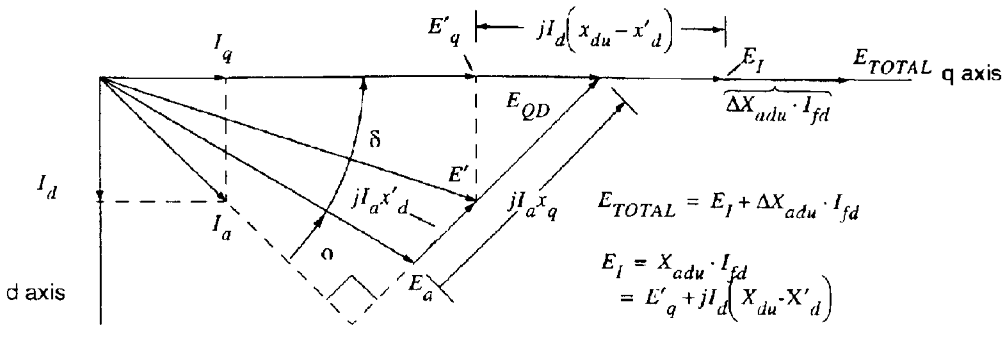


Figure 5.8—Phasor diagram for calculating $X_{adu} \cdot I_{fd}$ (=E_I)

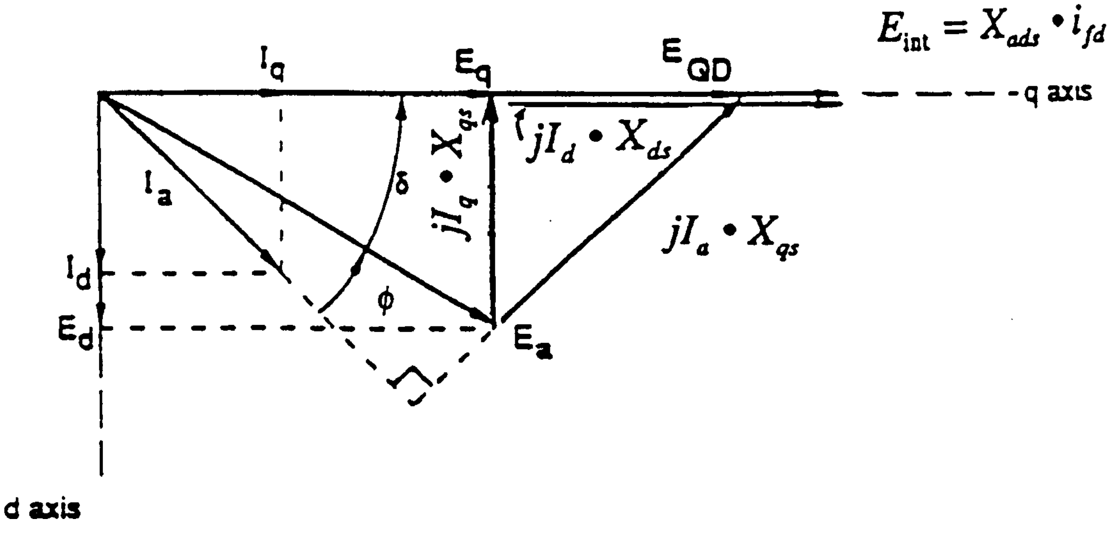


Figure 5.9—Phasor diagram for calculating $X_{ads} \cdot i_{fd}$

In the second approach, described in annex 5C of the IEEE Std 1110-1991, all synchronous machine flux linkages are related to the corresponding stator and rotor currents. This relationship is based, for both direct and quadrature axes, on a knowledge of given stability model networks for each d-axis and q-axis. Such model networks consist of inductances and resistances (see sections 2 and 6 of IEEE Std 1110-1991) . Rotor and stator currents for each axis are calculated, along with appropriate flux linkages, to give the same torque equation (see equation 5-12) as used in the first method. Third-order models, corresponding to transient, subtransient and sub-subtransient regimes, are easily accounted for when using this method.

The field excitation calculation is based on the phasor diagram shown in figure 5.9. Thus

$$X_{ads} \cdot i_{fd} = E_q + X_{ds} \cdot jI_d \tag{5-14}$$

Field current i_{fd} in per unit is calculated directly and is based on the reciprocal system B25. X_{ads} equals X_{adu} divided by the saturation factor K_d ($X_{ds} = X_{ads} + X_l$). A similar factor K_q may be calculated for the quadrature axis, using a q-axis saturation curve (if available). See annex 5C of IEEE Std 1110-1991 for more detail, including the derivation of a q-axis curve from measurements of machine terminal conditions and internal angle δ.

K_d is obtained from points on the air-gap (agl) line or open circuit saturation curve (occ) corresponding to E_l, the voltage behind X_l.

Then $$K_d = \frac{I_{fdocc}}{I_{fdagl}} \tag{5-15}$$

A similar procedure can be used for calculating K_q, using a q-axis "air gap line" and a derived q-axis curve, as described also in annex 5C of IEEE Std 1110-1991.

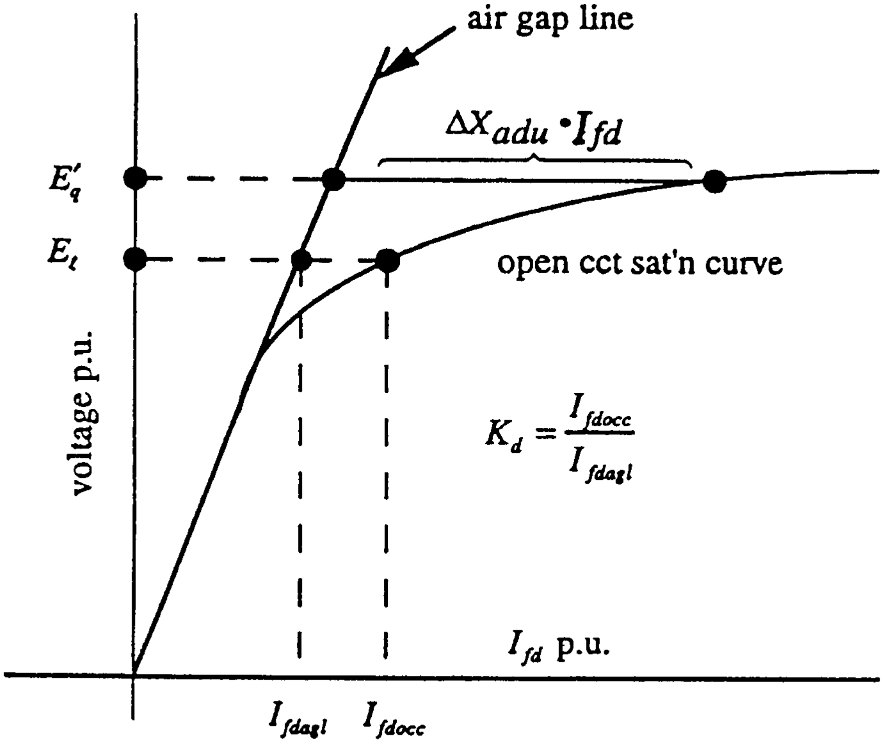


Figure 5.10—Calculation of saturation functions for adjustments to equations 5-13 and 5-14

5.5 Voltage regulation

5.5.1 Definition

For the definition of voltage regulation, see IEEE Std 100-1992.

5.5.2 Regulation

After the field current at specified armature current, power factor, and rated voltage has been obtained by one of the methods in 5.3 or 5.4, the p.u. voltage regulation may be obtained by the following equation:

$$\text{Regulation} = \frac{E_a - E_{ao}}{E_{ao}} \text{ p.u.} \tag{5-16}$$

where

E_a is the voltage on the open-circuit saturation curve corresponding to the test load field current
E_{ao} is the rated terminal voltage
E_a and E_{ao}should be in consistent terms.

Annex 5A

(informative)

Consideration and discussion of leakage reactance and Potier reactance

5.A.1 Introduction

Subclause 5.2.2 pointed out that *theoretically*, the Potier reactance and the leakage reactance are one and the same. However, in practice this seldom happens. Local saturation of the steel of the slots, ventilating ducts, and other irregularities give rise to differing values for the leakage and Potier reactances. If one has either leakage or Potier reactance but not both, one calculates the excitation field-current using the reactance in hand as described in 5.3.3 or 5.3.4. A problem arises when one has both the leakage and Potier reactances available.

Potier reactance has been described as a fictitious (or non-constant) reactance. This is because a portion of it can be calculated, but its value is further affected by changes in magnetic saturation, as well as by changes in machine flux form. One of the ways it has been tested (see 5.2.2) is straightforward. However, the Potier reactance triangles on which the standard test is based are subject to varying interpretations, which depend on the armature voltage at which the test is made. The extension or translation of the Potier triangle from its zero armature voltage value to a normal (or 1.0 p.u.) value gives the Potier reactance commonly quoted, and which is at a field current corresponding a generator (or motor) zero power factor overexcited, with rated (1.0 p.u.) armature current.

Reference [A1] by Beckwith describes how the variation in Potier reactance can be graphically measured (or calculated) when armature voltage is above or below 1.0 p.u. In addition, if armature current, (and corresponding field current) are less than normal, this may also be taken into account when measuring X_p. Thus, the machine loading condition has a decided effect on the actual value of X_p.

Reference [A2] by Crary and March discusses the empirical relationship between Potier reactance and armature leakage reactance. It is shown that Potier reactance decreases and approaches armature leakage reactance in value when the armature voltage (at zero power factor overexcited) is raised above normal. Ranges of up to 1.25 p.u. are chosen to show this effect of X_p approaching the calculated value of leakage reactance (X_l).

In [A2] it is also noted that the Potier reactance of turbogenerators does not vary as much as that of hydrogenerators for the above-described conditions. Another conclusion in the paper is that the calculation of armature leakage reactance has shown that it is relatively independent of saturation since much of the armature winding leakage flux is in air. Reference [A3] by Kilgore extends and confirms the armature leakage flux calculations of Reference [A2].

In summary, [A2] recommends that the use of leakage reactance, as quoted by machine designers, gives more consistent results when calculating field excitation than does the use of Potier reactance.

In recent years, the widespread use of digital computer stability programs has necessitated an alternative and usually preferable approach to calculating field excitation requirements. The general approach to such stability studies has been to represent the synchronous machine (particularly generators) by use of Park's direct (d) and quadrature (q) axis equations. When using voltage E_l behind leakage reactance X_l, the calculation of E_l (instead of E_p) is done in a similar way to that for E_p. A factor K_d is obtained by dividing the p.u. excitation on the open circuit saturation curve at voltage E_l, by the excitation at E_l p.u. voltage on the air gap line. K_d (always equal to or greater than unity) is divided into X_{adu}.

Park's two-axis equations for flux linkage representation of both the stator and field has several variations involving the machine inductances and currents. Two of the approaches are described generally in IEEE Std 1110-1991, Chapter 5, and specifically in annexes 5B and 5C of that document.

5.B.1 Bibliography for Annex 5A

[A1] Beckwith, Sterling. "Approximating Potier Reactance," *AIEE Transactions*, vol. 56, pp. 813–818, July 1937.

[A2] Kilgore, L. A. "Calculation of Synchronous Machine Constants," *AIEE Transactions*, vol. 50, pp. 1201–1213, Dec. 1931.

[A3] March, L. A. and Crary, S. B. "Amature Leakage Reactance of Synchronous Machines," *AIEE Transactions*, vol. 54, pp. 378–381, April 1935.

Annex 5B

(informative)

Example of the calculation of per unit field current (I_F)

Generator	MVA = 0.900 + j.435 = S	Generator steady		
Output:	E_a = 1.10 per unit	State constants:	$R_a = 0.0107$;	$X_{du} = 0.906$
	$I_a = 0.909\underline{/-25.8}$; $\phi = -25.8°$	(in per unit)	$X_p = 0.136$;	$X_{qu} = 0.546$

a) Calculation of internal angle δ
(see equation 5-3), or alternatively:

$$E_{QD} = E_a + I_a \cdot R_a + jI_a \cdot X_{qu} = 1.3246 + j\,0.4423 = 1.3965\,\underline{/18.47°}$$

$\delta = 18.47°$ [See also figure 5.3(a)].

b)

$$\begin{aligned} I_d &= 0.909\sin(18.47° - (-25.8°))\ \underline{/18.47° - 90°} \text{ (see equation 5-4)} \\ &= 0.6345\underline{/-77.53°} \\ I_q &= 0.909\cos(18.47° - (-25.8°))\ \underline{/18.47°} \text{ (see equation 5-5)} \\ &= 0.6909\ \underline{/18.47°} \end{aligned}$$

c)

$$\begin{aligned} E_{GU} &= E_a + I_a \cdot R_a + jI_d \cdot X_{du} + jI_q \cdot X_{qu} \\ &= 1.5414 + \text{j}\ 0.5150 \\ &= 1.6252\ \underline{/18.47°} \end{aligned}$$

d) $I_{GU} = 1.625$ for $E_{GU} = 1.625$ on air gap line (see figure 5.4)
e) $E_p = E_a + I_a \cdot R_a + jI_a \cdot X_p = 1.1675 + \text{j}\ 0.1071 = 1.1675\ /\underline{5.26°}$
f) For $E_p = 1.167$ on air gap line, and on open circuit sat. curve $I_{FS} = 1.59 - 1.167 = 0.423$ per unit
g) $I_F = I_{FU} + I_{FS} = 1.625 + 0.423 = 2.048$ p.u.

NOTES:

1 — Neglecting resistance

$$\begin{aligned} E_{QD}\ /\underline{\delta} &= 1.3898\ \underline{/18.75°} \\ E_P &= \underline{\qquad}^{\circ} \end{aligned}$$

2 — For machines larger than 500–1000 kW, R_a tends to fall in the range of 0.002 p.u. to 0.003 p.u.

6. Temperature tests

6.1 General

Temperature tests are made to determine the temperature rise of certain parts of the machine above some reference temperature when running under a specified loading condition. This reference temperature has been widely referred to as the ambient temperature (or internal ambient temperature). Such reference temperatures depend on the manner by which the machine is cooled. International practice suggests that the term *coolant temperature* is an acceptable way of describing this reference condition, and this term will be used below, where applicable.

6.2 Methods of loading

Temperature tests may be made with the machine operating at any one of many loading conditions. The information, which usually is required, is the temperature rise of a machine at one or more specified values of load. Since loading at a desired load condition is not always possible or practical, several other loading methods may be utilized to obtain data, which may be used to determine the temperature rise of the machine for the desired load. The following four methods are most commonly used for temperature testing.

6.2.1 Method 1. Conventional loading

The preferred method of making a temperature test is to hold the specified conditions of armature current, power, voltage, and frequency until the machine reaches constant temperature, taking readings every half hour or less. If the machine is equipped with a voltage or other regulator, it should be made inoperative during this test so that the field current will be constant.

While this method is the most straightforward, experience has shown that it is difficult at times to keep machine terminal voltages close to rated values. Some utility test procedures have sought to overcome this problem by plotting per unit $(MVA)^2$ rather than armature per unit $(A)^2$ against temperature rise, the latter being shown in figure 6.1. Use of per unit $(MVA)^2$ has some limitations because certain machine design *may* have unequal voltage-related or current-related losses. The following recommendations for carrying out method 1 tests are summarized in the following:

a) Maintain, where possible, machine terminal voltage within ±2% of rated during the tests with the data plotted as in figure 6.1.
b) Perform a series of tests at various voltage levels near rated, and interpolate the results, using, for example, linear regression methods. Data plotted as in figure 6.1.

NOTE — Figure 6.2 shows a plot of temperature rise against field losses. Similar plots of armature and stray load losses may be performed as shown in 4.2. These are not part of method 1.

6.2.2 Method 2. Synchronous feedback

When a synchronous machine similar to the one to be tested is available, considerable energy savings result from this method of loading. It also enables full-load testing of machines rated far in excess of the available power supply capability.

The two machines are coupled together and connected electrically so that one serves as a motor and the other as a generator. The output of the generator is fed electrically to supply the motor. Either of these machines may be the tested machine. The losses of the two machines are supplied by a third machine (a motor), deriving its power from an available source such as the local electrical utility. The third machine supplies power to the other two machines mechanically through a suitable coupling, gear, or belt arrangement. An alternate method of supplying losses is to use an electrical power source in place of the third machine (a motor). The voltage and frequency of the electrical power source must match those of the machines on test and suitable means to reach operating speed must be employed to prevent damaging electrical or mechanical transients.

This method of loading requires that two similar synchronous machines be coupled in such a manner that their rotors are physically displaced in an angular direction or rotation by their combined load angle (see 10.8.2). In the following discussion, the term *rated* refers to the machine under test. The coupled rotors are driven at the rated speed. Armature circuits of the similar machines are tied together in the phase sequence (see 3.7) corresponding to their direction of rotation and to the polarity of their rotor fields. The tie may be provided with a suitable circuit breaker and instrumented with wattmeters, voltmeters, and ammeters. Either frequency or speed shall also be measured. Both rotor field circuits are instrumented with voltmeters and ammeters and connected to separately adjustable dc power supplies. All other electrical instrumentation is optional.

With the tie closed, the field current of one machine is increased while the other is decreased until the specified current at rated voltage appears in the tie. With the coupled machines operating at rated voltage and frequency, the specified apparent power (kVA) is thus exchanged between the two machines at the desired power factor. The real and reactive power interchanged between the two machines on test is a function of the angular displacement between the two rotors, as determined by the coupling assembly, and by the levels of excitation applied to the field windings of the two machines.

6.2.3 Method 3. Zero power factor

This method consists of operating the machine at no load as a synchronous condenser, maintaining appropriate conditions of armature current, voltage, and frequency until the machine reaches constant temperature.

6.2.3.1 Power factor less than 0.9

Since the voltage back of Potier reactance, E_p, at zero power factor, overexcited, is greater than it is at higher power factors for the same terminal voltage and armature current, the test terminal voltage should be reduced to a value that results in a voltage back of Potier reactance (this voltage may be calculated by equation 5-10, using either a measured or calculated value of reactance), which is the same as the voltage back of Potier reactance at rated load conditions. This voltage may also be calculated by equation 5-7 using I_aX_p as determined from 5.2.2 or 5.2.3, thus using either a measured or calculated value of Potier reactance X_p. The resulting armature temperature rises will be very nearly the same as if the machine had been loaded at rated conditions. A typical curve is shown in figure 6.1. It is sometimes impractical to use a variable voltage power supply for testing of large machines in this manner. Refer to 6.2.3.2 if the armature voltage cannot be adjusted in accordance with 6.2.3.1.

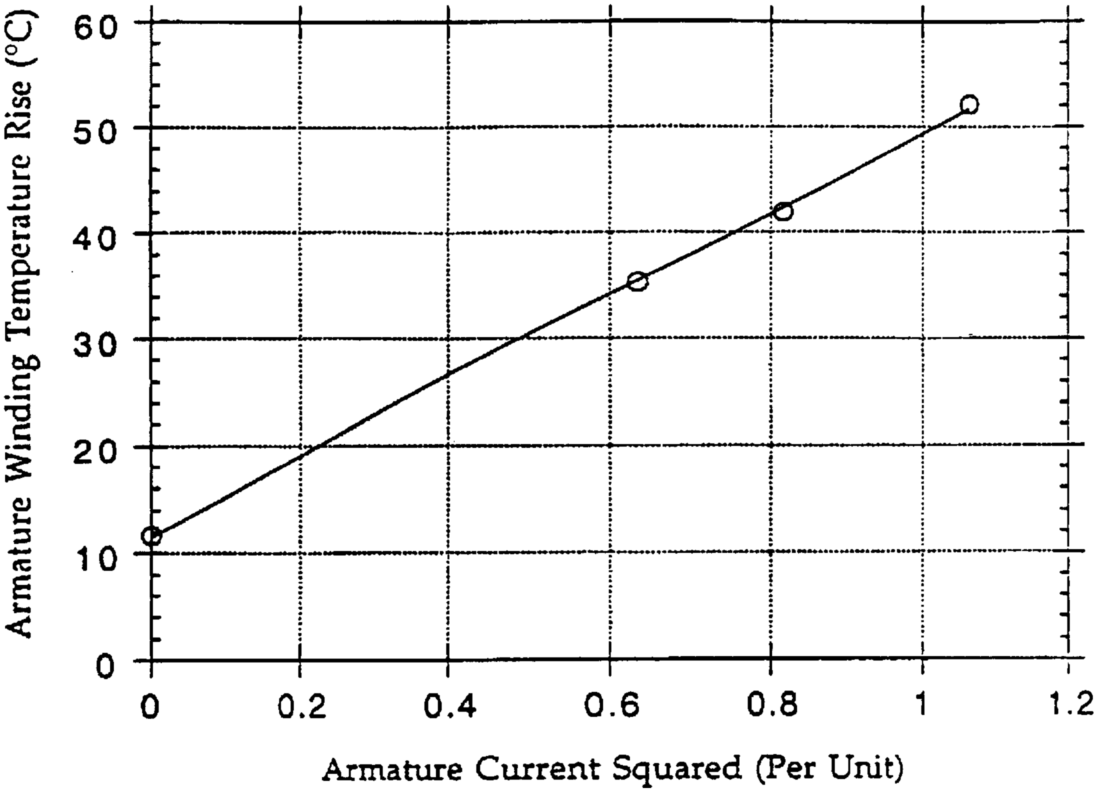


Figure 6.1—Typical plot of armature winding temperature rise vs. armature current squared

The field-winding losses differ considerably from those of normal operating conditions and the observed temperature rises of the field should be corrected to correspond to the specified field current. Two equations have been used to make this correction. They appear below as equations 6-5 and 6-8. There are elements of approximation in both equations.

As seen in figure 6.2, the field winding temperature rise above the temperature of the cooling medium leaving the fan is linearly proportional to the I^2R loss in the field winding, P_s. This includes the effect of temperature on field resistance, but neglects any indirect effects that stator, rotor-surface, or windage losses may have on field winding temperature. Using the nomenclature appearing after equation 6-8 below, this linear relationship can be expressed as

$$\Delta t_s + t_{c,s} = (\Delta t_{fan} + t_{c,s}) + \beta P_s \qquad (6\text{-}1)$$

where

β	is the slope of the temperature rise, which can be determined empirically:

$$\beta = \frac{(\Delta t_t + t_{c,\,t}) - (\Delta t_{fan} + t_{c,\,t})}{P_t - 0} = \frac{\Delta t_t - \Delta f_{fan}}{P_t} \tag{6-2}$$

Equations 6-1 and 6-2 can be combined to form:

$$\Delta t_s = \Delta t_{fan} + \frac{P_s}{P_t}(\Delta t_t - \Delta t_{fan}) \tag{6-3}$$

where

$$\frac{P_s}{P_t} = \left(\frac{I_{f,\,s}}{I_{f,\,t}}\right)^2 \frac{R_s}{R_t} \tag{6-4}$$

When the effects of resistance are negligible, then $R_s = R_t$ and

$$\Delta t_s = \Delta t_{fan} + \left(\frac{I_{f,\,s}}{I_{f,\,t}}\right)^2 (\Delta t_t - \Delta t_{fan}) \tag{6-5}$$

Otherwise, one must account for the temperature effect on resistance in equation 3-1 as found in 3.3.2.

$$\frac{R_s}{R_t} = \frac{k + t_{c,\,s} + \Delta t_s}{k + t_{c,\,t} + \Delta t_t} \tag{6-6}$$

Successive substitution of equation 6-6 for R_s/R_t in equation 6-4, and then equation 6-4 for P_s/P_t in equation 6-3 yields

$$\Delta t_s = \Delta t_{fan} + \left(\frac{I_{f,\,s}}{I_{f,\,t}}\right)^2 \left(\frac{k + t_{c,\,s} + \Delta t_s}{k + t_{c,\,t} + \Delta t_t}\right) (\Delta t_t - \Delta t_{fan}) \tag{6-7}$$

which now shows a dependence on Δt_s in the numerator of the second term. By collecting terms in $\Delta t_s - \Delta t_{fan}$, one obtains the following expression for the specified temperature rise as a function of specified field current:

$$\Delta t_s = \Delta t_{fan} + \left(\frac{I_{f,\,s}}{I_{f,\,t}}\right)^2 (\Delta t_t - \Delta t_{fan}) \left(\frac{k + t_{c,\,s} + \Delta t_{fan}}{k + t_{c,\,t} + \Delta t_t - (I_{f,\,s}/I_{f,\,t})^2 (\Delta t_t - \Delta t_{fan})}\right) \tag{6-8}$$

where

Δt_s	is the temperature rise (°C) corrected to correspond to a field current $I_{f,s}$ for a specified load
k	is the constant of the field winding material (see 6.4.4.)
$t_{c,s}$	is the specified coolant temperature (°C) for specified field current $I_{f,s}$
$t_{c,t}$	is the reference coolant temperature (°C) obtained during test measurement of temperature rise Δt_t
Δt_t	is the temperature rise (°C) for test field current $I_{f,t}$
Δt_{fan}	is the temperature rise (°C) through fan (or blower)
$I_{f,t}$	is the field current (Amperes) under test conditions
$I_{f,s}$	is the field current (Amperes) corresponding to a specified load
P_s	is the field current losses at a specified load
P_t	is the field current losses at the test load

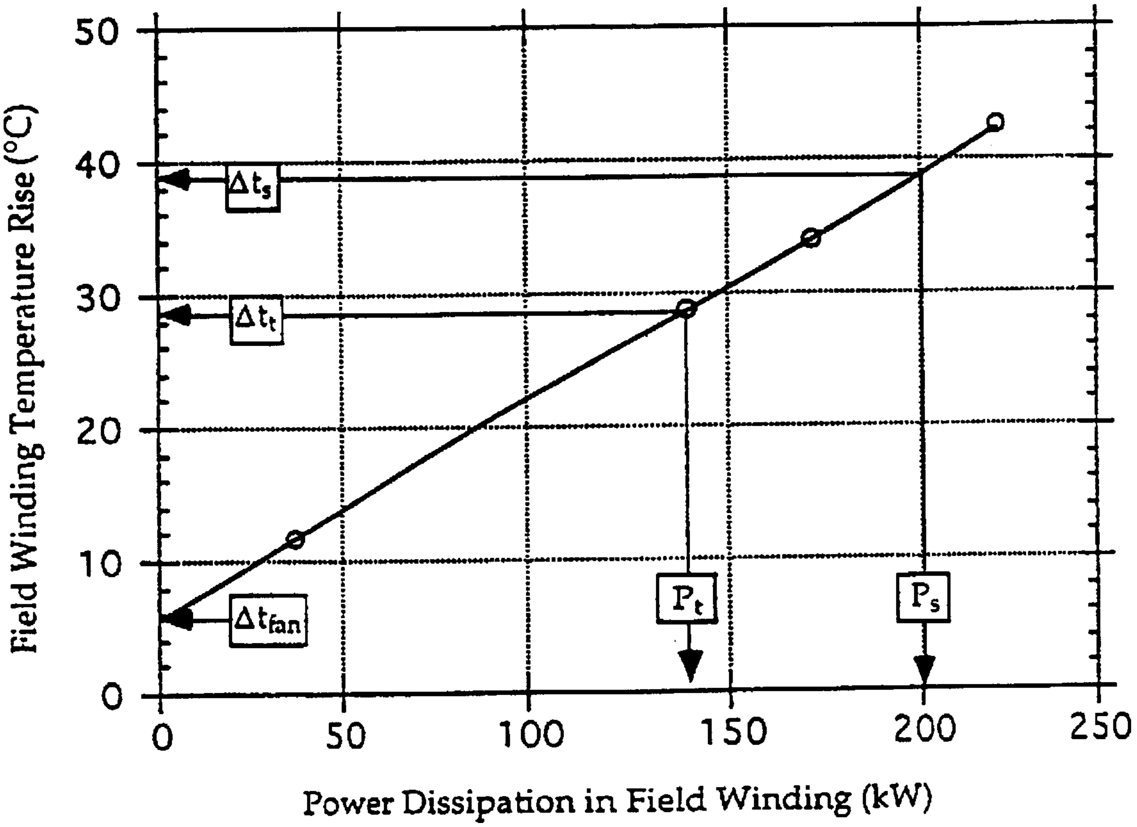


Figure 6.2—Typical curve of field temperature vs. field power

6.2.3.2 Power factor larger than 0.9

For generators and motors rated at power factors above 0.9 (and particularly those rated at unity power factor), it may be impractical to apply the zero-power-factor method at specified armature current and the proper voltage behind Potier reactance, E_p, as described in 6.2.3.1 because of field heating limits. In such cases, the armature current or the terminal voltage must be reduced. The choice as to which should be reduced depends on the relative magnitudes of the copper and core losses in the particular machine.

Unless the load is reduced to give rated field current, the field temperature should be corrected as shown in equation 6-8. An approximate correction in armature temperature should be made according to the manufacturer's recommendations as to the contribution of the various losses to the observed temperature.

Realistic temperature tests of large machines with long thermal time constants are possible by alternating the over- and underexcitation for short time periods in such a manner that the loss energy inputs into the armature and into the field remain constant for each period of temperature reading (typically 30 min). Successful application of this method requires that loss curves (figure 4.2) for the tested machine be determined prior to the temperature tests. Armature overcurrent due to an underexcitation (possibly even a negative excitation) and the field overcurrent are selected in such a way that satisfies the following conditions:

$$P_A \Delta t_R = \sum_{t_1}^{t_2} (P_V + P_I)_o \cdot \Delta t_o + \sum_{t_1}^{t_2} (P_V + P_I)_u \cdot \Delta t_u kW \cdot s \qquad (6\text{-}9)$$

$$P_F \Delta t_R = \sum_{t_1}^{t_2} P_{Fo} \cdot \Delta t_o + \sum_{t_1}^{t_2} P_{Fu} \cdot \Delta t_u \cdot kW \cdot s \qquad (6\text{-}10)$$

where

P_A	is the total armature losses at the specified load, kW
P_F	is the total field losses at the specified load, kW
Δt_R	is the time interval of test = $(t_2 - t_1)$, s
P_{Fo}	is the field loss during overexcitation, kW
P_{Fu}	is the field loss during underexcitation, kW
P_I	is the current dependent armature losses, kW
P_V	is the voltage dependent armature losses, kW
t_1	is the time at start of test, s
t_2	is the time at finish of test, s
Δt_o	is the test time interval for overexcitation, s
Δt_u	is the test time interval for underexcitation, s

The maximum armature current obtainable with the negative excitation is less than $1/X_q$ p.u. and can be determined in accordance with 10.4.3 for the actual line voltage conditions during the test. Best results are obtained when $\Delta t_R \geq 2 (\Delta t_o + \Delta t_u)$ and the temperatures are continuously recorded by graphical instruments. In such a case, it is possible to average the high and low readings within each interval. If the field loss energy equation cannot be completely satisfied, the heat run is continued at the rated field condition after stabilized armature temperatures have been reached and recorded. The stabilized field temperature readings are then obtained during the extended heat run period while the machine is still hot.

Due to its imperfect simulation of the loss energy dissipation rates, this method should be limited to continuous duty machines (see 6.3.1).

6.2.4 Method 4. Open-circuit and short-circuit loading

This method consists of the following three separate heat-run tests:

a) Specified voltage with the terminals open-circuited
b) Specified armature current with the terminals short-circuited
c) Zero excitation

For conventional machines the armature temperature rise is computed as the sum of the temperature rises for the open-circuit and short-circuit tests, and corrected for the duplication of heating due to windage. The zero-excitation no-load heat run will yield data for determination of the temperature rise due to windage.

For machines with water-cooled armature windings, the armature temperature can be obtained directly from short-circuit tests. The ground wall insulation is sufficiently thick and heat transfer to the water ducts inside the armature bars, sufficiently high that the temperature of the armature winding copper is largely insensitive to temperature variations outside the winding. Thus, armature copper winding temperature is only dependent on dc and ac losses in the armature copper, on the flow rate of the water coolant, and on its cold liquid temperature.

Another heat run at no-load overvoltage will provide improved accuracy for the temperature rise of the field. The manufacturer's approval should be obtained since a rated field current run with open- or short-circuit loading for prolonged periods could result in armature damage. It is possible to combine the heat runs into one by application of the principles outlined in 6.2.3.2. The same loss energy equations apply if the variables subscripted with "o" are referred to the open-circuit excitation and those subscripted with "u" are referred to the short-circuit excitation. In most cases, discharging of the field winding for several seconds prior to each closure of the armature short-circuiting contactor is recommended in order to limit the subtransient and transient armature current to acceptable values.

Suitable field discharge circuits should be used (see figure 6.3). Such precaution is also required if excessive terminal voltage is expected prior to opening the armature circuit.

NOTE — On-site testing of salient-pole generators by conventional loading (method 1) indicates that temperature rises are usually higher than the rises found by calculation, as in method 4. Experience using *both* method 1 and method 4, on hydrogenerators in the 50–370 MVA range, shows that method 4 can give calculated temperature rises which on occasion may be as much as 7 °C lower than method 1. Method 1 is the preferred method of making these tests.

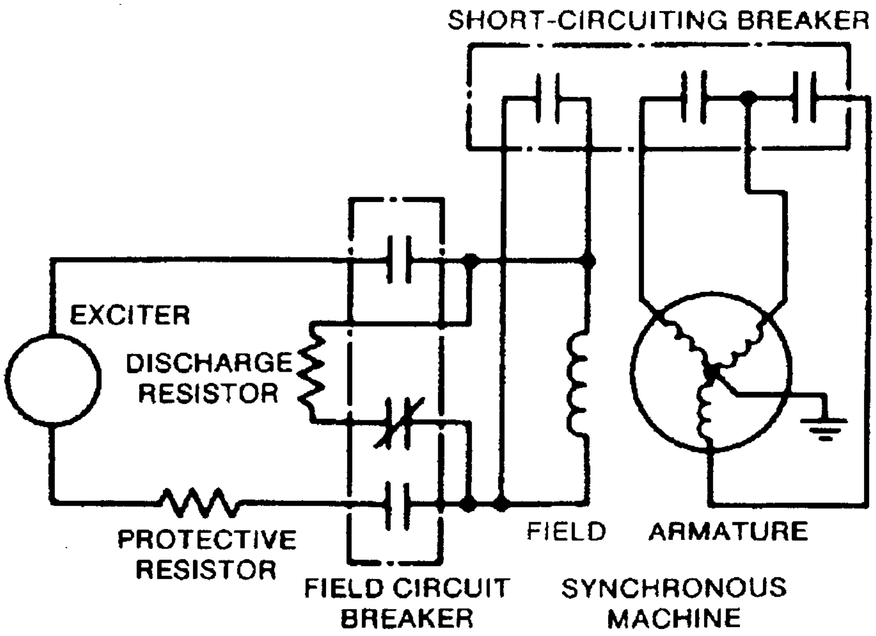


Figure 6.3—Field winding circuit for 6.2.4, method 4, open-circuit and short-circuit loading

6.3 Duration of test

6.3.1 Continuous loading

Continuous loading tests should be continued until machine temperatures have become constant within ± 2 °C of the rise value for three consecutive half-hourly readings. If the coolant temperature is not constant, the test may be terminated when the temperature rise, based on at least three consecutive half-hourly readings, does not exceed the maximum previously observed rise. If the coolant temperature for three half-hourly readings varies by more than 2 °C, the test should be continued.

6.3.2 Short-time ratings

For loads corresponding to the short-time rating of the machine, the tests should be started from conditions as specified, and continued for the time specified.

6.3.3 Intermittent loads

For intermittent loads, the load cycle specified should be applied and continued until the temperature rise at the end of the load causing greatest heating varies by less than 2 °C for three consecutive cycles.

6.4 Methods of measuring temperature

6.4.1 General

The following are four methods of determining temperatures:

a) Resistance thermometer or thermocouples
b) Embedded detector
c) Winding resistance
d) Local temperature detector

It is sometimes desirable to use one method as a check on another.

6.4.2 Method 1

This method is the determination of temperature by resistance thermometer, or by thermocouples, with any of these instruments applied to the hottest part of the machine which is accessible.

6.4.3 Method 2. Embedded detector

This method is the determination of temperature by thermocouples or resistance temperature detectors built into the machine in accordance with ANSI C50.10-1977 or NEMA MG1-1978.

6.4.4 Method 3. Resistance

This method is the determination of temperature by comparing the resistance of the winding at the temperature to be determined with the resistance at a known temperature. The temperature of the winding is calculated by the following equation:

$$t_t = t_b + \left(\frac{R_t - R_b}{R_b}\right)(t_b + k) \tag{6-11}$$

where

t_t is the total temperature of winding when R_t was measured, °C
R_t is the resistance measured during test, ohms (see 3.3.5)
R_b is the reference value of resistance previously measured at known temperature, t_b, ohms (see 3.3.3 and 3.3.4)
t_b is the temperature of winding when reference value of resistance R_b was measured, °C
k is 234.5 for pure copper, °C
k is 225 for aluminum based on a volume conductivity of 62% of pure copper, °C

For values of k for other materials, refer to the manufacturer. For windings consisting of a copper portion connected in series with an aluminum portion, an equivalent value of the constant k, should be used.

$$k = \frac{R_O}{\frac{R_{Oa}}{k_a} + \frac{R_{Oc}}{k_c}} \tag{6-12}$$

where

R_O is the calculated total resistance of the winding at 0 °C (ohms)
R_{Oa} is the calculated resistance of the aluminum portion of the winding at 0 °C (ohms)
R_{Oc} is the calculated resistance of the copper portion of the winding at 0 °C (ohms)
k_a is 225 for aluminum based on a volume conductivity of 62% of pure copper
k_c is 234.5 for pure copper, °C

Since a small error in measuring the reference value resistance will make a comparatively large error in determining temperature, the winding resistance should be measured by a double bridge or other means of equivalent accuracy, and checked by a second instrument if possible.

CAUTION — The presence of residual voltage on the field of the machine requires that this measurement be made with the unit at standstill.

6.4.5 Method 4. Local temperature detector

The local temperature of various parts of a machine can be determined using a local temperature detector. The detecting element is placed in close thermal proximity to the part where the local temperature is to be measured. Examples of local temperature detectors are infrared sensor, thermocouple, small resistance thermometer, and thermistor. These are frequently installed as permanent parts of a machine. They are used to determine local temperature of winding conductors, core laminations within a package, and winding temperature between coil sides. Since the temperatures measured by local temperature detectors may deviate substantially from those determined by the other method, the temperatures so measured should not be interpreted in relation to standards written in terms of these other methods.

6.5 Preparation for test

6.5.1 Location of measuring devices

Local temperature devices should be checked for proper functioning and appropriate calibration before installation. Non-insulated devices such as thermocouples shall be installed on grounded parts of the machine or used only in de-energized runs with appropriated protection for personnel and instruments. Insulated measuring devices or devices without physical connections should be installed to avoid influencing the temperature being measured and should not compromise the electrical integrity of the apparatus under test.

6.5.2 Enclosed machines

The armature coils and cores of some enclosed machines may not be readily accessible, and if temperatures are to be obtained by the thermometer method, thermocouples or resistance thermometers may be placed on these parts and the leads brought out of the enclosures. However, when these machines have embedded detectors, it is usually unnecessary to determine temperatures by the thermometer method.

6.5.3 Open-ventilated machine

When preparing for a temperature test, an open-ventilated machine should be shielded from currents of air coming from adjacent pulleys, belts, and other machines, as unreliable results are obtained when this is not done. A very slight current of air may cause discrepancies in the heating results. Consequently, a suitable screen should be used to protect the machine under test when necessary. Great care should be used, however, to see that the screen does not interfere with the normal ventilation of the machine under test. Care should always be taken to see that sufficient floor space is left around the machine under test to allow free circulation of air. Under ordinary conditions, a distance of about 2 m (6 ft) is sufficient.

6.5.4 Precautions

If temperatures are to be obtained by infrared sensors, thermocouples, resistance thermometers, or other electric temperature-measuring devices, care should always be taken to ensure that these elements and their indicating instruments are functioning properly. The wiring between the detecting elements and the indicating instrument should be installed so there are no loose connections. The machine should be shut down long enough before the start of the test so that all parts will be essentially at the same temperature. A complete set of readings should then be taken of the electric temperature devices, and these readings should be compared with the temperature of principal metal parts of the machine, as measured with several reliable mercury or alcohol thermometers. The electric devices should indicate consistent temperatures in close agreement with the stem-type thermometers. If appreciable temperature differences exist, a check should be made for loose connections, stray fields, and the possibility that the machine has not reached a uniform temperature. It may be necessary to replace or omit the faulty device.

A check on stray-field effects produced by the machine may be made by comparing readings of the electric devices taken immediately before and after the windings are energized or de-energized. The use of closely twisted or coaxial leads for the temperature devices will minimize the effects of stray fields.

6.6 Determination of coolant temperature

6.6.1 General

The rise in temperature is usually the characteristic to be determined rather than the total temperature. Therefore, it is important that the actual coolant temperature at the time of the test be accurately established. Further, the coolant temperature should not change appreciably during the test (see 6.3.1). The method of determining the coolant temperature is dependent on the method of cooling the machine.

6.6.2 Machines cooled by surrounding air

The coolant temperature is the mean of the air temperature measurements made by several thermometers placed between about 1 m and 2 m (about 3 ft and 6 ft) from the machine under test, half-way up the machine in the area from which cooling air is drawn. They should be so placed that they are not affected by abnormal heat radiation, drafts, and rapid erratic variations in temperature of the surrounding air. It is desirable to use oil cups (see 6.6.7) to stabilize the thermometer readings. If the rate of variation in air temperature exceeds 2 °C per hour, it is particularly important to use oil cups.

Where an open machine is partly below the floor line in a pit, the temperature of the rotor is referred to an air temperature, which is a weighted mean of the pit and room temperatures, the weight of each being based on the relative proportions of the machine in and above the pit. Parts of the stator that are in the pit are referred to the internal air temperature in the pit.

6.6.3 Duct and pipe-ventilated machines

The coolant temperature is the weighted mean of the air or gas temperature measured at the intakes of the machine. The weighting of each temperature reading is determined by the portion of the total flow of air or gas which is at that temperature.

When a separately driven ventilating blower is mounted integrally with the machine and draws air from the room, the coolant temperature should be taken as the weighted average of the air temperature measured at the inlet of the blower.

6.6.4 Machines with a recirculating cooling system

The coolant temperature is the temperature of the internal coolant (which cools the machine parts) leaving the heat exchanger. If more than one heat exchanger is provided, the coolant temperature is the weighted mean of the temperatures of the internal coolant leaving the heat exchangers. The system of weighting described in 6.6.3 should be used. The distribution of the external cooling medium should be adjusted so that the temperatures of the internal coolant leaving each heat exchanger are approximately equal.

When measuring the internal coolant temperature, the thermometers should be located far enough from the heat exchangers to avoid errors caused by radiation to the cool surfaces of the heat exchanger. A constant value of internal coolant temperature may be maintained by controlling the total flow of the external cooling medium to the heat exchangers. To avoid condensation, the internal coolant temperature should usually be held to a value equal to or above the temperature outside the machine housing.

In some instances, the temperature rise is specified above the temperature of the external cooling medium. In such cases, the coolant temperature is the weighted mean temperature of the external cooling medium as it enters the heat exchangers. The weighting is in proportion to the fraction of the medium which enters at each temperature.

6.6.5 Machines cooled by other means

These machines should be considered individually and the special methods to be used to determine the coolant or equivalent temperature should be specified by the purchaser or mutually agreed on before the test.

6.6.6 Test reference coolant temperature defined

The value of the reference coolant temperature to be used for any given test is the mean of the coolant temperature values for the last three half-hourly reading of that test.

6.6.7 Thermometer oil cups

Thermometers should be immersed in a suitable liquid such as oil in a heavy metal cup if the cooling air temperature is subject to rapid variations. A convenient form for such an oil cup consists of a metal cylinder with a hole drilled into it axially. This hole is filled with oil and the thermometer is placed therein with its bulb well immersed. The response of the thermometer to various rates of temperature change will depend largely upon the thermal-time characteristics of the cup, which in turn depend on the size, kind of material, and mass of the containing cup, and may be further regulated by adjusting the amount of oil in the cup. The larger the machine under test, the larger should be the metal cylinder employed as an oil cup in the determination of the cooling air temperature. The smallest size of an oil cup employed in any case should consist of a metal cylinder about 2.5 cm (1 in) in diameter and about 5 cm (2 in) high.

6.7 Temperature readings

6.7.1 General

In the following subclauses, readings are described for several methods of temperature measurement. These are used to measure temperature of the windings, the stator core, the incoming cold coolant, and the exhaust hot coolant. Each method of measurement is best suited for particular parts of a machine. Thus, in a given test, it may be desirable to use all three methods to measure the temperature in the various parts of the machine.

6.7.2 Thermometer method

Temperatures taken by the thermometer method (see 6.4.2) should be measured on the following parts or flow paths during the temperature tests and, if specified, after shutdown:

a) Armature coils should be measured in at least four places
b) Armature core should be measured in at least four places
c) Field should be measured after shutdown (see 6.8.2)
d) Coolant (see 6.6)
e) Air discharged from frame or air discharge ducts, or internal coolant discharged to the inlet of coolers of machines with recirculating cooling system
f) Frame
g) Bearings (when part of the machine)

The temperature sensing elements should be located to obtain the highest temperatures, except for ingoing and discharge air, or other coolant temperature, for which they should be placed to obtain average values.

6.7.3 Embedded-detector method

Temperatures of the armature winding of machines equipped with embedded detectors should be determined by the embedded-detector method (see 6.4.3) during the temperature test. It should be recognized that in many larger machines, the discrepancy between the temperature as measured by the embedded detector and the hottest-spot temperature of the winding as defined in IEEE Std 1-1986 can be significant. This discrepancy is particularly large in hydrogen-cooled machines, especially those using gas pressure higher than about 3.5 kPa (0.5 lb/in^2) gage.

In machines with conductor-cooled armature windings, the difference between embedded-detector temperature and conductor temperature varies considerably depending on many design factors. For some types of construction, the embedded-detector measurements are in close agreement with the conductor temperature. For others, alternate methods may be preferable. The manufacturer's recommendations based on local temperature detector measurements (see 6.4.5) on prototype machines indicate preferred methods of test and of correlating the results with conductor temperature.

6.7.4 Resistance method for fields

Temperatures of the field winding should be determined by the resistance method (see 3.3 and 6.4.4) during the temperature test. Where the machines have field coils accessible to thermometers after shutdown, the temperatures taken by thermometers furnish a useful check on the temperature by the resistance method.

6.7.5 Resistance method for armature

Temperatures of the armature winding may be determined by the resistance method (see 3.3 and 6.4.4) after shutdown. The resistance should be measured across any two-line terminals for which a reference value of resistance has been measured at a known temperature. The resistance should be measured directly at the machine terminals. If the neutral is not connected internally, the neutral terminals of the three phases should be connected directly if a wye-connection is to be used.

6.7.6 Resistance method for brushless machines

Temperatures of the rotating field directly connected to a brushless exciter armature cannot be monitored during the temperature test without a suitable test fixture or telemetry provisions. Shutdown resistance may possibly be used to determine the temperature if the time to bring the rotor to rest is not excessive (see 6.4.4). General principles outlined in 6.8 are followed and the shutdown resistance is obtained from the semilogarithmic plot of resistance change measurements taken at regular time intervals after shutdown and extrapolated to the time interval given for the rating of the machine by the table in 6.1. The temperature of the brushless exciter field is also normally determined by the resistance method during the temperature test (see 3.3 and 6.4.4).

6.8 Shutdown temperatures

6.8.1 General

The application of the thermometer method to rotating parts, or the resistance method to armature windings, requires a quick shutdown of the machine at the end of the temperature test. A carefully planned procedure and an adequate number of people are required to obtain readings soon enough to give reliable data. When practicable, the machines should be stopped within a time interval as given in the following table:

Table 6.1—Shutdown times for machines

Rating	Time (s)
50 kVA and less	30
51 kVA to 200 kVA	90
201 kVA to 5000 kVA	120
Above 5000 kVA	note a

[a] Subject to agreement between the manufacturer and user depending on braking method.

Under these conditions, correlations of observed temperatures are not necessary. If the initial resistance reading cannot be made within the time interval after shutdown in the table, the temperatures should be corrected in accordance with 6.8.2, and extrapolated to the time of shutdown.

6.8.2 Location of measuring devices

Thermometers should be placed on the collector rings, pole tips, amortisseur winding, and field windings, so far as these parts are accessible, as quickly as possible after the rotating parts have come to rest.

It may be impracticable to stop the machine in a short enough time to obtain temperature readings of any value from the thermometer applied after shutdown. In such cases, it is necessary to rely on other readings such as temperature sensitive paint, or the use of suitable test fixture or telemetry in combination with thermocouples or temperature detectors.

If armature resistance measurements are to be obtained after shutdown, they should be made as quickly as possible. No attempt should be made to take resistance measurements until the rotor has stopped completely. Any apparatus that is connected to the armature terminals should be disconnected.

If the initial resistance reading cannot be made within the time interval given for the rating of the machine in table 6.1, it should be made as soon as possible and additional resistance readings should be taken at intervals of approximately 60 s until resistance readings have begun a decided decline from their maximum values. A curve of these readings should be plotted as a function of time and extrapolated to the time interval given for the rating of the machine by table 6.1. A semilogarithmic plot is recommended where resistance (or temperature) change is plotted on the logarithmic scale. The value of resistance (or temperature) thus obtained is considered as the resistance (or temperature) at shutdown. If successive measurements show increasing temperatures after shutdown, the highest value should be taken. Where the first reading cannot be taken within twice the time interval given by the table, the time should be subject to agreement between the manufacturer and the user.

In many tests, the more accurate temperatures are obtained from thermometers on the machine, from the embedded detectors, and from resistances taken while the machine is running.

6.9 Temperature rise

6.9.1 Running test

The temperature rise corresponding to readings of a particular temperature measuring device during a continuous loading test is obtained by subtracting the test reference coolant temperature (see 6.6.6) from the average of the last three half-hourly readings of the highest temperature reading device.

6.9.2 Shutdown

The temperature rises corresponding to the various readings taken on shutdown are obtained by subtracting the test reference coolant temperature (see 6.6.6) from the temperatures at shutdown as defined in 6.8.

7. Torque tests

7.1 General

For the definitions of the quantities in table 7.1, refer to IEEE Std 100-1992.

Table 7.1—Classification of various torque tests

Asynchronous quantities	Synchronous quantities
locked-rotor torque pull-up torque breakdown torque pull-in torque locked-rotor current	pull-out torque

Specific methods of test are provided for locked-rotor torque (see 7.2.2) and pull-out torque (see 7.4). Values of all synchronous quantities may be obtained from the speed-torque curve tests (see 7.3); however, other test methods are required to determine the frequencies of the pulsating torque components present at each speed.

An accurate measurement of the frequencies of the pulsating torque components is very important, specially for large salient pole synchronous motors. These torques can incite resonances with the connected mechanical systems causing excessive torsional oscillations. Unless there is sufficient damping in the system, these oscillations may grow to levels causing damages to the shaft, couplings, or gears in the drive train.

It is customary to measure the armature current and the induced field current (or voltage) during the torque tests. Specific methods of such measurements are provided as applicable.

Since most machines are designed for closed-field starting, the following procedures are written for such machines. For machines designed for open-field starting, the field voltage should be measured with a potential transformer and ac voltmeter. In this case, the field voltage should be plotted and corrected in the manner indicated for field current.

In many cases it is impractical to conduct torque tests at rated voltage. Therefore, the procedures provide for tests at reduced voltage. The results are then adjusted to specified voltage if necessary. Due to different saturation effects present at different voltages, tests at two or preferably three voltages may be necessary to enable a reasonably accurate adjustment to the specified voltage (see 7.3.6). In making this adjustment, use is made of the air-gap torque, which is the total torque applied to the rotor by the stator. At any speed, the air-gap torque is a function of voltage and frequency. The net output torque is equal to the air-gap torque minus the friction and windage torque, if the machine is running.

7.2 Locked-rotor current and torque

7.2.1 General

This test is taken to determine the armature current drawn by the motor during starting, the locked-rotor torque developed, and the resulting induced field current. It may be taken with a prony brake adjusted to prevent the motor from rotating, or a beam clamped rigidly to the motor shaft with its free end resting on a scale to measure the torque developed. An adjustable alternating-voltage supply of specified frequency is connected to the armature. The field should be closed through its starting resistance (if closed-field starting is used). In this test, the amortisseur and stator circuits heat very rapidly and the test should be made as quickly as possible. The initial test should be made at the maximum current that will not cause injurious heating during the test. Subsequent tests should be made at successively lower currents. Armature voltage, current, power, torque, and induced field current are to be recorded at each point.

For certain types of machines, the torque varies with rotor angle within a stator coil pitch. For such machines, it is necessary to make a series of preliminary tests at a constant low voltage for each of several rotor positions. The rotor should be located at the position giving the minimum torque for the subsequent tests.

7.2.2 Determination of locked-rotor current

When the machine does not have saturation effects, the locked-rotor current varies directly as the voltage, and the power as the square of the voltage. If saturation effects are present, the test should be taken at enough values to plot a curve of current vs. voltage that may be extrapolated to give the current at the specified voltage. The armature current to be plotted is the average of all phases. The data from the tests are plotted as shown in figure 7.1.

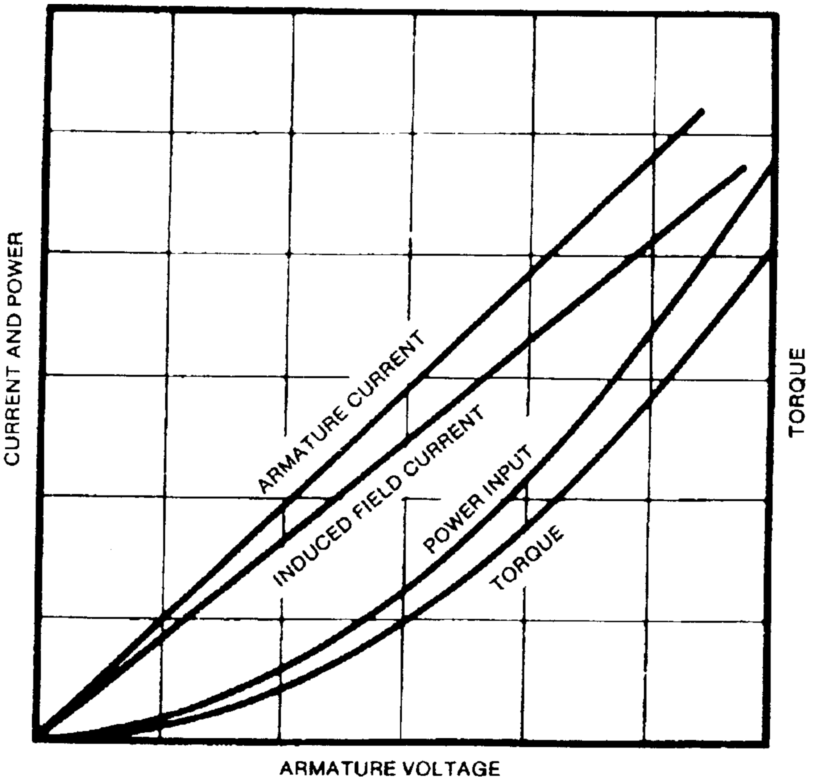


Figure 7.1—Torque characteristics with locked rotor

7.2.3 Method 1. Torque by scale and beam

In making this test, it is necessary for the beam to be perpendicular to the direction of movement of the scale. The tare of the locking beam should be subtracted from the scale reading to obtain the net force. The length of the lever arm from the center of the shaft to the point of support on the scale should be measured. The motor torque, T_t, is the product of the net force and the length of the lever arm. The air-gap torque in this case equals the mechanical output torque and hence may be calculated using equations 7-1 and 7-2.

$$T_g = T_t / T_n \text{ p.u.} \tag{7-1}$$

where

T_g is the air-gap torque at test conditions, p.u. on output base
T_t is $F \cdot l$ = mechanical output torque of motor at test condition
F is the net force, N
l is the length of lever arm, m
T_n is the base mechanical output torque of motor
T is $\dfrac{k \cdot P_{MN}}{n_s}$ (7-2)
n_s is the synchronous speed, r/min
k is 9549
P_{MN} is the rated output of motor being tested, kW

The air-gap torque is adjusted to torque at specified conditions in accordance with 7.2.5.

7.2.4 Method 2. Torque by electric input

If means for measuring the torque are not available, the rotor may be locked against turning and the torque calculated from electrical measurements. The p.u. air-gap torque is calculated as power input to the rotor in kilowatts divided by rated power output converted to kilowatts. The input to the rotor is determined by subtracting the short-circuit loss (see 4.2.8, 4.3.14, and 4.4.4) at the test current from the test power input.

For machines that have part-winding starting, or two-speed machines with consequent-pole windings, this method may have appreciable errors due to harmonics, and the locked-rotor torque should be taken by scale and beam as described in 7.2.3.

The air-gap torque is adjusted to specified conditions in accordance with 7.2.5.

7.2.5 Torque at specified conditions

Locked-rotor torque is defined as the value for the rotor position giving the minimum torque, with rated voltage applied.

The torque as determined by methods 1 or 2 may be adjusted to a value corresponding to specified voltage by the following equation:

$$T_{LR} = T_g \left(\frac{I_s}{I_t} \right)^2 \text{ p.u.} \tag{7-3}$$

where

T_{LR}	is the locked-rotor torque corresponding to specified voltage, p.u. on output base
T_g	is the air-gap torque at test conditions, p.u.
I_s	is the locked-rotor current at specified voltage (usually rated) (obtained in 7.2.2)
I_t	is the value of locked-rotor current from same test used to determine T_g, I_s and I_t should be in consistent terms.

This method of adjustment is more accurate than adjusting in proportion to the square of the voltage when saturation effects are present.

7.2.6 Determination of induced field current or voltage

For closed-field starting, the induced field current is obtained to evaluate the adequacy of the starting resistor. (For open-field starting, the induced field voltage is obtained to determine the duty on the field insulation.)

A reasonable approximation of the induced field current (or voltage) at specified armature voltage is obtained by multiplying the highest test value by the ratio of the specified armature voltage to the armature voltage corresponding to the highest-test value of induced field current (or voltage).

7.3 Speed-torque tests

7.3.1 General

Any one of the following methods may be used to determine sufficient data to plot a speed-torque curve for a motor. The selection of the method will depend upon the size and the speed-torque characteristics of the machine and the testing facilities. In all four methods, sufficient test points should be recorded to ensure that reliable curves, including irregularities, can be drawn in the regions of interest from the test data. It is important that the frequency of the power supply be maintained throughout the test at the rated value of the motor.

Methods 1 and 4 require the maintenance of constant speed for each reading. Therefore, they cannot be used in regions where the torque of the machine increases with speed increase more rapidly than that of the loading device.

From the results of the following tests, adjusted to specified voltage, curves of per-unit torque, per-unit armature current, and induced field current in amperes should be plotted vs. speed. The adjusted values for each test point should be shown on the curves. The curves for torque should always be drawn through zero at rated speed, neglecting reluctance torque near synchronous speed.

7.3.2 Method 1. Measured output

A dc generator that has had its losses previously determined, is coupled or belted to the motor being tested. The field of the motor should be closed through its normal starting resistor (if closed-field starting is used). An adjustable alternating-voltage supply of specified frequency is connected to the motor terminals. The voltage should be as high as can be impressed upon the motor terminals without excessive heating, at least 50% of rated voltage if possible. The speed of the motor for each test point is controlled by varying the load on the generator.

In this test, readings are taken at speeds between approximately 1/3 speed and the maximum speed obtainable as an induction motor. The speed should be constant at the instant the readings are taken so that acceleration or deceleration power does not affect the results. At each speed setting, readings of armature voltage, current, power, speed, and induced field current are taken for the synchronous motor, armature voltage and current, and field current for the dc generator. A record should be made of the value of the resistance connected across the field of the motor. Care should be taken not to overheat the motor at the lower speeds.

The accuracy of speed measurement is particularly important at low slip. The speed-measuring device should be accurately adjusted or calibrated at synchronous speed. All points should be read as soon as the instruments have settled, without waiting for the slow creep in the indications to disappear.

The total power output of the motor is the sum of the output and losses of the dc generator.

The air-gap torque, T_g, at each speed is calculated using equation 7-4.

$$T_g = \frac{k(P_{GO} + P_{GL})n_s}{P_{MN}(n)} + T_{FW} \qquad \text{p.u. on output base} \tag{7-4}$$

where

P_{GO} is the output of dc generator, kW
P_{GL} is the losses of dc generator (including friction and windage), kW
T_{FW} is $\frac{k(P_{FW})n_s}{P_{MN}n}$
T_{FW} is the motor friction and windage torque, per unit on output base
P_{FW} is the motor friction windage loss at speed for test point (see 4.2.6 and 4.4.2), kW
n_s is the synchronous speed of motor, r/min
n is the test speed of motor, r/min (if directly coupled, $n=n^s$)
P_{MN} is the rated output of motor being tested, kW
k is 1.0

At the speed for the test point, the torque of the motor T, adjusted to specified voltage E, is obtained from equations 7.8 or 7.10 (see 7.3.6).

7.3.3 Method 2. Acceleration

In the acceleration method the motor is started as an induction motor with no load and the value of acceleration is determined at various speeds. The torque at each speed is determined from the acceleration and the moment of inertia of the rotating parts. Accurate measurements of speed and acceleration are an essential requirement of this method. The motor should be operated from a suitable source of rated-frequency alternating-current power with adjustable voltage. The field should be closed through its starting resistor throughout the test (if closed-field starting is used).

The rate of acceleration to be used and consequently the duration of the test are determined by the type of instruments that are used to make the measurements indicated in 7.3.1. The accelerating time should be long enough so that electric transient effects do not distort the speed-torque curve. For this limitation, a minimum time of 5 s to 15 s, depending upon the characteristics of the motor and the value of the field starting resistance, is usually satisfactory. The accelerating time shall also be long enough to permit recording the necessary number of mechanical and electrical measurements with sufficient accuracy for plotting the required curves (see 7.3.1).

Where suitable automatic high-speed recorders are available, this test can be conducted with rapid acceleration consistent with the above limits. Simultaneous recordings of speed, line voltage-current, power, and induced field current vs. time should be made. Recording instrumentation is preferred to the indicating instruments. The air-gap torque at each point can be obtained by equation 7.5.

If indicating instruments are used, the accelerating time should be increased by using a lower applied voltage to permit manual recording of the required data at each point. Tachometers with significant time lag are not suitable for this test.

First the motor should be started on the minimum voltage, which will cause it to break away from rest, and its starting time should be observed. If the motor requires more than approximately 1.5 min to accelerate from 30% speed to 95% speed, the voltage should be increased until the acceleration is at about this rate. If the accelerating time is too short at minimum starting voltage, a lower voltage should be used during the test and starting friction should be overcome by turning the rotor by mechanical means or by applying a momentary higher voltage. Readings, except speed and time (at approximate 5 s intervals), need not ordinarily be taken between rest and 30% speed, since, in this range, the line currents and voltages are likely to be considerably unbalanced and fluctuating. However, in this range the average values of current and voltage change but little. From 30% speed to maximum speed, simultaneous readings should be taken at 5-s intervals of line voltage of one phase, line current in one phase, induced field current (by ac current ammeter), speed, and time in seconds.

If method 3 (see 7.3.4) is to be used as a check, line power with a polyphase wattmeter or two single-phase wattmeters should be measured at each point, and the stator winding temperature should be taken at the completion of each test.

Occasional confusion in recording data may be avoided if the timekeeper calls off the seconds—*5, 10, 15,* etc., instead of merely *read, read,* etc. It may sometimes be necessary to take more than one run at different voltages in order to get satisfactory readings throughout the curve especially when there are appreciable cusps in the speed-torque characteristic. Each test should be run at least twice at the same voltage to verify the data.

Speed-time curves should be drawn very carefully to a large scale. The acceleration, *dn/dt,* is measured at various points along the curve by holding a straight edge tangent to the curve or by the method given in 4.4.9.3.

7.3.3.4 The air-gap torque, T_g, at each speed is calculated from the acceleration using equation 7-5

$$T_g = \left(\frac{k \cdot 10^{-6} \cdot J \cdot n_s \cdot (dn/dt)}{P_{MN}}\right) + T_{FW} \qquad \text{p.u. on output base} \tag{7-5}$$

where

n_s is the synchronous speed, r/min
dn/dt is the acceleration at each speed, (r/min)/s
T_{FW} is the torque due to friction and windage at each speed (see equation 7-4), p.u. on output base
J is the moment of inertia of rotating parts, kg · m^2
P_{MN} is the rated output of motor being tested, kW
k is $(\pi/30)^2 \cdot 1000 = 10.97$

At the speed for the test point, the torque of the motor *T,* adjusted to specified voltage *E,* is obtained from equations 7-8 or 7-10 (see 7.3.6).

7.3.4 Method 3. Input

In this method, the torque is determined by subtracting the losses in the machine from the input power. It is a valuable check on the other methods, and is particularly useful when the machine cannot be unloaded to determine torque by acceleration. In practice the method is approximate because the stator losses cannot be readily determined for the actual operating conditions and shall be approximated by the losses determined from open-circuit and short-circuit tests. This method is also subject to error in the case of special machines, which may have substantial positive or negative harmonic torques that are not readily evaluated.

The machine is started as described in 7.3.3, except that it does not have to be unloaded. The input reading called for in 7.3.3.3 for the various repeated runs are plotted against the speed readings. The scale should be as large as can conveniently be used and the actual instrument readings plotted, including the wattmeter readings and the time in seconds. Average values of the zero-speed readings from the locked test, as described in 7.2, adjusted to the voltage at which the other readings were taken, should be included.

The air-gap torque, T_g, at each speed is determined from the input power using equation 7-6.

$$T_g = k\left(\frac{P_{si} - P_{sc} - P_c}{P_{MN}}\right) \quad \text{p.u. on output base} \tag{7-6}$$

where

P_{si} is the input power to stator, kW
P_{sc} is the short-circuit loss at test current (see 4.2.8, 4.3.14, and 4.4.4), kW
P_c is the open-circuit core loss at test voltage, kW
P_{MN} is the rated output of motor being tested, kW
k is 1.0

Because of the use of approximate losses in this method, no temperature correction is suggested in the short-circuit loss.

At the speed for the test point, the torque of the motor T, adjusted to specified voltage E, is obtained from equations 7.8 or 7.10 (see 7.3.6).

7.3.5 Method 4. Direct measurement

The torque may also be measured by loading the machine at various speeds with a dynamometer or prony brake. The procedures in 7.3.2 apply except that the dc generator is replaced by a dynamometer or prony brake, and torque readings only are taken in place of electrical data on the dc generator. The use of a prony brake is limited to tests on very small machines because of its limited capacity to dissipate heat. The torque of a prony brake is approximately constant at a given setting.

The air-gap torque, T_g, at each speed is calculated from the torque readings, T_t, using equation 7-7.

$$T_g = \frac{T_t}{T_n} + T_{FW} \quad \text{p.u. on output base} \tag{7-7}$$

where

T_t is the mechanical output torque of motor at test conditions
T_n is the base mechanical output torque of motor (see equation 7-2)
T_{FW} is the torque due to motor friction and windage at each speed (see equation 7-4), p.u. on output base

At the speed for the test point, the torque of the motor T, adjusted to specified voltage E, is obtained from equations 7-8 or 7-10 (see 7.3.6).

7.3.6 Correction for voltage effects

At the speed for each test point, the net output torque of the motor T, and the armature current I, corrected to specified voltage E, is obtained from equations 7-8 through 7-11, as applicable.

When the difference between the test voltages and the specified voltage is small, constant exponent correction is sufficiently accurate as follows:

$$T = T_g\left(\frac{E}{E_t}\right)^{K_1} - T_{FW} \quad \text{p.u. on output base} \tag{7-8}$$

$$I = I_t\left(\frac{E}{E_t}\right)^{K_2} \quad \text{p.u. on output base} \tag{7-9}$$

where

E_t is the line-to-line voltage of motor at test point, p.u.
T_g is the air-gap torque at test point corresponding to voltage E_t p.u. on output base
T_{FW} is the torque due to motor friction and windage at speed for the test point (see equation 7.4), p.u. on output base
I_t is the armature current at test point corresponding to voltage E_t p.u.
K_1 is $\dfrac{\log_{10}(T_1/T_2)}{\log_{10}(E_1/E_2)}$
K_1 is the torque exponent of voltage ratio ($K_1 = 2$, neglecting saturation effects)
K_2 is $\dfrac{\log_{10}(T_1/T_2)}{\log_{10}(E_1/E_2)}$
K_2 is the current exponent of voltage ratio ($K_2 = 1$, neglecting saturation effects)
E_1 is the convenient line voltage at which T_1 and I_1, were measured, p.u.
E_2 is the convenient line voltage at which T_2 and I_2 were measured, p.u.
T_1 is the air-gap torque measured at line voltage E_1, p.u. on output base
T_2 is the air-gap torque measured at line voltage E_2, p.u. on output base
I_1 is the armature current measured at line voltage E_1, p.u.
I_2 is the armature current measured at line voltage E_2, p.u.

For maximum accuracy of correction for voltage effects, tests at three different voltages are required. Uncorrected values of air-gap torque and armature current are plotted on semilogarithmic paper, with corresponding line voltages on the linear scale. A straight line is drawn through each set of test points. Such plots, as shown in figure 7.4, provide a convenient means of extrapolation to any specified voltage up to 120% of the highest voltage test point.

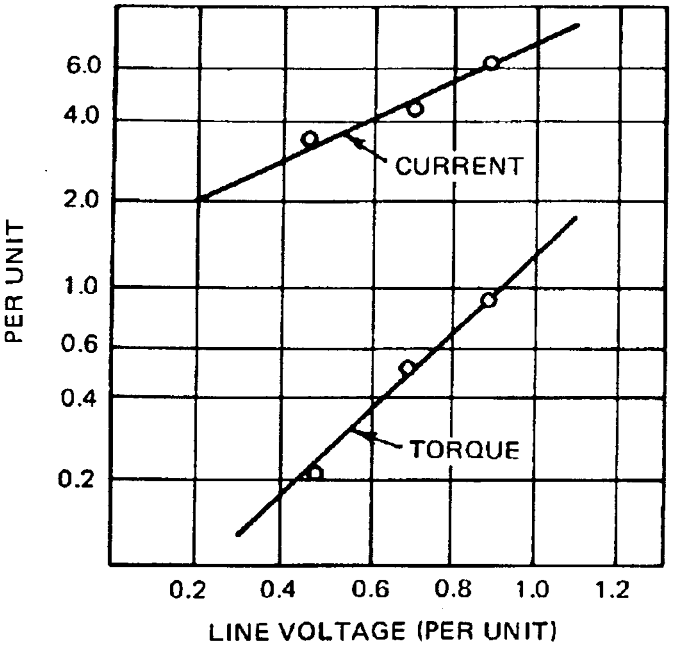


Figure 7.2—Correction for voltage effects

Corrected air-gap torque and armature current values for any specified voltage condition can be calculated from equations 7-10 and 7-11, respectively:

$$T_g \quad \text{is } \varepsilon^{f1(E)} \quad \text{p.u. on output base} \tag{7-10}$$

$$T \quad \text{is } \varepsilon^{f2(E)} \quad \text{p.u.} \tag{7-11}$$

where

T_g is the air-gap torque, corrected to specified voltage, E, p.u. on output base
I is the armature current, corrected to specified voltage E, p.u.
$\in$ is the base of natural logarithms (ln)
$\in$ is 2.71828...

$f_1(E)$ is $\frac{E-E_1}{E_2-E_1}\ln\frac{T_2}{T_1} + \ln T_1$ where $f_1(E)$ is the saturation function, torque

$f_2(E)$ is $\frac{E-E_1}{E_2-E_1}\ln\frac{I_2}{I_1} + \ln I_1$ where $f_2(E)$ is the saturation function, current

E_1 and $E_2$are convenient test voltages, p.u.
T_1 is the air-gap torque measured at a low voltage E_1, p.u. on output base
T_2 is the air-gap torque measured at a high voltage E_2, p.u. on output base
I_1 is the armature current measured at a low voltage E_1, p.u.
I_2 is the armature current measured at a high voltage E_2, p.u.

The air-gap torque, which is the total torque applied to the rotor by the stator, is the torque that should be adjusted to specified voltage. Usually the magnitude of the torque due to friction and windage is large enough to be a significant part of the air-gap torque; therefore equations 7-4, 7-5, and 7-7 contain the term T_{FW}. Equation 7-6 contains this quantity because the friction and windage loss is not subtracted from the input power. If the torque, due to friction and windage, is not a significant part of the air-gap torque, it may be omitted from the calculations.

The induced field current should be adjusted in direct proportion to the ratio of armature current adjustment.

For greater accuracy, the adjusted values of torque, armature current, and induced field current obtained from equations 7-10 and 7-11 should be used in place of equation 7-3 to plot the curves described in 7.2.

7.4 Pull-out torque

7.4.1 Method 1. Direct measurement

The motor is operated and the load is increased, keeping the voltage, frequency, and field current at specified values (normally rated-load values) until pull-out occurs. The armature input power and current are read at various points up to the maximum stable load. The losses of the motor at this maximum load are determined and subtracted from the input to obtain the maximum output power. The maximum output power divided by rated output in consistent units is the per-unit pull-out torque. This method is usually not practicable for large machines.

7.4.2 Method 2. Calculation from machine constants

For machines for which it is impracticable to employ method 1, an approximate value of the pull-out torque, T_{PO}, at specified voltage and field current (normally rated-load values) may be calculated by the following equation:

$$T_{PO} = \frac{KI_{FL}E_s}{I_{FSI}\eta\cos\theta}\text{ p.u.} \tag{7-12}$$

where

T_{pO} is the pull-out torque, p.u. of base mechanical output torque
E_S is the specified terminal voltage, p.u.
I_{FL} is the specified field current, A or p.u.
I_{FSI} is the field current corresponding to base armature current on the short-circuit saturation curve, in same units as I_{FL}
$\cos\theta$ is the rated power factor
η is the efficiency at rating, p.u.

The factor K in equation 7-12 is to allow for reluctance torque and for positive-sequence I^2R losses. This factor may be obtained from the machine manufacturer. It is usually in the range from 1.00 to 1.25 and may occasionally be as large as 1.5. If the positive-sequence resistance (R_1) is less than 0.01 p.u. (the usual case), the factor K can be calculated by determining the maximum value of equation 7-13 as a function of δ.

$$K = \sin\delta + \frac{I_{FSI}E_S(X_{ds} - X_{qs})}{2I_{FL}X_{ds}X_{qs}}\sin 2\delta \tag{7-13}$$

where

X_{ds} is the direct-axis saturated synchronous reactance, p.u.
X_{qs} is the quadrature-axis saturated synchronous reactance, p.u.
δ is the load angle between terminal voltage and the voltage that would be generated by field current acting alone.

Losses at pull-out condition are neglected in this analysis. This does not affect appreciably the accuracy of this approximate method.

8. Sudden short-circuit tests

8.1 Mechanical integrity of machine

One of the purposes of short-circuit testing is to ensure the mechanical integrity or fitness of the machine. During its lifetime of service, depending upon its use either as a generator, or as a large industrial-size motor, the machine will be subject to sudden changes in load, either due to faults on the power system (or industrial system) or due to full load rejection, or sudden requirements for increases or decreases in power output due to governor action.

Thus, in addition to meeting the mechanical stresses due to (usually) three-phase short-circuit tests, the mechanical strength of the machine is measured in a qualitative manner.

Before making these tests the manufacturer should be consulted. The machine should be carefully inspected to see that the bracing of the stator coil ends is satisfactory, the foundation is in good condition, and the hold-down bolts are tight. The rotor should be inspected to see that all keys and bolts are in place and properly tightened.

8.2 Electrical integrity of machine

Insofar as the electrical integrity of the machine is concerned, there are insulation and other types of overvoltage tests to quantify the electrical operation performance, per IEEE Std 4-1995 and IEEE Std 43-1974.

During short-circuit testing, certain precautions are required in preparing the electric connections because of the abnormal conditions that attend a sudden short-circuit test. Very heavy currents flow, particularly on large machines, resulting in great forces on the test conductors. To prevent damaging movement, test conductors should be securely braced.

The armature circuit should be solidly grounded at a single point using a conductor of size comparable to the leads from the machine terminals. There are two choices for the location of this ground connection: the neutral of a wye-connected armature winding, or the point common to the three contacts of the shorting circuit breaker. If shunts are used in measuring the currents, their common point should be where the ground connection is made so as to avoid hazardous voltages at the oscillograph or recorder in case of a mishap. If current transformers are used in measuring armature current, the point common to their primaries should be where the ground connection is made, unless they are insulated to withstand full line-to-line armature voltage. If the armature circuit is not solidly grounded, then high-voltage insulation equipment should be used between the shunts or current transformers and the data-taking devices.

All protective relays which could cause the field circuit breaker to trip should be made inoperative. A discharge resistor of sufficiently low value should be used so that if the field circuit breaker were to trip, the voltage across the field winding would not be excessively high.

The electric or mechanical integrity of the machine is not a major consideration during standstill frequency response testing. Those factors, which experience has shown should be at least recognized, are spelled out in chapter 12 of part II on standstill frequency response (SSFR) testing.

IEEE Guide: Test Procedures for Synchronous Machines

Part II—Procedures for parameter determination for dynamic analysis

9. Applications of machine electrical parameters

9.1 General

The original background work on IEEE Std 115 was published in 1945, and the first "official" version of the standard is dated 1965. Prior to the period from 1945 to 1965, synchronous machine transient and subtransient quantities had been originally developed and applied to determine fault currents under both balanced and unbalanced conditions.

Some of these short circuit "parameters" were also converted for use in stability studies, using analog (of network) computers, starting in the 1930s and subsequently continuing up to the 1950s. These relatively simple analogue studies considered a synchronous machine's stability response to be provided by a constant voltage behind a transient reactance. This simplification provided suitable answers to a majority of power system analysts. Exceptions to this were studies conducted using mechanical or electronic differential analyzers.

The advent of high-initial-response excitation systems, along with the development of digital computers, brought forth more sophisticated modelling of the dynamic properties of both machines and their associated excitation controllers. In addition to time-domain digital simulations, small-signal, linear eigenvalue analyses became prevalent for synchronous machines connected through power system networks.

All this analytical activity commencing around the time of the first publication of IEEE Std 115 in 1965 has accentuated the requirements for additional methods for determining synchronous machine stability or electrical quantities. Such features as determining characteristic quantities (time constants and reactance) or stability (network) models for both direct- and quadrature-axis representation became the norm. While second-order models had been used extensively from 1945 to 1965 and beyond, third-order (or higher-order) models appeared to be required for some types of excitation-system studies. These requirements led to IEEE Std 115A-1987 for describing standstill-frequency-response testing. This dealt with testing of turbo alternators, particularly for parameter determination and third-order d- and q- axis model development.

Section 10 discusses those synchronous machine quantities required for system studies and analysis of steady-state operation.

Procedures for testing and parameter determination methods for short-circuit testing are given in section 11, while similar tests and stability model development through standstill-frequency-response methods are given in section 12.

Synchronous-machine electrical parameters are used in a variety of power system problems. In the steady state, a knowledge of the direct-axis synchronous reactance X_{du}, and the quadrature axis synchronous reactance X_{qu} is required to determine, after appropriate adjustments for saturation, the maximum value of reactive power output (Q), for certain armature terminal conditions. Such maximum reactive power outputs are basically a function of the field excitation. Calculation of field excitation, using saturated values of X_{du} and X_{qu} is discussed in section 5 of Part I. The reactive power output capabilities of generators are used in load-flow studies for control of power systems (grid) voltages and supply of load reactive powers. As a corollary to this, the above mentioned synchronous reactances are used to determine the approximate values of reactive-power which can be absorbed by a synchronous machine. This is sometimes studied in load-flow studies under system minimum-load conditions.

The transient or subtransient reactances whose derivation will be discussed in section 11 are used in relay application studies of system protection. Included in this area of analysis are circuit-breaker fault interruption requirements. The effect of magnetic saturation on synchronous reactance must also be accounted for. For the purposes of specification and/or test, the values of transient or subtransient reactance shall be determined for one or more nominal conditions, i.e., rated voltage or rated current. This is also discussed in 6.3 of IEEE Std 1110-1991.

Since the correction for other conditions is usually not large, the nominal values may be used or the correction may be estimated or determined approximately from empirical curves based upon tests of typical machines. However, when agreed upon, values for other conditions may be determined by test, as described in sections 10, 11, or 12.

Synchronous-machine reactances are generally substantially equal in magnitude to their corresponding impedances and are usually so considered in interpreting test results, the resistance components being disregarded.

In all of the above mentioned sections, the distinction between test procedures and parameter determination has been stressed.

9.2 Per unit quantities

9.2.1 Comments

Subsequent sections of this guide provide methods for determining machine reactances and resistances in per unit, because this is the form most often desired by the user, and is frequently the basis for guarantees when included in contracts. Time constants are evaluated in seconds. (See IEEE Std 86-1987.)

To avoid error in the use of per-unit quantities, care should be used in defining clearly the per-unit base used for each quantity and making sure all base quantities are consistently chosen. The preferred procedure is to select only three base quantities and to derive the others from these three. The three normally chosen are three-phase base power, $S_{N\Delta}$, line-to-line base voltage, $E_{N\Delta}$, and base frequency, f_N. Each physical measurement is expressed in per-unit when so desired by dividing the physical value by the corresponding base quantity, expressed in the same units. Conversely, any quantity in per unit can be converted to physical units by multiplying by the base value. Any per-unit quantity expressed on one base can be converted to another base by multiplying by the old base quantity and dividing by the new.

9.2.2 Base power

For a generator, base three-phase power ($S_{N\Delta}$) is taken as the rated kilovoltampere output of the machine.

For a motor, base three-phase power is taken as the apparent power *input* to the machine when operating at rated voltage and power factor and delivering rated load.

The base power is usually expressed in kilovoltamperes, but multiple or submultiple units, such as mega-voltamperes and voltamperes, can be used, with appropriate modifications in the equations (see 9.2.4).

Single-phase power measurements, as may be needed in a test procedure, are normally expressed in per unit of the base power for one phase. Base single-phase power, S_N, is derived from the base three-phase power, $S_{N\Delta}$, by equation 9-1.

$$S_N = \frac{S_{N\Delta}}{3} \text{ base single-phase power, in kilovoltamperes, or megavoltampe} \tag{9-1}$$

where

$S_{N\Delta}$ is the base three-phase power, in kilovoltamperes, or megavoltamperes

9.2.3 Base voltage and current

Base line-to-neutral voltages and other single-phase voltages, as may be specified in this guide, are expressed in per unit by dividing by the base line-to-neutral voltage, E_N. The base line-to-neutral voltage is obtained from the base line-to-line voltage by equation 9-2.

$$E_N = \frac{E_{N\Delta}}{\sqrt{3}} \text{ base line-to-neutral voltage, in volts, or kilovolts} \tag{9-2}$$

where

$E_{N\Delta}$ is the base line-to-line voltage, in volts, or kilovolts

Base line-to-line voltage, $E_{N\Delta}$, is normally selected equal to the rated line-to-line voltage, $E(_{LL})$. Both the volt and kilovolt (rms) are in common use as the unit in which the base voltage is expressed. In this guide, the volt (rms) will normally be used, but the kilovolt (or other multiple) will be used with appropriate modifications in the equations. A line-to-line voltage (whether alternating or direct) is expressed in per unit by dividing its value by the base line-to-line voltage, expressed in the same units.

For balanced sinusoidal conditions the per unit values of corresponding line-to-line and line-to-neutral voltages are the same.

Base line current, I_N, is obtained from the base power and base voltage and is equal to the current per line when the circuit is carrying base power at base voltage. It may be derived either from the base three-phase power and base line-to-line voltage or from the base single-phase power and base line-to-neutral voltage by equation 9-3.

$$I_N = \frac{1000\ S_{N\Delta}}{\sqrt{3}E_{N\Delta}} = \frac{1000\ S_N}{E_N} \text{ base line current amperes} \tag{9-3}$$

where

$S_{N\Delta}$ is the base three-phase power, kilovoltamperes
S_N is the base single-phase power, kilovoltamperes
$E_{N\Delta}$ is the base line-to-line voltage, volts
E_N is the base line-to-neutral voltage, volts

Alternatively,

$$I_N = \frac{S_{N\Delta}}{\sqrt{3}E_{N\Delta}} = \text{ base line current kiloamperes} \tag{9-4}$$

where

$S_{N\Delta}$ is the base three-phase power, megavoltamperes
$E_{N\Delta}$ is the base line-to-line voltage, kilovolts

For delta-connected machines, a base current for one phase of the delta winding, denoted by $I_{N\Delta}$, would be appropriate for expressing individual winding currents in per unit. If needed, it would be found from equation 9-5.

$$I_{N\Delta} = \frac{S_{N\Delta}}{3E_{N\Delta}} = \text{ base delta current, kiloamperes} \tag{9-5}$$

where the quantities are expressed in the same units as in equation 9-4.

Each current is expressed in per unit by dividing its value by the corresponding base, in the same units.

If instantaneous currents or voltages are to be expressed in per unit, it is recommended that the same base values be used as for root-mean-square (rms) currents and voltages. If this practice is followed, the usual relations between instantaneous, average, and rms currents or voltages will apply, whether the results are expressed in physical values or in per-unit values.

9.2.4 Base impedance

$$Z_N = \frac{E_N}{I_N} \text{ base impedance, ohms } = \frac{E_N}{I_N} \cdot \frac{E_N}{E_N} = \frac{(E_N)^2}{\text{VA}} \tag{9-6}$$

The base impedance is that value of impedance which would allow base line current to flow if base line-to-neutral voltage were impressed across it, as expressed by equation 9-6.

The results can also be expressed in terms of the base power and base voltage by substituting from equations 9-2 and 9-3, as shown by equation 9-7.

$$Z_N = \frac{(E_{N\Delta})^2}{1000\ S_{N\Delta}} = \frac{(E_N)^2}{1000\ S_N} \text{ base impedance, ohms} \tag{9-7}$$

where the quantities are expressed in the same units as in equation 9-3.

The same base shall be used whether the impedance is a resistance, a reactance, or any combination.

9.2.4.1 Additional comments on stator and rotor base impedances

In the latter part of this subclause, the nomenclature used for stator *per unit* voltage is E_a, and for stator *per unit* current is I_a. This corresponds to the nomenclature used in clause 2 of IEEE Std 1110-1991. It is also used in 5.2.2 of Part I of this document. Note also that base voltage is expressed above in 9.2.3 as $E_{N\Delta}$ or E_N (see equation 9-2). Base current is expressed as I_N (see equation 9-3). An alternate expression to equation 9-7 for stator base impedance, applied especially for larger size machines, is as follows:

$$Z_N = \frac{(E_{N\Delta})^2}{S_{N\Delta}} \text{ base impedance, ohms} \tag{9-8}$$

where

$E_{N\Delta}$ is the machine stator terminal base kilovolts, line to line
$S_{N\Delta}$ is the three-phase megavoltamperes of the machine

Z_N can also be expressed in a single phase basis as follows:

$$Z_N = \frac{(E_N)^2}{S_N}, \text{ base impedance, } \Omega \tag{9-9}$$

where

E_N is the machine stator terminal base kilovolts, line-to-neutral
S_N is the single-phase megavoltamperes of the three-phase machine

The base impedance Z_N is in terms of single phase, line-to-neutral ohms. This holds true irrespective of whether one is calculating on a single-phase, line-to-neutral basis, or calculating on a three-phase, line-to-line basis.

In some of the issues being discussed in section 12 of this document, the field circuit base ohms, referred to the stator is given as

$$Z_{fdbase} = \frac{\text{machine voltamperes (three phase)}}{(i_{fdbase})^2} = \frac{3(E_N \cdot I_N)}{(i_{fdbase})^2}\ \Omega \tag{9-10}$$

where

E_N and I_N are as defined in equations 9-2 and 9-3

The i_{fdbase} is that field current excitation in amperes required to induce a per unit voltage E_a on the open circuit air gap line of the machine equal to $I_a \cdot X_{adu}$. E_a is in per unit of $E_{N\Delta}$ or E_N kilovolts. I_a is 1.0 per unit stator current on the machine stator current base of I_N. X_{adu} in per unit is defined in 10.2.1.

The convention is to per-unitize field circuit, and the rotor equivalent circuit resistances and inductances, and to refer these physical resistance and inductance values to per unit values as viewed from the stator terminals. In so doing direct and quadrature axis stability models can be readily applied and analyzed in large power system studies.

There is a relationship between the i_{fdbase} and the more commonly encountered I_{fdbase}. This was originally discussed by A.W. Rankin in great detail in B25[8]. Rankin designated the i_{fdbase} as the reciprocal system. Rankin developed this system by indicating that the stator to field and field to stator per unit mutual inductances were equal or reciprocal in value. An alternate (non-reciprocal) I_{fdbase} was also discussed in B25. This non-reciprocal base field current in amperes is that required to induce 1.0 per unit volts (or kilovolts), E_a, on the open circuit air gap line.

The relationship between the two field current bases is

$$i_{fdbase} = I_{fdbase}(\bar{X}_{adu}) \tag{9-11}$$

The equation 9-11 relationship is also shown graphically in figures 9.1 and 9.2. This conversion from the reciprocal system to the non-reciprocal system is also discussed more fully, with numerical examples, in section 7 of IEEE Std 1110-1991.

9.2.5 Base frequency

The base frequency is regularly selected as equal to rated frequency. From this value, base electrical angular velocity, ω_N, and base time, t_N, if needed, are obtained by equation 9-10.

$$\omega_N = 2\pi f_N \ \text{rad/s, or} \ t_N = \frac{1}{f_N} \tag{9-12}$$

A time constant, given in seconds, may be converted to per unit by dividing by t_N. However, in accordance with usual practice, this guide is arranged so that the formulas express time constants in seconds.

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[8] The numbers in brackets correspond to those bibliographic items listed in annex C.

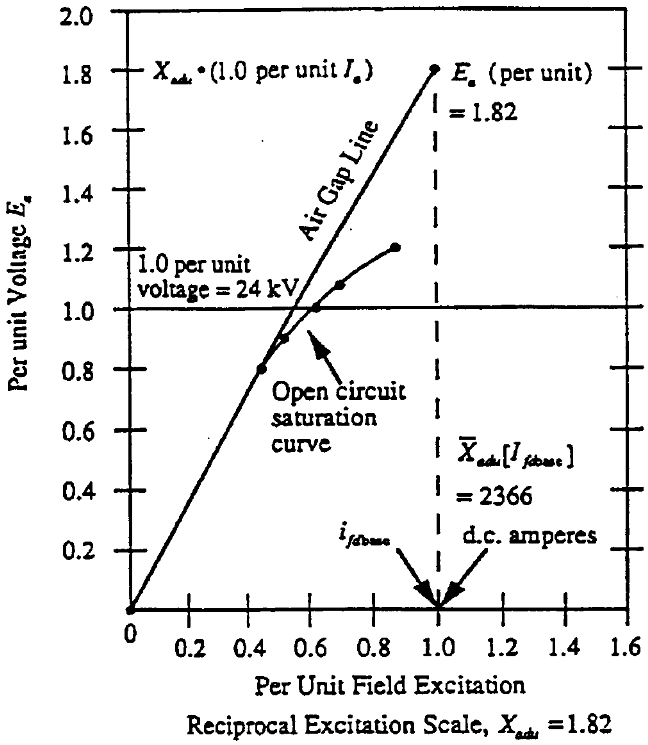


Figure 9.1—Per unit field excitation Reciprocal excitation scale, $X_{adu} = 1.82$

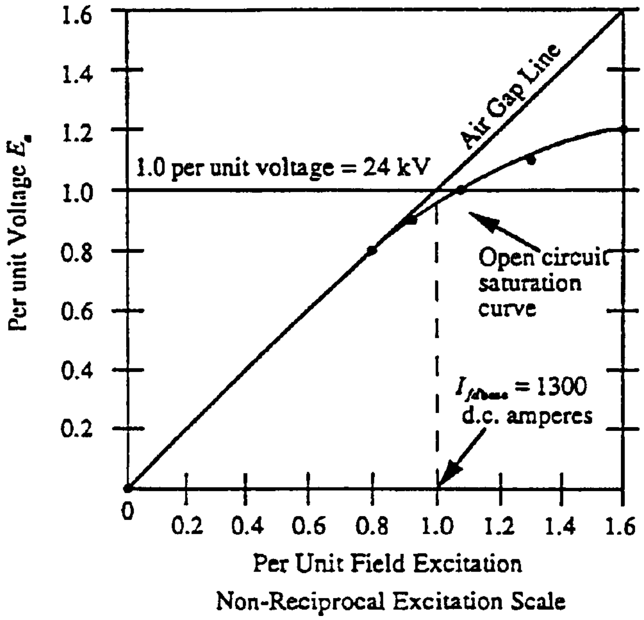


Figure 9.2—Per unit field excitation Non-reciprocal excitation scale

10. Tests for determining parameter values for steady-state conditions

10.1 Purpose

Some of the steady-state tests suggested in this section are required for analyzing the performance of a synchronous machine under normal operating conditions. Under such conditions, changes in MVA output or in terminal voltage conditions are relatively small or slow. In addition, machine conditions are balanced; that is, all three phases are carrying the same current and each of the three-phase voltages are equal and 120° apart in electrical displacement.

Unbalanced but relatively steady conditions are also of interest, even though they can sometimes be tolerated only for a few seconds or at most a few minutes. Negative or zero sequence reactances or resistances are used for analyses of these conditions. Such quantities affect the performance of the machine and, in this sense, could also have been considered in Part I of this document. However, since some of these sequence quantities are used in stability studies or in dynamic analyses they are included in Part II. In any case, tests for such parameters sometimes need to be performed to ensure compliance with design values.

This section starts with an investigation of synchronous reactance and concludes with recommended practices for determining internal electrical (load) angles. For single-phase machines or for polyphase machines of other than three phases, modifications to some tests may be required, but test procedures can usually be determined after consultations with designers or manufacturers of such machines.

10.2 Instrumentation

The instrumentation required for most of the tests outlined in this clause is the usual array of current and/or voltage transformers, and the associated ammeter, voltmeter or wattmeter configurations required in three-phase measurements. Phase-angle measurements require special instrumentation as described in 10.8.2.

10.2.1 Types of parameters to be determined

The following is a list of quantities some of which are derived (usually in per unit) from steady-state tests. Parameters are listed in the order in which the test procedures occur and are described in 10.3 to 10.8 (see IEEE Std 100-1992) .

X_{du}	Unsaturated direct-axis synchronous reactance, as defined by test
X_{ds}	Some particular saturated value of X_{du}, which depends on synchronous machine terminal voltage, as well as machine MVA and power factor
X_{adu}	Unsaturated direct axis synchronous mutual reactance which is the portion of X_{du} assumed to be subject to saturation. $X_{du} = X_{adu} + X_l$. X_l is the synchronous machine stator leakage reactance.
X_{ads}	The saturated portion of X_{ds}, where $X_{ds} = X_{ads} + X_l$.
X_q	The quadrature axis synchronous reactance
X_{qs}	The quadrature axis synchronous reactance, as defined by tests
X_2	Negative-sequence reactance, as defined by tests
R_2	Negative-sequence reactance, as definted by tests
X_0	Zero-sequence reactance, as defined by tests
R_0	Zero-sequence resistance, as defined by tests
SCR	Short Circuit Ratio, as defined by test
δ	Internal electrical angle

10.3 Direct-axis synchronous reactance (X_d)

For 10.3 and 10.4, the determination of parameters follows immediately after the description of the test procedures.

For the definitions of direct-axis synchronous reactance and impedance, see IEEE Std 100-1992. The definitions are not test-related, and are based on rated armature current.

For machines of normal design, the magnitude of the direct-axis synchronous reactance is so nearly equal to that of the direct-axis synchronous impedance that the two may be taken to have the same numerical value.

The unsaturated direct-axis synchronous impedance can be derived from the results of the open-circuit saturation test (see 4.2.4) and the short-circuit saturation test (see 4.2.7). This synchronous impedance in per unit is equal to the ratio of the field current at base armature current, from the short-circuit test, to the field current at base voltage on the air-gap line (see 4.2.5).

In terms of the quantities identified in figure 5.1 in part I, synchronous reactance can be calculated using equation 10-1. In figure 5.1, base values are plotted as 1.0 p.u. Figure 5.1 can also be plotted with base values in actual amperes or volts.

$$X_{du} = \frac{I_{FSI}}{I_{FG}} \quad \text{in per unit} \tag{10-1}$$

where

X_{du} is the unsaturated synchronous reactance
I_{FSI} is the field current corresponding to base armature current on the short-circuit saturation curve
I_{FG} is the field current corresponding to base voltage on the air-gap line

Saturated values of synchronous reactance (X_{ds}) depend upon synchronous machine operating conditions. As noted in section 5, X_d is assumed to be composed of X_{ad}, the stator to rotor mutual reactance plus X_l the stator leakage reactance. Thus, in general

$$X_d = X_{ad} + X_l$$

where

X_{ad} is the saturated portion of X_d

As a corollary,

$$X_{du} = X_{adu} + X_l$$

When X_{ad} is saturated to any degree, (X_{ads}), then

$$X_{ds} = X_{ads} + X_l$$

10.4 Quadrature-axis synchronous reactance (X_q)

10.4.1 General

For the definition of quadrature-axis synchronous reactance, see IEEE Std 100-1992. This definition is not test related, and is based on rated armature current. There is no clear definition of either the unsaturated or the saturated value of X_q, but the usual assumption is that $X_q = X_{aq} + X_l$. X_{aq} is that portion of X_q subject to saturation, similar to the practice in 10.3.3. As a corollary $X_{qu} = X_{aqu} + X_l$. Similar assumptions regarding X_{qs} are that it equals $X_{aqs} + X_l$.

10.4.2 Procedures for conducting a slip test—Method 1 for measuring X_{qs}

The slip test is conducted by driving the rotor at a speed very slightly different from synchronous with the field open-circuited and the armature energized by a three-phase, rated-frequency, positive-sequence power source at a voltage below the point on the open-circuit saturation curve where the curve deviates from the air-gap line. The armature current, the armature voltage, and the voltage across the open-circuit field winding are observed. Best results are obtained from oscillograms. If meters are used, the field voltage should be measured by a zero-center dc voltmeter. (Since the currents and voltages in the three phases are balanced, any line-to-line voltage and the current in any line can be used). Figure 10.1 illustrates the method, although the slip shown to illustrate the relationships is higher than should be used in practice.

The slip may be determined as the ratio of the frequency of the voltage induced in the field to the frequency of the applied voltage.

The slip may also be determined by the use of a stroboscope energized from the same frequency as the applied voltage illuminating equally spaced marks on the rotor, the number of marks being equal to the number of poles. The slip frequency is the apparent rate of progression of the marks in the revolutions per second multiplied by the number of pairs of poles, and the slip is the ratio of slip frequency to the frequency of the applied voltage.

10.4.2.1 Precautions

It is sometimes quite difficult to maintain constant speed when the slip is sufficiently low for an accurate determination of the quadrature-axis synchronous reactance, because the effects of salient poles and the currents induced in the amortisseur winding produce a pulsating torque. In such cases, a series of readings may be taken, starting with the smallest slip at which constant or nearly constant speed can be maintained and making three or more tests at progressively greater slips.

The induced voltage in the open field circuit may reach dangerous values when the slip is large (more than approximately 5%), or when switching surges occur due to opening the ac lines. To guard against damage from high voltage, a fast-acting short-circuiting switch (such as a remote-controlled field circuit breaker) should be connected across the field. As an additional protection, a low-voltage spark gap may also be connected across the field. The switch should be closed except when it is known that the slip is near zero and readings are to be taken. The instruments should be disconnected from the field circuit until it is assured that induced voltages are less than the voltage ratings of the instruments. Because of the difficulty frequently encountered in maintaining the desired slip during the test, it is necessary to observe continuously the field voltage and to be prepared to short-circuit the field promptly to avoid dangerously increasing the voltage across the instruments.

If the slip is sufficiently low and the speed is quite constant, indicating instruments will follow the voltage and current variations accurately enough to permit their use. Simultaneous readings of current and voltage should be made when the current reaches its lowest and highest values. The synchronous reactance is determined in the same way as when an oscillograph is used.

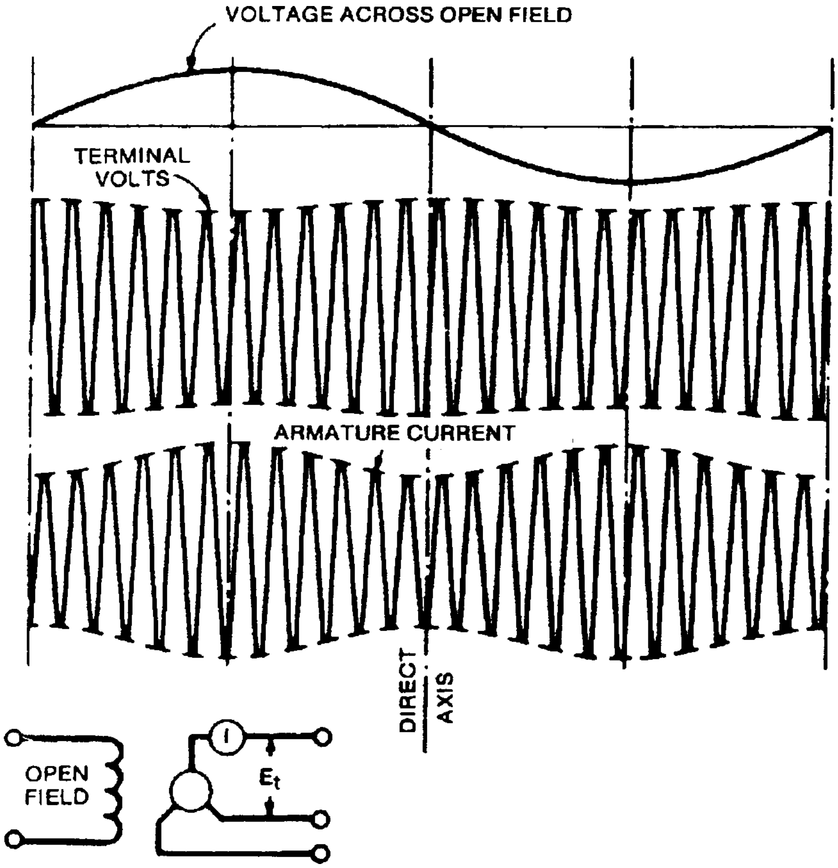


Figure 10.1—Slip method of obtaining quadrature-axis synchronous reactance, method 1

10.4.2.2 Determination of the parameter X_{qs} from method 1—Slip test

The minimum and maximum ratios of the armature voltage to the armature current are obtained when the slip is very small. From these, approximate values of quadrature-axis and direct-axis synchronous reactance (X_{qs} and X_{ds}) can be obtained by equations 10-2 and 10-3, but for best results these values are not taken as final values. The most accurate method is to determine the direct-axis synchronous reactance (X_{du}) by test (see 10.3.3) and to obtain the quadrature-axis synchronous reactance by equations 10-4 or 10-5.

$$X_{qs} = \frac{E_{min}}{I_{max}} \quad \text{p.u. (a certain saturated value)} \qquad (10\text{-}2)$$

$$X_{ds} = \frac{E_{max}}{I_{min}} \quad \text{p.u. (a certain saturated value)} \qquad (10\text{-}3)$$

$$X_{qu} = X_{du}\left(\frac{X_{qs}}{X_{ds}}\right) \quad \text{p.u.} \qquad (10\text{-}4)$$

$$X_{qu} = X_{du}\left(\frac{E_{min}}{E_{max}}\right)\left(\frac{I_{min}}{I_{max}}\right) \quad \text{p.u.} \qquad (10\text{-}5)$$

The minimum ratio (see equation 10-2) occurs when the field voltage is a maximum while the maximum ratio (see equation 10-3) occurs when the field voltage passes through zero, as indicated in figure 10.1.

If the slip is not extremely low, currents induced in the amortisseur winding will produce an appreciable error.

NOTE — A curve of "apparent" quadrature-axis synchronous reactance as a function of slip may be extrapolated to zero slip to give the test value of the quadrature-axis synchronous reactance.

10.4.3 Method 2—Maximum lagging current

The machine to be tested is run as a synchronous motor with no driven load, with applied test voltage not greater than 75% of normal, and with approximately normal no-load excitation. The field excitation is then reduced to zero, reversed in polarity, and then gradually increased with the opposite polarity, causing an increase in armature current. By increasing the negative excitation in small increments until instability occurs, the p.u. armature current I_t corresponding to the maximum stable negative excitation is determined. This gives a saturated value, X_{qs}.

10.4.3.1 Determination of X_{qs} from method 2

The quadrature-axis synchronous reactance is obtained as follows:

$$X_{qs} = \frac{E}{I_t} \qquad \text{p.u.} \tag{10-6}$$

where

E is the p.u. armature voltage
I_t is the p.u. armature current at stability limit

10.4.4 Method 3—Empirical

The ratio of the quadrature-axis synchronous reactance to the direct-axis synchronous reactance, for a conventional machine, can be determined by an empirical function of a few significant machine dimensions and can therefore be calculated by the manufacturer from these dimensions. The quadrature-axis unsaturated synchronous reactance is then determined by multiplying the direct-axis unsaturated synchronous reactance, determined by test (see 10.3.3), by the ratio furnished by the manufacturer.

NOTE — Since the empirical function usually used does not provide for all the factors affecting the ratio of X_{qu} to X_{du}, this method is not exact. When the machine is not of conventional design proportions, or a more realistic value of X_{qs} is required, method 1 or 2 could be used.

10.4.5 Method 4—Load angle

The various load angle determinations of section 10.8.2 may be used with voltage and current measurement to determine X_{qs}. Equation 10-28 of 10.8.2.2 may be used to derive X_{qs} from such data.

10.5 Negative-sequence quantities (Steady state)

10.5.1 Negative-sequence reactance (X_2)—General

For the definition of negative-sequence reactance, see IEEE Std 100-1992.

10.5.1.1 Precautions

As is pointed out in the definition referred to in 10.5.1, the presence of current harmonics may modify the fundamental negative-sequence voltage without a corresponding change in the fundamental negative-sequence current. Therefore, the apparent negative-sequence reactance is affected by the presence of harmonic currents. These effects are most pronounced in salient-pole machines without amortisseur windings or with amortisseur windings that are not connected between poles. They are usually insignificant in solid-steel cylindrical-rotor machines or in machines with effective amortisseur windings in both axes that are directly connected between poles. The basic test for negative-sequence reactance would require the application of sinusoidal fundamental-frequency negative-sequence *currents* and the measurement of the fundamental-frequency component of the negative-sequence terminal voltage. However, for certain types of machines (see 10.5.2) it may be impractical to maintain sinusoidal test currents. Also, it is almost always impracticable to make such a test at conditions that correspond to the rated-voltage value of negative-sequence reactance. Therefore, it is frequently desirable to determine the negative-sequence reactance by other test methods, and to allow for the effects of harmonic currents by applying a suitable correction factor. In the following subclauses, correction factors are specified which depend upon a knowledge of the direct-axis subtransient reactance, X''_d, determined for comparable conditions, by the short-circuit tests given in section 11. When the test value of reactance has been corrected by the application of the correction factor, the result will correspond closely to the defined value of negative-sequence reactance based on sinusoidal negative-sequence currents. The correction factors have been derived from equations published in B1.

10.5.1.2 Test conditions

Rated-current negative-sequence reactance is defined for negative-sequence current equal to rated armature current, and may be obtained by methods 1 through 3.

Rated-voltage negative-sequence reactance may also be defined for sudden short-circuit conditions and may be obtained using a method described in section 11, following the three-phase sudden short-circuit discussions.

10.5.2 Determination of negative-sequence reactance from applying a negative-sequence current to the synchronous machine terminals—Method 1

The machine to be tested is operated at rated speed with its field winding short-circuited. Symmetrical sinusoidal three-phase currents of negative (that is, reverse) phase sequence are applied from a suitable source. If the rated-current value of negative-sequence reactance is to be determined, the current should be adjusted until it is approximately equal to rated current of the machine. Two or more tests should be made with current values above and below rated current, to permit interpolation.

For salient-pole machines that do not have continuous amortisseur windings (connected between poles) it is important that the source has a linear impedance several times the negative-sequence reactance being determined, so that approximately sinusoidal negative-sequence currents can be maintained during the test. If a low-impedance source is used, linear series reactors should be inserted in the test leads. Otherwise another test method is preferable.

For machines of other types, such as cylindrical-rotor machines or salient-pole machines with continuous amortisseur windings, the impedance requirement is not of major importance, and low applied test voltages obtained from step-down transformers may be used satisfactorily.

This test produces abnormal heating in the rotor of the machine being tested and should be concluded as promptly as possible. The maximum value and duration of test current specified by the manufacturer should not be exceeded.

The line-to-line terminal voltages, the line currents, and the electric power input are measured and expressed in p.u. If either the currents or voltages contain harmonics of more than a few percent, oscillographic measurements of steady-state currents and voltages should be made. This may require that the test currents be applied for several seconds before the oscillograms are recorded. The wave form should be analyzed for fundamental and third harmonic components. If the rms value of the fundamental and third-harmonic components of current taken together is more than a few percent greater than that of the fundamental, the test will be subject to appreciable error.

10.5.2.1 Parameter determination from method 1

The negative-sequence reactance for this test is obtained from the following equations:

$$Z_2 = \frac{E}{I} \qquad \text{negative-sequence impedance, p.u.} \tag{10-7}$$

$$R_2 = \frac{P}{I^2} \qquad \text{negative-sequence resistance, p.u.} \tag{10-8}$$

$$X_2 = \sqrt{(Z_2)^2 - (R_2)^2} \qquad \text{negative-sequence reactance, p.u.} \tag{10-9}$$

where

E is the average of rms values of fundamental component of the three line-to-line voltages, per unit
I is the average of rms values of fundamental component of the three line currents, per unit
P is the electric power input in per unit of base three-phase power

Note that this method also yields a value of Z_2 (negative-sequence impedance) and R_2 (negative-sequence resistance). (See also 10.5.6.)

10.5.3 Determination of negative-sequence reactance by applying a negative-sequence voltage to the synchronous machine terminals—Method 2

This method is a variation of method 1 and is for use with relatively small salient-pole machines that do not have continuous amortisseur windings or the equivalent. It requires that the impedance of the voltage source be a small fraction of the negative-sequence reactance being tested so that the terminal voltages of the machine being tested will be substantially sinusoidal. The procedure is the same as for method 1, oscillographic measurements of currents and voltages being included. However, the test value of negative-sequence reactance, given by equation 10-9, but identified in this case as X_{2t}, should be corrected according to 10.5.3.1.

From an analysis of the oscillograms of current, the average of the rms values of the fundamental component of the three line currents, in p.u., is used for I in equations 10-7 and 10-8. From analysis of the voltage oscillograms, it should be verified that the rms value of each line-to-line voltage is not appreciably affected by harmonics present. If the voltages are essentially sinusoidal, as determined by the foregoing, the average of the three rms voltages, expressed in p.u., determined from instrument readings or from oscillograms, may be used in equation 10-7 and no corrections to the values of power are needed.

If the voltage harmonics discussed above are substantial, the rms values of each line-to-line voltage may be affected by these harmonics. A correction procedure for method 2 is presented in the following subclause.

10.5.3.1 Correction for applied negative-sequence voltage procedure for determining X_2

The negative-sequence reactance, as defined in 10.5.1 for sinusoidal negative-sequence current is obtained from the value derived from an applied sinusoidal negative-sequence-voltage test by equation 10-10.

$$X_2 = \frac{(X''_d)^2}{2X''_d - X_{2t}} \qquad \text{p.u.} \tag{10-10}$$

where

X_{2t} is the negative-sequence test reactance obtained by using equation 10-9, p.u.
X''_d is the direct-axis subtransient reactance, p.u.

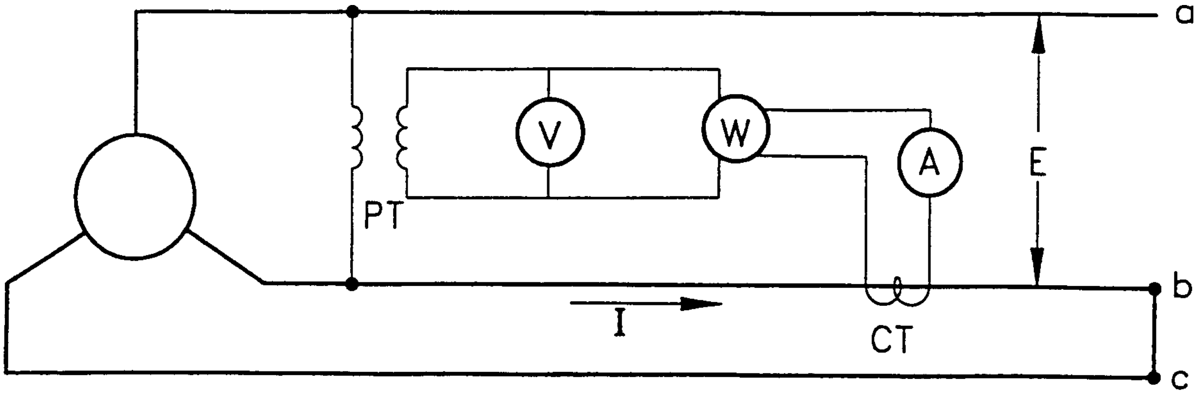
To make this correction, the direct-axis sub-transient reactance should be known for approximately the same conditions. (To correct the rated-current value of X_{2t}, the rated current value of X''_d should be used.) (See 11.8.4.)

It may be seen that if $X_{2t} = X''_d$, as is approximately true for most cylindrical-rotor machines or salient-pole machines with continuous amortisseurs, the correction produces no change.

10.5.4 Determination of negative-sequence reactance by applying a single-phase line-to-line sustained short circuit across two of the machine terminals—Method 3

10.5.4.1 Instrumentation and precautions

The machine is driven at rated speed with a sustained single-phase short circuit between two of the armature line terminals. A current transformer in the short-circuit connection provides current for an ammeter and the current coil of a single-phase wattmeter, as shown in figure 10.2. A potential transformer connected between one of the short-circuited terminals and the line terminal of the open phase provides voltage for a voltmeter and the potential coil of the wattmeter.



NOTE—The light lines are metering circuits supplied from the potential or current transformers.

Figure 10.2—Diagram for determination of negative-sequence impedance, method 3

With the machine excited at reduced field current, a series of readings is taken of the ammeter, voltmeter, and wattmeter for several different field currents, in increasing order. In this test the rotor should be guarded against overheating. For each value of field current, the readings should be taken as rapidly as possible as soon as steady conditions are reached, and the field should be de-energized immediately thereafter. Between readings, the rotor should be allowed to cool if necessary. The test should be discontinued if evidence of rotor overheating is observed. The danger of rotor overheating may limit the test to a field current less than the value for rated voltage, no load, particularly for cylindrical-rotor machines.

10.5.4.2 Parameter determination for method 3

The p.u. negative-sequence impedance for this line-to-line sustained short-circuit test is obtained using equation 10-11.

$$Z_{2(LL)} = \frac{E}{I} \quad \text{p.u., negative sequence impedance} \qquad (10\text{-}11)$$

where

E is the fundamental component of voltage expressed in p.u. of base line-to-line voltage
I is the fundamental component of short-circuit current expressed in p.u. of base line current

The p.u. negative-sequence reactance for a line-to-line test is obtained using equation 10-12

$$X_{2(LL)} = \left(\frac{P_{v-a}}{\sqrt{3} \cdot E \cdot I}\right) Z_{2(LL)} \qquad \text{p.u.} \tag{10-12}$$

where

$P_{v\text{-}a}$ is the wattmeter reading expressed in p.u. of base *single-phase* power (see 9.2.2)

If both the voltage and current contain significant third-harmonic components the procedure of 10.5.4.3c should be followed.

10.5.4.3 Additional comments on parameter determination using method 3

a) The values of negative-sequence reactance may be plotted as a function of the negative-sequence current. In this test the negative-sequence current is the short-circuit current divided by $\sqrt{3}$. From the curve, the value of $X_{2(LL)}$ corresponding to negative-sequence current equal to rated current is the rated-current value.

b) *Correction for a line-to-line sustained short circuit.* The defined negative-sequence reactance, for sinusoidal negative-sequence current, is obtained from the value obtained during a line-to-line short circuit.

$$X_2 = \frac{X_{2(LL)}^2 + (X''_d)^2}{2X''_d} \tag{10-13}$$

To make this correction, the p.u. direct-axis subtransient reactance X''_d shall be known for approximately the same conditions. To correct the p.u. rated-current value of $X_{2(LL)}$ the rated current value of X''_d may be used. To correct the rated-voltage value of $X_{2(LL)}$, the value of X''_d determined at rated voltage by a sudden short circuit should be used (see 11.8.4). The results give the p.u. rated-current and rated-voltage values of the negative-sequence reactance, respectively.

c) The presence of harmonics may influence the results from this test. In tests of machines without connected amortisseur windings using method 3, it is advisable to take oscillograms in addition to meter readings, and use the oscillograms to obtain the rms values of the fundamental and third-harmonic components of voltage and current. If both the voltage and current contain significant third-harmonic components, the p.u. value of the wattmeter reading should be corrected in accordance with equation 10-14 as follows:

$$P'_{v-a} = P_{v-a} - \sqrt{3} E_3 I_3 \tag{10-14}$$

where

$P'_{v\text{-}a}$ is the adjusted value of wattmeter reading to be used in equation 10-12
$P_{v\text{-}a}$ is the actual wattmeter reading in p.u. of base *single-phase* power
E_3 is the rms third-harmonic voltage in p.u. of base line-to-line voltage
I_3 is the rms third-harmonic current in p.u. of base line current

See 11.13.4 for the method 4 of determining X_2 from a sudden short circuit.

10.5.5 Determination of negative-sequence reactance from an applied line-to-line voltage—Method 5

This method will be described more fully in section 11 since, even though the particular tests are sustained or steady state, they are a complementary procedure to the sudden short-circuit tests for X''_d and X''_q parameter determination, which are detailed in the appropriate clauses and subclauses of section 11, particularly 11.7.1 (for X''_d) and 11.13.5 (for X''_q).

A few notes and precautions are given below for general information. If the test is made at rated frequency, the frequency of the rotor current will be one-half of that of the negative-sequence current under normal operating conditions. If the effects of rotor-current frequency on negative-sequence reactance are appreciable, method 5 should not be used.

In terms of the quantities defined in 11.13.1.1 and 11.13.1.2, negative-sequence reactance can be calculated using equation 10-15 as follows:

$$X_2 = \frac{K}{2} \qquad \text{p.u.} \tag{10-15}$$

where

K is defined in equation 11-33

The negative-sequence current in each test is the p.u. value of the fundamental component of the test current divided by $\sqrt{3}$. However, the level of magnetic saturation is associated with the sum of the negative-sequence and positive-sequence component. The test reactance may be plotted as a function of the sum of the positive-sequence and negative-sequence currents, which may be obtained by multiplying the test current by $2/\sqrt{3}$. The rated-current value of negative-sequence reactance is the value at rated current on the curve.

10.5.6 Negative-sequence resistance (R_2)—General

For the definition of negative-sequence resistance, see IEEE Std 100-1992.

If negative-sequence resistance varies appreciably with current, the value for rated-current may be determined by plotting the resistance as a function of negative-sequence current and selecting the value corresponding to rated current.

10.5.6.1 Method 1 for measuring R_2—Applied negative-sequence current

An applied sinusoidal negative-sequence current test is made in accordance with 10.5.2. The negative-sequence resistance is obtained by equation 10-8. No correction for temperature is included because of the uncertain nature of the correction. The connections, precautions, etc. are identical to method 1 for determining negative-sequence reactance.

If the test current is not substantially sinusoidal, an appreciable error in the negative-sequence resistance may result.

10.5.6.2 Method 2 for measuring R_2—Single-phase line-to-line sustained short circuit

A sustained single-phase short-circuit test is made in accordance with 10.5.4.2. From this test, values of impedance, Z_2 and reactance, X_2, are obtained (see 10.5.4.2). From these two values, the negative-sequence resistance is determined using equation 10-16.

$$R_2 = \sqrt{Z_2^2 - X_2^2} \tag{10-16}$$

If the rated-current value is determined by plotting resistance from test as a function of negative-sequence current, it should be noted that negative-sequence current for this test equals test current divided by $\sqrt{3}$.

No correction for temperature is included because of the uncertain nature of the correction and the approximate nature of the test value of the resistance.

NOTE — The corrections, precautions, etc. are identical to method 3 for determining negative-sequence reactance.

10.6 Zero-sequence quantities

10.6.1 Zero-sequence reactance (X_0)—General

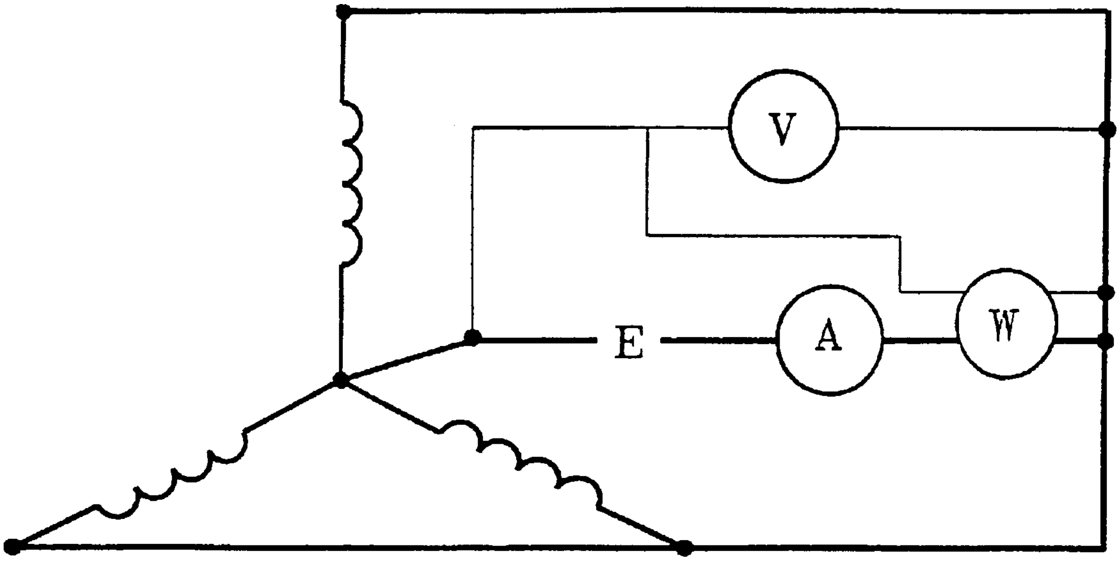
For the definition of zero-sequence reactance, see IEEE Std 100-1992. The zero-sequence reactance has significance only for a wye-connected machine with accessible neutral.

10.6.2 Values of zero-sequence reactance

For currents equal to or less than rated current, zero-sequence reactance usually varies only slightly with current. However, if the value of zero-sequence reactance varies appreciably with test current, it may be plotted as a function of the zero-sequence current and the value for rated current determined from the curve. No rated-voltage value of zero-sequence reactance is recognized.

10.6.3 Methodology and connections for determining synchronous machine zero-sequence quantities—Method 1: Parallel circuit

With the neutral terminals of the windings connected together as for a normal operation, the three-line terminals are also connected together so that the three phases are in parallel. A single-phase alternating voltage is applied between the line terminals and the neutral terminals (see figure 10.3). It is preferable that the machine be driven at normal speed, with the field short-circuited and with normal cooling. However, nearly the same values will be obtained with the rotor at standstill, and the test may therefore be conducted under this condition providing heating is not excessive. The conditions of the test should be stated.



NOTE—Light lines are shown for metering circuits for voltmeter and wattmeter potential coils.

Figure 10.3—Test set-up for Z_0 measurement—Method 1

For several values of applied voltage producing, if possible, total test current up to three times rated current or higher, readings should be taken of voltage and current. If the zero-sequence resistance is to be determined, or if a resistance correction is to be applied, readings of power input should also be taken. If the zero-sequence resistance is to be corrected for temperature, the temperature of the armature winding, by resistance (see 6.7.5) or detector, should be determined for two or three of the higher currents as promptly as possible after these readings are taken, and extrapolated back to the instant of reading.

10.6.3.1 Parameter Determination for zero-sequence quantities using method 1

The zero-sequence impedance is obtained by equation 10-17 as follows:

$$Z_0 = \frac{3E}{I} \quad \text{p.u.} \tag{10-17}$$

where

E is the test voltage, expressed in p.u. of base *line-to-neutral* voltage
I is the total test current, expressed in p.u. of base line current

In most cases the zero-sequence reactance may be taken as equal to the zero-sequence impedance. However, for small machines, or where the armature resistance is relatively large and the zero-sequence reactance relatively small, as for example in machines having a winding of two-thirds pitch, correction for resistance may be needed. For such cases equation 10-18 can be used.

$$X_0 = Z_0\sqrt{1-\left(\frac{P}{EI}\right)^2} \quad \text{p.u.} \tag{10-18}$$

where

P is the wattmeter reading (expressed in per unit of base *single-phase* power) corresponding to the values of E and I used to determine Z_0.

10.6.4 Methodology and connections for determining synchronous machine zero sequence quantities—Method 2: Series circuit

In this method, the windings of the three phases are connected in series, as shown in figure 10.4. This method can be used only when both terminals of each phase are accessible for external connection. In other respects this method is similar to method 1 (see 10.6.3). A single-phase alternating voltage is applied across the windings of the three phases in series, and readings of voltage and current are taken, if possible, for several values of current up to rated current or higher. If the zero-sequence resistance is to be determined, or if the resistance correction is to be applied, readings of power input should also be taken. If the zero-sequence resistance is to be corrected for temperature, the temperature of armature winding, by resistance (see 6.7.5) or detector, should be determined for two or three of the higher currents as promptly as possible after the readings are taken, and extrapolated back to the instant of reading.

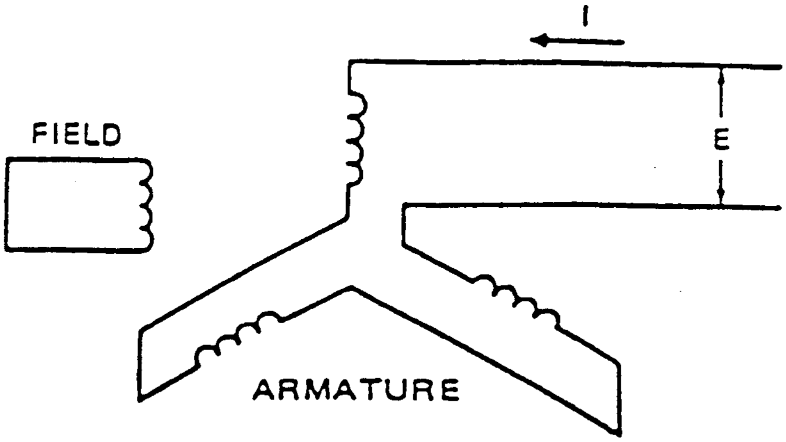


Figure 10.4—Diagram for determination of zero-sequence reactance, method 2

10.6.4.1 Parameter determination for zero sequence quantities using method 2

The zero-sequence impedance for the series circuit connection is obtained by the following equation:

$$Z_0 = \frac{E}{3I} \quad \text{p.u.} \tag{10-19}$$

where

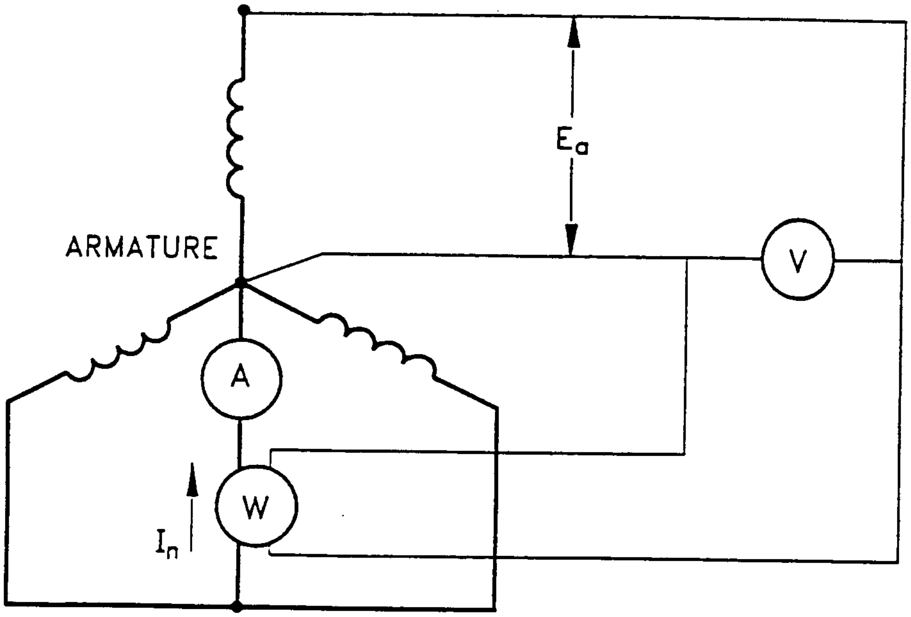
E is the voltage, expressed in p.u. of base *line-to-neutral* voltage
I is the current, expressed in p.u. of base line current

The correction for resistance, if needed, is made using equation 10-18. For this test, the zero-sequence current is equal to the test current.

10.6.5 Methodology and connections for determining synchronous-machine zero-sequence quantities—Method 3: Sustained short circuit

The machine is driven at rated speed with a sustained short circuit from two lines to neutral, as shown in figure 10.5. Light lines are shown for metering circuits. Readings are taken of the voltage from the open terminal to neutral and of the current in the connection of the two short-circuited terminals to neutral. If the zero-sequence resistance is to be determined, or if a resistance correction is to be applied, readings of the power represented by the test voltage and test current should also be taken. The field excitation is adjusted to give a series of readings for values of the normal current, if possible, up to three times rated current or higher.

CAUTION — This test should be terminated as promptly as possible. Serious overheating may result if the currents are carried too high or sustained for too long a time, particularly for cylindrical-rotor machines.



NOTE—Light lines are shown for potential coils

Figure 10.5—Diagram for determination of zero-sequence reactance and resistance (method 3)

10.6.5.1 Parameter determination of zero-sequence quantities using method 3

The zero-sequence impedance is obtained by equation 10-20.

$$Z_0 = \frac{E_a}{I_n} \quad \text{p.u.} \tag{10-20}$$

where

E_a is the line-to-neutral voltage of the open phase, in p.u. of base *line-to-neutral* voltage
I_n is the neutral current, in p.u. of base line current

In most cases, the zero-sequence reactance may be taken as equal to the zero-sequence impedance. However, for small machines, or where the armature resistance is relatively large and the zero-sequence reactance is relatively small, as for example in machines having a winding of two-thirds pitch, correction for resistance may be needed. When a correction is made, the zero-sequence reactance is obtained from equation 10-21.

$$X_0 = Z_0\sqrt{1-\left(\frac{P_{an}}{E_aI_n}\right)^2} \quad \text{p.u.} \tag{10-21}$$

where

P_{an} is the wattmeter reading expressed in per unit of base *single-phase* power, S_N (see 9.2.2)

For this test, the zero-sequence current is one-third of the neutral current.

10.6.5.2 Additional notes

a) If the speed of the machine is not equal to rated speed at the moment the readings are taken, correction for small speed deviations may be made by multiplying the value of zero-sequence reactance by the ratio of the rated speed to actual speed.
b) Since any impedance in the neutral circuit of figure 10.4 will be measured as part of the machine's zero-sequence reactance and since the latter can be very small. It is important to select the current transformer, ammeter, and leads to minimize the impedance.

10.6.6 Zero-sequence resistance (R_0)

10.6.7 General

For the definition of zero-sequence resistance, see IEEE Std 100-1992. The zero-sequence resistance has significance only for a wye-connected machine with accessible neutral.

Ordinarily, zero-sequence resistance does not vary appreciably with current. If it does vary, the value for rated current may be determined by plotting the resistance as a function of zero-sequence current and selecting the value corresponding to rated current.

No correction for temperature is included because of the complex nature of the correction and the approximate nature of the test value of the resistance.

10.6.8 Method 1. Parallel circuit

When making a test for zero-sequence reactance in accordance with 10.6.3.1, the power input, *P*, is measured by a single-phase wattmeter. The zero-sequence resistance is determined by the following equation:

$$R_0 = \frac{3P}{I^2} \quad \text{p.u.} \tag{10-22}$$

where

P is the test power input expressed in p.u. of base *single-phase* power, S_N
I is the total test current, expressed in p.u. of base line current

For this test, the zero-sequence is one-third of the total test current.

10.6.9 Method 2. Series circuit

When making a test for zero-sequence reactance in accordance with 10.6.4, the power input, *P*, is measured be a single-phase wattmeter. The zero-sequence resistance is determined by equation 10-23.

$$R_0 = \frac{P}{3I^2} \qquad \text{p.u.} \tag{10-23}$$

where

P is the test power input expressed in p.u. of base *single-phase* power, S_N
I is the test current, expressed in p.u. of base line current

For this test, the zero-sequence current is equal to the test current.

10.6.10 Method 3. Sustained short circuit

When making a test for zero-sequence reactance in accordance with 10.6.5, the power, P_{an}, represented by the test voltage and test current is measured by a single-phase wattmeter. The zero-sequence resistance is determined as follows:

$$R_0 = \frac{3P_{an}}{I_n^2} \qquad \text{p.u.} \tag{10-24}$$

where

P_{an} is the wattmeter reading expressed in per unit of base *single-phase* power S_N (see 9.2.2)
I_n is the neutral current, in p.u. of base line current

10.7 Testing procedures and parameter determination for positive-sequence resistance for a synchronous machine

10.7.1 General

Positive-sequence resistance (R_1) may be used on occasion for a complete simulation of unbalances at or near the stator terminals of a machine. If the total stator losses are of interest under running conditions the positive-sequence resistance should be used in calculations.

The issue of using R_a, the dc armature resistance, rather than R_1, arises also in section 12 when discussing the determination of operational quantities as viewed from the machine stator terminals.

For the definition of positive-sequence resistance, see IEEE Std 100-1992.

10.7.2 Determination from test

First, the dc armature resistance, R_a, is determined by test and corrected to a specified temperature (see 3.3 of Part I).

The stray-load loss, W_{L0}, is determined according to 4.2.8. No correction for temperature is included. The positive-sequence resistance is determined by equation 10-25 or equation 10-26.

$$R_1 = R_a + \frac{W_{LO} \cdot 10^3}{3I_N^2}\ \Omega \tag{10-25}$$

$$R_1 = \frac{1}{Z_N}\left(R_a + \frac{W_{LO} \cdot 10^3}{3I_N^2}\right) \qquad \text{p.u.} \tag{10-26}$$

where

R_a is the armature resistance per phase corrected to specified temperature, Ω
W_{L0} is the stray-load loss at base line current, kW
I_N is the base line current, amperes (see 9.2.3)
Z_N is the base armature impedance, Ω (see 9.2.5 or 9.2.7)

The temperature, (t_s), for which the positive sequence resistance is determined should be stated.

10.8 Additional miscellaneous steady-state tests for synchronous machines

10.8.1 Determination of Short-Circuit Ratio (SCR)—General

The test procedures required for determining the Short-Circuit Ratio (SCR) are very similar to those described in 10.3 for calculating the direct-axis synchronous reactance. These are detailed in 4.2.4 and 4.2.7 of part I.

Although the SCR is not used in stability calculations (as is X_{du} or X_{ds} the direct-axis synchronous reactance), it has been a practice to use this value to give some idea of the machine's steady-state characteristics, and it is also used as an approximate guide to size and relative synchronous machine costing.

For the definition of short-circuit ratio, see IEEE Std 100-1992.

10.8.1.1 Calculation

The field currents from the open-circuit saturation curve and from the synchronous impedance test, at rated frequency in each case, are used in determining the short-circuit ratio, in accordance with equation 10-27. (See figure 5.1 of Part I.)

$$SCR = \frac{I_{FNL}}{I_{FSI}} \tag{10-27}$$

where

I_{FNL} is the field current for rated voltage, rated frequency, and no load
I_{FSI} is the field current for rated armature current on a sustained three-phase short circuit at rated frequency

10.8.2 Determination of internal load angle

10.8.2.1 General

The definition of internal load angle (δ) is given in IEEE Std 100-1992 as follows: "The angular displacement, at a specified load, of the center-line of a field pole from the axes of the armature mmf pattern."

An accurate knowledge of generator internal angle is essential when studying various types of stability performance, particularly for large turbine generators. This applies to either large disturbance (non-linear) dynamic performance, or to small disturbance (linear, eigenvalue) analysis.

This issue is discussed in more detail in IEEE Std 1110-1991, where different saturation effects occurring in the direct axis of the machine, compared to the quadrature axis, are covered. See in particular annexes 5B and 5C of IEEE Std 1110-1991. An examination of a phasor diagram from annex 5C, and repeated below as figure 10.6 will assist in a better grasp of the dictionary definition given above.

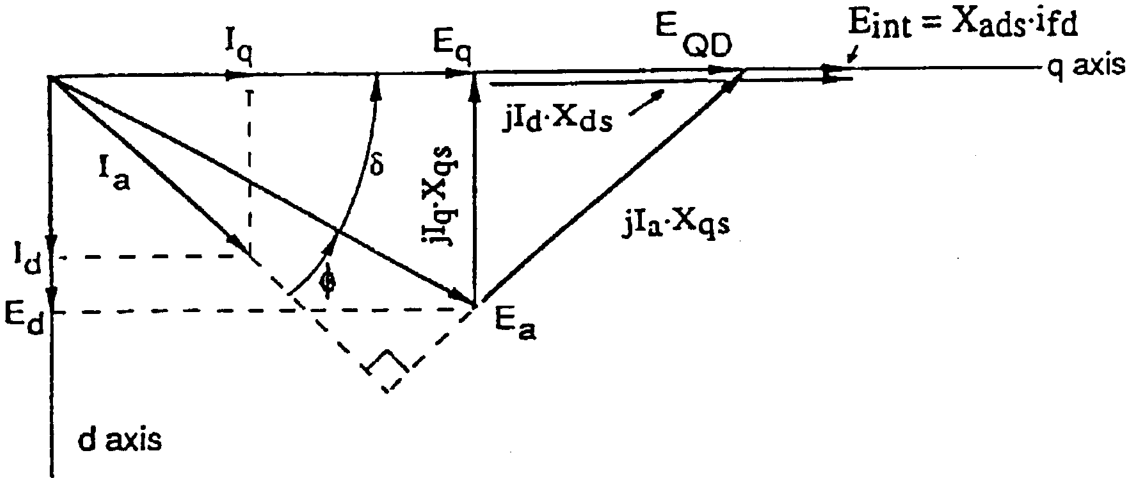


Figure 10.6—Phasor diagram for a synchronous machine

The figure below indicates how the internal angle, \`δ', may be calculated, knowing X_{qs}, the saturated quadrature-axis synchronous reactance. The excitation of the machine field winding can also be calculated, knowing X_{ds}, the saturated direct axis synchronous reactance, and X_{ads}, where $X_{ds} - X_l = X_{ads}$. The stator leakage reactance is X_l. The phasor $X_{ads} \cdot i_{fd}$ (product) corresponds to the internal field excitation in the Rankin reciprocal per unit system, and this phasor is located on the quadrature axis. If δ is known, from some type of measurement (to be described below), certain quotients, in the form of phasor magnitudes shown in figure 10.6 may be used to calculate saturation factors K_d or K_q. These are numbers (unity or greater) to be divided into X_{adu} and X_{aqu}, respectively. (See annex 5C of IEEE Std 1110-1991 for more detail.)

10.8.2.2 Calculation of internal angle (δ)

A method of *calculating* δ may be approximated, in accordance with the following expression

$$\delta = \tan^{-1}\frac{I_a \cdot X_{qs}(\cos\phi)}{E_a + I_a \cdot X_{qs}(\sin\phi)} \qquad (10\text{-}28)$$

Referring again to the above figure, E_a, and I_a are armature voltage and current (in per unit), X_q is the *known* quadrature axis synchronous reactance (usually X_{qs}) and ϕ is the generator power factor angle. X_{qs} is used here in place of X_q to accentuate that saturation exists under normal loading of the machine.

10.8.3 Stroboscope technique of measurement

The following stroboscopic method can still be used, but has been replaced, for turbogenerators especially, by the electronic processing techniques described in 10.8.4.

This particular type of test is made by noting the shift in rotor position (load angle) when the load is changed from a specified power, power factor, and voltage to a zero-MW, synchronized condition with the same specified voltage. The test is made at rated frequency. The shift in rotor position is observed using the change in signal time difference between an optical tachometer (which has a target fixed to a rotating part of the machine) and a terminal voltage waveform. The target is usually attached to the generator shaft. The signal generated by the optical tachometer is compared to the terminal voltage sinusoidal waveform by noting where a zero crossing time occurs, just as the sine wave is becoming positive.

The load angle, δ, in electrical radians, is calculated as follows:

$$\delta = 2\pi f \cdot \Delta t \tag{10-29}$$

where

f is the frequency
Δt is the change in signal time difference

While this optical method requires only one target (or marking) on the shaft, it is not considered as accurate as the electronic method described in the next subclause. This applies in particular to shafts of hydrogenerators.

10.8.4 Electronic measuring of angle

All of the preceding terminal quantities shown in the phasor diagram in figure 10.6 are (usually) available via metering circuits in the generator control area; however, the internal load angle (sometimes referred as rotor field angle) signal is not normally provided. Internal load angle is measured by comparing the phase difference between a once-per-pole-pair pulse on the shaft and a "squared-off" terminal voltage signal. This phase difference is "zeroed" once the generator is synchronized with no load; i.e., active power is zero. Thereafter, as the generator is loaded, the magnitude of the phase difference increases. If the once-per-revolution pulse signal is not installed on the generator end of the shaft then a correction of shaft twist must be applied to the angle readings. On four-pole machines the once-per-revolution pulse signal must be doubled in order to properly compare it with the "terminal voltage" square wave.

The internal load angle measuring unit may be calibrated in degrees/volt and a bias is added to the angle signal when the unit is first synchronized to the power system. As the generator is loaded the internal load angle may be measured directly. A "zero crossing" triggering device is considered necessary for this technique. The same voltage should be used for zeroing of the no-load setting as that used and obtained at the actual power angle measurement condition at some megawatt loading.

Extension of this method to hydraulic machines and to synchronous motors would seem to require markings on some fraction or portion of the total number of poles in order to remove the effects of rotor eccentricity or shaft wobble.

11. Tests for evaluating transient or subtransient characteristic values

11.1 General

Tests for transient and subtransient parameters involve sudden changes to any or all of the three-phase circuits at or electrically near the machine armature terminals. Sudden changes to the field electrical circuit are also included. Changes at or near the armature terminals could result from single or multiple faults between phases or faults from one or more phases to the machine neutral.

The term "characteristic values," as applied to transient or subtransient time constants and reactances indicates that such values generally fall within typical ranges for various classifications and sizes of synchronous machines.

Because of the predominance of three-phase machines with revolving field windings, the following tests are described specifically for such machines. For single-phase machines or for polyphase machines of other than three phases, modifications will be needed in some cases, but they can usually be readily determined.

11.2 Reasons for conducting tests involving sudden changes to the armature or field electrical circuits

The characteristic values of transient and subtransient reactances (and time constants) of synchronous machines have been used for about 75 years, and for many purposes. Initially such reactances and time constants were calculated to give both machine designers, and users, of synchronous machines a first-hand knowledge of short-circuit current magnitudes and their rate of change or decay. Such magnitudes are important in establishing switchgear fault ratings. This knowledge also enables mechanical stresses to be calculated between armature windings resulting from excessive currents that occur during electrical disturbances at or near the synchronous machine terminals. In addition, protective schemes could be devised so that relays could be correctly calibrated to trip armature or field circuit breakers, and thus remove the faulted machine from the power system.

In addition to calculating these characteristic short-circuit reactance values, the time taken for fault currents to decay or pass through various states after a fault was of interest. Original analysis of short-circuit currents by machine designers, commencing about 75 years ago, indicated that there were basically two periods during which the rates of current decay could be easily identified. The initial and shorter period was named the subtransient regime. The subsequent and much longer period was called the transient regime. Such regimes of time could be associated with a time constant. This characteristic value can be identified as the time taken for exponentially decaying current or voltage to change to $1/\in$ or 0.368 of its original value.

11.3 Methodology to be followed when conducting short-circuit current tests

Testing for such reactances and time constants was initially performed by applying a three-phase solid (or "bolted") fault on the machine terminals with the machine unloaded and on open-circuit. Values obtained from such tests were, on the basis of Park's two-reaction theory, direct-axis values. Direct-axis parameters could be found by holding the pre-fault field excitation at a constant value during the decay of the three-phase fault currents to steady state values.

Quadrature-axis transient or subtransient values could be calculated but could not be tested for by tests from open-circuit pre-fault conditions. See Annex 11A for special *q*-axis test descriptions.

There is a theoretical justification for developing short-circuit equations, which give results matching the short-circuit test values. This is known as the constant field flux-linkage theorem, and is the basis for assuming a constant voltage behind transient reactance.

11.4 Procedural details and instrumentation for short-circuit test data extraction

11.4.1 Consultation with manufacturer

This process of consulting the manufacturer is also covered in section 8 of part I.

11.4.2 Calibration of test equipment including use of current shunt or current transformers

When test results are to be determined from the varying values of current and voltage during the early stages of a short circuit before steady state has been reached, the currents and voltages should be determined from oscillograms or equivalent means. When the short circuit involves two or more phases, it is essential that the short circuit be applied by a switch that closes all phases at almost exactly the same instant, to avoid errors caused by the non-simultaneous start of the short circuit in the different phases. Suitable noninductive shunts or Hall probe sensors will, in general, give more accurate results than current transformers of conventional design, but current transformers with an unusually large core section designed to transform currents containing large, slowly decaying dc components may be used successfully. Leads from shunts or current-transformer secondaries should be kept close together, twisted, or in conduit to minimize induced voltages in the instrument circuits. Alternatively, use of optical fiber technology is strongly suggested. Along with digital data transmission facilities, these modern features virtually eliminate the effect of induced voltages in the recording of short-circuit current waveforms.

11.4.3 Three-phase armature connections

In the following subclauses, the test results are based on line currents, and are therefore applicable to system studies whether the machine is wye-connected or delta-connected.

11.4.4 Interpretation of test data—General

Should currents and voltages be still read from oscillograms, the results would also usually be expressed as p.u. values. If the waveform is sinusoidal or nearly so, as is usually true for three-phase short circuits, the rms magnitude of the alternating component of current or voltage in p.u. is best determined by dividing the vertical distance from crest to crest on the oscillogram by the distance from crest to crest for base rms current or voltage, as may be required. When the rms value is varying with time, envelope curves may be drawn through the peaks of the waves, and the p.u. rms value of the ac component at any time is taken as the ratio of the vertical distance between envelopes to the corresponding distance for the base quantity. In determining values from oscillograms it was important to allow properly for the width of the line or trace because the width of the line may be a substantial fraction of the distance to be measured. As noted above these problems are largely obviated by modern digital data recording techniques.

11.4.4.1 Allowances for distortion in test oscillographic results

If oscillograms from single-phase line-to-line, line-to-neutral, or two-phase line-to-neutral short circuits are used for evaluation of impedances, waveform distortion may render the method of 11.4.4 inaccurate, particularly for such machines as salient-pole machines without continuous damper windings. If the wave shape is significantly distorted so that an appreciable error would result from measuring only the peaks of the current wave, a harmonic analysis should be made. If the decrement of any substantial component is quite rapid, the accepted methods of harmonic analysis will not give accurate results, and the separation of the wave into components can only be approximated. If the measurements are calibrated by steady state data, the wave distortion effect is eliminated.

11.4.4.2 Effects of unsymmetrical current plots, or plots containing harmonics

When the short-circuit current is unsymmetrical, but the alternating component is sinusoidal or nearly so (or contains odd harmonics only), the (decaying) dc component may be readily found from the plots by drawing a curve midway between the envelopes (as determined in 11.4.4). If the current contains even harmonics of appreciable magnitude, the line representing the direct-current component is not midway between the envelopes and can be located only by wave-form analysis which determines the even harmonics and allows for the resulting displacement from the mid location. Recent more powerful methods of analyzing and accounting for distortions or dysymmetry are discussed in 11.12. This covers the general subject of computerized analyses of current decrement wave forms. It also relates to the recording procedures of 11.7.1.3 and parameter determination discussed in 11.8 and 11.9 for reactances and time constants.

11.4.5 Measurement and control of field quantities—Pre-transient states

Recordings should be taken of the voltage of at least one phase (usually line-to-line, but line-to-neutral where indicated in later sections), of the armature current in each short-circuit phase, and of both the field current and field voltage. On units with brushless exciters, field-current digitized information may be obtained from a shaft-mounted current shunt read through temporary slip rings or telemetry. The armature voltage and field current just before the machine is short-circuited should be read by means of indicating instruments. The excitation system should not buck or boost the field voltage during the test. For example, a rotating exciter AVR should be on manual, or a static exciter firing angle should be held constant.

11.4.6 Measurement of steady-state quantities—Post-transient states

The steady-state values of the short-circuit armature currents are required for analysis of the reactance and time constants (see 11.6). These may be obtained by continuing the record until steady state has been reached. Because the final decay of armature current is very gradual, it is difficult to determine by examining a record that steady state has actually been reached. As an alternative, the steady-state armature currents may be obtained by stopping the record after the first few seconds and restarting it after steady state has been reached. Readings of the steady-state armature current and the corresponding field current by indicating instruments may be used as a check or calibration of the oscillogram.

The steady-state armature current may also be determined from the short-circuit saturation test data (see 4.2.7) at the field current measured after steady state is reached.

11.5 Precautions required in conducting short-circuit tests

Recommendations for safety precautions have already been spelled out in section 8. Those recommendations cover both the mechanical and electrical integrity of the machine.

Such aspects of security involve bracing of armature coils, where considered necessary. Also included are grounding requirements for the armature windings, as well as for current shunts which measure armature current. A review of protective devices which should be made inoperative during the tests is also recommended.

11.5.1 Speed and field voltage control before and during tests

To avoid error, particularly in the determination of time constants, and to avoid high transient voltages in the field circuit, excitation should be supplied from a constant-voltage low-impedance source. This may require an independent separately excited and driven exciter without series field winding. Field current should be adjusted by means of exciter field control to avoid inserting resistance in the field circuit of the main machine. If the capacity of the exciter used is at least as great as that of the exciter used in normal service, and additional impedance is not inserted, the resistance and inductance of the circuit external to the field of the machine under test will generally have a negligible effect on the accuracy of determination of the quantities measured during short-circuit tests.

11.6 Theoretical background for determination of short-circuit reactance and time constant values

The synchronous reactance (X_d), transient reactance (X'_d) and subtransient reactance (X''_d), and the transient short-circuit time constant (τ'_d) and subtransient short-circuit time constant (τ''_d) are used to describe and machine's behavior on sudden short circuit. This can be done in accordance with the following equation for the ac rms components of current following a three-phase short-circuit from no load neglecting armature-circuit resistances and assuming constant exciter voltage.

$$I(t) = \frac{E}{X_{ds}} + \left(\frac{E}{X'_d} - \frac{E}{X_{ds}}\right)\varepsilon^{\frac{-t}{\tau'_d}} + \left(\frac{E}{X''_d} - \frac{E}{X'_d}\right)\varepsilon^{\frac{-t}{\tau''_d}} \tag{11-1}$$

where

$I(t)$	is the ac rms short-circuit current, p.u.
E	is the ac rms voltage before short circuit, p.u.
t	is the time in seconds, measured from the instant of short circuit.

NOTE — Reactances must be in p.u. on the machine MVA rating.

X_{ds} and X_{du} are discussed and defined in 10.3. X_{ds} is used for short circuits tested at normal open circuit (rated) voltage since there will be a small degree of direct axis machine saturation. X_{du} may be used in place of X_{ds} if the test is performed at around 0.4 p.u. of normal voltage, or below 0.4 p.u.

X'_d and τ'_d are defined in IEEE Std 100-1992, respectively.

X''_d and τ''_d are defined in IEEE Std 100-1992.

In this expression, it is assumed that the current is composed of a constant term and two decaying exponential terms where the third term of the equation decays very much faster than the second. By subtracting the first (constant) term and plotting the remainder on semi-logarithmic paper as a function of time, the curve would appear as a straight line after the rapidly decaying term decreases to zero. The rapidly decaying portion of the curve is the *subtransient* portion, while the straight line is the *transient* portion.

Because of several factors, including saturation and eddy-current effects, the actual short-circuit current may not follow the above form of variation precisely; the two exponential functions only approximate the true current behavior. Hence, the transient portion of the semi-logarithmic plot may actually be slightly curved. Any relatively short portion of this curved line can be well approximated by a straight line. It will be appreciated however, that both the slope of this line and its intercept with the zero-time axis will vary, depending on which part of the curve is approximated. Therefore, the obtained value of transient reactance X'_d, (determined by the zero-time intercept) is somewhat arbitrary because it depends on how the test data are interpreted.

To establish a test procedure that will produce a definite transient reactance and hence definite transient and subtransient time constants, the range of time to be used in making the semi-logarithmic plot is established *as a minimum* as the first second following the short circuit, unless another value is specified for the particular machine, by the purchaser.

Open circuit values of transient (τ'_{do}) and subtransient (τ''_{do}) time constants can be calculated from the tested short circuit time constant values (see section 6 of IEEE Std 1110-1991). Special tests for open circuit values of τ'_{do} and τ''_{do} are discussed later in this chapter (see 11.10).

11.7 Specific tests for determination of transient and subtransient direct axis parameters (reactance values)

11.7.1 Determination of direct-axis reactance parameters by sudden short circuit

11.7.1.1 Method 1

The direct-axis transient reactance is determined from the current waves of a three-phase short-circuit suddenly applied to the machine operating open-circuited at rated speed. The direct-axis transient reactance is equal to the ratio of the open-circuit voltage to the value of the armature current obtained by the extrapolation of the envelope of the ac component of the armature current wave to the instant of application of the short circuit, neglecting the rapid variation of current during the first few cycles. Figures 11.1 and 11.2 illustrate this method of determining the direct-axis transient reactance.

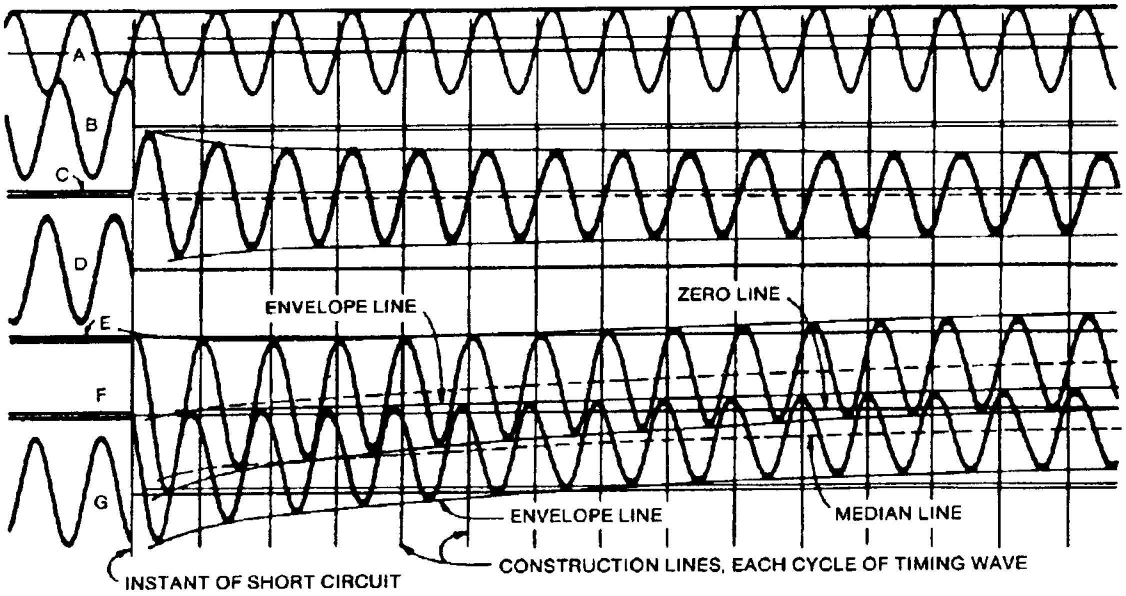


Figure 11.1—Oscillogram of three-phase sudden short circuit
1) Timing wave—Trace A; 2) Armature current—Traces C, E, and F; 3) Armature voltage—Traces B, D, and G

For each test run, oscillograms should be taken, as described in 11.4.2 to 11.4.4, showing the short-circuit current in each phase and an *independent* timing wave of uniform frequency or an equivalent record. Records of the armature voltages and the field current are also desirable, but are not essential for this test if the armature voltages just before the short-circuit and the final steady-state field current are determined by indicating instruments. An oscillogram of field current is required if method 3 (see 11.11.4) is to be used to determine the short-circuit armature time constant. The voltage readings of the three phases should be well balanced.

The rated-voltage value of direct-axis subtransient reactance may also be obtained using method 1 above or method 2 (see 11.7.1.2).

The direct-axis subtransient reactance is determined from the same three-phase suddenly applied short-circuit test as used for determination of the transient reactance. For each phase, the values of the difference between the ordinates of curve B and the transient component (line C) as determined in 11.7.1.1, are plotted as curve A (on the same sheet) to give the subtransient component of the short-circuit current as shown in figure 11.2. The result is expected to be very nearly a straight line on the semilogarithmic plot. Extending the straight line (line D) drawn to fit these points back to zero time gives the initial value of the subtransient component of the short-circuit current. Preference in locating line *D* should be given to the first few points, corresponding to the first few cycles after application of the short circuit, as they are normally the points that can be determined most accurately. The sum of the initial subtransient component, the initial transient component, and the sustained component for each phase gives the corresponding value of I''.

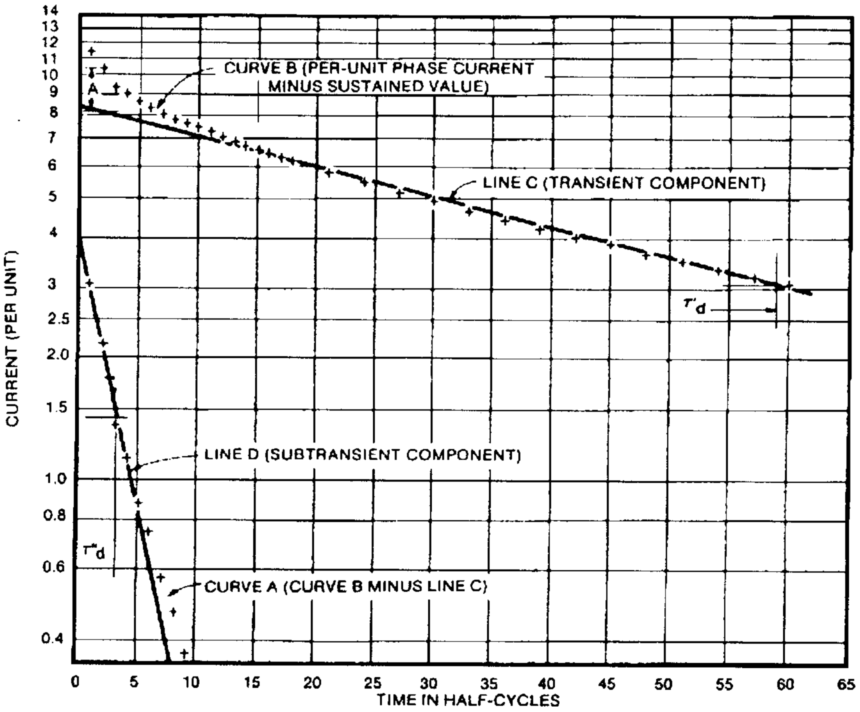


Figure 11.2—Analysis of ac component of short-circuit current (for one of three phases)

11.7.1.2 Method 2. Direct currents from sudden short circuit

A second method of evaluating the direct-axis subtransient reactance from the oscillograms of the three-phase short-circuit test of 11.7.1.1 may be used as a check of method 1 when it is known that the short circuit of all three phases is established at very nearly the same instant, preferably within five electrical degrees. (Method 1 is preferred as it is a more direct test.) The per-unit magnitude of the dc component for each phase is determined as described in 11.4.4.2 for several values of time. The values of dc component for each phase may now be plotted on a semilogarithmic plot similar to that used for the ac components (see figure 11.5). The initial values of the dc component for the three phases are obtained by extrapolating the plotted curves of current back to zero time.

11.7.1.3 Practical comments and suggestions on graphical procedures for interpreting short-circuit waveforms

If it is not possible to provide a constant-voltage low-impedance source of excitation, method 2 should be used. If the field current, measured after steady state is reached, differs appreciably from the value before the short circuit, method 2 should be considered (see 11.7.2).

The envelopes of the current waves are drawn as shown in figure 11.1. Because of possible speed changes of the machine under test, all time intervals are determined from the timing record rather than from a current trace. Suitable time intervals, from the beginning of the short circuit, are laid off on the axis of abscissas, as shown. For the first few cycles, measurements every cycle or every half cycle are desirable, but as the short circuit progresses, measurements at increasing time intervals up to several cycles are adequate. The p.u. values of the alternating components of the currents at each value of time may be obtained from the envelopes by the method discussed in 11.4.4 and 11.4.4.1. It is not necessary to obtain a value for zero time by extrapolating the envelopes.

The p.u. steady-state component of short-circuit current for each phase should now be determined as accurately as possible from the oscillograms, from indicating instruments, or from both (see 11.4.6). The steady-state component for each phase should now be subtracted from the total alternating component to obtain the varying current for each phase, which should be plotted on semi-logarithmic paper, with current on the logarithmic scale, as a function of time. These curves will be similar to curve B in figure 11.2. The current should decrease rapidly during the first few cycles, then more slowly, and then the curve should become approximately a straight line, as shown. The plot should extend *for at least 1 s*, unless another time is specified (see 11.6). The straight line (line C), which most closely fits the curve disregarding the rapid decay during the first few cycles is then drawn in and extended back to zero time, and its intersection with the axis of ordinates gives the initial transient component of the short-circuit current. To this initial current for each phase is added the value of the steady-state short-circuit current for that phase to obtain the corresponding value of I'. These three values are averaged to obtain the value of I' to be used in 11.8.1 and in the parameter determination sections dealing with subtransient quantities. In general, the longer the time of the plots, the more reliable will be the results of the current waveform analyses. This applies especially to the calculation of transient reactances and time constants.

11.7.2 Description of method 2 for determining direct-axis reactance parameters by sudden short-circuit of three armature phases and the field

The direct-axis transient reactance is determined from the armature current waves of a three-phase short circuit suddenly applied to the armature of a machine simultaneously with a short circuit to the field winding. Prior to the short circuit, the machine is operated at rated speed with the armature open-circuited and the field excited with current corresponding to the desired voltage. This method may be used when the excitation cannot be supplied from a constant voltage low-impedance source. This may result from the necessity of using a remote exciter, or if the effect of the heavy transient exciter currents causes it to change the operating point on its hysteresis curve, resulting in a significantly different field current after steady state is reached from that which existed prior to the short circuit.

Equation 11-1 would be considered to apply to the current in this test if the two E/X_{ds} terms of the formula in equation 11-1 are eliminated. There is zero steady-state armature current. Therefore, the portion of the current which decays according to the transient time constant is larger than for method 1. (see 11.8.2)

The diagram of figure 11.3 shows the connections which may be used for this test. One pole of the short-circuiting breaker may be used to short-circuit the field winding. A suitably sized protective resistor is used to prevent short-circuiting the exciter. An exciter circuit breaker is controlled to open shortly after the short-circuiting breaker is closed.

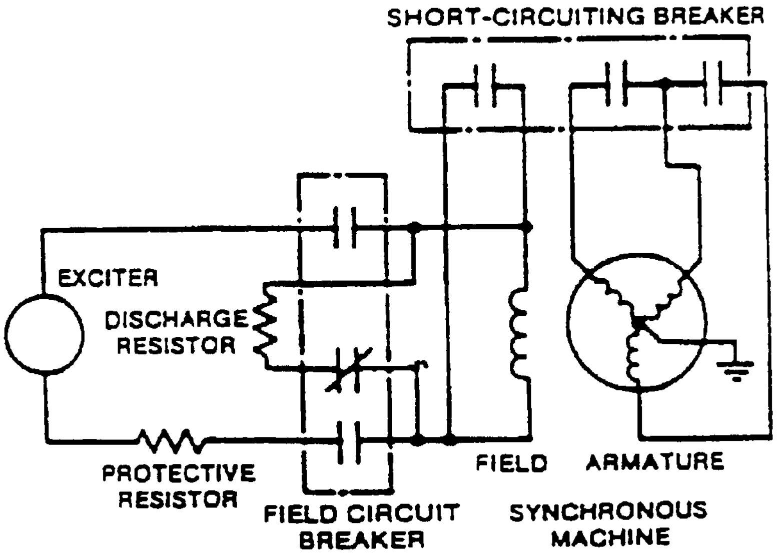


Figure 11.3—Diagram for sudden short-circuit test for direct-axis transient reactance, method 2

11.7.3 Description of method 3 for determining direct-axis reactance values by the voltage recovery test

The direct-axis transient reactance can be obtained from an oscillographic record of the line-to-line armature voltages following the sudden opening of a steady-state three-phase short circuit of the armature when the machine is running at rated speed with a selected value of excitation. The values of armature current in each phase are measured prior to opening the circuit. The circuit breaker should open all three phases as simultaneously as possible. In addition to the oscillographic record of the armature voltages during the transient, the steady-state voltages should be obtained either by stopping the oscillograph and then restarting it, or by instruments. The differential voltage (ΔE) is obtained at frequent intervals by subtracting the average of the three rms voltages (obtained from the oscillogram) from the average of the three rms steady-state voltages. A semi-logarithmic plot of the differential voltage is made versus time with the differential voltage on the logarithmic axis (see curve B of figure 11.4). The transient component of differential voltage is the slowly varying portion of the plot and should be extrapolated back to the instant of the open circuit, neglecting the first few cycles of rapid change (see line C of figure 11.4). The time-zero value of this transient differential voltage is denoted by $\Delta E'_o$, as shown in the figure.

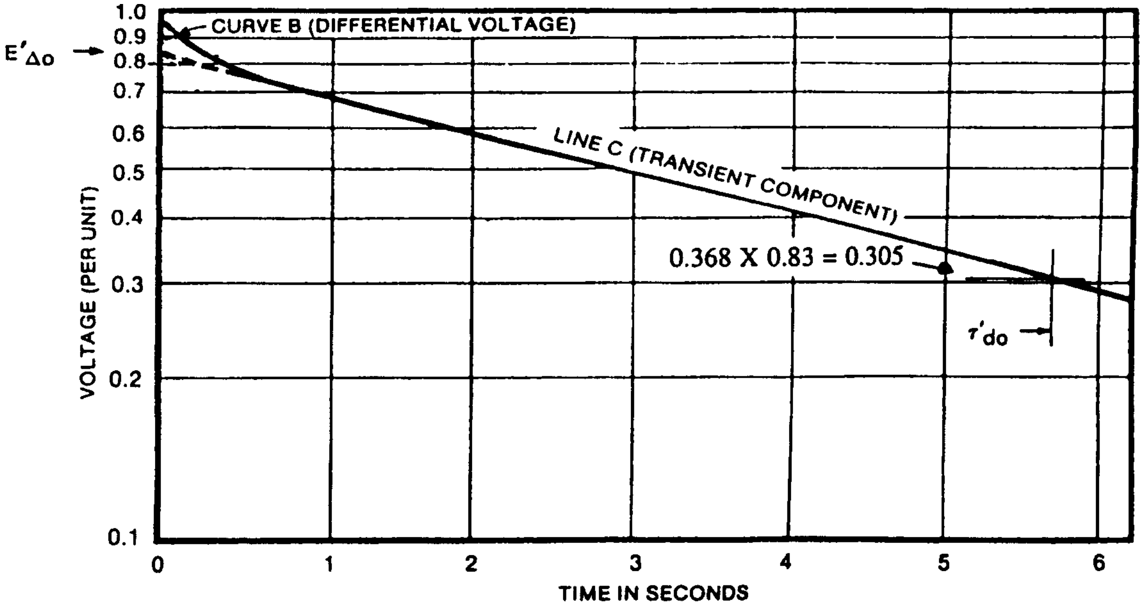


Figure 11.4—Voltage recovery test for transient reactance and time constant

11.8 Determination of transient and subtransient reactance values, based on methods 1, 2, and 3

11.8.1 Transient reactance parameter determination—Method 1 (three-phase sudden-short circuit)

The reader should refer back to the end of 11.7.1.3. The values of I' for each of the three-phase currents are averaged. I' is the current magnitude obtained, for each of the phases, by projecting the log-linear time plot of such currents back to zero time.

The transient reactance for the value of current I' is then obtained using equation 11-2 (refer also to table 1).

$$X'_d = \frac{E}{I'} \quad \text{p.u.} \tag{11-2}$$

where

E is the p.u. open-circuit armature voltage at normal frequency determined as the average for the three phases immediately before short circuit

I' is the p.u. transient component of current at the moment of short circuit, plus the steady-state component, as determined in 11.7.1.3 (see figure 11.2 and table 1)

Table 1—Example of determination of transient and subtransient reactance

	Phase 1	Phase 2	Phase 3	Average
(1) Initial voltage	—	—	—	0.994
(2) Steady-state current	1.4	1.4	1.4	—
(3) Initial transient component (See 11.7.1.1)	9.4	10.2	9.3	—
(4) I' = (2) + (3)	10.8	11.6	10.7	11.0
(5) Transient reactance X'_d = (1) ÷ (4) (See 11.8.1)	—	—	—	0.0904
(6) Initial subtransient component (See 11.7.1.1)	3.6	5.8	3.8	—
(7) I'' = (4) + (6)	14.4	17.4	14.5	15.4
(8) Subtransient reactance X''_d = (1) ÷ (7) (See 11.8.4.1)	—	—	—	0.0645
(9) Initial direct current component (See 11.8.4.2)	11.0	25.0	13.6	—
Identified as phase:	c	a	b	
	$I''_{(1)}$	$I''_{(2)}$	$I''_{(3)}$	**Weighted Average**
(10) (See equations 11-8, 11-9, 11-10)	17.7	17.7	17.4	17.6
(11) X''_d = (1) ÷ (10) (See equation 11-12 and 11.8.4.2)	—	—	—	0.0565

NOTE — All values are in p.u.

11.8.1.1 Error correction for speed changes

The error resulting from minor speed changes is negligible provided the machine is operating at rated speed at the instant the voltages are measured, just before short circuit. If the initial speed deviates slightly from rated speed, correction may be made by multiplying the voltage E by the ratio of rated speed to actual speed. As an alternative, the voltage E may be determined from a open-circuit saturation curve as the voltage corresponding to the field current immediately preceding the short circuit.

11.8.1.2 Accounting for saturation effects due to heavy currents or high initial terminal voltage

The value of transient reactance is influenced by saturation and thus by the initial voltage before the short circuit is applied.

To obtain the rated-current value, tests from initial voltages that have p.u. values in the vicinity of the calculated value of X'_d should be made. The rated-current value is found by plotting the test values of transient reactance as a function of I', and taking the value of reactance corresponding to I' equal to the p.u. value of rated current. An alternate method is to plot X'_d as a function of the initial voltage, E, and take the value of X'_d, which equals the corresponding E.

To obtain the rated-voltage value of transient reactance, tests with initial voltages from 75% up to 100% or 105%, as may be agreed upon, should be made. The rated-voltage value is found by plotting the test values of transient reactance as a function of initial voltage, and taking the value of reactance corresponding to rated voltage.

Each short-circuit test imposes severe mechanical stresses on the machine. Therefore, the number of tests should be limited to those necessary to provide the required information.

11.8.2 Parameter determination—Method 2: Combined short circuit of the armature and field

Equation 11-1 would be considered to apply to the current in this test if two of the terms of the formulae (E/X_{ds}) are eliminated. This follows because there is zero steady-state armature current. Therefore, the portion of the current which decays according to the transient time constant is larger than that found in method 1.

The test is made and analyzed in a manner similar to method 1. In making the semi-logarithmic plot of figure 11.2, it is not necessary to subtract the steady-state armature current, since it is zero.

The value of I' from this second method, to be used in equation 11-2, is the true transient component of short circuit current.

11.8.3 Parameter determination—Method 3 (voltage recovery)

The direct-axis transient reactance, X'_d is obtained as

$$X'_d = \frac{E_\infty - E'_{\Delta o}}{I} \qquad \text{p.u. reactance} \tag{11-3}$$

where

$E'_{\Delta O}$ is the initial transient component of differential voltage, p.u.
E_∞ is the steady-state voltage, p.u.
I is the armature current before opening the circuit, p.u.

Refer again to figure 11.4.

If the speed of the machine differs from rated speed or varies during the test, it is necessary to correct the voltages measures from the oscillogram. Equation 11-4 gives the corrections applied to E, the time-varying value of the voltage recovery. Equation 11-5 gives the speed corrections to the steady-state (or final) values of the voltage recovery

$$E_c = E\frac{n_R}{n_T} \tag{11-4}$$

and

$$E_{\infty c} = E_{\infty}\frac{n_R}{n_{\infty}} \qquad (11\text{-}5)$$

The steps in this correction process are

a) The speed-corrected voltage recovery curve should be replotted, where the voltage values at frequent intervals may be subtracted from $E_{\infty c}$ at the same particular point in time.
b) A new differential voltage curve similar to figure 11.4 is then drawn, and projected back to zero time to obtain a speed-corrected value of $E'_{\Delta O}$, now called $E'_{\Delta OC}$. This is a semi-logarithmic plot.

Then X'_d corrected for speed changes is

$$X'_d = \frac{E_{\infty c} - E'_{\Delta oc}}{I} \quad \text{p.u. reactance} \qquad (11\text{-}6)$$

where

E	is the voltage measured from the oscillogram at each time point
E_c	is the corrected value of E
E_{∞}	is the steady-state voltages
$E_{\infty c}$	is the corrected steady-state voltages
n_R	is the rated speed
n_T	is the speed at time of E (can be obtained approximately by linear interpolation from initial speed to steady-state speed)
n_{∞}	is the speed corresponding to reading of steady-state voltage
I	is the armature current before circuit opening in p.u.

To obtain a value of transient reactance corresponding closely to a specified load condition, the initial excitation should approximately correspond to the voltage back of transient reactance on the air-gap line.

11.8.4 Specific calculations for subtransient reactance parameter determination—Methods 1 and 2

11.8.4.1 Method 1

Referring to 11.7.1, the values of I'' determined in that way are generally more accurate than those obtained by extrapolating the envelopes back to the beginning of the short circuit. In this way advantage is taken of all the readings in deriving the values of I''. The three values are averaged to obtain the value of I'' to be used. The subtransient reactance for the value of current I'' is obtained as follows (see table 1).

$$X''_d = \frac{E}{I''} \quad \text{p.u.} \qquad (11\text{-}7)$$

where

E	is the p.u. open-circuit voltage at normal frequency determined as the average for the three phases immediately before short-circuit
I''	is the p.u. initial ac component of short-circuit current, as determined in 11.7.1.1 (see figure 11.2 and table 1)

11.8.4.2 Method 2

Referring to 11.7.1.2, the *absolute* values of the initial dc components in p.u. are designated (a), (b), and (c), where (a) is the largest value and (b) and (c) are smaller. Table 1 gives an example and figure 11.5 should be examined.

A weighted average of the initial ac components of the three short-circuit currents can be found by calculating and $I''_{(1)}$, $I''_{(2)}$, and $I''_{(3)}$ taking a weighted value. The weighting is somewhat arbitrary. The three values of the p.u. ac component of current, I'', are obtained from the following equations:

$$I''_{(1)} = \sqrt{\frac{2}{3}(a^2 + b^2 - ab)} \tag{11-8}$$

$$I''_{(2)} = \sqrt{\frac{2}{3}(a^2 + c^2 - ac)} \tag{11-9}$$

$$I''_{(3)} = \sqrt{\frac{2}{3}(b^2 + c^2 - bc)} \tag{11-10}$$

If the three values of I'' differ, a weighted average should be used, assigning weights based upon the estimated accuracies of the current measurements. Since larger currents can usually be determined more accurately on oscillograms, it is suggested that weights 3, 2, and 1 be used, in that order, giving greater weight to the determination using the larger currents, unless circumstances of the test would suggest other weighting. If these weights are used, I'' would be taken as the following value:

$$I'' = \frac{3I''_{(1)} + 2I''_{(2)} + I''_{(3)}}{6} \tag{11-11}$$

I'', the weighted average, is substituted in equation 11-12; and

$$X''_d = \frac{E}{I''} \quad \text{p.u.} \tag{11-12}$$

where

E is the same as for transient reactance in 11.8.1 and equation 11-2
I'' is the p.u. ac component of current, at the moment of short circuit

This second method takes advantage of the fact that the maximum possible value of the dc or offset component of the short-circuit current is equal to the envelope (that is, zero-to-rest value) of the ac component, extrapolated back to the moment of short circuit.

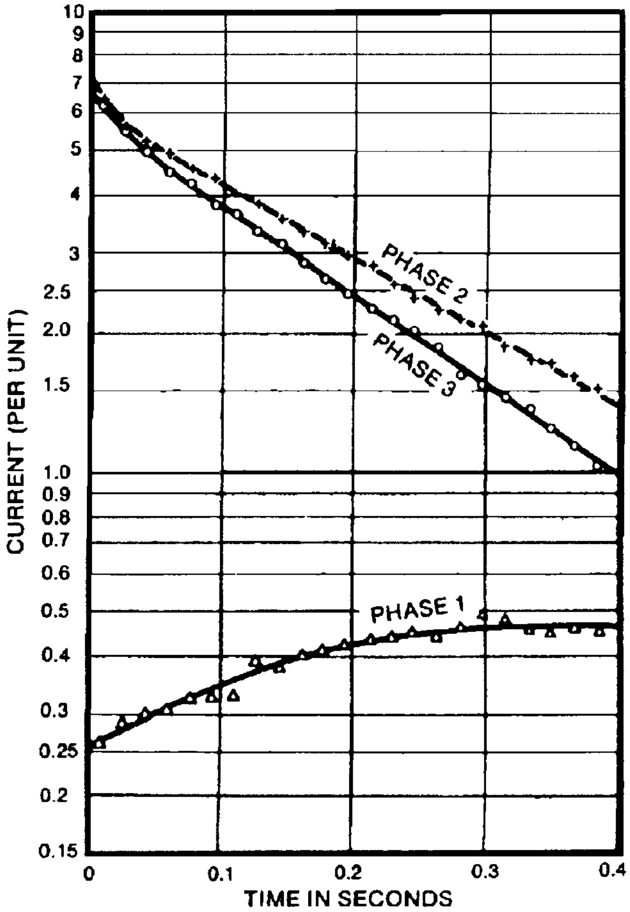


Figure 11.5—DC components of phase currents

11.9 Tests for transient and subtransient direct axis time constants

11.9.1 Determination of the direct-axis transient short-circuit time constant (τ'_d)

11.9.2 Determination from test

The direct-axis transient short-circuit time constant is obtained from the sudden short-circuit test data used to determine the direct-axis transient reactance (see 11.7.1.1). It is the time, in seconds, required for the transient alternating component of the short-circuit current (figure 11.2, line C), to decrease to 1/∊ or 0.368 times its initial value. The determination of direct-axis transient short-circuit time constant is shown in figure 11.2.

A rated-current value of this time constant is the value, which is applicable when the initial value of the transient plus sustained components of the short-circuit current, I' (see 11.7.1.1) is equal to rated current. A rated-voltage value is the value which is applicable when the short circuit is applied at rated voltage, rated speed, no load. If a test at the required current or voltage was not made, and the time constant is found to vary appreciably with test current, the values for the several test runs may be plotted as a function of I' and E (corrected for speed variation if necessary), and the required time constant may be found from these curves.

11.9.2.1 Correction to specified temperatures

The direct-axis transient short-circuit time constant may be corrected to a specified temperature. The average value of field resistance, R_f, during the test is obtained from readings of field voltage and current taken before and after the short-circuit test. The temperature, t_t of the field winding during the test is determined using 6.4.4 based on the field resistance, R_{fd}. The direct-axis transient short-circuit time constant can be corrected to specified temperature by using the following:

$$\tau'_d = \tau'_{dt}\left(\frac{k + t_t}{k + t_s}\right) \quad \text{s} \qquad (11\text{-}13)$$

where

τ'_d is the direct-axis transient short-circuit time constant at specified temperature
τ'_{dt} is the direct-axis transient short-circuit time constant at test temperature
t_t is the average temperature of the field winding during the test, °C
t_s is the specified temperature, °C
k is the factor defined in 6.4.4, which depends on current conducting material (copper, aluminum, etc.)

11.9.3 Determination of the direct-axis subtransient short-circuit time constant (τ''_d)

11.9.4 Determination from tests

The direct-axis, subtransient short-circuit time constant, τ''_d, is obtained from the short-circuit test data used to determine the direct-axis subtransient reactance, method 1 (see 11.8.4.1). It is the time, in seconds, required for the subtransient alternating component of the short-circuit current, (see figure 11.2, line D), to decrease to 0.368 times its initial value. The determination of this time constant is shown in figure 11.2.

The rated-current value of the direct-axis sub-transient short-circuit time constant is the value that is applicable when the initial value of the transient plus sustained components of the short-circuit current, I' (see 11.7.1.1), is equal to rated current. The rated-voltage value of this time constant is the value which is applicable when the short circuit is applied at rated voltage, rated speed, no load. If a test at the required current or voltage was not made and the time constant is found to vary appreciably with the test current, the values for the several test runs may be plotted as a function of I'' or of E (corrected for speed variation if necessary), and the values at rated voltage may be found from the curves.

No correction for temperature is included because of the uncertain nature of the correction.

11.10 Test for determination of the direct-axis transient and subtransient open circuit time constants (τ'_{do}, τ''_{do})

11.10.1 General

For the definition of τ'_{do} see IEEE Std 100-1992.

11.10.1.1 Method 1. Field short circuit

The machine is operated at rated speed and specified voltage with the armature open-circuited. The field is excited from an exciter or equivalent source through a field circuit breaker using the connections of figure 11.6. The series resistor is used when necessary to protect the exciter from a momentary short circuit during the overlap of the field circuit breaker contacts. The normal arrangement is "make before break." In this case, the field discharge contact closes just before the main field current breaker opens. When it is necessary to protect the exciter, but impracticable to use a series resistor because of the heat, which would have to be dissipated, or because the exciter used in this test would have to be too large, method 2 should be used. This latter method is preferred.

The field current and voltage should first be measured simultaneously by instruments to obtain the field temperature by resistance (see 6.4.4) at the time of test. Immediately thereafter, the field circuit breaker is opened to short-circuit the field winding, and the armature voltage of one phase, field current, and field voltage are recorded by oscillograph.

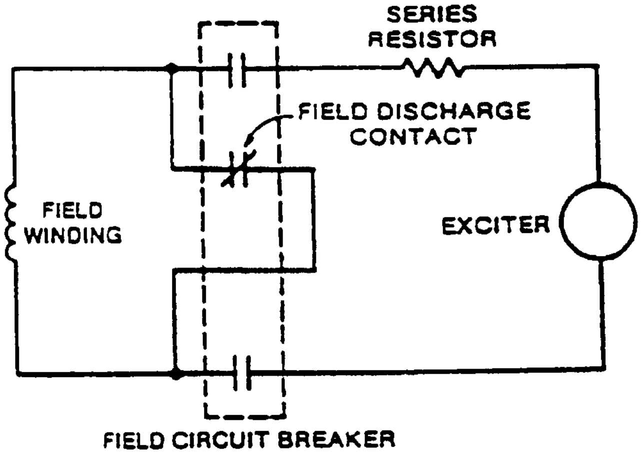


Figure 11.6—Field-winding circuit for direct-axis transient open-circuit time constant, method 1

11.10.1.2 Method 2. Discharge resistor connection

The procedure for making this test is similar to that of method 1. The connections of figure 11.7 are used. A field circuit breaker and a suitably-sized linear discharge resistor are required as shown in the figure. The discharge resistor is used to prevent a momentary short circuit of the source of excitation during the overlap of the field circuit-breaker contacts with the field discharge contact.

The field voltage and current should be determined from the oscillogram at several instants of time during the portion of the transient which will be used in the analysis. The ratio of voltage to current is the resistance of the discharge resistor and should be calculated for each of these instants so that the variation in the value of resistance during the test can be examined. If the sum of the discharge resistance and field resistance varies more than 5% during the period of interest, a discharge resistor of greater heat dissipation or of less temperature-sensitive material should be used.

Substitution of a suitable semiconductor diode in place of the discharge resistor may be made. In this case, R_D may be quite small after opening the exciter circuit breaker and may be considered to be zero if justified by the trace of field voltage. Care should be exercised in the diode selection to ensure that its current carrying capability is matched to the expected field discharge currents.

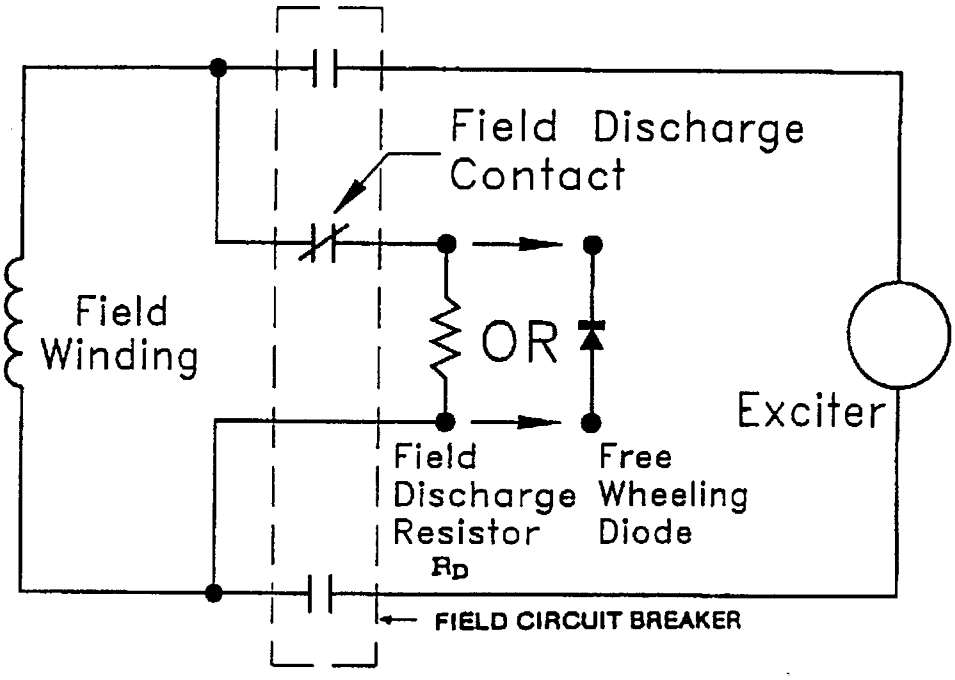


Figure 11.7—Field-winding circuit for direct-axis transient open-circuit time constant, method 2

11.10.2 Parameter determination for τ'_{do} from method 1—Field short circuit

The rms residual armature voltage is determined with the field winding open and with the machine operated at rated speed. This residual voltage is subtracted from the rms of armature voltage obtained from the oscillogram at selected points of time. The resulting varying component of voltage is plotted against time on semilogarithmic paper with the armature voltage on the logarithmic scale, as shown in figure 11.8. Normally, the curve is approximately a straight line if the few initial points of rapid decay are neglected. Extrapolation of the curve, neglecting the first few cycles, back to the moment of closing of the field-discharge contact, gives the effective initial voltage. The time in seconds for the armature voltage to decay to $1/\epsilon$ or 0.368 times the effective initial voltage is the open-circuit transient time constant τ'_{do}.

The time constant τ'_{do} can be corrected to a specified temperature, t_s, using the following simple algorithm:

$$\tau'_{do} = \tau'_{dot}\left(\frac{k + t_t}{k + t_s}\right) \quad \text{s} \tag{11-14}$$

where

τ'_{dot}	is the direct-axis transient open-circuit time constant from tests, s
t_t	is the field winding temperature during test (obtained according to 6.4.4), °C
t_s	is the specified temperature, °C
k	is the factor defined in 6.4.4 in Part I (for field winding material)

The oscillogram of field voltage can be used as a check to determine whether the field is effectively short-circuited during the transient.

The oscillogram of field current can be used to obtain a check value of the direct-axis transient open-circuit time constant using method 3 (see 11.10.4).

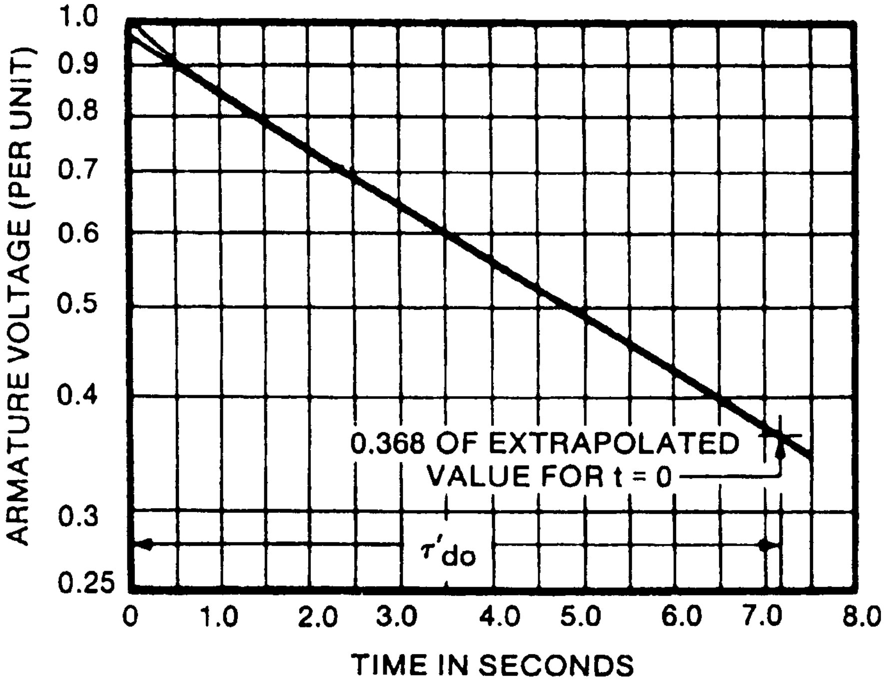


Figure 11.8—Determination of direct-axis transient open-circuit time constant

11.10.3 Parameter determination for τ'_{do} from method 2—Discharge resistor connection

A semilogarithmic plot of the time-varying component of armature voltage is obtained as described in method 1. The time required for the transient component of voltage to decay 1/ϵ, or 0.368, of its effective initial value neglecting the few initial points of rapid change is a modified direct-axis transient open-circuit time constant τ'_{doR}, including the effects of external field-circuit resistance.

The modified time constant should next be corrected to an apparent direct-axis transient open-circuit time constant at a specified temperature without external resistance. The field resistance, R_{fd}, is obtained (see 3.3.5) from the field current and voltage, and is measured just before the field circuit breaker is opened. The field resistance, R_{fds}, at specified temperature (normally 75 °C) is determined by the method of 3.3.2 using a previously determined reference value of field resistance at a known temperature (see 3.3.3 of part I).

The apparent direct-axis transient open-circuit time constant, corrected to the specified temperature, is calculated using equation 11-15 as follows:

$$\tau'_{doA} = \tau'_{doR}\left\{\frac{R_{fd}+R_D}{R_{fds}}\right\} \quad \text{s} \qquad (11\text{-}15)$$

where

τ'_{doA} is the apparent direct-axis open-circuit transient time constant (which has been corrected to eliminate the resistive effect of the discharge resistor), s
τ'_{doR} is the modified time constant obtained from semilogarithmic plot (which includes resistive effect of the discharge resistor), s
R_{fd} is the measured field resistance, Ω
R_{fds} is the field resistance at a specified temperature, Ω
R_D is the median resistance of discharge resistor during the period of analysis, Ω

11.10.3.1 Corrections to allow for presence of discharge resistor (method 2)

The discharge resistor in figure 11.7 may have an effect which cannot be completely accounted for by the method of 11.10.3. This is because the apparent transient open-circuit time constant may be affected by currents induced in the damper windings or solid iron magnetic paths of the rotor. The effect of these currents depends on the rate of decay of field current which, in turn, is affected by the discharge resistor.

Tests made with different values of discharge resistors should be made. If the apparent time constant has the same value, when calculated from test results using different discharge resistors. The apparent value from equation 11-15 is the direct-axis transient open-circuit time constant corrected to the temperature specified.

If the apparent time constant varies with the value of discharge resistor, a plot should be made of apparent time constant as a function of discharge resistance. By extrapolating the data to the value corresponding to zero discharge resistance, a value of direct-axis transient open-circuit time constant can be obtained.

11.10.4 Determination of τ'_{do}—Method 3: Field current

An *approximate* value of the direct-axis transient open-circuit time constant can be obtained by plotting field current, obtained by the oscillograph in method 1 or 2, as a function of time on semilogarithmic paper with field current on the logarithmic axis. The time constant is obtained from this plot in the same manner as in method 1 (or 2). The time constant thus obtained will usually approximate that obtained from the armature voltage. Method 3 should be used only as a check on the result of method 1 (or 2) and one of the latter methods should be used as the test result.

11.10.5 Determination of τ'_{do} by method 4: Voltage recovery

The direct-axis transient open-circuit time constant is obtained from the voltage-recovery test data used to determine the direct-axis transient reactance. It is the time, in seconds, required for the differential voltage to decrease to $1/\in$ or 0.368 times the time-zero intercept of the straight-line portion of the semilogarithmic plot. Correction for temperature can be made as in method 1 (see figure 11.4.)

11.10.6 Determining the direct-axis subtransient open-circuit time constant (τ''_{do})

11.10.6.1 General

For the definition of direct-axis subtransient open-circuit time constant, see IEEE Std 100-1992.

11.10.6.2 Determination directly from test

The direct-axis subtransient open-circuit time constant is determined from the voltage-recovery test data used to determine the direct-axis transient reactance, method 3 (see 11.7.3). The subtransient voltage (curve A of figure 11.9) is obtained by subtracting the transient component of differential voltage (line C) from the differential voltage (curve B).

NOTE — Line C and curve B are replotted from figure 11.4 to obtain a better time scale. A semilogarithmic plot of the subtransient voltage is made vs. time with the voltage on the logarithmic axis.

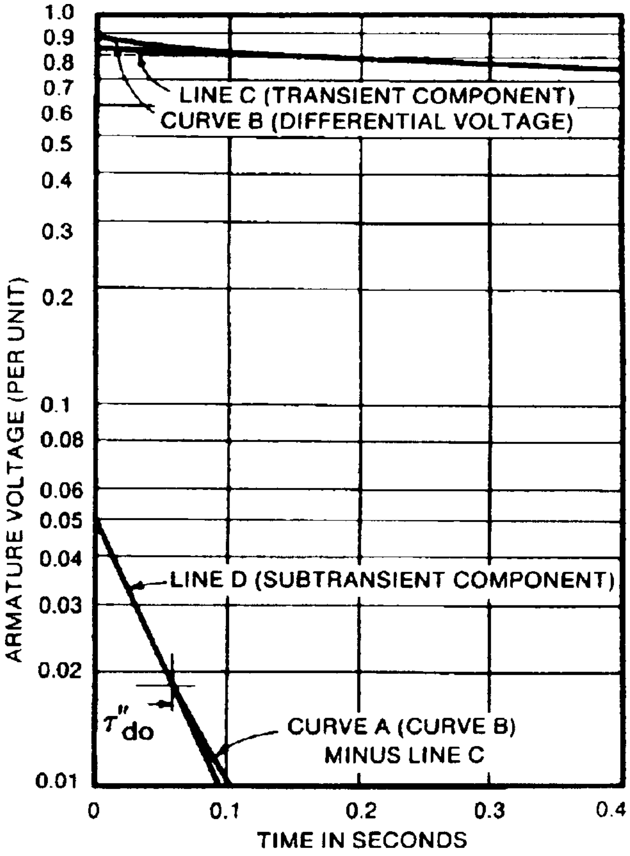


Figure 11.9—Voltage recovery test for direct-axis subtransient open-circuit time constant

A straight line (line D of figure 11.9) is fitted to this plot, giving preference to the earliest points if they do not follow a linear trend. The direct-axis subtransient open-circuit time constant is the time, in seconds, on the straight line corresponding to 1/∈ or 0.368, times the ordinate of the line at the instant of opening the circuit.

11.11 Determining the short-circuit armature time constant (τ_a)

11.11.1 General

For the definition of short-circuit time constant of the armature winding, see IEEE Std 100-1992.

The short-circuit armature time constant is obtained from the sudden short-circuit tests used to determine the direct-axis subtransient reactance, method 2 (see 11.7.1.2). All of the following methods may be used to obtain the time constant from the test data.

11.11.2 Determination of τ_a from resolved dc component—Method 1

Values of the dc components for the three-phase currents are obtained from the plots described in 11.8.4.2 for several values of time. A resolved value of the dc components, I_{dc} in p.u. is calculated for each value of time, using equation 11-16.

$$I_{dc} = \sqrt{\frac{4}{27}(a^2 + b^2 - ab)} + \sqrt{\frac{4}{27}(a^2 + c^2 - ac)} + \sqrt{\frac{4}{27}(b^2 + c^2 + bc)} \quad \text{p.u.} \tag{11-16}$$

where

a is the largest value of dc component of the three phase currents at the selected time, p.u. (see 11.4.4.2)
b is the second largest value of dc component, p.u.
c is the smallest value of dc component, p.u.

The values of resolved current from equation 11-16 are plotted as a function of time on semilogarithmic paper with current on the logarithmic axis. By extrapolating the curve back to the moment of the short circuit, the effect of the initial current is obtained. The short-circuit armature time constant is then determined as the time, in seconds, required for the resolved current to reach $1/\in$ or 0.368 times its initial value.

11.11.3 Determination of τ_a from dc components of phase currents—Method 2

The plots of the dc components of the currents in the three phases, extended to the start of the short circuit, are described in 11.7.1.2. A value of short-circuit armature time constant for each phase is obtained as the time, in seconds, required for the current to reach $1/\in$ or 0.368 of its initial value. The time constant is taken as the average of the values for each phase. If the initial dc component of any phase is less than 0.4 times the initial resolved value, the time constant for that phase should be disregarded because such a small value of current frequency produces inconsistent results due to extraneous effects (note the curve for phase 1 in figure 11.5). Method 1 is preferred because it makes better use of the data.

11.11.4 Determination of τ_a from field current response—Method 3

Values of the ac component of field current are obtained at frequent intervals from an oscillographic record of field current (see 11.7.1.1). A semilogarithmic plot is made of the amplitude of the alternating component of field current as a function of time with the alternating field current on the logarithmic axis. The armature time constant is the time required for the amplitude to reach $1/\in$ or 0.368 of its initial value.

11.11.5 Rated-current and rated-voltage values of τ_a—Saturation effects

The rated-current value of the short-circuit armature time constant is the value which is applicable when the initial value of the transient plus sustained components of the short-circuit current I' (see 11.7.1.1) is equal to rated current. The rated-voltage value of the short-circuit armature time constant is the value that is applicable when the short circuit is applied at rated voltage, rated speed, no load. If a test at the required current or voltage, or sufficiently close to it, was not made and the time constant is found to vary appreciably with test current, the values of the time constant for the several test runs may be plotted as a function of I' or E (corrected for speed variation if necessary), and the values at rated current or rated voltage can be found from the curves.

11.11.6 Correction of τ_a to a specified temperature

To correct the short-circuit armature time constant to a specified temperature (usually 75°C), it is necessary to measure armature temperature, t_t, preferably by embedded detector before the sudden short-circuit test. The short-circuit armature time constant, τ_a is corrected to the specified temperature using the following simple formulas:

$$\tau_a = \tau_{at}\left(\frac{k + t_t}{k + t_s}\right)s \qquad (11\text{-}17)$$

where

τ_{at} is the short-circuit armature time constant at test temperature, s
t_t is the temperature of armature winding by detector before the test, °C
t_s is the specified temperature, °C
k is as defined in 6.4.4 (part I) for field winding material

11.12 Computerized implementation of the general procedures noted in 11.7, 11.8, 11.9, and 11.10

This automated procedure is based primarily on IEEE papers listed as examples in the Bibliography in annex Annex C (see B5, B6, B7). The transient and subtransient reactances discussed in previous sections are based essentially on much-used graphical methods. The same applies to transient and subtransient time constants that are derived in subclauses of 11.9 and 11.10.

Short-circuit test currents $i_a(t)$, $i_b(t)$ and $i_c(t)$ are sampled simultaneously at a rate of at least 2 kHz, with the instruments zeroed and not saturated. The data is stored digitally in kA values, along with the nominal nameplate specifications of the machine V_{nom} (phase to phase rms in kV) and I_n (rms phase current in kiloamperes). These are the usual nominal voltage values and current values in machines of about 5 MVA or larger. For much smaller machines V_{nom} could be in volts and I_n could be in amperes. For checking purposes, a record length of N_f cycles is assumed. The value of N_f will depend upon the transient time-constant of the machine and should certainly be greater than 120 (2 s at 60-Hz rated-frequency), since T'_d is generally greater than 0.5 s for most large synchronous machines. An equation similar to equation 11-1 is chosen, but including as well the effect of T_a, the armature short-circuit time constant. However, this new equation excludes any subtransient saliency and ignores any possible second-harmonic terms in the current waveforms.

11.12.1 Peak search

Using a simple algorithm for local extrema detection (a so-called peak search routine), the time-current (T-I) coordinates of the upper and lower envelopes of each waveform (T_{upp}, I_{app}) and (T_{low}, I_{low}) are determined for the total window length of N_f cycles. Time and current are respectively in seconds and kiloamperes.

11.12.2 Envelope synchronization

Generally, the data composing the upper and lower envelopes as obtained from the peak search step do not correspond to identical points in time. Therefore, one cannot use simple addition and subtraction to derive the unidirectional and dc components of the original phase-current. To circumvent this problem, two different approaches can be applied.

11.12.2.1 Polynomial fitting

The approach first consists in fitting each envelope with a high order polynomial. If the same order is used for both envelopes, then all the necessary algebraic operations can be performed using the two polynomial models P_{upp} and P_{low}.

For instance, if the chosen order is 10, the two polynomials may be expressed as follows:

$$P_{upp}(t) = A_{upp0} + A_{upp1}t + \ldots + A_{upp10}t^{10}$$

$$P_{low}(t) = A_{low0} + A_{low1}t + \ldots + A_{low10}t^{10}$$

Hence, for a given working time coordinate T_{upp}, the value corresponding to the addition of the envelopes is obtained by direct substitution of T_{upp} in $P_{total}(t) = P_{upp}(t) + P_{low}(t)$, yielding the following result:

$$\begin{aligned} P_{total}(T_{upp}) &= (A_{upp0} + A_{low0}) + (A_{upp1} + A_{low1})T_{upp} \\ &+ \ldots + (A_{upp10} + A_{low10})T_{upp}^{10} \end{aligned}$$

that is actually two times the dc component at time T_{upp}. The symmetrical component is computed similarly, based on the half-difference of the basis polynomials expressed as follows:

$$P_{total}(t) = (P_{upp}(t) - P_{low}(t))/2.$$

11.12.2.2 Application of spline interpolation

Spline functions yield smooth interpolating curves that are less likely to exhibit the large oscillations characteristic of high-degree polynomials B26. Briefly speaking, a cubic spline consists of cubic polynomials pieced together in such a fashion that their values and those of their first two derivatives coincide with the envelope samples $I(t_i)$ at the *knots* t_i, $i=1,2,\ldots, N_f$. For instance, a spline representation of an envelope permits one to compute $I(t)$, for all $0<t<N_f$, based on the discrete tabular data $(t_i, I(t_i))$ obtained from the peak search routine. Thus, starting with (T_{upp}, I_{upp}) as the given working coordinates, the lower envelope data (T_{upp}, I_{lows}) is computed for the same time-coordinate T_{upp} from a cubic-spline interpolation of the original lower envelope data set (T_{low}, I_{lows}): I_{lows} = spline $(T_{low}, I_{low}, T_{upp})$ (subscript "s" stands for spline).

An example of envelope data obtained using cubic spline interpolation, in the case of a typical salient-pole machine, is shown in figure 11.10.

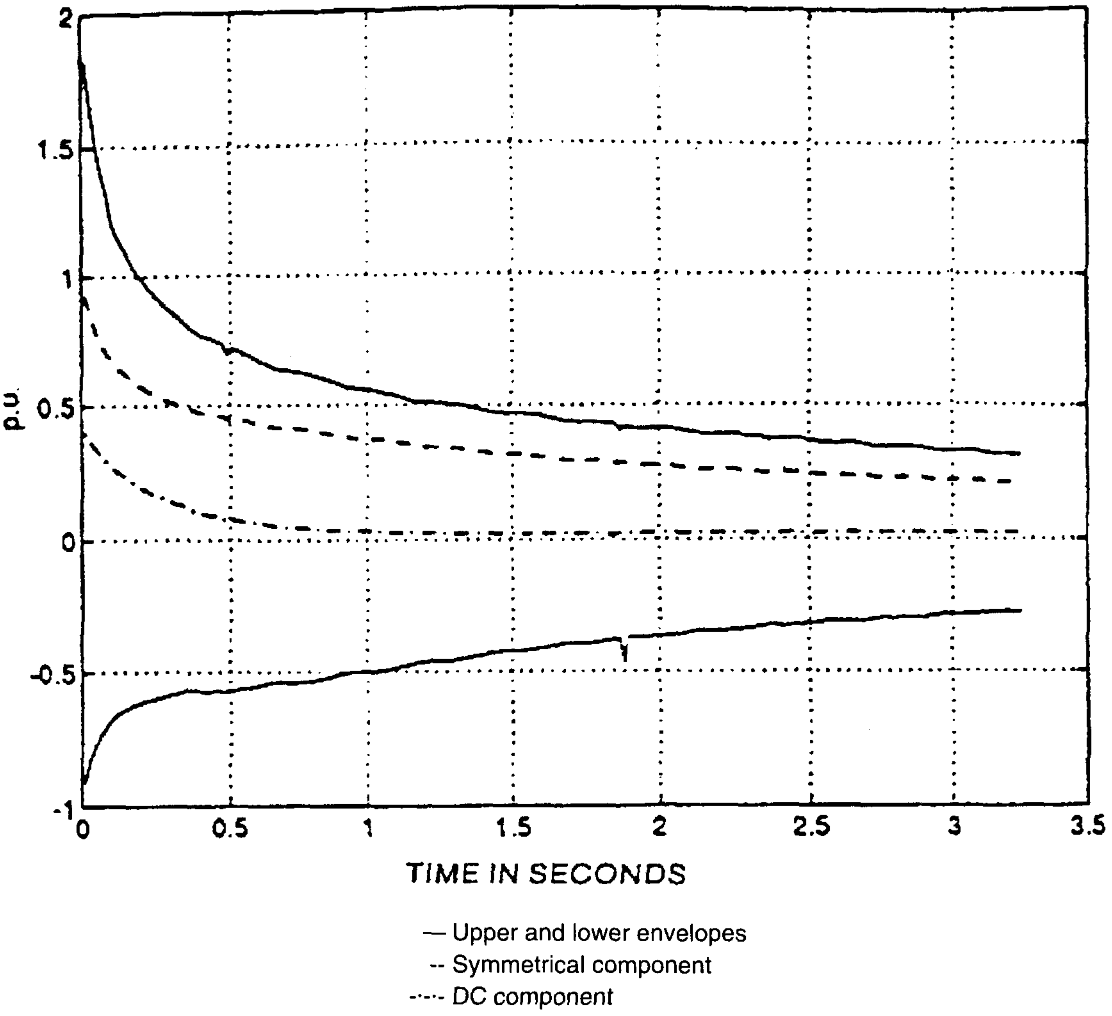


Figure 11.10—Component data for automatic analysis

11.12.3 Computation of symmetrical and dc components

Once the upper and lower envelopes have been converted to the same time-coordinates, the symmetrical component is determined by

$$i(t) = \frac{[I_{upp}(t) - I_{low}(t)]}{2\sqrt{2}I_n} - \frac{I_{ss}}{I_n} \qquad \text{p.u. A} \tag{11-18}$$

where

I_{ss} is the steady-state current finally reached after short circuit
I_n is the normal (or base) current of the machine in kiloamperes

The dc component is calculated as follows:

$$i_{dc}(t) = \frac{[I_{upp}(t) + I_{low}(t)]}{2\sqrt{2}I_n} \qquad \text{p.u. A} \tag{11-19}$$

The factor $\sqrt{2}$ converts the peak amplitude into rms value. Symmetrical and direct current components obtained from spline interpolation of equations 11-18 and 11-19 are illustrated in figure 11.10.

11.12.4 Transient straight-line representation

In addition to the hypotheses used in the second paragraph of 11.12, assume that after about 10–20 cycles, both the subtransient and armature winding effects have completely disappeared or been reduced to insignificant levels. Therefore, the signal *i(t)* from about 20 cycles up to say, 150 to 200 cycles consists of one time-constant only, which presumably corresponds to transient effects. A straight-line logarithmic model can be fitted to this data, using standard polynomial-regression procedures as follows:

$$\ln \Delta i'(t) = \ln i(t) = A't + B' \tag{11-20}$$

for t in the range beyond 20 cycles.

Note than *ln* is a natural logarithm to the base $\in$, where $\in = 2.71828$. Applying this model to the data in figure 11.10, between 10 cycles and about 160 cycles, we obtain the following parameters:

$A' = -0.6661$; and $B' = -0.5471$

The fit of this linear regression model between 10 cycles and 160 cycles, compared with the original data, is illustrated in figure 11-11a).

The actual transient parameters can be determined in as follows using:

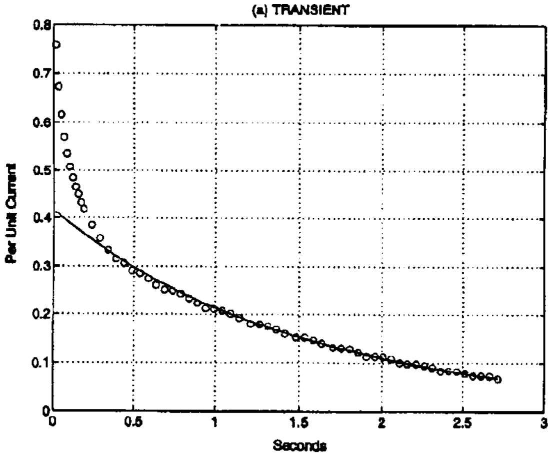
$$\tau'_d = -\frac{1}{A'} \qquad \text{s} \tag{11-21}$$

$$\Delta i'(0) = \varepsilon^{B'} \qquad \text{p.u. A} \tag{11-22}$$

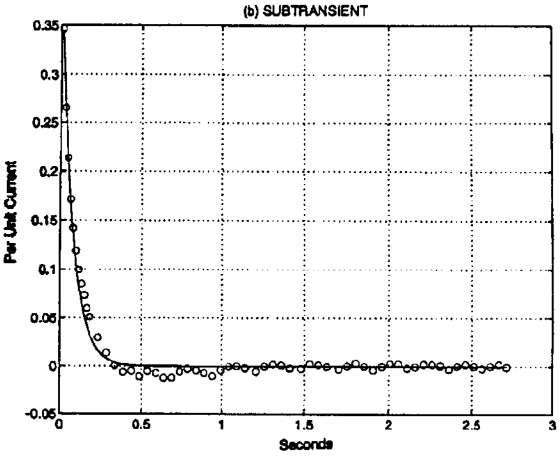
$$X'_d = \frac{V_0/V_n}{[\Delta i'(0) + I_{ss}/I_n]} \qquad \text{p.u. reactance} \tag{11-23}$$

where
V_0 is the terminal phase-voltage prior to the short-circuit in rms kilovolt values

a) Transient data:
$\Delta i'(t)$



b) Subtransient data:
$\Delta i''(t)$



c) Direct current data:
$abs[i_{dc}(t)]$.____Model. o Test

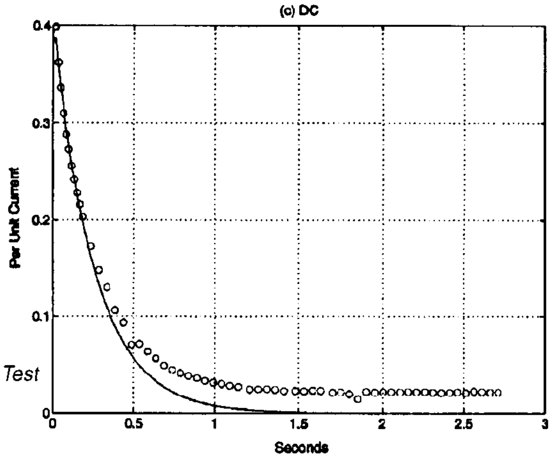


Figure 11.11—Decoupled time-scales analysis

11.12.5 Subtransient straight-line representation

Since the transient behavior is now well known from the preceding step, its effect can be eliminated from the original data, prior to subsequent analyses as follows:

$$\Delta i''(t) = i(t) - \Delta i'(t) = i(t) - \varepsilon^{A't + B'} \tag{11-24}$$

Assuming that the subtransient effects predominate over the armature direct current offset effects for the first few (3–4) cycles, a single time-constant model can be fitted to $\Delta i''(t)$ as follows:

$$\ln \Delta t''(t) = A''t + B'' \tag{11-25}$$

for t in the range from zero to 3-4 cycles. For example, in the envelope data in figure 11.10, for 3 cycles, one can obtain the following regression parameters: $A'' = -13.9119$ and $B'' = -0.0050$. The closeness of fit of this linear model for $\Delta i''(t)$ is assessed in figure 11-11b).

The actual subtransient parameters are then derived in p.u. and seconds using

$$\tau'_d = -\frac{1}{A''} \qquad \text{s} \tag{11-26}$$

$$\Delta i''(0) = \varepsilon^{B''} \qquad \text{p.u. A} \tag{11-27}$$

$$X''_d = \frac{V_0/V_n}{[\Delta i''(0) + \Delta i'(0) + I_{ss}/I_n]} \qquad \text{p.u. reactance} \tag{11-28}$$

11.12.6 Direct-current (dc) component straight-line representation

Having assumed that the subtransient and transient effect dominate respectively in the ranges 0 to 4 cycles and 20 to 150 cycles, it is reasonable to conclude that armature effects, which determine the main behavior of the dc component, are most active between about 4 and 20 cycles. It follows that a single time-constant model can be fitted to $i_{dc}(t)$, in the following linear logarithmic form:

$$\ln abs(i_{dc}(t)) = A_{dc}t + B_{dc} \tag{11-29}$$

for t in the range 4 to about 20 cycles. For the i_{dc} data in figure 11.10, the statistical analysis leads to $A_{dc} = -3.9532$ and $B_{dc} = -0.8961$. From figure 11-11c) this single-exponential model compares quite well with the original data in the same interval. The dc parameters in p.u. and seconds are finally computed from

$$\tau'_a = -\frac{1}{A_{dc}} \qquad \text{s} \tag{11-30}$$

$$i_{dc}(0) = \varepsilon^{B_{dc}} \qquad \text{p.u. A} \tag{11-31}$$

11.12.7 Averaging

Steps 11.12.1 to 11.12.6 are applied to each phase-current, leading to three separate sets of transient, subtransient and dc parameters. The nominal values of transient and subtransient parameters are obtained by a direct averaging of the three elementary phase values.

11.13 Stationary or unbalanced tests for determining X''_d, X_2 or X''_q

11.13.1 Specific tests and data gathering for a stationary test for determining X''_d

11.13.1.1 Applied voltage test—Method 3

For this test the rotor is stationary and the field winding is short-circuited through a suitable ac ammeter or current transformer supplying an ammeter. Single-phase voltage of rated frequency is applied to any two stator terminals, the third being isolated. The connections are shown in figure 11.12. The armature voltage and current and the field current are recorded. To avoid possible injurious rotor heating during the test, reduced voltage is normally used (particularly for cylindrical-rotor machines) and the limitations of voltage, field current and duration of test specified by the manufacturer should not be exceeded.

A quantity "X" can be obtained from the readings of current and voltage using the following equation:

$$X = \frac{E}{I} \quad \text{p.u.} \tag{11-32}$$

where

E is the applied line-to-line voltage, in p.u. of base *line-to-neutral* voltage
I is the line current, in p.u. of base line current

As quickly as possible the test voltage is removed and the same voltage is applied to another pair of terminals in the same way. A quantity "Y" is determined from these readings by the method of equation 11-32. Then the test voltage is applied to the third pair of terminals, from which "Z" is obtained in a similar manner. The order in which the terminal pairs are selected is immaterial. It is important that the rotor position remain the same throughout this test. Blocking of the rotor to prevent turning should be used if necessary.

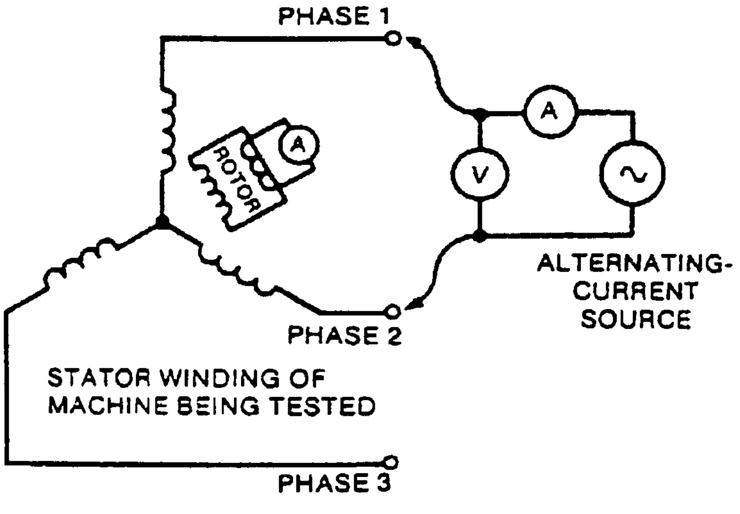


Figure 11.12—Diagram for determination of direct-axis subtransient reactance by method 3

11.13.1.2 Parameter determination for method 3

It is assumed that the single-phase stationary rotor reactance, determined for any one pair of terminals as in 11.13.1.1, would vary if the rotor were turned, as a constant term plus a sinusoidal function of rotor angular position. If the three phases are symmetrical, the results X, Y, and Z are then equal to three values of the stationary rotor impedance, for one pair of terminals, at positions of the rotor differing by 120 electrical degrees. Based upon these assumptions, the constant term is given by

$$K = \frac{X + Y + Z}{3} \tag{11-33}$$

and the amplitude of the sinusoidal component of voltage reactance variation is given by

$$M = +\sqrt{(Y - K)^2 + \frac{(Z - X)^2}{3}} \tag{11-34}$$

If any two of the values, X, Y, or Z are equal, the values may be reassigned so that Z and X are the two equal values and M then becomes simply Y-K. The sign of M is selected as positive. The direct-axis subtransient reactance is then given by equation 11-35. Usually, the direct-axis reactance corresponds to the smallest possible stationary-rotor reactance. For this case, the use of the negative sign in equation 11-35 is suggested.

$$X''_d = \frac{K \pm M}{2} \qquad \text{p.u.} \tag{11-35}$$

For solid-steel cylindrical-rotor machines under certain conditions, the direct-axis reactance may correspond to the maximum stationary-rotor reactance. If this is the case, the maximum measured field current corresponds to the largest of the three measured single-phase reactances (in 11.13.1.1) and the plus sign should be used in equation 11-35.

NOTE — This will not normally be the case.

The tests may be repeated with the rotor turned to any new position, and the same values of K and M should be obtained. Thus, the first tests may be checked by a second series of tests.

For solid-steel cylindrical-rotor machines and for salient-pole machines with damper windings connected between poles, the value of M is expected to be very small compared with that of K.

When the reactance is to be determined corresponding to a specified current, two or more series of tests may be needed at different voltages (see 11.13.3). For currents up to rated current, the variation of the subtransient reactance is usually small and determination at the precise current may often not be necessary.

For certain types of machines, such as solid-steel cylindrical-rotor machines, the values of reactance obtained from this test may not agree with values obtained from sudden short-circuit tests. For such machines this method cannot be expected to give values of *rated-current or rated-voltage* reactances, and method 1 should be used.

11.13.2 Indirect method for determining X''_d—Method 4

This method is applicable only to cylindrical-rotor machines and to salient-pole machines having continuous amortisseur windings (connected between poles). For such machines the direct-axis subtransient reactance is very nearly equal to the negative-sequence reactance (X_2), and may be taken equal to the negative-sequence reactance as determined by 10.5.4.

11.13.3 Rated-current and rated-voltage values—Effects of saturation on determining X''_d

Because the direct-axis subtransient reactance varies with armature current, the result of any test should be associated with the appropriate value of current or voltage. It should be noted that the rated-current value is, by definition, the value applicable when the sum of the initial transient and sustained components of current (see I' of 11.7.1.3) has rated value. The corresponding total ac component (see I'' of 11.7.1.1) including the subtransient component would therefore be somewhat greater. In methods 1 and 2, (see 11.8.4) the direct-axis subtransient reactance is determined from the same tests that are used for the determination of transient reactance (see 11.7.1.1). The rated-current value of direct-axis subtransient reactance may therefore be determined in the same way as the rated-current value of transient reactance by plotting it as a function of the same current (I') and taking the value of subtransient reactance corresponding to rated current. If the transient reactance was plotted as a function of voltage according to 11.8.1.2, X''_d may also be plotted on the same paper. The rated-current value of subtransient reactance corresponds to the same voltage as X'_d.

The rated-voltage value is determined from a sudden short-circuit test made at rated voltage, no load (see method 1 or 2).

When method 3 or 4 is used, there is neither direct association of the test results with a corresponding transient plus sustained component of current (I'), nor is it assured that the reactance will be the same during a line-to-line test as it would be for a three-phase test at the same test current. Probably the best evaluation of the rated-current value of direct-axis subtransient reactance (if the reactance varies appreciably with current in the region near rated current) is to assume that during a line-to-line test the reactance by method 3 or 4 is the value determined from a test (or by graphical interpolation of data from a series of tests at different currents) in which the line-to-line test current, multiplied by $(2X''_{di} / \sqrt{3} X'_{di})$ is equal to the rated current. (X'_{di} and X''_{di} are the rated-current values of direct-axis transient and subtransient reactances, respectively.) See also 6.3 of IEEE Std 1110-1991. To permit this determination, the approximate ratio of the rated-current direct-axis transient reactance to the rated-current direct-axis subtransient reactance must be known. The foregoing is based on considering saturation effects to be determined by the sum of the positive-sequence and negative-sequence currents during the test.

It is improbable that methods 3 or 4 can be safely used at sufficiently high currents to permit direct determination of the rated-voltage value. Therefore, empirical or calculated correction factors should be used to determine the approximate rated-voltage value.

11.13.4 Additional line-to-line sudden short circuit test for determining X_2—Method 4

11.13.4.1 Methodology

The data available may be determined from the oscillogram of a single-phase, line-to-line short circuit, suddenly applied to a synchronous machine operating at no load, open circuit, and at rated speed.

11.13.4.2 Determining the parameter X_2

The open-circuit voltage, E, in p.u. of rated voltage is as measured before the short circuit, and the rms value of the initial ac component of armature current, I'', in p.u. of rated current, is determined as for a three-phase short circuit (see 11.7.1 and 11.8.2). Then the line-to-line value of negative-sequence reactance is obtained by the following:

$$X''_{2LL} = \frac{\sqrt{3}E}{I''} - X''_d \qquad \text{p.u.} \tag{11-36}$$

where

X''_d is the direct-axis subtransient reactance corresponding to a three-phase short circuit at the same initial voltage as the line-to-line short circuit.

The correction of the line-to-line value of negative-sequence reactance is made as in 10.5.4.3.

To determine the rated-current value, a series of tests may be needed at different values of open-circuit voltage.

If the values of reactance X_2 are plotted as a function of negative-sequence current (which equals $\frac{I''}{\sqrt{3}}$), the rated-current value is the value corresponding to rated current.

The rated-voltage value is the value determined from tests at rated voltage, no load.

11.13.5 Quadrature-axis subtransient reactance (X''_q)

11.13.5.1 General

For the definition of quadrature-axis subtransient reactance, see IEEE Std 100-1992.

The rated-current value of quadrature-axis subtransient reactance may be obtained using method 1 and an approximation to the rated-voltage value from method 2. Since the description of both methods is short, the parameter determination follows in the same subclause as in methods 1 and 2.

11.13.5.2 Method 1. Applied voltage

The quadrature-axis subtransient reactance is determined from the data obtained in the determination of the direct-axis subtransient reactance by method 3. In terms of the quantities defined in 11.13.1.2, the quadrature-axis subtransient reactance is obtained by equation 11-37. Usually, the quadrature-axis reactance corresponds to the largest stationary-rotor reactance. For this case, the use of the positive sign is suggested.

$$X''_q = \frac{K \pm M}{2} \qquad \text{p.u.} \tag{11-37}$$

where

K and M are determined from equations 11-33 and 11-34, respectively.

For solid-steel cylindrical-rotor machines under certain conditions, the quadrature-axis subtransient reactance may correspond to the minimum stationary-rotor reactance. If this is the case, the maximum measured field current corresponds to the largest of the three measured single-phase reactances (in 11.1.1) and the minus sign should be used in equation 11-37.

The test current to be used for determining the rated-current value of quadrature-axis subtransient reactance is the same as for the determination of the rated-current value of direct-axis subtransient reactance, as given in 11.13.3. If the values of X''_q are plotted on the same graph as those of X''_d, the rated-current value can be read from the curve at the same current.

11.13.5.3 Method 2. Sudden short circuit

A value of quadrature-axis subtransient reactance can be obtained from two sudden short-circuit tests taken from no-load conditions at the same voltage and at rated speed; one three-phase short circuit (see 11.7.1) and one sudden single-phase line-to-line short circuit (see 11.13.4). The direct-axis subtransient reactance obtained from the three-phase test is designated as X''_{d3}. For the single-phase test (see 11.13.4), the open-circuit voltage, E, and the initial ac component of armature current (I'' by the method of 11.7.1.1) are obtained and used in the following equation:

$$X_{LL} = \frac{\sqrt{3}E}{I''} \qquad \text{p.u.} \tag{11-38}$$

The quadrature-axis subtransient reactance is obtained using the following equation:

$$X''_q = \frac{(X_{LL} - X''_{d3})^2}{X''_{d3}} \quad \text{p.u.} \tag{11-39}$$

11.13.6 Effect of saturation in determining rated current or rated voltage values of the parameter X''_q

Because of saturation effects, particularly on solid-steel cylindrical-rotor machines, the values of machine subtransient reactances will vary depending on the actual conditions of operation. Therefore, this method is approximate because the current level on a single-phase line-to-line sudden short circuit is substantially less than on a three-phase sudden short circuit from the same voltage while the flux level in the machine for the two conditions is the same. There will be a certain mismatch in the saturation pattern in the machine under these two test conditions (as well as under any other combination of initial voltages).

A value of rated-voltage quadrature-axis subtransient reactance can be obtained by this method based on sudden short-circuit tests from rated voltage. Because of the situation discussed above, this can be considered only as an approximation to the rated voltage value, but a more precise method has not been investigated.

Annex 11A

(informative)

Quadrature axis transient or subtransient tests

11.A.1 General

As noted in the introduction to section 11 (11.1–11.3 inclusive), sudden short-circuit procedures for determining transient and subtransient characteristic quantities result only in direct axis values. Such test procedures are undertaken from machine open circuit conditions, with direct-axis field current excitation adjusted to produce a range of stator terminal voltage (E_a) from low values up to around 1.0 p.u.

Although the following tests are not at all prevalent in North America, it was suggested that certain tests, published in IEC 34A (1985), be noted here. The ones to be briefly described are used in determining transient and subtransient *quadrature* axis synchronous machine characteristic values—both reactances and time constants. Annex A of IEC 34-4 (1985) describes such tests and is titled "*Unconfirmed* test methods for determining synchronous machine quantities."

11.A.2 Description of tests for quadrature axis values

The methodology for the above-noted quadrature axis values involve operating the synchronous machine at a low voltage, at low power and connected synchronously (or asynchronously) to a power system source. Three procedures (two of them related) are noted below. The descriptions have been summarized in the interests of brevity, but are intended to generally indicate the methodology.

11.A.2.1 Disconnecting applied low armature voltage at a very low-slip test

The sudden disconnection of the applied low armature voltage during a low-slip test is performed on a machine running at a slip considerably less than 0.01 p.u. with the armature (primary) winding connected to a rated frequency symmetrical three-phase low-voltage supply (5% to 10% of normal voltage).

NOTE — The excitation winding is short-circuited for direct-axis quantities. When determining quantities in the quadrature axis the excitation winding may be open-circuited.

The applied voltage is suddenly disconnected when the rotor is magnetized in the quadrature axis. The rotor position is checked by measuring the internal angles between the armature voltage and the quadrature magnetic rotor axis. Armature current and voltage, and rotor position indication are measured and recorded.

At the instant of switching off the machine from the low voltage supply, the armature (primary) winding voltage suddenly drops to a particular value and then gradually decays.

This initial voltage drop is independent of the residual voltage. In determining time constants, the residual voltage must be less than 0.2 of the applied voltage, and accordingly its value need not be taken into account for determining time constants along the *q*-axis with the required accuracy.

NOTE — In many types of machines it is difficult to segregate transient and subtransient voltage components along the *q*-axis because the high decrement components may not be clearly separated from the remainder.

11.A.2.2 Disconnecting applied low armature voltage test—The machine running asynchronously on load

The disconnecting applied low armature voltage test, the machine running asynchronously on load, is performed with the armature (primary) winding connected to a rated frequency symmetrical three-phase low-voltage supply to avoid influence of saturation, and the excitation winding is short-circuited.

By means of positioning signals on the shaft, the direct- and quadrature-axis components of voltage and current are determined.

The positioning signals are set to correspond to the quadrature (magnetic axis) by means of a line-to-line voltage at no load.

The transmitter producing the positioning signal should be displaced round the shaft until its signal coincides with the instant when the line-to-line voltage E_{12} passes through zero. At this position the signal will coincide with the maximum of phase voltage E_3 which, at no load, corresponds to a *q*-axis voltage.

When the machine is loaded, the instantaneous values of the phase voltage E_3, and of the phase current I_3 at the instant of the signal coincide with the *q*-axis components of this voltage and current.

After adjusting the recorders, the test measurements are performed. When the machine has reached an internal angle approaching 90±20 electrical degrees, an oscillogram is taken of the line-to-line voltage E_{12}, the phase current I_3 and the *q*-axis signal, showing a time interval that includes switching off. Before disconnecting the applied voltage, the current $I_q(0)$ and the voltage $E_d(0)$ are measured. The sequence voltages after switching off are determined from an oscillogram. These voltages, are plotted on a logarithmic scale against time and the initial transient and subtransient components are found in the usual way. Residual voltages are subtracted before the plotting.

11.A.2.3 Sudden short-circuiting of machine, running on load at low-voltage—Test

The sudden short-circuiting of the machine is performed while it is running on load with the armature winding connected to a rated-frequency symmetrical three-phase low-voltage supply, at about 10% of normal. The excitation winding is short-circuited.

Care has to be taken in choosing the proper voltage to ensure that the machine can be loaded up to 90±20 electrical degrees, and also that no damage is done when short-circuiting the machine. The voltage supply is disconnected after short-circuiting the machine.

The positioning signals on the shaft are adjusted in a similar way to that described in 11.A.2.2. The *q*-axis current is measured using the current in phase 3 at the time of the *q*-axis signal. The *d*-axis voltage may be measured at the same time as the line-to-line E_{12} voltage. The test is performed by short-circuiting the machine after it has reached an angle approaching 90 electrical degrees ($t=0$). It may also slip very slowly. Values of $I_q(0)$, and $E_d(0)$, and after the short circuit I_{q1}, I_{q2}, etc., are measured on an oscillograph. The plot of current value against time on a natural time scale is to be obtained from the oscillogram; the initial values $\Delta I'_q(0)$ and $\Delta I''_q(0)$ and variations of transient $\Delta I'_q$ and subtransient $\Delta I''_q$ current components with respect to time are determined and drawn on a semi-log scale.

11.A.3 Terminology and definitions for transient and subtransient reactances

11.A.3.1 Description of tests for reactances

The definitions listed in annex A of IEC 34-4 (1985) for X'_q (quadrature axis transient reactance) and X''_q (quadrature axis subtransient reactance) are essentially the same, and conform in principle and theory to those listed in IEEE Std 100-1992.

The test-derived descriptions of X'_q and X''_q in IEC 34-4 (1985) (annex Annex A) are, for practical purposes as follows:

a) X'_q—The quotient of the initial value of a sudden change in that fundamental ac component of armature voltage, which is produced by the total quadrature-axis flux, and the value of the simultaneous change in the fundamental ac component of quadrature-axis armature current, the machine running at rated speed, and high-decrement components during the first cycles being excluded.
b) X''_q—The test derived description for this quantity is essentially that described in a) except that the high-decrement components during the first cycles are included.

NOTE — See 11.A.2.3 above for actual methodology.

11.A.3.2 Parameter determination from tests

Parameter determination for X'_q and X''_q is based on the test procedures detailed in 11.A.2.3.

a) $$X'_q = \frac{E_d(0)}{\{I_q(0) + \Delta I'_q(0)\}}$$ (all quantities in p.u.)

where

$E_{d(0)}$ and $E_{q(0)}$are the components of the voltage and current at the time of short circuit.

b) $$X''_q = \frac{E_d(0)}{\{I_q(0) + \Delta I'_q(0) + \Delta I''_q(0)\}}$$ (all quantities in p.u.)

NOTE — $\Delta I'_q(0)$ and $\Delta I''_q(0)$ are the sudden changes in the quadrature axis current at the time of short circuit.

The derivation of X'_q and X''_q by the methods of 11.A.2.1 and 11.A.2.2 are not detailed in this annex, but can be found in IEC 34-4 , annex Annex A. The above derivation is given as a typical example.

11.A.4 Terminology and definitions for quadrature axis transient and subtransient short-circuit time constant

Terminology and definitions for quadrature axis transient and subtransient short-circuit time constant (τ'_q and τ''_q).

11.A.4.1 Description of tests for short-circuit time constants

The quadrature axis transient short circuit time constant is summarized below.

The time required for the slowly changing component of quadrature-axis short-circuit armature winding current following a sudden change in operating conditions, to decrease to $1/\in$, or to 0.368 of its initial values, the machine running at rated speed.

The test procedure for the quadrature axis subtransient short-circuit time constant is summarized below.

The time required for the rapidly changing component, present during the first few cycles in the quadrature-axis short-circuit armature winding current following a sudden change in operating conditions, to decrease to $1/\in$ or to 0.368 of its initial value, the machine running at rated speed.

The above two quantities can be also derived following the test procedures described in 11.A.2.3.

11.A.5 Terminology and definitions for quadrature axis transient and subtransient open circuit time constant (τ'_{qo} and τ''_{qo})

The procedures described in 11.A.2.2 are quoted in annex A of IEC 34-4 (1985), as one of the two ways of determining values of open circuit time constants. This procedure basically involves suddenly disconnecting the synchronous machine when operating asynchronously at a low value of power and low value of stator terminal voltage.

11.A.5.1 τ'_{qo} Quadrature axis open circuit transient time constant

This is the time required for the slowly changing component of the open-circuit armature winding voltage winding voltage that is due to the quadrature-axis flux, following a sudden change in operating conditions, to decrease to $1/\in$ or to 0.368 of its initial value, the machine running at rated speed.

11.A.5.2 τ''_{qo} Quadrature axis open circuit subtransient time constant

This is the time required for the rapidly changing component present during the first few cycles in the open-circuit armature winding voltage that is due to the quadrature-axis flux, following a sudden change in operating conditions, to decrease to $1/\in$ or to 0.368 of its initial value, the machine running at rated speed.

11.A.6 Bibliography for Annex 11A

[11A1] Canay, I. M., "A new method of determining *q*-axis quantities of a synchronous machine," *ETZ A*, vol. 86, 1965, pp. 561–568.

[11A2] IEC 34-4 (1985), Rotating electrical machines—Part 4: Methods for determining synchronous machine quantities from tests.

12. Standstill frequency-response testing

12.1 General considerations and basic theory

12.1.1 Purpose of this form of testing

In section 8 and in the introduction to section 11, the reasons for short-circuit tests were presented. One reason is to show that the mechanical design of the synchronous generator (or motor) is adequate to withstand the mechanical stresses arising from short-circuit currents, which can be many, many times the normal stator stresses due to operating currents. A second and equally important reason is to facilitate the determination of various synchronous machine characteristics such as transient or subtransient reactances and time constants. Such characteristic values enable one to predict the machine's dynamic performance under transient or changing conditions.

Two direct-axis transient and subtransient reactances, and two corresponding short-circuit time constants have historically been determined from the short circuit testing procedures described in section 11. Accordingly, it has been customary to assume a two-rotor-circuit direct axis model to represent the synchronous machine in stability simulations and other related analyses. The assumed quadrature-axis equivalent circuit is similar in structure, except that the field winding is replaced by a second (equivalent) amortisseur circuit, representing damper bars or slot wedges.

It is also possible to derive corresponding quadrature axis quantities by resorting to special procedures with a synchronous machine at low load and connected at low voltage to a power network. These quadrature axis tests are summarized in Annex 11A. It is widely accepted that present day stability studies require both direct and quadrature axis synchronous machine characteristics for adequate simulation of power system dynamic responses.

An alternative exists to the above tests covered in section 11, and these alternate procedures are called Standstill Frequency Response (SSFR) testing. An IEEE Committee Report B8 covers the theoretical background, including the Laplace transform analysis of a synchronous machine (see 12.1.3). Generally speaking, stability parameters can be obtained by performing frequency response tests, with a synchronous machine preferably at standstill. Such responses describe the rates of change of various stator or field quantities over a range of sinusoidal excitations from very low frequencies up to and considerably beyond nominal 50 Hz or 60 Hz values.

12.1.2 Advantages of SSFR test procedures

One noteworthy advantage as to why SSFR testing has become an acceptable alternative to short-circuit testing is that identification of field responses is possible. This is described more fully in the two-port direct axis concept discussed further in 12.1.3.

Another specific advantage of frequency response methods is that they can be performed, and with relatively modest expense, either in the factory, or on site. They pose a low probability of risk to the machine(s) being tested, and data in both direct and quadrature axes are available, with little change in the test set-up, and without resorting to special short circuit and/or low voltage tests.

In general it would seem logical that a frequency-domain approach in describing the dynamic performance of machine models is preferable (at times) to a time-domain or step-response approach. The latter is inherent in most forms of current decrement testing and identification of two time constants and two inductances limits the decrement approach to models of second order. However machine dynamic models of higher order (rather than second) are available from the frequency domain approach, since testing embraces more than three decades, from about 0.01 Hz through to well over 100 Hz.

12.1.3 Theoretical background

The IEEE Committee Report B8 published in 1980 provided the basic theory for frequency response testing. In that report, equations were given describing the concept of an operational approach to synchronous machine dynamics. This concept describes the electrical responses of a synchronous machine to small perturbations. Such perturbations of stator and rotor quantities about some operating point involve basic transfer function parameters noted below in the direct and quadrature axes of a machine.

Thus

$$\begin{aligned} \Delta\psi_d(s) &= G(s)\Delta e_{fd}(s) - L_d(s)\cdot\Delta i_d(s) \\ \Delta\psi_d(s) &= \qquad\qquad\quad - L_d(s)\cdot\Delta i_d(s) \end{aligned} \tag{12-1}$$

where

Ψ_d and Ψ_q	are direct or quadrature axis stator flux linkages
i_d and i_q	are corresponding stator currents, at some operating point
e_{fd}	is the machine field voltage at a particular operating point
Δ	is a small perturbation around some operating point

$L_d(s)$, $L_q(s)$ and $G(s)$ (or $sG(s)$) are described below.

These equations also lead to the concept of a two port network for the direct axis, and one port for the quadrature axis. Figure 12.1 is a block diagram representation of equation 12-1. Note that a second "port" has been drawn for the quadrature axis for completeness, but it, in fact, is inaccessible.

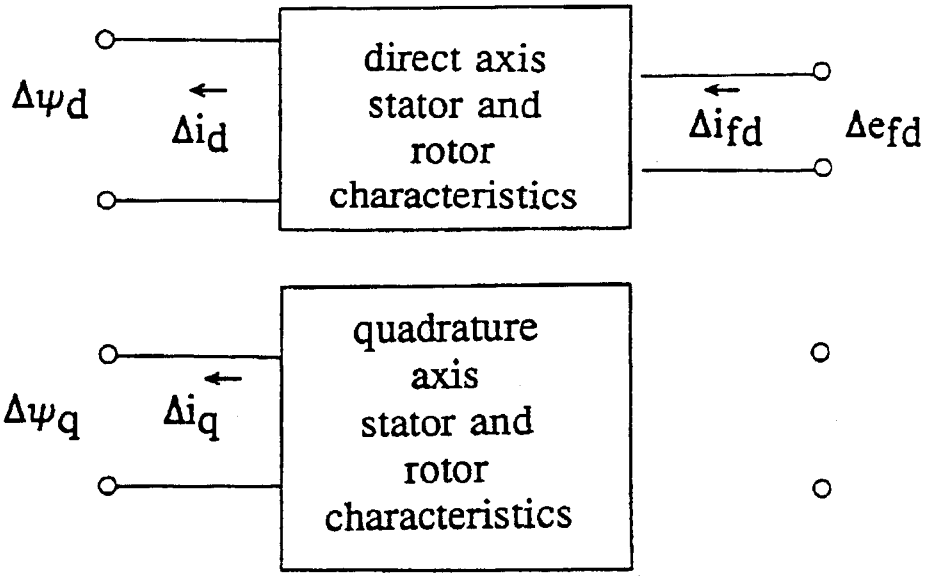


Figure 12.1—Two-port direct and quadrature axis representation based on equation 12-1

12.1.3.1 Definition of operational parameters for the direct and quadrature axes

The definitions below are the principal ones which power system analysts have found convenient when describing the response of synchronous machines B8. Note that functions of s are complex quantities, where $s = j\omega = j2\pi f$ rad/s.

$L_d(s)$	*The direct-axis operational inductance.* It is the Laplace transform of the ratio of the direct-axis armature flux linkages to the direct-axis current, with the field winding short-circuited.
$L_q(s)$	*The quadrature-axis operational inductance.* It is the Laplace transform of the ratio of the quadrature-axis armature flux linkages to the quadrature-axis current.
$G(s)$	*The armature to field transfer function.* It is the Laplace transform of the ratio of the direct-axis armature flux linkages to the field voltage, with the armature open-circuited.

An alternative way of describing the armature to field transfer function follows. $sG(s)$ is the Laplace transform of the ratio of the direct-axis stator current to the Laplace transform of the field current, with the field winding short-circuited.

Another useful transfer function is

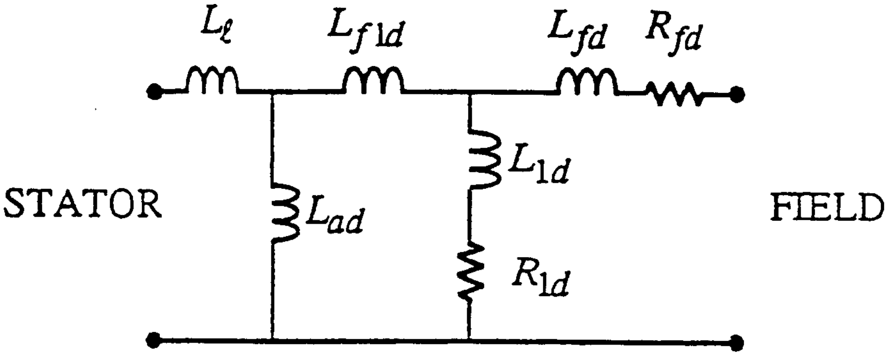
$Z_{afo}(s)$	It is ratio of the Laplace transform of the field voltage to the direct-axis stator current, with the field circuit winding open.

12.1.4 Model representation possible from this form of testing

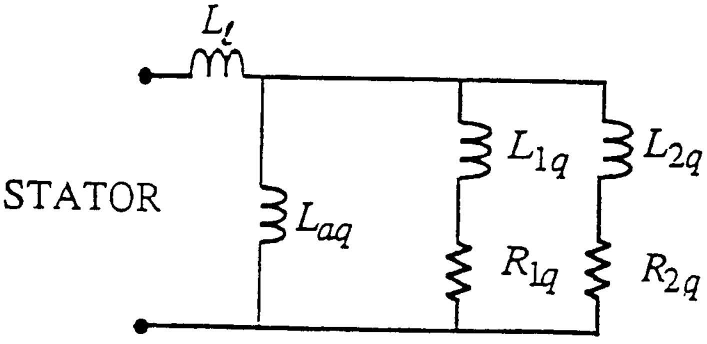
Reference B9 is an original paper that describes how the above noted transfer functions may be developed into specific models. In that paper, second order models are chosen and a closed form set of equations are listed which describe the rotor model elements of figure 2. Although the values of L_{ad} and L_{aq} in figure 2 can be derived from measurements described in section 10, they are often taken from generator design data. L_l is almost always taken from design data.

Note that in figure 12.2, on the direct axis, an additional inductance is shown (L_{fld}). This inductance has been identified in recent literature as a differential leakage inductance. In Reference B9 by Canay it was shown that L_{fld} equals the difference between the relatively large mutual inductances. L_{mfld} is the mutual inductance from the field winding to an equivalent rotor iron circuit or rotor damper bar circuit. L_{ad} is the mutual inductance between the field winding and the stator. Thus $L_{fld} = L_{mfld} - L_{ad}$. In turbine-generators L_{mfld} is slightly greater than L_{ad}, and thus L_{fld} usually has a positive value. In hydrogenerators the opposite is true and L_{fld} often has a negative value. Reference B9 also shows that ignoring L_{fld}, by assuming L_{mfld} equals L_{ad}, results in inaccurate calculation of field current responses, under generator transient conditions. This omission of L_{fld} is permissible if stator responses to generator transient conditions are only of importance, and if field excitation is held constant.

Alternate forms of model representation are available in transfer function form, or in inductance-matrix form. These are discussed in 6.5 of IEEE Std 1110-1991.



d-axis



q-axis

Figure 12.2—Complete direct-axis equivalent and quadrature-axis equivalent (second order model)

12.1.5 Additional comments on application of operational methods to a synchronous machine

As noted above, in considering appropriate models of a synchronous machine derived from SSFR test data, a synchronous machine is basically equivalent to a one-port network in the *q*-axis and a two-port network in the *d*-axis. Some implications of this equivalency are

a) For a complete mathematical description of the direct axis device, three transfer functions are needed. The set ($L_d(s)$, $sG(s)$, and $Z_{afo}(s)$) as determined in subsequent clauses appears to constitute a useful group.

b) When focusing on stator voltage perturbations, the third transfer function $Z_{afo}(s)$ is not generally used. This is the basis for using only $L_d(s)$ and $sG(s)$ in determining models for stability studies. As long as the excitation source impedance is unimportant (low) during excitation system voltage excursions, and the excitation source voltage is constant, there is no pressing need for matching $Z_{afo}(s)$ in the higher frequency ranges beyond 1–10 Hz. The use of $Z_{afo}(s)$ in determining the effective stator to rotor turns ratio is important, and is discussed in subclauses of 12.5.

c) In the *q*-axis, just one transfer function, $L_q(s)$ is sufficient to fully characterize the machine stator terminal behavior.

The SSFR test described in following clauses requires that magnitude and phase of the various transfer functions be measured at several frequencies. The analysis procedure then consists of deriving from these measurements, the characteristic parameters that, as known for many decades, can be given in terms of either time constants with their associated transient and subtransient reactances, or can be derived as equivalent circuits.

Characteristic quantities such as reactances and time constants are fundamental parameters helpful for describing a synchronous machine. The utilization of SSFR frequency-response data will provide time constants and reactances in transfer function form. Alternatively, there exist direct-axis and quadrature-axis model structures that also have a realistic relationship to the physical or operating processes of synchronous machines. Such relationships are usually described in terms of stator and rotor flux linkages and currents. From these model structures consisting of resistances and reactances, the corresponding transient, subtransient or sub-subtransient quantities follows. See B19 for a detailed exposition of the above comments.

Aspects of standstill frequency-response testing that are different from the short-circuit current testing procedures in section 11 are the measurement accuracy requirements and the complexity of the data reduction techniques. Instrumentation capable of resolving magnitudes and phase angles of fundamental components of ac signals at low frequencies (possibly down to 0.001 Hz or 0.002 Hz) is required. In addition, accurate and reliable procedures for translating the test data into synchronous machine stability study constants virtually requires some form of computerized curve-fitting technique. Illustrative examples will be shown in 12.5.3 and 12.5.4.

Users of these test methods are urged to compare, where possible, the simulated performance of the standstill models with actual generator or system responses under loaded conditions. In some instances, it is quite likely that on-line or open-circuit rated speed, frequency-response testing, or line switching tests, are needed either to confirm the validity of the standstill models, or to adjust their rotor equivalent circuit parameters to reflect loaded conditions at rated speed. The effect of centrifugal forces on slot wedge characteristics in cylindrical rotor machines or the construction of retaining rings are examples of possible electrical or magnetic rotor circuit changes under operating loaded conditions, as is the effect of saturation in both the direct and quadrature axes.

References B10, B11, B12, B13, and B14 discuss the theory of developing SSFR models, and some of the applications of such models to turbogenerator dynamic performance.

Work is currently underway (1995) in an exploratory stage in applying these techniques to machines of salient pole construction. When the measurement techniques described in 12.2 and 12.3 have been successfully applied to several salient pole machines, they will be included in future revisions to this document. Locating one of the many direct axis field positions, and then moving the standstill multi-pole rotor through 90 electrical degrees may prove to be time-consuming. Users should also be cautioned that fractional slots/pole/ phase machines may require repeating the *d* and *q*-axis test for various pole positions.

12.2 Testing conditions for SSFR procedures and instrumentation requirements

12.2.1 Machine conditions for standstill frequency-response tests for turbine generators

The machine shall be shut down, disconnected from its turning gear, and electrically isolated. The unit transformer shall be disconnected from the armature terminals and any armature-winding grounds removed. Also all connections to the field terminals shall be taken off. This can be done by removing the brushgear or, in the case of a brushless exciter, electrically disconnecting the complete exciter from the generator field windings.

It is important to maintain the armature-winding temperature at a constant value during the measurements since the low-frequency test points are very sensitive to the armature resistance. To this end, the machine should be cooled as close to ambient temperature as possible, and any stator heat exchangers should be turned off.

Circulation of the water through the stator winding should be maintained to ensure that stagnation does not cause the water conductivity to change.

It must be possible to turn the machine rotor to a precise position prior to the tests. This is most easily done by hand cranking the turning gear. If this is not possible, a hydraulic jack can be used against a coupling bolt. Although a gantry crane may be helpful in making large movements, it is not precise enough for the final positioning of the shaft.

12.2.2 Instrumentation and connections

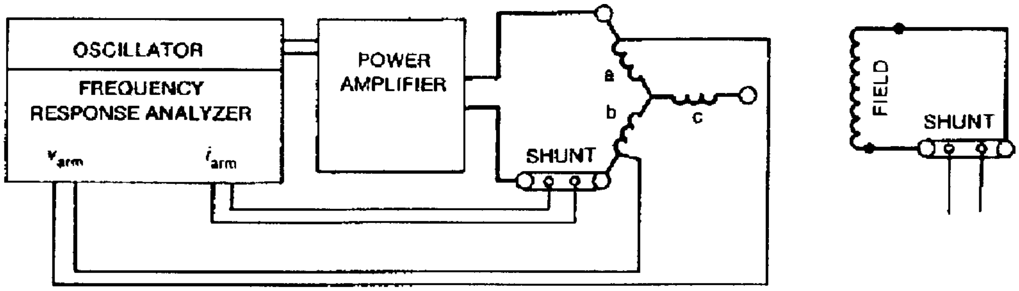
The frequency-response measurements are performed, most conveniently, with a low-frequency, dual-channel spectrum analyzer. This type of instrument will measure the magnitudes and relative phase-angle of two signals and extract only the fundamental components from any distorted waveforms. The basic specifications of the analyzer should include frequency measurement in the range 0.001 Hz to 1 kHz, phase resolution down to at least 0.1 degrees and differential inputs capable of up to 100 V input signals. Some programming capability within the analyzer would permit unattended operation of parts of the frequency-response test, especially during the time-consuming sweep of the low-frequency decade from 0.01 Hz down to 0.001 Hz.

12.2.3 Typical test setups (see figure 12.3)

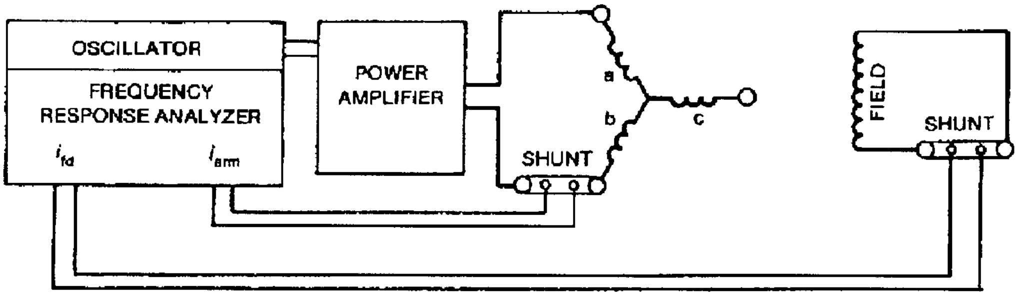
The relationship between the *measured* quantities and the *desired* variables is given in 12.2.6. An oscillator, sometimes an integral part of the above-mentioned analyzer, provides the test signal. This goes to a power amplifier, the output of which is connected to two terminals of the generator armature winding. The metering error of any measured transfer function should not exceed one percent at any point in the frequency range. Refer also to 12.3.1. Several variations in the testing procedures are shown in figures 12.3 a), b), c), and d).

The power amplifier must create readily measurable signal levels for the armature and field winding voltages and currents. For example, signals of up to 40 A rms and 15 V rms are required for machines in the 500–900 MW range. Test currents should be small enough to avoid temperature changes in the armature, field, or damper circuits during the test. Voltages at the armature or field winding terminals shall not exceed rated voltage levels. As a general guide, test currents would not be expected to exceed one-half of 1% of rated armature current (see 12.2.5).

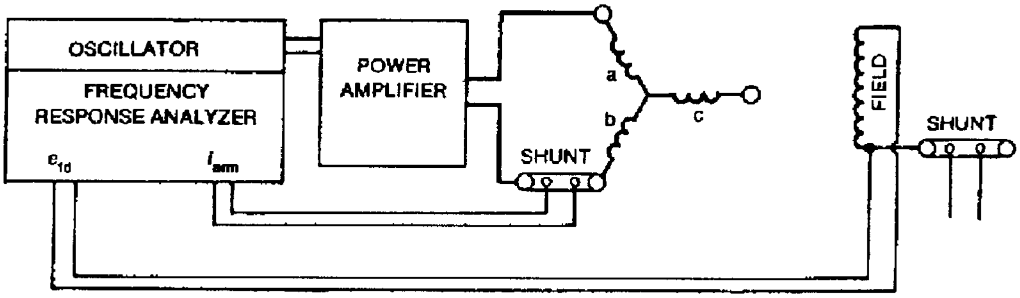
Normal precautions to avoid overloading inputs and outputs of instruments should be observed. The impedance measured at the armature terminals at very low frequencies will be approximately twice the armature phase resistance. The maximum measured impedance will be approximately $2(R_2 + j\omega L_2)$ where R_2 and L_2 are the negative sequence resistance and inductance and ω is the highest angular frequency used for the test. Both the power amplifier and the measuring instrument must be suitable for this impedance range.



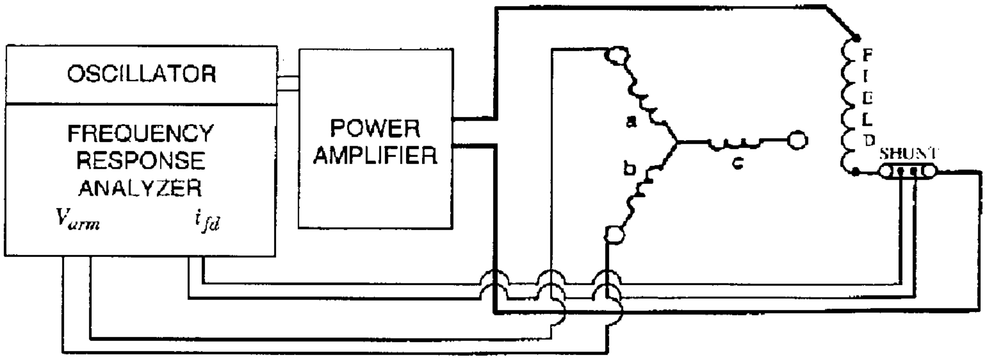
a) Measurement of $Z_d(s)$



b) Measurement of $\Delta i_{fd}/\Delta i_{arm}$



c) Measurement of $\Delta e_{fd}/\Delta i_{arm}$



d) Measurement of $\frac{\Delta v_{arm}}{\Delta i_{fd}}$

Figure 12.3—Test setup for direct-axis measurements

12.2.4 Measurement accuracy

Reducing or eliminating the effect of contact resistances is very important to the accuracy of the measurements, particularly on the armature winding. The current metering shunt for the armature should be bolted directly to the conductor in the isolated phase bus, as close to the generator terminals as possible; conducting grease should be used to enhance the contact. As noted in 12.2.2, an instrument having differential inputs is preferred for making the measurements. Figure 12.4 shows the proper connection of the test leads for such a device. If an instrument with single ended inputs (common low side) is used, then the connections in figure 12.5 are appropriate.

Current metering shunts are used to measure the test current supplied to the armature winding and the induced field current. Shunt rating should be matched to the maximum and minimum currents to appear in the respective windings. For the test schematics in this specification, the induced field current will not exceed

$$\sqrt{3}I_s(I_{fd}(\text{base})/i_a(\text{base}))$$

where

I_{fd}(base)	is the field current required for rated armature voltage on the air gap line
i_s	is the peak value of the largest armature current used during the test
i_a(base)	is the peak value of the rated armature current

All currents are expressed in A.

The resistance of the field winding shunt should not make the total dc resistance of the field circuit significantly greater than the field resistance at rated operating temperature.

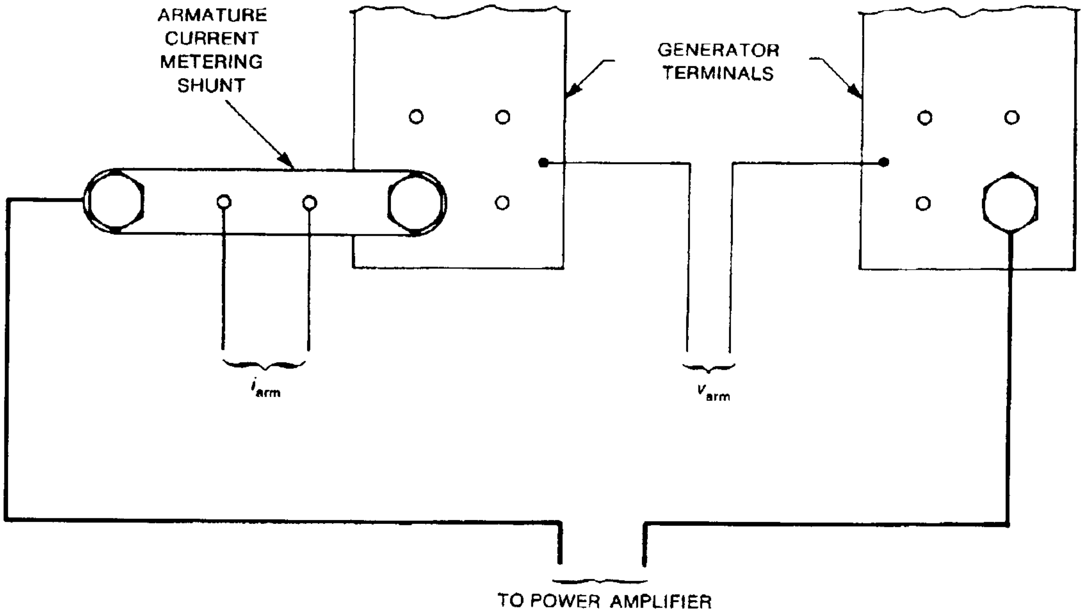


Figure 12.4—Connections for differential inputs

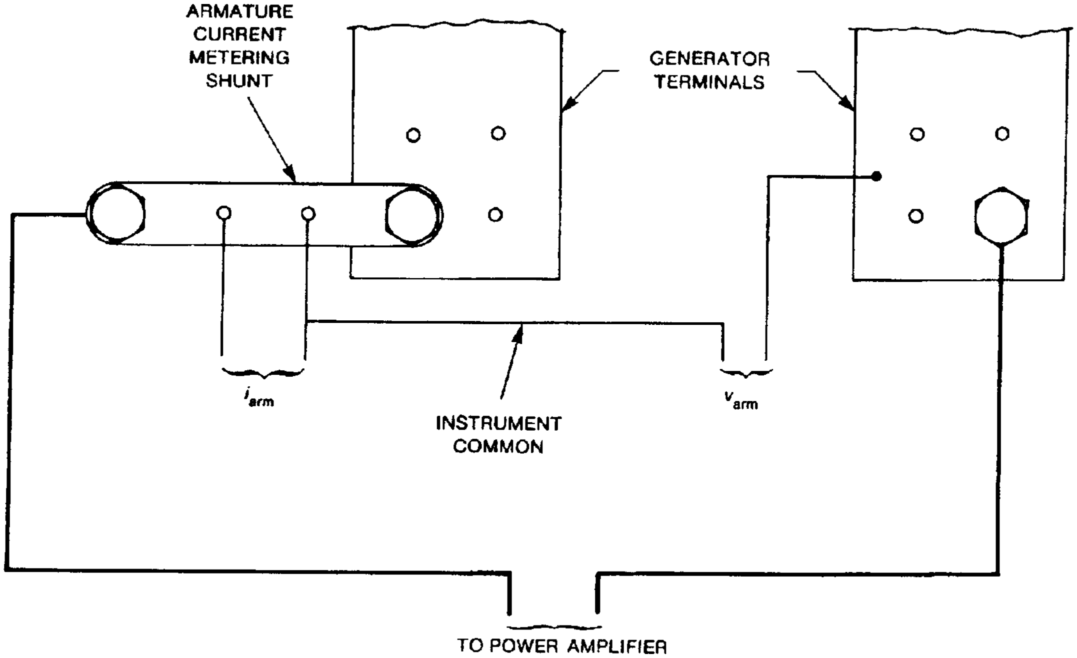


Figure 12.5—Connections for single-ended inputs

12.2.5 Precautions and ancillary matters relating to machine safety

It shall be recognized that during standstill frequency-response tests, the thermal capability of the generator will be reduced with respect to its capability at normal operating conditions. Therefore, test levels of currents and voltages must be maintained sufficiently low to avoid any possible damage to either stator or rotor components. This can be achieved by limiting the maximum output of the power source to levels equal to or less than the standstill capability of the generator. The manufacturer should be consulted to identify the applicable limits.

12.2.6 Measurable parameters available during standstill tests

The following five operational quantities have been found useful in developing transfer functions or equivalent direct-axis or quadrature-axis models for synchronous machines. The above quantities can be obtained from other measurable parameters with the machine at standstill. Early works that include discussions on the concepts of rotating machine operational impedances, and by implication, operational inductances have been authored by Concordia and Adkins, among others.

The three principal parameters noted below relate to the three definitions listed in 12.1.3.1.

a) $Z_d(s)$. The synchronous machine direct-axis operational impedance is equal to $R_a+sL_d(s)$, where R_a is the armature resistance per phase. The dc value of R_a is used because it is measurable, and, as will be seen in the numerical example in 12.5.4, its contribution to the total impedance is only significant at low frequencies. Also,

$$Z_d(s) = \left.\frac{\Delta e_d(s)}{\Delta i_d(s)}\right|_{\Delta e_{fd} = 0\ \Omega} \tag{12-2}$$

b) $Z_d(s)$ in physical terms is measured as an rms complex magnitude of a ratio of input and output signals. In the terminology used here, the numerator is always the input signal. These comments apply as well to the quantities described in equations 12-3 to 12-7.

   Note the vertical bar to the right of the transfer function expression, along with the notation at the side of the bar. This indicates the stator or field physical connection during the test. Thus $\Delta e_{fd} = 0$ means that the field is shorted during the test measurements, for example in equation 12-2. $\Delta i_{fd} = 0$ in equation 12-6 means that the field is open during this test measurement.

c) $Z_q(s)$. The synchronous machine quadrature-axis operational impedance is equal to $R_a + sL_q(s)$ where R_a is the dc armature resistance per phase.

$$Z_q(s) = -\frac{\Delta e_q(s)}{\Delta i_q(s)}\bigg|\Omega \tag{12-3}$$

A third machine quantity is given by the relation

$$G(s) = \frac{\Delta e_d(s)}{s\Delta e_{fd}(s)}\bigg|_{\Delta i_d = 0} \tag{12-4}$$

An alternative method of measuring this parameter is suggested as follows:

$$sG(s) = \frac{\Delta i_{fd}(s)}{\Delta i_d(s)}\bigg|_{\Delta e_{fd} = 0} \tag{12-5}$$

The advantage of the above form of measurement in equation 12-5 is that it can be measured at the same time as $Z_d(s)$.

A fourth measurable synchronous machine parameter at standstill is the armature-to-field transfer impedance as follows:

$$Z_{afo}(s) = \frac{\Delta e_{fd}(s)}{\Delta i_d(s)}\bigg|_{\Delta i_{fd} = 0}\ \Omega \tag{12-6}$$

A fifth measurable synchronous machine parameter at standstill may be obtained by exciting the field with the armature open. It has been called the field to armature transfer impedance.

$$Z_{fao}(s) = \frac{\Delta e_d(s)}{\Delta i_{fd}(s)}\bigg|_{\Delta i_d = 0}\ \Omega \tag{12-7}$$

The limited application of this last function is discussed in B16.

12.3 Test procedures

12.3.1 Required measurements

The magnitude and phase angle of $Z_d(s)$, $sG(s)$, and $Z_q(s)$ shall be measured over a range of frequencies. The minimum frequency (f_{min}) should be at least one order of magnitude less than that corresponding to the transient open-circuit time constant of the generator, that is,

$$f_{min} \cong \frac{0.016}{T'_{do}} \tag{12-8}$$

The maximum frequency for the test should be somewhere between two and three times the rated frequency of the generator being tested, perhaps 200 Hz for a 60 Hz machine. Approximately 10 test points logarithmically spaced, per decade of frequency, is a satisfactory measurement density. From practical experience of frequency-response measurements on turbo-generators, ten steps/decade will provide adequate resolution in the range of 0.01 Hz to 200 Hz. However, for the low-frequency stator-impedance measurements, ($Z_d(s)$ and $Z_q(s)$), in the range 0.01 Hz down to 0.001 Hz, a measurement resolution of 40 steps per decade is preferable. The phase-angle difference between the voltage and current signals is very small and as the frequency decreases, the magnitude approaches twice the stator resistance—a relatively small value. Therefore, a higher number of points/decade is required to achieve an accurate measurement of the effective stator resistance, R_a, at the time of the frequency-response test.

The mutual inductance between the field and armature windings, L_{afd}, shall also be measured, where

$$L_{afd} = \frac{2}{3}\frac{1}{s}\lim_{s \to 0}[Z_{afo}(s)] \tag{12-9}$$

The most direct way is to obtain the magnitude of the low-frequency asymptote of the transfer function $\Delta e_{fd}(s)/\Delta i_d(s)$, measured during the direct-axis tests with the field open. Alternatively, it can be calculated by multiplying the low-frequency asymptote of the magnitude of $\Delta i_{fd}(s)/\Delta i_d(s)$ by r_{fd}. r_{fd} is the total resistance in the field winding circuit during the measurement of $\Delta i_{fd}/\Delta i_d(s)$, namely the field resistance plus metering shunt plus connecting lead and contact resistances.

12.3.2 Positioning the rotor for *d*-axis tests

This is performed by temporarily connecting the power amplifier as in figure 12.6. Drive the amplifier with an approximately 100 Hz sinusoidal signal, and measure the induced field voltage with an oscilloscope. Turn the generator rotor slowly until the induced field voltage observed on the oscilloscope is nulled. At this point, the magnetic axis of the field winding is aligned with that of the series connection of phases *a* and *b* that will be used for the direct-axis tests.

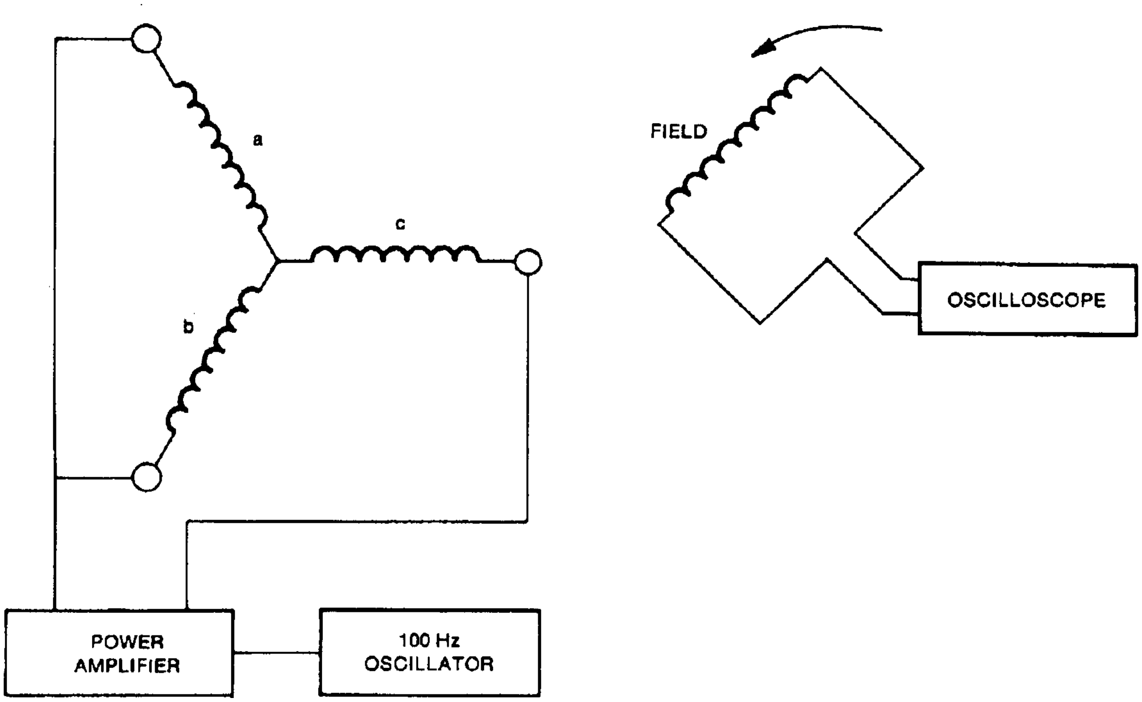


Figure 12.6—Positioning the rotor for direct-axis tests

12.3.3 Direct axis tests

12.3.3.1 $Z_d(s)$ as defined above, and stator resistance R_a

Referring to figure 12-3a), connect the power amplifier to terminals *a* and *b* of the armature winding through the metering shunt. Short the field winding through a non-inductive metering shunt, making solid connections to the field winding. This can be done by wrapping copper bands around the slip rings, taking care not to damage the slip rings, and bolting the shunt to the bands. In the case of a brushless exciter, it may be possible to bolt the shunt directly to the field terminals.

Refer again to any of the four signal measuring configurations a) to c) in figure 12.3. The following notations are used to distinguish between the mathematical quotients in equations 12-2 through 12-7, and the *actual* armature and field measurements being instrumented. Thus, V_{arm} is proportional to e_d and i_{arm} is proportional to i_d. Field quantities e_{fd} and i_{fd} can be used *directly.*

To commence with the actual measurements, connect the V_{arm} and i_{arm} signals to the frequency-response measuring instrument so that it will measure $Z_{armd}(s) = \Delta V_{armd}(s)/\Delta i_{armd}(s)$. Perform this measurement over the frequency range 0.001 Hz to 200 Hz.

Instrument readings obtained from the test set-up of figure 12-3a) permit the stator direct-axis operational impedance and stator resistance to be obtained as follows:

$$Z_d(s) = \frac{1}{2} Z_{armd}(s)\ \Omega \qquad (12\text{-}10)$$

$$R_a = \frac{1}{2}\left\{\lim_{s \to 0}[Z_{armd}(s)]\right\}\Omega \tag{12-11}$$

$Z_d(s)$ quantities are plotted in figure 12.7 and figure 12.8.

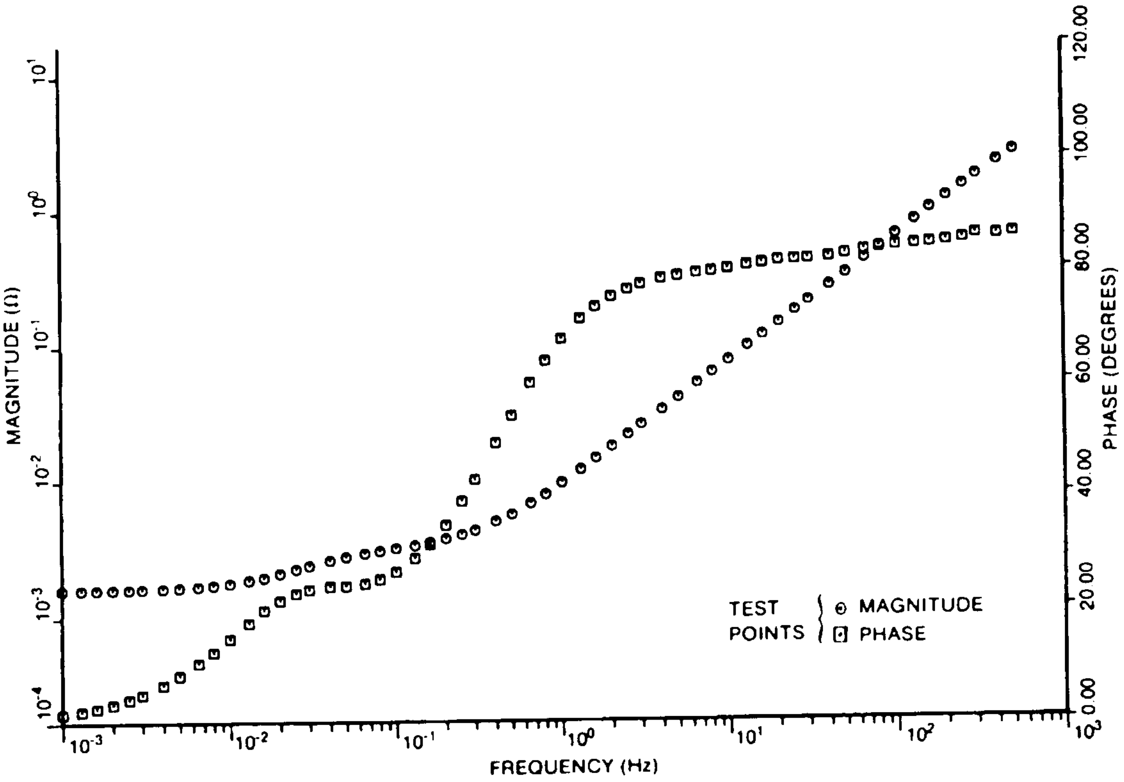


Figure 12.7—*d*-axis impedance (field-shorted)

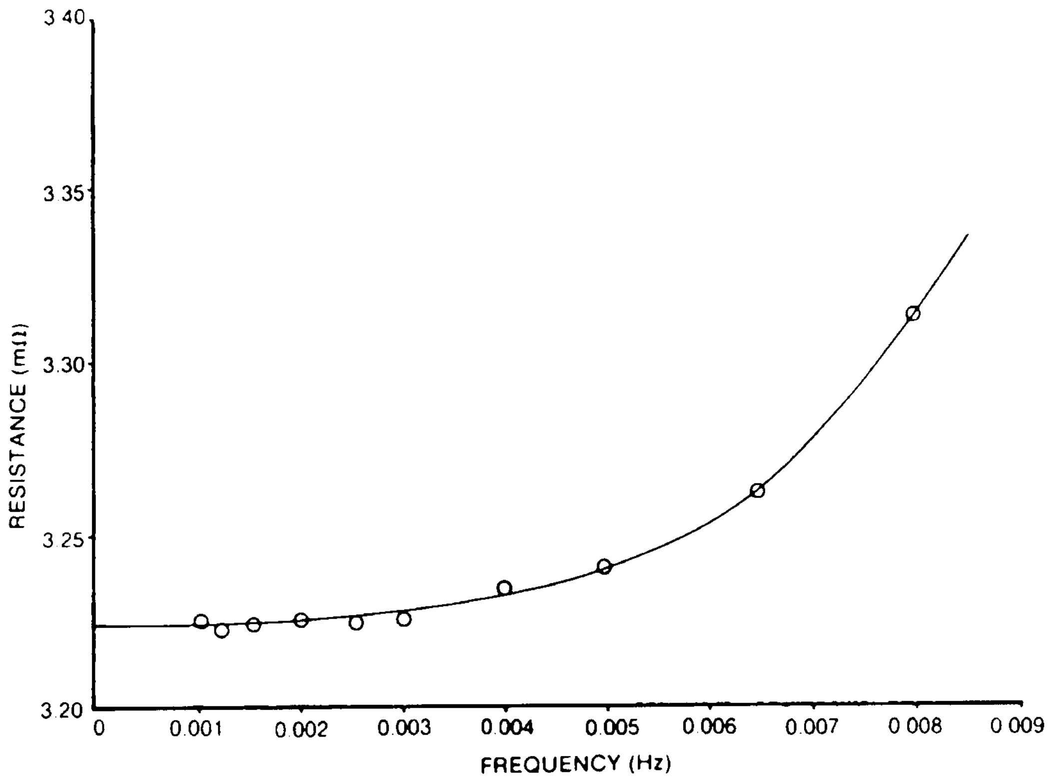


Figure 12.8—Resistive component of $Z_{armd}(s)$

To obtain R_a, plot the real, or resistive, component of armature impedance $Z_{armd}(s)$ as a function of frequency, and extrapolate it to zero frequency to get the dc resistance of the two phases of the armature winding in series, $2R_a$. Care should be taken to obtain this resistance with as much accuracy and resolution as possible; otherwise, large errors in the low-frequency values for operational inductance will result. Typically, a measurement resolution of 1 part in 1000 is required at the very low frequencies. If the instrument being used cannot achieve this, satisfactory results can be obtained by spacing the measurements closer than 10 per decade and drawing a line through the scatter of test points. Note that R_a obtained by this method should be close to the value for the armature resistance quoted by the manufacturer.

$Z_d(s)$ and R_a will be used to calculate $L_d(s)$, where

$$L_d(s) = \frac{Z_d(s) - R_a}{s} \quad \text{henries} \tag{12-12}$$

s is defined in 12.1.3.1.

Interpretation and utilization of $L_d(s)$ data, which are plotted in figure 12.9, are considered in detail in 12.5.

12.3.3.2 *sG(s)*

Now, connect the instrument to the i_{fd} and V_{arm} signal leads, figure 12-3b), and measure the transfer function $\Delta i_{fd}(s)/\Delta i_{arm}(s)$ over the frequency range as described in 12.3.3.3. Then, calculate

$$\frac{\Delta i_{fd}(s)}{\Delta i_d(s)} = \frac{\Delta i_{fd}(s)}{\Delta i_{arm}(s)/\cos 30^\circ} = \frac{0.86603\Delta i_{fd}(s)}{\Delta i_{arm}(s)} \tag{12-13}$$

which will lead to a plot similar to figure 12.10. The cosine 30° factor in equations 12-13, 12-14, and 12-15 recognizes the physical or electrical phase displacement between the field (as aligned above in 12.3.2) and either phases *b* or *c*.

12.3.3.3 $Z_{afo}(s)$

Finally, open the field winding by removing the field current metering shunt, and connect the i_{fd} and i_{arm} signal leads to the measuring instrument, figure 12-3c). While ten measurements per decade are the norm, additional measurements between 0.001 Hz and 0.01 Hz are recommended in order to obtain a good fit to any assumed transfer function. See 12.3.1. Measure $\Delta e_{fd}/\Delta i_{arm}$ at the necessary number of frequencies and calculate

$$Z_{afo}(s) = \frac{\Delta e_{fd}(s)}{\Delta i_d(s)} = \frac{\Delta e_{fd}(s)}{\Delta i_{arm}(s)/\cos 30^\circ} = \frac{0.86603\Delta e_{fd}(s)}{\Delta i_{arm}(s)}\ \Omega \tag{12-14}$$

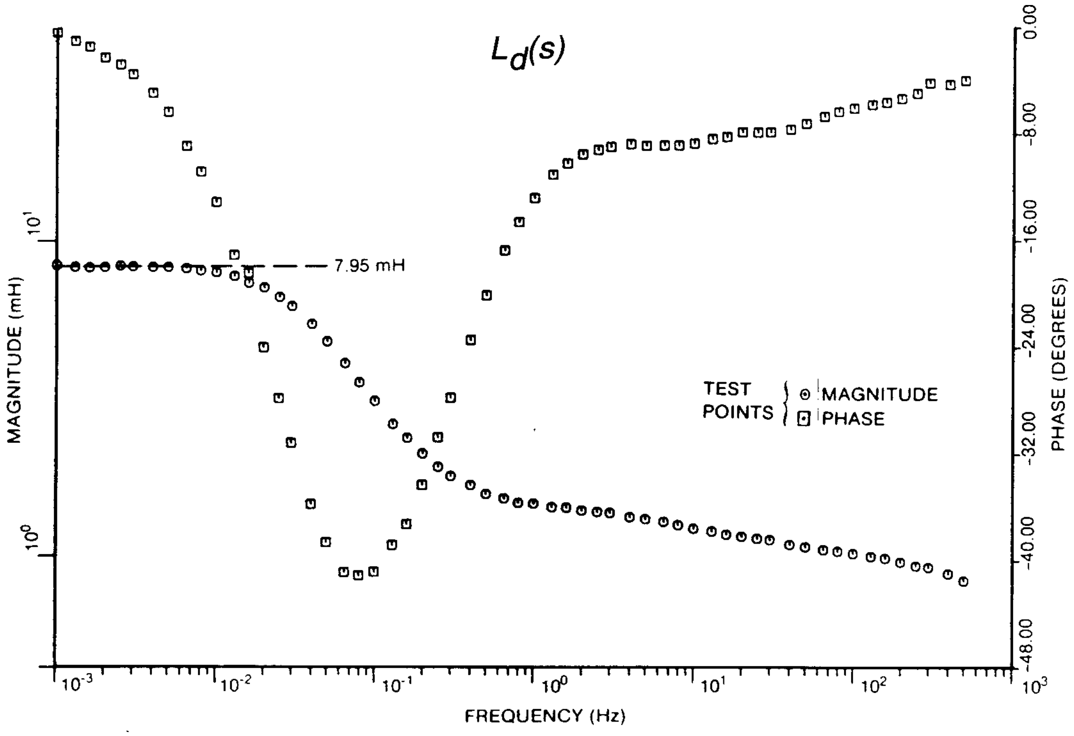


Figure 12.9—*d*-axis operational inductance (field-shorted)

When plotted, these points will be similar to figure 12.11. This completes those direct-axis tests that are usually performed.

12.3.3.4 $Z_{fao}(s)$

This measurement of field to stator transfer impedance is occasionally required. For this, the test setup of figure 12-3c) can be modified to that of figure 12-3d). The i_{arm} leads would then be connected to the field shunt. The e_{fd} leads of figure 12-3c) would be connected between terminals *a* and *b* of the stator after removing the power amplifier leads and the shunt from the stator. The power amplifier leads would connect to one field terminal and the open end of the shunt connected to the field, shown in figure 12-3d). Then $Z_{fao}(s)$ is determined as

$$Z_{fao}(s) = \frac{\Delta e_d(s)}{\Delta i_{fd}(s)} = \frac{1}{2}\left\{\frac{\Delta v_{arm}(s)/\cos 30°}{\Delta i_{fd}(s)}\right\} = \frac{0.577\Delta v_{arm}(s)}{\Delta i_{fd}(s)}\ \Omega \qquad (12\text{-}15)$$

When the $Z_{fao}(s)$ measurement is not required, the *q*-axis tests may now be performed by aligning the rotor with phase *a*. This is described in the next section.

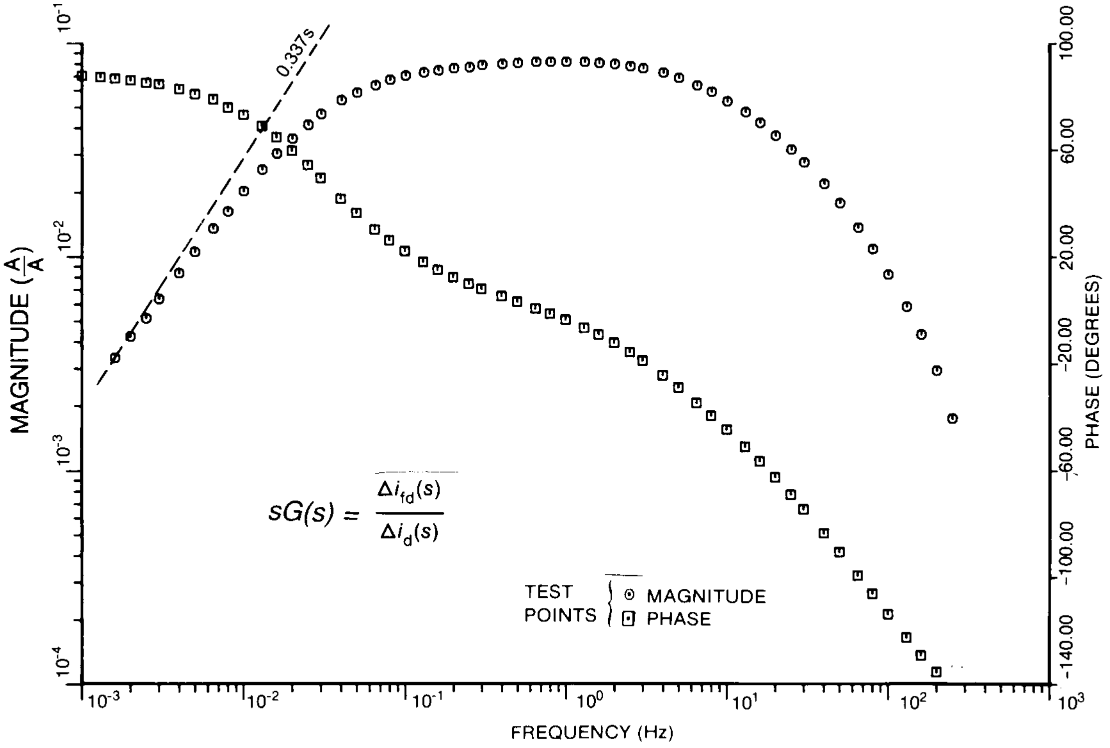


Figure 12.10—Standstill armature to field transfer function = *sG(s)*

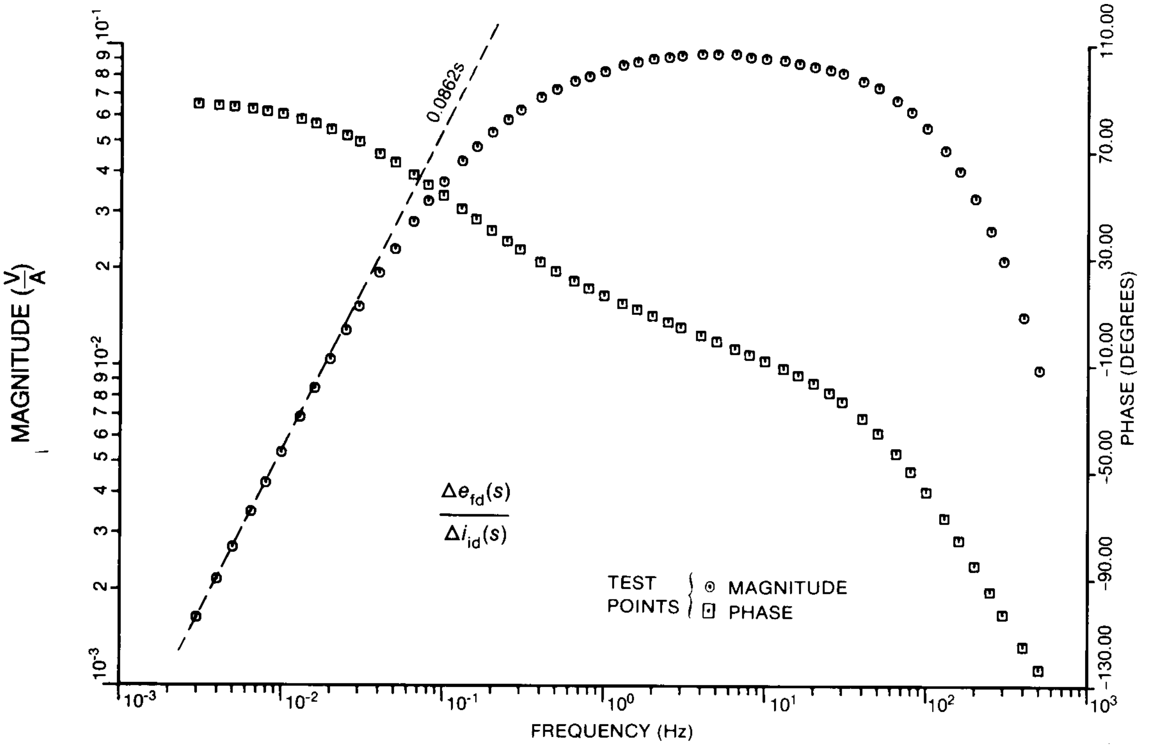


Figure 12.11—Standstill armature to field transfer impedance

12.3.4 Positioning the rotor for *q*-axis tests

Connect the power amplifiers across phases *a* and *b* as in figure 12.3 for the direct-axis measurements. Remove the field current metering shunt, and set the oscillator frequency to approximately 100 Hz. Observe the induced field voltage on an oscilloscope, and turn the generator rotor slowly until a null in the induced field voltage is achieved. The visible rotor position will be changed 90 mechanical degrees for a two-pole machine and 45 mechanical degrees for a four-pole machine. The rotor is now positioned for the quadrature-axis tests.

12.3.5 Quadrature-axis tests

Connect the V_{arm} and i_{arm} signal leads to the instrument to measure $Z_{armq}(s) = \Delta v_{arm}(s)/\Delta i_{arm}(s)$, as was done on the direct-axis in figure 12-3a).

Instrument readings over the complete frequency range obtained from the new test set-up of figure 12-3a) permit the stator quadrature axis operational impedance and stator resistance to be obtained as follows:

$$Z_q(s) = \frac{1}{2}Z_{armq}(s)\ \Omega \tag{12-16}$$

$$R_a = \frac{1}{2}\left\{\lim_{s \to 0}[Z_{armq}(s)]\right\}\ \Omega \tag{12-17}$$

$Z_q(s)$ quantities are plotted in figure 12.12.

Note that R_a, the dc resistance of one phase of the armature winding, should be nominally the same as obtained during the direct-axis tests. However, because of the sensitivity of the results to this value, it should be obtained again using the *q*-axis data and the techniques in 12.3.3.1 in case a change in the winding temperature has altered its value since the *d*-axis tests.

$Z_q(s)$ and R_a will be used to calculate $L_q(s)$

where

$$L_q(s) = \frac{Z_q(s) - R_a}{s} \qquad \text{henries} \qquad \text{(12-18)}$$

s is defined in 12.1.3.1.

Interpretation and utilization of $L_q(s)$ data, which are plotted in figure 12.13, are considered in detail in 12.5.

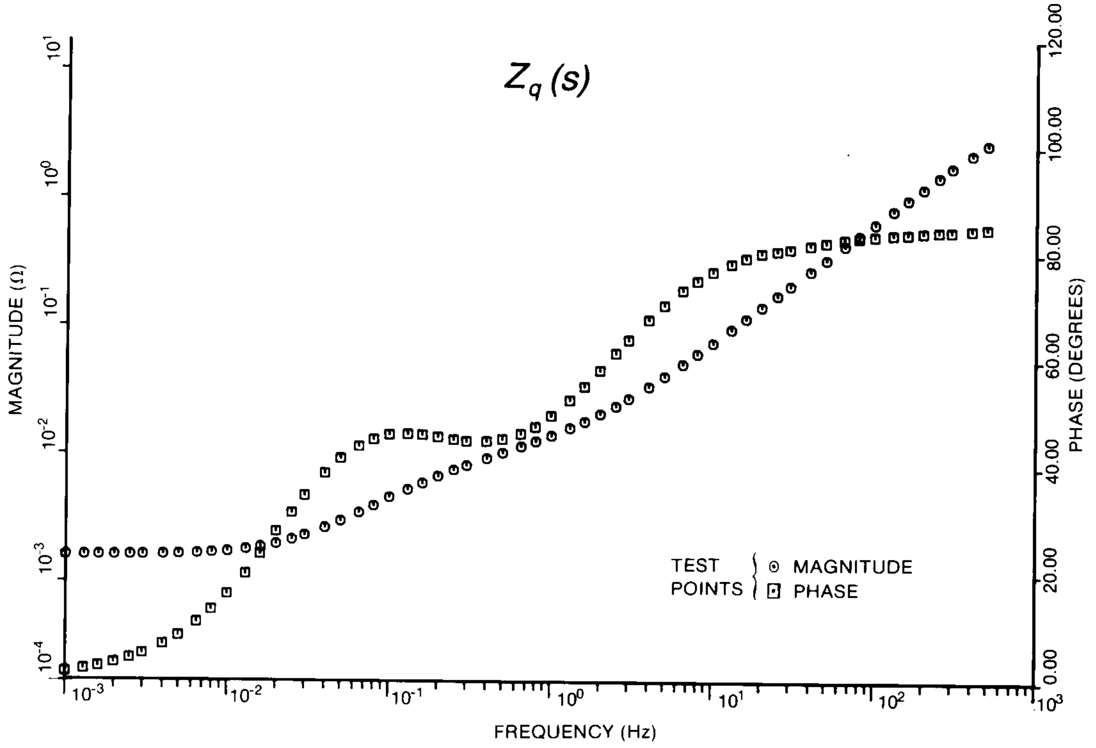


Figure 12.12—*q*-axis impedance

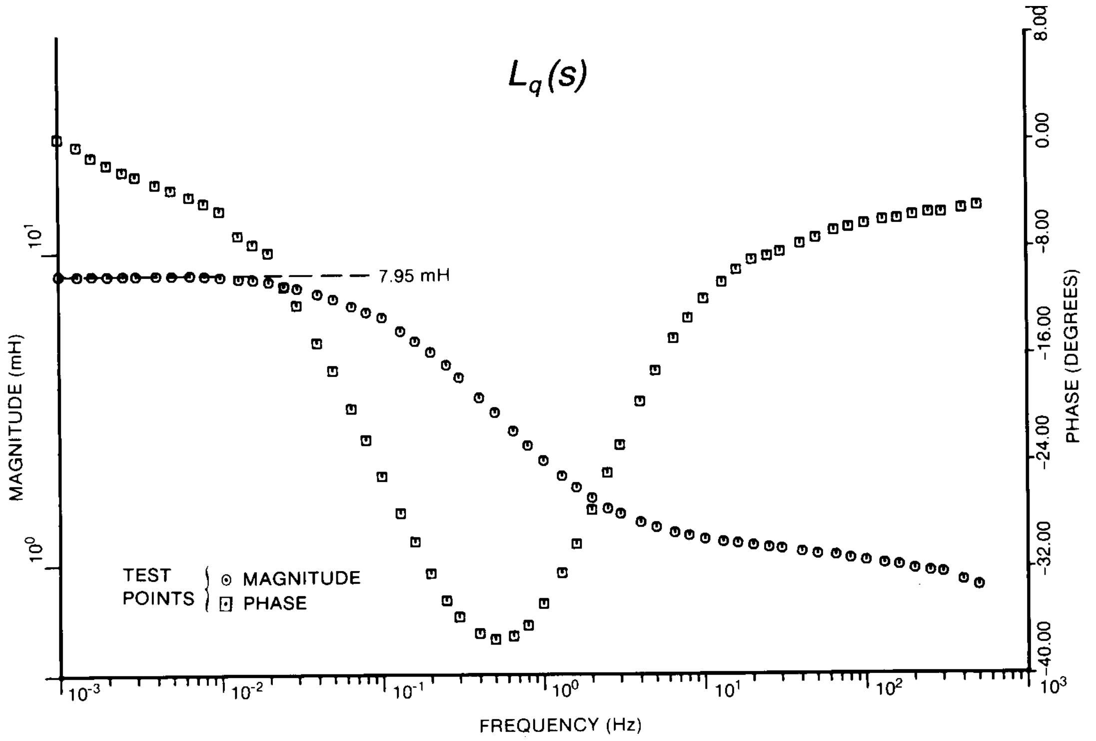


Figure 12.13—*q*-axis operational inductance

12.4 Interpretation of test data

This issue is one of the practical problems in fitting operational test data to a particular chosen model network. It has been maintained that the presence of "noise," particularly in the frequency range below 0.01 Hz, has a "corrupting" effect on the matching process below that frequency. This might be the case infrequently, but recent experience by users indicates that there may be several issues involved in the fitting process. Some of these are listed below:

1) *Structure:* For the *d*-axis network, it is possible to choose between the structures proposed by IEEE Std 1110-1991 and those recently proposed by Bissig et.al. B20. Figures 12-14a), b), c), or d) for the direct axis, and figures 12-15a), b), or c) for the quadrature axis are representative of commonly used models for fitting of SSFR test data, as recommended in IEEE Std 1110-1991.

   For each of the direct-axis models in figure 12.14, be they first, second, or third order, the test data must be interpreted as a complete set. The same applies to the quadrature axis models, of figure 12.15. For consistency, if a third order model is chosen for the direct-axis, a third order model is also recommended for the quadrature axis. It is not considered a valid procedure to develop a second order model from a data-fitted third order model by network reduction, and this artifice is to be deprecated.
2) *Per-unit system:* It is well known that different choices of the p.u. system and/or the armature leakage reactance can lead to networks with markedly different parameter values. In particular, a network *with* or *without* L_{fld}, L_{fl2d}, or L_{f2d} can be constructed for the same machine B17.
3) *Incomplete modeling:* Since the machine's *d*-axis is a two-port network, the use of only two transfer functions in the fitting leads to incomplete specification of the network. Therefore, even with a given topology, there will be a number of models matching two transfer functions but not the third.

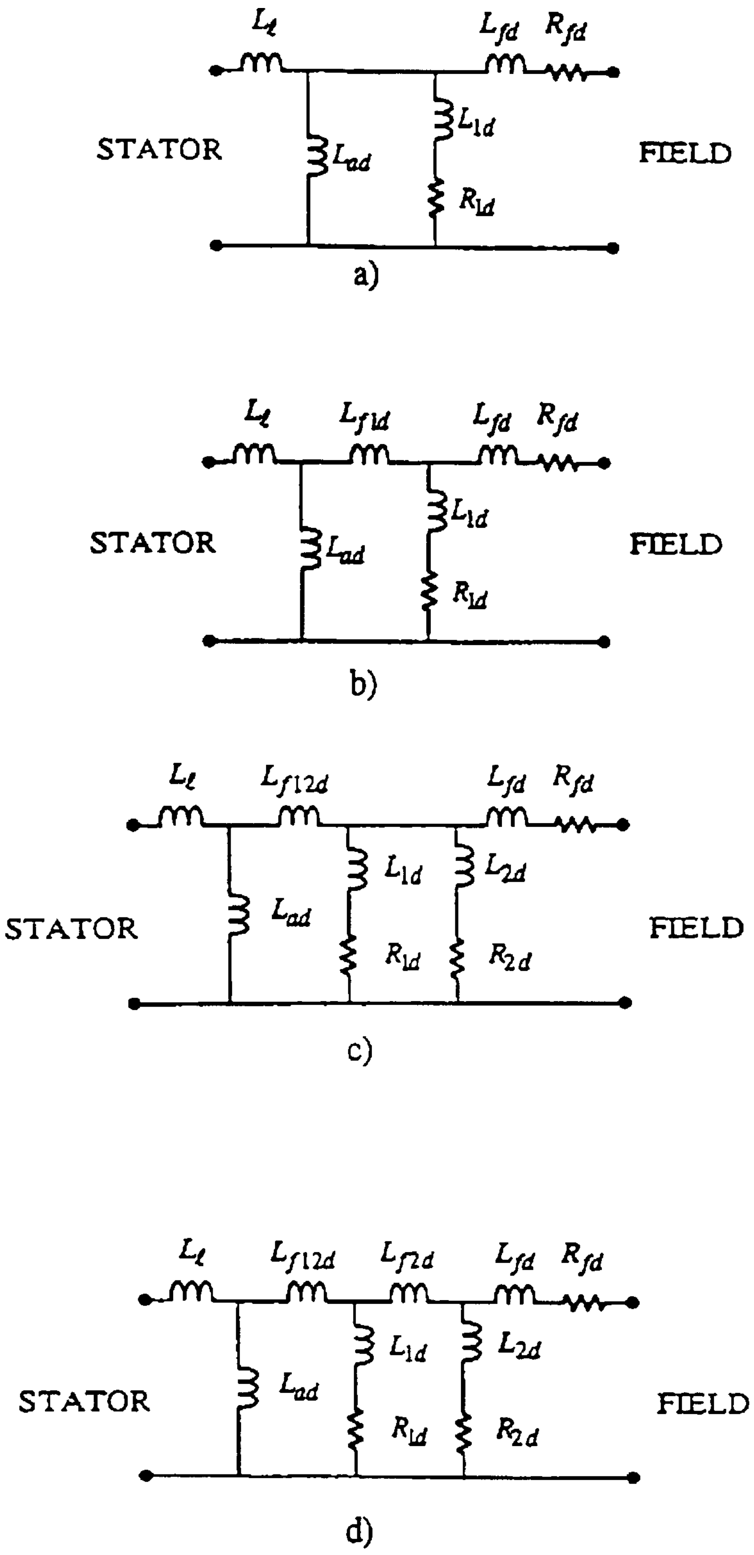


Figure 12.14—Direct-axis equivalent circuits

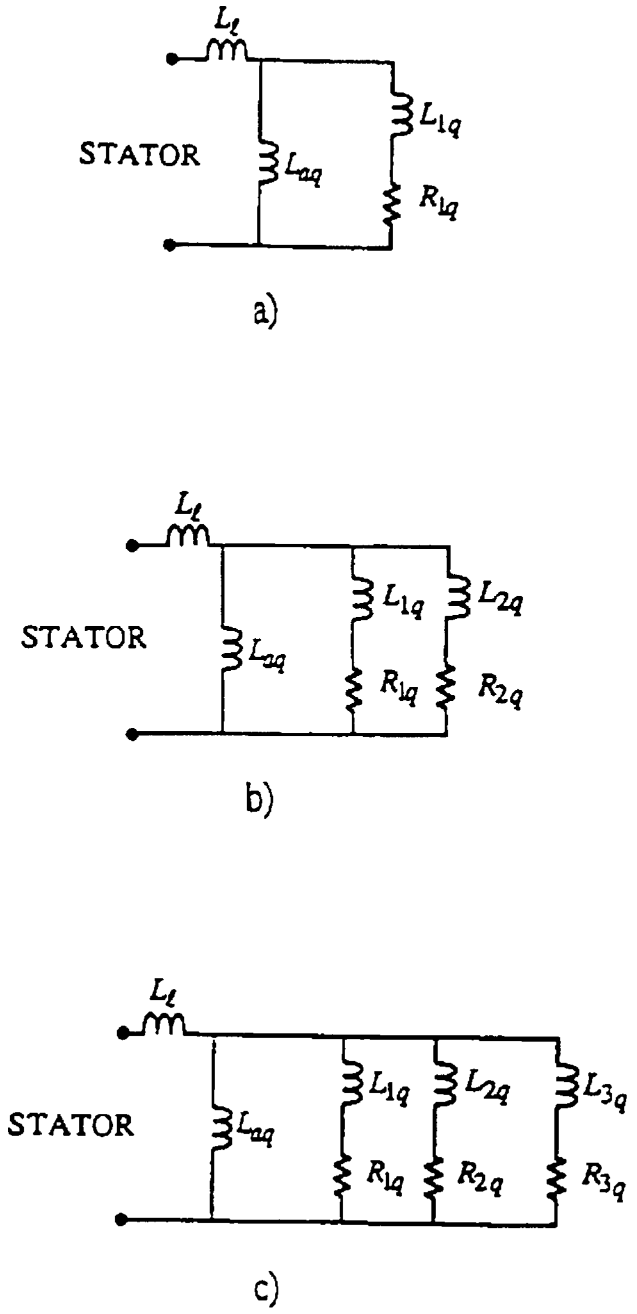


Figure 12.15—Quadrature-axis equivalent circuits

To summarize, the direct fitting of equivalent circuits, (even though this involves possible solutions which are non-unique), leads to a simpler translation problem; characteristic quantities; i.e., time constants and reactances, are easily derived from equivalent circuits while the reverse is basically a nonlinear problem B18, and difficult to solve in the general case of two transfer functions [$L_d(s)$, $sG(s)$] especially of third order or higher.

12.4.1 Parameter determination based on SSFR test results

12.4.1.1 General comments

In IEEE Std 115A-1987, the suggestions for modelling, based on SSFR testing, proposed that a specific stability model be assumed for both the direct- and quadrature-axis of a turbogenerator. This approach to modelling was in contrast to the long accepted reactance and time constant approach used for example in IEEE Std 115-1985. Around this time, Umans, et. al. B15 pointed out that other approaches to using the test data were available. Two papers B19 published in 1993 documented an alternate approach to fitting SSFR data. In the first stage, reactances and time constants formed the bases for obtaining *transfer functions*, which match the SSFR test results. Then the characteristic data (X'_d, X''_d, T'_{do}, etc.) were translated into an equivalent direct axis circuit. This translation process from characteristic values to model elements is linear in the cases of using just $X_d(s)$ or $X_q(s)$ values. It ceases to be linear when sG(s) is considered at the same time as $X_d(s)$.

12.4.1.2 Models and model parameters vs. characteristic quantities

Although the characteristic quantities are the parameters most descriptive of the "filtering" or transfer-function properties of a synchronous machine, network representation has also been used, for two main reasons—physical interpretation and computational efficiency.

It is shown in B19 how the parameters of the conventional network model structures can be interpreted in the light of the main physical magnetic paths of a machine. If one changes the network structure, the physical interpretation may be lost. If the internal description of the rotor and stator flux-current distribution is desired for any reason, a network model similar to one of those proposed in IEEE Std 1110-1991 or in figure 12.14 should be retained.

Generally speaking, the conventional network model is computationally more efficient than any conceivable model based on characteristic quantities, even though they correspond to each other mathematically. It is not easy to set up the simulation flow-chart diagram in terms of time constants and reactances for models with more than two dampers in the *d*-axis. When the state-space model of the *d* and *q* axis networks is known, any single transfer function is easily derived. Once the admittance matrix of the machine at rest is evaluated using conventional linear-algebra tools, all operational impedances can be computed, followed by the associated dynamic reactances and time constants.

The question of choosing time constants and reactances, as opposed to equivalent network models, is basically the option of the power system analyst. The remarks above should be of some use in deciding on the computational structure of the synchronous machine from the viewpoint of its dynamic response to various power system disturbances.

12.5 Suggested procedure for development of a third-order model

12.5.1 General

As discussed in 12.4, there are a number of possible models and procedures for reducing stand-still frequency response data to model parameters. Thus, the SSFR data obtained from the tests described in 12.3 can be used to obtain a wide range of models depending upon the desires and capabilities of the user. It is not the intent of 12.5 to prescribe either specific models, structures, or methods of obtaining model parameters from the SSFR data. This subclause illustrates one possible route to the derivation of generator models from a given set of data. This is neither the only method nor is it necessarily the best.

The approach followed leads to an equivalent circuit model that is a linear lumped parameter model selected to have the same frequency, and hence, time domain characteristic as the generator. To avoid confusion, the calculations are done in volts, amperes, ohms, and henries. Then, the resulting equivalent circuit elements are normalized to p.u. values by dividing the base impedance or inductance of the machine, as appropriate.

12.5.2 Mathematical background

The steps for the direct axis are

a) Assume the best available estimate for the stator leakage inductance L_l. Typically these could be the value supplied by the manufacturer.

b) $L_d(o)$ is the low-frequency limit of $L_d(s)$.

$$L_{ad}(o) = L_d(o) - L_l \text{ henries} \qquad (12\text{-}19)$$

NOTE — This value of $L_{ad}(o)$ is appropriate to the flux levels that existed during the test; in general, it will be lower than the unsaturated value associated with the air-gap line. This is further discussed in annex Annex 12A.

c) When the information in b) has been determined, use the $Z_{afo}(s)$ transfer function defined in equation 12-14 to find a field to armature turns ratio as follows:

$$N_{af}(o) = \left\{ \frac{1}{sL_{ad}(o)} \lim_{s \to o} \left[\frac{\Delta e_{fd}(s)}{\Delta i_d(s)} \right] \right\} \qquad (12\text{-}20)$$

The letter *(o)* refers to the low-frequency limit of each respective variable.

In discussing and utilizing this turns ratio, the actual machine physical turns ratio is the total number of turns in the field *divided by* the armature turns per phase.

In presenting these concepts, Rankin B25 noted that the physical turns ratio must be adjusted by several factors. Among these factors are the armature winding pitch and distribution factors, the field flux form factor and others. These can be combined for the purposes of this discussion into one factor K. The relationship between the physical turns ratio and the effective (or base) turns ratio as stated by Rankin can be formulated here as follows:

$$\frac{P \cdot N_{fd}}{N_a}[K] = \frac{3}{2}\,\frac{(i_a\ base)}{(i_{fd}\ base)} = N_{af}\ (base) \qquad (12\text{-}21)$$

where

P	is the number of field poles
N_{fd}	is the number of field winding turns per pole
N_a	is the number of stator turns (in parallel) per phase
K	is the combination of design and physical factors as noted above
i_a(base)	is the peak armature rated current per phase, A
i_{fd}(base)	is the I_{fd}(base) · (L_{adu}), where I_{fd}(base) is the excitation in A (dc) to produce rated armature volts on the air gap line, and L_{adu} is in p.u.

It should be noted that $N_{af}(o)$ and N_{af}(base) are usually very close to each other in value. In the following *d*-axis model development $N_{af}(o)$ will be used. The use of both $N_{af}(o)$ and N_{af}(base) will be discussed in annex Annex 12B.

d) The field resistance, referred to the armature winding, is

$$R_{fd} = \frac{sL_{ad}(o)}{\lim\limits_{s \to 0} \left\{ \frac{\Delta i_{fd}(s)}{\Delta i_d(s)} \right\} \frac{2}{3}(N_{af}(o))} \text{ ohms} \qquad (12\text{-}22)$$

NOTE — This method is used rather than direct measurement to account for the resistance of the metering shunt and connecting leads that are a part of the field circuit during the tests. However, a direct measurement of the field resistance plus the metering shunt resistance is a useful check.

e) Choose an equivalent circuit structure for the direct axis.
f) Use an iterative technique (see 12.5.3) to find values for the unknown circuit elements that produce the best fit to the two direct-axis functions $L_d(s)$ and sG(s).

NOTE — L_l and R_{fd} are already determined from the previous calculations.

g) Adjust L_{ad} calculated in (b) above to its unsaturated value L_{adu} (see annex 12A).
h) Measure the resistance of the field winding itself at the field terminals, convert it to the desired operating temperature, and refer it to the stator. For example, consider a copper winding converted to 100 °C:

$$R_{fd} \text{ at } 100°\text{C} = \left[\frac{234.5+100}{234.5+T_f}\right][r_{fd}]\left[\frac{3}{2}\right]\left[\frac{1}{N_{af}(o)}\right]^2 \text{ ohms} \qquad (12\text{-}23)$$

where

r_{fd} is the field resistance measured at the field terminals
T_f is the average field winding temperature in °C during the measurement

Substitute this value for R_{fd} in the equivalent circuit. For field winding materials other than copper, appropriate values of temperature coefficients (234.5 for copper) shall be used.

i) Normalize the equivalent circuit elements to p.u. values.
j) To determine as an initial value, the quantity i_{fd}(base) in the reciprocal system B25, refer back to equation 21.

$$i_{fd}(base) = \frac{3}{2}\, i_a(base)\left[\frac{1}{N_{af}(o)}\right] \text{ amperes (dc)} \qquad (12\text{-}24)$$

Note the use of $N_{af}(o)$ in place of N_{af}(base).

The steps for the quadrature axis are

1) Assume the same value for the armature leakage inductance that was used in the *d*-axis.
2) $L_q(o)$ is the low-frequency limit of $L_q(s)$.

$$L_{aq}(o) = L_q(o) - L_l \quad \text{henries} \qquad (12\text{-}25)$$

Again, this value is correct for the test conditions but may be different at operating flux densities.

3) Choose an equivalent circuit structure for the quadrature axis.
4) Use an iterative technique to find values for the unknown circuit elements that produce the best fit to $L_q(s)$. L_l and $L_{aq}(o)$ are known.
5) Convert $L_{aq}(o)$ to its unsaturated value L_{aqu} (see annex Annex 12A).
6) Normalize the equivalent circuit elements to p.u. values.

12.5.3 Curve-fitting procedures

Numerical values for the equivalent circuit parameters are derived from the standstill frequency response tests by curve-fitting techniques applicable to nonlinear functions (also known as nonlinear regression analysis). Typical nonlinear curve-fitting algorithms include the Levenberg-Marquadt, Maximum-Likelihood, and "Pattern-Search" methods.

Computer programs suitable for this application typically take two forms. In one form, the user must compute only the value of a specific dependent variable—$L_q(s)$, for example—for any set of unknown parameters. Unknown parameters could be either the constants appearing the operational form for the dependent variable; for example

$$L_q(s) = \frac{L_q(o)(1+sT_1)(1+sT_2)(1+sT_3)}{(1+sT_4)(1+sT_5)(1+sT_6)} \qquad (12\text{-}26)$$

for the quadrature axis, or the actual equivalent circuit elements [see figure 12-15c) for example].

There is a tendency on the part of some analysts to assign, for example, quadrature-axis time constants to the quantities in equation 12-26 B19. Thus T_1 would be considered to be representative of T'_q, and T_4 to be representative of T'_{qo}, and so on. Such time constants derived from equation 12-26 may be reasonably close in value to the quadrature axis time constants described in Annex 11A, but they are not identically the same. Similar comments apply to transfer functions developed from *d*-axis test data. The direct axes transfer function expressions are not identical in time constant values to those developed in section 11 from various short-circuit or voltage recovery tests, such as T'_d, T''_d, T'_{do}, etc.

The second (equivalent circuit) form requires computation of both the partial derivatives of the dependent variable with respect to each of the unknown parameters and the value of the chosen independent variable. Either of these techniques might be used for the curve-fits of the direct- and quadrature-axis functions. Programs or procedures that could be suitable for curve-fitting the results are described in B21, B22, B23, and B24. Refer also to annex Annex 12B.

One approach is to use a "pattern search" technique. Briefly, the "pattern search" technique is a general method for linear and non-linear parameter fitting using a set of data points with individual weighted functions [$L_d(s)$, $sG(s)$ and $L_q(s)$, for example] of the fitted parameters. For this method, it is not necessary to provide partial derivative functions with respect to each of the parameters. Given an initial equivalent circuit parameter vector, Γ_0, calculate its error, e_0, as the sum of the weighted squared differences between the SSFR data points and the responses calculated using the parameters Γ_0. The j^{th} element of this sum for the transfer function frequency response, FR_i, would be

$$\begin{aligned}\Gamma_0 = \Big[& j\omega L_l,\ j\omega L_{aq}(o),\ j\omega L_{1q},\ \mathrm{R}_{1q}\ldots \\ & \ldots j\omega L_{ad}(o),\ j\omega L_{f12d},\ j\omega L_{1d},\ R_{1d}\ldots \\ & \ldots j\omega L_{fd},\ R_{fd},\ \frac{1}{N_{af}(o)}\Big]\end{aligned} \qquad (12\text{-}27)$$

The letter *(o)* refers to the low-frequency limit of each respective variable.

$$\Gamma_o = [\gamma_1, \gamma_2, \ldots\ldots\gamma_n], \qquad (12\text{-}28)$$

where

n is the number of elements in the vector

$$e_{ij} = \omega_i \omega_j [FR_{i\ \mathrm{data}}(\omega = 2\pi r f_j) - FR_{i\ \mathrm{calc}}\{(\omega = 2\pi f_j),\ \Gamma_0\}]^2 \qquad (12\text{-}29)$$

Each frequency point, $2\ \pi f_j$ has a weighting factor, ω_j, associated with it. Usually the SSFR data in the frequency range of 0.5 Hz to 5 Hz is given the most weighting to yield an equivalent circuit model suitable for stability studies. Each transfer function, FR_i, [(i.e., $L_d(s)$, $sG(s)$, and $L_q(s)$, for example)] also has a weighting, ω_i. It is necessary to assign weightings to each transfer function because functions such as $sG(s)$ contain less information about the stator circuit due to the stator-to-field transformation. As a result $sG(s)$ should be given a weighting of perhaps 1 while $L_q(s)$ and $L_d(s)$ would each be assigned a weight of 10. The error, e_0, for the given parameter vector, Γ_0, is expressed as

$$e_0 = \sum_{\forall ii} e_{ij} \qquad (12\text{-}30)$$

NOTE — $\forall$ is a symbol stating that the summation is executed for all values of *i* and *j* as indicated in equation 12-29.

Change each non-fixed parameter, γ_k, by a fixed amount $+\Delta\gamma_k$ and then $-\Delta\gamma_k$ in turn and calculate the error. Retain the changes that reduce the error (i.e., $\gamma_k + \Delta\gamma_k$, $\gamma_k - \Delta\gamma_k$ or γ_k) in a new parameter vector, Γ_1, with an error e_1. If e_1 is greater than or equal to e_0 then decrease the $\Delta\gamma_k$ by some factor and alter each parameter in turn. This is called the "explore" phase of the algorithm.

If $e_1 < e_0$, then calculate a new set of parameter values by the "pattern" $\Gamma_2 = 2\Gamma_1 - \Gamma_0$, assuming the difference will be a vector in parameter space pointing towards the minimum error. Calculate the error, e_2, with the parameter values, Γ_2. If $e_2 > e_1$, then let $\Gamma_0 = \Gamma_1$ and $e_0 = e_1$ and return to the "explore" phase. If the error is the same or less then try to "improve" the pattern by changing each parameter in Γ_2 as in the "explore" phase. If the new error, e_2 is less than e_1, then let $\Gamma_0 = \Gamma_1$, $\Gamma_1 = \Gamma_2$ and $e_2 = e_1$ Loop back and try the improved "pattern" again; otherwise, go back to the "explore" phase and try to create a new "pattern." The process terminates when the changes, $\Delta\gamma$, are too small to affect the significant digits of Γ, the fitted equivalent circuit parameter values.

12.5.4 Numerical example

Machine rating: 192.3 MVA, 18 kV, 60 Hz

X_{du} (quoted by manufacturer) = 2.02 p.u.

$$\text{Armature base impedance} = \frac{(18)(18)}{192.3}$$
$$= 1.685\ \Omega$$

$$\text{Armature base inductance} = \frac{1.685}{120\pi}$$
$$= 4.469\ \text{mH}$$

Thus, $X_{adu} = X_{du} - X_l = 1.842$ p.u. based on above quoted values in the proposal from the manufacturer.

The four measured functions that will be used are as follows:

$$Z_d(s); \qquad \frac{\Delta e_{fd}(s)}{\Delta i_d(s)}; \qquad \frac{\Delta i_{fd}(s)}{\Delta i_d(s)}; \qquad Z_q(s)$$

The functions are shown in figures 12.7, 12.11, 12.10, and 12.12, respectively.

Figure 12.8 is a plot of the resistive component of $Z_{armd}(s)$ at the low-frequency end of the measurements. At zero frequency, its value is $2R_a$. Accordingly, from figure 12.8, $R_a = 0.001612\ \Omega$ for the example machine. This value of 0.001612 is 1/2 of the measured quantity with two armature windings in series. The operational inductance can be calculated at each frequency. For example, at 0.13 Hz, $Z_d = 0.003370\ \underline{|30.6^\circ}\ \Omega$. The corresponding operational inductance for this particular frequency is

$$L_d = \frac{0.003370\underline{|30.6^\circ} - 0.001612}{j(0.13)(2\pi)}\ \text{H}$$
$$= 0.002627\underline{|-36.9^\circ}\ \text{H}$$

The unit H (Ω-s/rad) is used with a complex inductance similar to what is commonly done with complex voltages and currents.

Similar calculations for each frequency at which $Z_d(s)$ was measured result in the direct-axis operational inductance plotted in figure 12.9. The quadrature-axis operation inductance, $L_q(s)$, plotted in figure 12.13, is obtained in the same way from $Z_q(s)$.

Beginning with the direct axis and following the steps in 12.5.2

a) L_l = 0.795; mH = 0.178 p.u. · base inductance of 4.469 mH

b) From figure 12.9
$L_d(o)$ = 1.779 p.u. or 7.950 mH
$L_{ad}(o)$ = (7.950 – 0.795) mH = 7.155 mH

c) From equation 12-20, and the information in figure 12.11

$$N_{af}(o) = \frac{1}{sL_{ad}(o)}\left\{\lim_{s \to o}\frac{\Delta e_{fd}(s)}{\Delta i_d(s)}\right\} = \frac{1}{s(0.007155)}\{0.0862\ s\}$$

$$\text{Then}\quad N_{af}(o) = \frac{0.0862}{0.007155} = 12.05$$

The low-frequency limit of 0.0862 used above can be obtained by fitting a simple first order transfer function Ks/1+sT to the low-frequency test points in figure 12.10. This function is, in the limit, *Ks*, *as s(=jω)* approaches zero. This is the straight dotted line (0.0862)*s* in figure 12.11. A similar straight line approximation is also used below to find the low-frequency values of sG(s).

d) From equation 12-22 and the information in figure 12.9:

$$R_{fd} = \frac{sL_{ad}(0)}{\lim\limits_{s \to 0}\left(\frac{\Delta i_{fd}(s)}{\Delta i_d(s)}\right)\left(\frac{2}{3}N_{af}(o)\right)} = \frac{s(0.007155)}{(0.3375s)\left(\frac{2}{3}\right)(12.05)}$$

$$R_{fd} = \frac{0.007155}{2.70233} = 0.002643\ \Omega,\ \text{referred to the stator}$$

Thus, a value of R_{fd} can be obtained directly from the standstill test data (at 20 °C). This is an alternative method of obtaining the field resistance.

e) The equivalent circuit structure in figure 12-14d) will be used for determining the direct-axis parameter values. The values of L_l $L_{ad}(o)$, $N_{af}(o)$, and R_{fd} are now established, and are thus fixed in the model parameter fitting process.

f) The iterative curve fit procedure described at the end of 12.5.3 yields the following values for the unknown elements:
L_{f12d} = 0.267 mH
L_{f2d} = 0 mH
L_{1d} = 0 mH
R_{1d} = 0.0263 Ω
L_{2d} = 2.82 mH
R_{2d} = 0.006574 Ω
L_{fd} = 0.726 mH

g) At rated armature voltage on the air-gap line of the open-circuit saturation curve, I_{fd}(base) = 590 A dc

$$L_{adu} = \left[\frac{3}{2}\right]\left[\frac{1}{12.05}\right]\left[\frac{18000\sqrt{2}}{(\sqrt{3})(120\pi)(590)}\right] = 8.225\ \text{mH referred to the armature}$$

Substitute 8.225 mH for the previous value of 7.155 mH in the direct-axis equivalent circuit.

h) The measured field winding resistance, r_{fd} was 0.2045 Ω at 20 °C. At 100 °C,

$$r_{fd} = \left[\frac{234.5 + 100}{234.5 + 20}\right][0.2045] = 0.2688\ \Omega$$

Then, referred to the armature at 100 °C

$$R_{fd} = 0.2688\left(\frac{3}{2}\right)\left(\frac{1}{N_{af}(o)}\right)^2 = 0.2688 \times \frac{3}{2} \times \left(\frac{1}{12.05}\right)^2 = 0.002777\ \Omega$$

i) The values of the unknown elements listed in f) above are in ohms and millihenries and have all been referred to the armature. Noting again

Z_{base} (armature) = 1.685 Ω
L_{base} (armature) = 4.469 mH

The p.u. values of all the desired elements are

$$L_l = \frac{0.795}{4.469} = 0.178 \text{ p.u.}$$

$$L_{adu} = \frac{8.225}{4.469} = 1.840 \text{ p.u.}$$

$$L_{f12d} = \frac{0.267}{4.469} = 0.060 \text{ p.u.}$$

$$L_{1d} = 0$$

$$R_{1d} = \frac{0.0263}{1.685} = 0.0156 \text{ p.u.}$$

$$L_{f2d} = 0$$

$$L_{2d} = \frac{2.282}{4.469} = 0.511 \text{ p.u.}$$

$$R_{2d} = \frac{0.006574}{1.685} = 0.00390 \text{ p.u.}$$

$$L_{fd} = \frac{0.726}{4.469} = 0.162 \text{ p.u.}$$

$$R_{fd} = \frac{0.002777}{1.685} = 0.00165 \text{ p.u.}$$

j) The base peak armature current, and the base field currents will now be established to check the value of N_{af}(base).

$$\text{base peak armature current } i_a(\text{base}) = \left(\frac{192.3 \text{ MVA}}{18\sqrt{3}}\right)\sqrt{2} = 8722.9 \text{ A}$$

(Use equation 12-21, but substitute the value of 12.05 for $N_{af}(o)$ determined from step c) above, rather than use N_{af}(base). A value of base field current can be closely approximated.)

$$i_{fd}(base) = \frac{3}{2}(8722.9)\left[\frac{1}{12.05}\right] = 1085.8 \text{ A dc}$$

k) Knowing i_{fd}(base) and i_a(base), a cross-check on N_{af}(base) may be obtained from equation 12-21:

$$N_{af}(base) = \frac{3}{2}\frac{(8722.9)}{1085.8} = 12.05$$

$N_{af}(o)$ was used on all previous calculations, since the low-frequency values of $Z_{afo}(s)$ were available.

l) i_{fd}(base) also equals I_{fd}(base) $\cdot L_{adu}$ where I_{fd}(base) is given in (7)=590 A dc. Therefore, i_{fd}(base) = 590 × 1.84 = 1086 A.

Z_{base} for the field, referred to the stator

$$= \frac{\text{Rated machine voltamperes}}{(i_{fd}base)^2} = \frac{192.3 \cdot 10^6}{(1086)^2} = 163.05\ \Omega$$

$$\text{again } R_{fd}\text{ p.u.} = \frac{r_{fd}(\text{corrected to }100°\text{C})}{163.05} = \frac{0.2688}{163.05} = 0.00168\text{ p.u.}$$

which agrees closely with the calculation in i) above.

The quadrature axis is considered next.

a) L_l = 0.795 mH
b) From figure 12.12

$L_q(o)$ = 7.950 mH
$L_{aq}(o)$ = (7.950 – 0.795) mH = 7.155 mH

The fact that the test value of $L_{aq}(o)$ equals the value of $L_{ad}(o)$, i.e. 7.155 mH, is worthy of note. Usually, some degree of saliency exists in round rotor machines due to the difference in construction detail of the pole face, as opposed to the area where the field turn slots are located. In general $L_{ad} > L_{aq}$ (saturated or unsaturated).

c) The quadrature-axis equivalent circuit structure is shown in figure 12-15c); L_l and $L_{aq}(o)$ are known.
d) An iterative procedure, identical to that described above, fitted to the quadrature-axis operational inductance, gave the following model element values:

L_{1q} = 6.045 mH
R_{1q} = 0.01355 Ω
L_{2q} = 0.735 mH
R_{2q} = 0.01525Ω
L_{3q} = 0.1578 Ω

$$L_{aq}(o) = L_{qa}\left(\frac{8.225}{7.155}\right)$$
$$= 7.155\left(\frac{8.225}{7.155}\right)$$
$$= 8.225\text{ mH}$$

e) Converting to p.u. values,

$$L_l = \frac{0.795}{4.469} = 0.178\text{ p.u.}$$

$$L_{aqu} = \frac{8.225}{4.469} = 1.840\text{ p.u.}$$

$$L_{1q} = \frac{6.045}{4.469} = 1.353\text{ p.u.}$$

$$R_{1q} = \frac{0.01355}{1.685} = 0.00804\text{ p.u.}$$

$$L_{2q} = \frac{0.01525}{1.685} = 0.00905\text{ p.u.}$$

$$L_{3q} = \frac{0.453}{4.469} = 0.101\text{ p.u.}$$

$$R_{3q} = \frac{0.1578}{1.685} = 0.0936\text{ p.u.}$$

These values constitute an unsaturated quadrature-axis model for the machine.

In the preceding example, the test data were fitted to the most complex models shown in figures 12-14d) and 12-15c). Furthermore, as a result of the calculations, all elements of the models were assigned specific values. It should be emphasized that if simpler models with a smaller number of elements are chosen, a completely new set of calculations is required in order to fit the elements of the simpler models to the data. In most cases a less exact fit will be obtained, but the values calculated for the simpler model structure may often be quite adequate for the stability requirements of the user.

12.5.5 General remarks and nomenclature

The preceding tests and calculations have been performed based on the field being aligned in a particular way for either the direct- or quadrature-axis tests. This is done to simplify the transformation of stator and field measurements of three-phase synchronous machine to the appropriate direct- and quadrature-axis quantities. The mathematical transformations and other expressions for such *d*- and *q*-axis quantities are given in detail (see B10). This reference also relates the measurements derived from the preceding equations (see equation 12-8 through to equation 12-17) to a particular complexity of model. As indicated in 12.5.1, as well as in B10, other *d*- and *q*-axis model structures can also be chosen, of higher or lower order. Nomenclature applying to sections 5, 9, 10, 11, and 12 is in annex Annex A.

Annex 12A

(Informative)

Magnetic nonlinearity

12.A.1 General

There are a number of ways to define inductance starting either from the point of view of flux linkage, energy, co-energy, or induced voltage in a circuit. For linear systems, all of these definitions are equivalent. For nonlinear systems, there is no unique way to define inductance and the appropriate value depends on its ultimate use. The difficulty lies in the material characteristic of magnetic steel. This is illustrated in figure 12A-1. The figure shows a family of hysteresis loops as would be measured with instruments such as a hysteresis-graph. The normal magnetization curve, which we often use in static field representation, is the curve passing through the tips of these hysteresis loops. This curve therefore represents the magnetic properties only in an approximate sense. We see from the normal magnetization curve of figure 12A-2 that the permeability is defined as

$$\mu = \frac{B}{H} \tag{12A-1}$$

where

B is the magnetic flux density in T
H is the magnetic field intensity in A/m

The permeability, μ, is small for low values of flux density, rises and then drops at high values of flux density (saturation). An inductance based on this permeability would therefore be low at both low and high values of flux density and reach a maximum somewhere in between. An alternate definition of inductance uses the slope of the normal magnetization curve, such as the open-circuit saturation curve of a generator. The slope is called the *incremental permeability*

$$\mu_{inc} = \frac{\partial B}{\partial H} \tag{12A-2}$$

and the inductance based on this value is called the *incremental inductance*. This value is often used in circuit calculations. The incremental inductance is low at both low and high flux densities and might reaches a maximum somewhere in between.

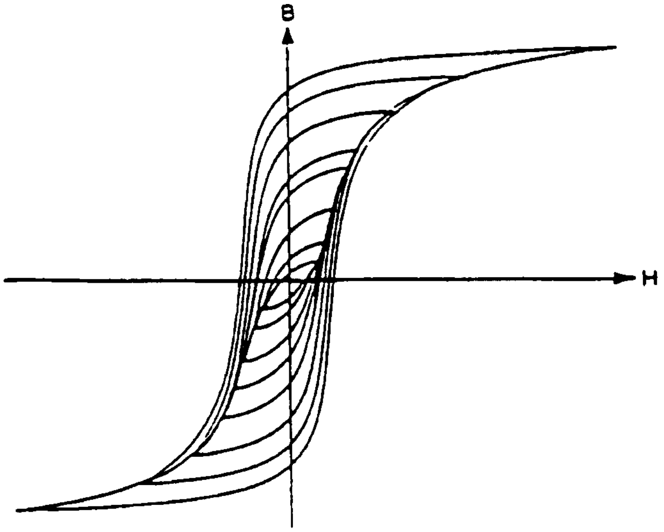


Figure 12A-1 —Magnetic nonlinearity of iron—B-H loops

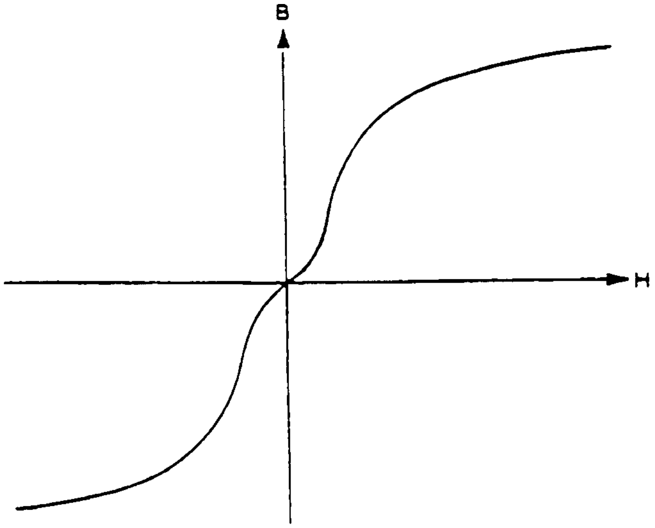


Figure 12A-2 —Magnetic nonlinearity of iron—Locus of tip of B-H loops

Since standstill frequency response tests are done using very low currents (typically 40 A), compared to rated armature current, the low level iron nonlinearity cannot be ignored. In short, the values of iron-dependent inductance measured during standstill frequency response tests will be lower than unsaturated values on the air-gap line. Therefore, L_{ad} and L_{aq} in the equivalent circuits derived to match standstill test data need to be adjusted upward to achieve an unsaturated model for the machine. Generally speaking, the size of the adjustments to L_{ad} and L_{aq} in the equivalent circuits derived to match standstill test data need to be adjusted upward to achieve an unsaturated model for the machine. Generally speaking, the size of the adjustments to L_{ad} and L_{aq} will be less, if higher test currents are used. These concepts have been discussed in more detail by S.H. Minnich in the reference cited in 12A.2.

An unsaturated value for L_{ad} in H can be calculated from the rated speed open-circuit saturation curve: (See item g) in 12.5.4.)

$$L_{adu} = \left(\frac{3}{2}\right)\left(\frac{1}{N_{af}(o)}\right)\left(\frac{V_t}{\omega_o \cdot I_{fd}}\right), \text{ H referred to the stator}$$

The value of $N_{af}(o)$ can be determined as shown in Step c) of the example in 12.5.4. V_t and I_{fd} define a point on the air-gap line, and ω_0 is the base or rated rotor speed in electrical radians per second. Note that V_t is the *peak* voltage, line-to-neutral and I_{fd} is in dc A. $L_{ad}(o)$ is substituted for $L_{ad}(o)$ determined in step b) of 12.5.2 in the direct-axis equivalent circuit. Similarly, in the quadrature-axis equivalent circuit, $L_{aq}(o)$, as determined in 12.5.2, must be adjusted to its unsaturated value. One possible approach is to multiply it by $L_{adu}/L_{ad}(o)$, the same factor that is used in the direct axis.

12.A.2 Bibliography to annex Annex 12A

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Annex 12B

(Informative)

Alternative approach to model development

12.B.1 Introduction

In the general remarks in 12.4.1, it is stated that the suggested procedure for development of a third-order model, was one of many possible routes. This applied in particular for turbogenerator models in the direct axis for determining model parameters from a given set of SSFR test data.

In this annex, an alternative procedure is documented albeit somewhat similar to 12.4.2 and 12.4.3. The example is based on work by the first mentioned author in B18. The machine chosen for analysis is an alternative one but identical in MVA rating, power factor and terminal voltage to one of the eight similar machines referred to in B11. The rotor amortisseur details in the machine being analyzed in this annex are much simpler than the original machine reported on and analyzed in B11.

12.B.2 Machine technical details

The machine constants required to initiate an analysis of the SSFR data are as follows:

$$\text{MVA base} = 588(S_{N\Delta}) \qquad \text{kV base} = 22(E_{N\Delta})$$

$$Z_{base}(\text{armature}) = \frac{(E_{N\Delta})^2}{S_{N\Delta}} = 0.8231\ \Omega \tag{12B-1}$$

$$i_a\ \text{(base) peak stator A} = \frac{588\times10^6\times\sqrt{2}}{22\times10^3\times\sqrt{3}} = 21823\ \text{A} \tag{12B-2}$$

I_{fd}(base) is the 1001 dc A, required to induce 22 kV line to line on the open circuit air gap line
L_{du} is the 2.348 p.u. by sustained short circuit test
L_l is the 0.190 p.u. from calculation by the manufacturer

A pre-processing stage was performed on the SSFR test data to determine values of $L_d(s)$ in ohms (as well as in measured decibels) and $L_d(s)$ corresponding phase angles at each test point. The armature to field transfer function data $sG(s)$ is given from test as amperes/amperes, and $Z_{afo}(s)$ the armature to field transfer impedance (of $L_{afo}(s)$ the transfer inductance) is given as volts/amperes.

An extract of the data available for analysis is shown in table 12B-1.

Table 12B-1 —Samples of frequency response data for a 588 MVA turbine-generator

Frequency Hz	$L_d(s)$		$sG(s)$		$Z_{afo}(s)$	
	Mag. (p.u. Ω)	Degrees	A/A (Ω)	Degrees	Mag. (Ω)	Degrees
0.001126	1.7532	-3.82	0.00355	86.65	0.01966	25.54
0.001413	1.7400	-3.88	0.00399	86.15	0.01966	25.54
0.001586	1.7384	-4.03	0.00447	85.73	0.00378	62.89
0.001778	1.7343	-4.50	0.00499	85.39	0.00073	99.86

12.B.3 Establishing a field to armature turns ratio

The following effective (or base) turns ratio between the field and one armature phase may be calculated using Rankin's formulae B25. The approach is centered on determining the base field amperes in the Rankin (or reciprocal) system.

Thus

$$i_{fd}\,(\text{base}) = I_{fd}\,(\text{base}) \cdot L_{adu} = 1001(2.158) = 2160\text{ A dc} \tag{12B-3}$$

N_{af} (base) is taken from equation 12-21 of 12.5.2

$$\begin{aligned} N_{fd}\,(\text{base}) &= \frac{1.5(i_a\,(\text{base})\text{ peak amperes})}{i_{fd}\,(\text{base})} \\ &= \frac{1.5(21823)}{2160} = 15.155 \end{aligned} \tag{12B-4}$$

12.B.4 Approach to model development

In the present example, we will consider only the *d*-axis network in order to illustrate alternative schemes for using the field-related frequency parameters in building the equivalent network. Advantage can be taken of the field-to-armature transfer function data based on the following two stage process:

1) Perform an accurate fitting of the low-frequency asymptotes of the three transfer functions [$Z_d(s)$, $sG(s)$, $Z_{afo}(s)$] to obtain the correct values of L_d(o), $N_{af}(o)$ and R_{fd}. To this end, only data in the frequency range of say 0 to 0.5 Hz are used in an iterative procedure similar to that in 12.5.3, in order to better define the asymptotes of these functions.
2) Keep L_d(o), $N_{af}(o)$ and R_{fd} fixed. By varying the remaining network parameters (see 2.5.3) iteratively, perform a global fit of the two transfer functions [$L_d(s)$, $sG(s)$], based on all relevant test data in the frequency range of interest. This range is usually, in this approach, from about 0.0016 Hz to 160-200 Hz. Although the data, as illustrated in table 12B.1, is given in ohms, a step suggested here is to use the $L_d(s)$ magnitudes in decibels. Some transfer function analysers print such information in either decibels or ohms. $sG(s)$ and $Z_{afo}(s)$ data are measured as noted in table 12B.1.

As opposed to the model chosen in the example of 12.5.4, a third order direct axis model is chosen with just one differential leakage inductance, L_{f12d}, as shown in figure 12.14(c).

Furthermore, the amplitudes are scaled in decibels so that they will show, over the whole frequency range, a spread comparable with that of phase data expressed in degrees. With such an approach, frequency weighting (ω_j in 12.4.3) is seldom necessary, since magnitude and phase errors are quite well distributed from low to high frequencies (see 12.B.8). However, transfer function weighting is still useful (ω_i in 12.4.3) since $L_d(s)$ is by intuition more informative about stability parameters than $sG(s)$. Experience suggests that one should weight the errors on $L_d(s)$ by 2 or 3, when $sG(s)$ is given a weight of 1.

The parameters in table 12B-2 were chosen to initialize the first identification stage mentioned above. The values attributed at this stage to the network parameters to be adjusted during the fitting are relatively unimportant. Only the armature leakage needs a pertinent value (taken here as equal to the manufacturer value of 0.19 p.u.). It will be in later stages kept constant. Other network values are somewhat arbitrarily chosen, using typical data (from the existing literature for instance) or from prior in-house knowledge. A zero value of the differential leakage L_{f2d} is assumed throughout this analysis.

Table 12B-2 —Initial network parameters (p.u.)

$L_l = 0.19$	$L_{ad} = 1.853$	$L_{ld} = 0.110$	$R_{ld} = 0.090$
$L_{fd} = 0.154$	$R_{fd} = 0.00097$	$L_{2d} = 0.110$	$R_{2d} = 0.38$
$L_{fl2d} = 0.0$	$L_{f2d} = 0.0$	$N_{af}(o) = N_{af}(\text{base}) = 15.173$	

12.B.5 First stage of fitting

In the first fitting stage, the data of the three-transfer function $\{Ld(s), sG(s), Z_{afo}(s)\}$ between 0.0016 and 0.3548 Hz are used simultaneously and the following unknown parameters are adjusted to minimize the sume of squared errors on the magnitude (dB) and phase (degrees):

$$\Gamma = [R_{fd}, R_{1d}, R_{2d}, L_{1d}, L_{2d}, L_{ad}(o), L_{f12d}, N_{af}(o)] \tag{12B-5}$$

This fitting process uses experiential weighting factors 2 for $L_d(s)$, 1 for $sG(s)$, and 1 for $Z_{afo}(s)$, and among the resulting network parameter values, only those associated with low-frequency asymptotes of the three-transfer functions are relevant. These are

$$L_{ad}(o) = 1.9273 \text{ p.u.}; \qquad N_{af}(o) = 15.111; \qquad R_{fd} = 0.0011435 \text{ p.u.}$$

Not all digits indicated above are significant but they are kept at this stage to limit rounding errors in subsequent numerical processing.

Since L_{ad}(o), $N_{afd}(o)$ and R_{fd} merely reflect a consistent set of constraints defining the Rankin "X_{ad}" p.u. system based on actual test data B23, it is reasonable to keep them constant, while fine-tuning the overall network in the useful frequency range (0.0016 Hz to 177.8 Hz. Furthermore, with the emphasis on models for stability studies (see 12.1), this final tuning makes use of $L_d(s)$ and $sG(s)$ data only, using weighting factors 3 and 1, respectively.

In a manner similar to example 12.5.4, the following subset of unknown parameters is then adjusted iteratively:

$$\Gamma = [R_{1d}, R_{2d}, L_{fd}, L_{1d}, L_{2d}, L_{f12d}] \tag{12B-6}$$

The optimum parameters obtained at convergence of the fitting process are given in table 12B-3. Least-squares statistical inference performed on the corresponding residuals gives rough, usually pessimistic, bounds on the estimated network parameters in the table below.

Table 12B-3 —
Final network parameters based on a measured Rankin "X_{ad}-base" (L_l = 0.19 p.u.)[*]

Resistances and inductances in p.u. on machine rating	
L_{fd} = 0.15152 ± 0.009 (5.9%)	R_{fd} = 0.0011435 ± 0.00004 (3.9%)
L_{ld} = 1.2672 ± 0.20 (15%)	R_{ld} = 0.0026787 ± 0.0002 (7.1%)
L_{2d} = 0.052634 ± 0.003 (5.6%)	R_{2d} = 0.031599 ± 0.001 (5.6%)
L_{f12d} = 0.009477 ± 0.006 (64%)	L_{f2d} = 0.0 ± 0.0 (0%)
$L_{ad}(o)$ = 1.9273 ± 0.05 (2.5%)	$N_{af}(o)$ = 15.111 ± 0.5 (3.8%)

[*] Field resistance not yet corrected for rated temperature.

12.B.6 Final fitting stage

The approach in this example is interesting because it uses the armature-to-field transfer function to establish a consistent p.u. system based on actual data. However, if this third transfer function is unavailable for analysis, an alternative procedure is to use the rated p.u. system defined by N_{af}(base) = 15.155. The unknown parameters then change as follows:

$$\Gamma = [R_{fd}, R_{1d}, R_{2d}, L_{fd}, L_{1d}, L_{2d}, L_{ad}(o), L_{f12d}] \qquad (12B\text{-}7)$$

where it is observed that the turns ratio is no longer an adjustable parameter. The rationale behind such a choice is that, without a third transfer function acting as a useful constraint, a pertinent value of $N_{af}(o)$ consistent with open-circuit measurements is hard to reach owing to random and/or systematic measurement errors, which usually bound the iterative fitting process to spurious convergence.

The results obtained this way with weighting factors 3 and 1 for $L_d(s)$ and $sG(s)$, respectively are given in table 12B-4.

To illustrate the performance achieved by the various models of this following example, the sum of residuals has been computed for $L_d(s)$ and $sG(s)$ in the frequency range 0.0016 Hz to 177.8 Hz:

Initial model (table 12B-2): 6922
Final model with measured "X_{ad}-base" (table 12B-3): 841.3
Final model with rated "X_{ad}-base" (table 12B-4): 774.1

It is observed that the model with the best performance from an engineering point of view (table 12B-3) is not necessarily the one giving the lowest sum of residual errors. In fact, the model in table 12B-4 uses its excess degrees of freedom to further minimize an error function, but the resulting network is not precisely consistent with open-circuit values of Z_{afo} measurements at low frequencies. This observation is illustrated graphically in figures 12B-1 and 12B-2 where the three models are compared against test data. $Z_{afo}(s)$ has not been plotted. Note that the plots of some of the models are close to each other in value, or tend to overlap in figures 12B-1 and 12B-2.

Table 12B-4 —
Final network parameters based on rated Rankin "X_{ad}-base"*

Resistances and inductances in p.u. on machine rating			
$L_l = 0.19$	$L_{ad}(o) = 1.8804$	$L_{1d} = 1.6633$	$R_{1d} = 0.0030316$
$L_{fd} = 0.14379$	$R_{fd} = 0.0010473$	$L_{2d} = 0.051548$	$R_{2d} = 0.031105$
$L_{f12d} = 0.006369$	$L_{f2d} = 0.0$	$N_{af}(o) = N_{af}(\text{base}) = 15.173$	

*Field resistance not yet corrected for rated temperature.

12.B.7 Presentation of data for stability studies

The last step of the analysis consists in computing characteristic stability constants (X'_d, T'_d, T'_d, etc.) based on the preferred model (table 12B-3). Prior to this task, the field resistance is corrected for an operating rotor temperature of 100 °C, and $L_{ad}(o)$ is replaced in the SSFR-based network by its unsaturated value at normal flux level, L_{adu}, as obtained from a standard steady-state measurement of the synchronous reactance L_{du}. Alternatively L_{adu} can be calculated from a knowledge of I_{fd}(base) A at rated voltage from the air gap line (singular), plus a knowledge of $N_{af}(o)$. The latter turns ratio is used to refer L_{afdu} in henries, to L_{adu} in henries [see 12.4.4h)].

Refer to the definitions associated with equation 12-21. For this two-pole machine, N_{fd}=120, and N_a=14. Then the PN_{fd}/N_a portion of equation 12-21 is calculated to be 2(120)/14 = 17.14.

This "ideal" turns ratio can be compared to N_{af}(base) = 15.155 or $N_{af}(o)$ = 15.173, obtained from the analyses outlined in 12.B.3 to 12.B.6.

12.B.8 Bibliography to annex Annex 12B

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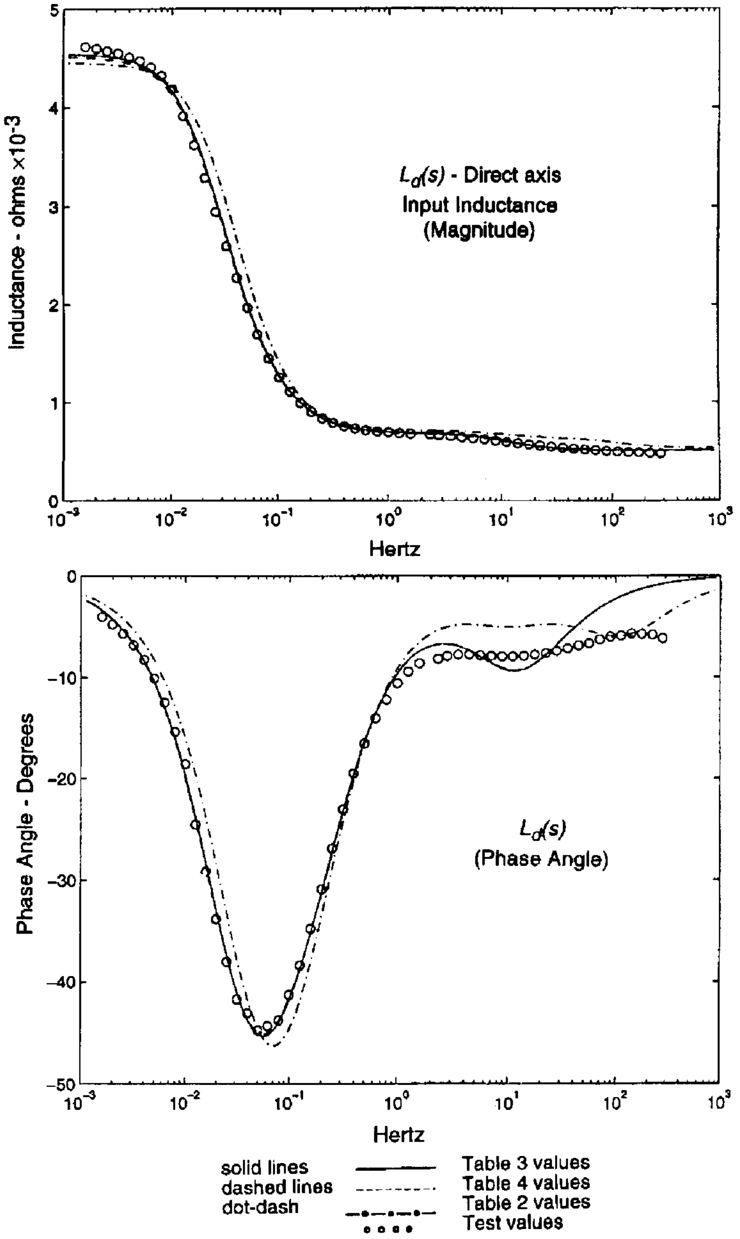

Figure 12B-1 —Plots of magnitude and phase angle of the direct axis operational inductance for a 588 MVA turbine-generator

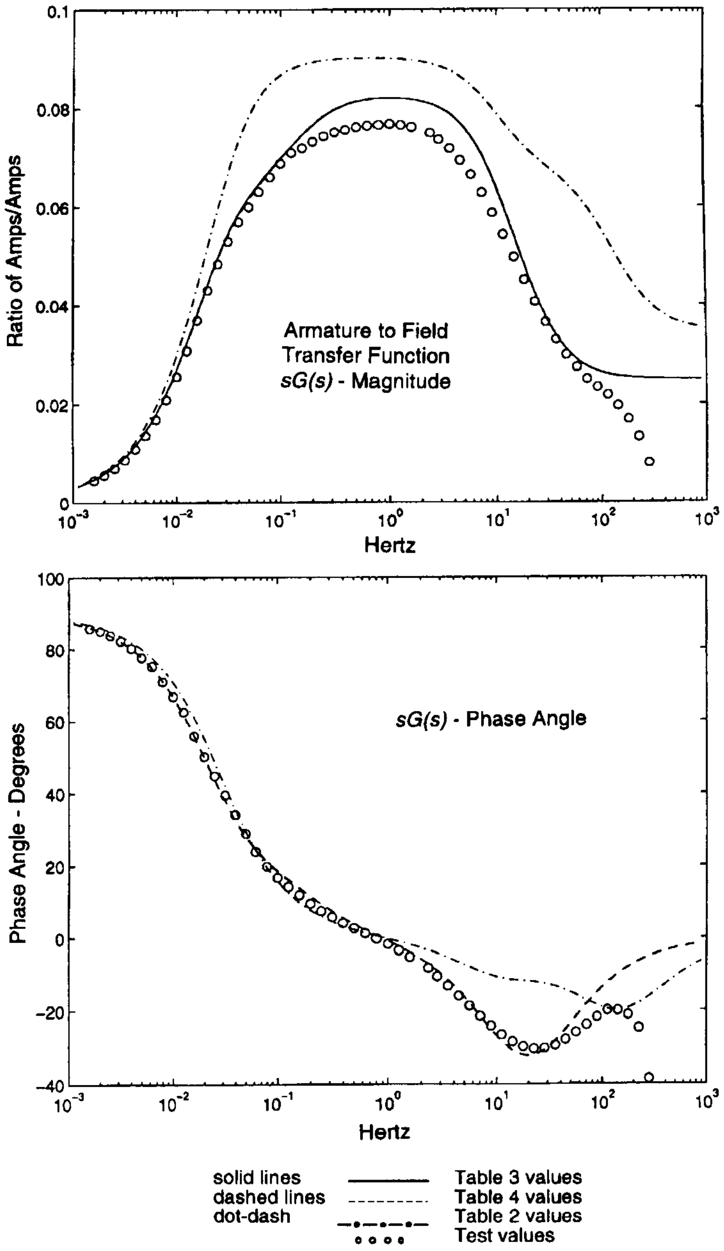

Figure 12B-2 —Plots of magnitude and phase angle of the armature to field transfer function for a 588 MVA turbine-generator

Annex A

(Informative)

Nomenclature

e_d	direct-axis armature voltage
e_{fd}	field voltage
e_q	quadrature-axis armature voltage
$G(s)$	armature to field transfer function
i_{arm}	instantaneous value of armature current during test
i_{ao}	peak value of rated armature current per phase
i_d	direct-axis armature current
i_{fd}	field current
i_{fdo}	field current for rated armature voltage on the air-gap line of the open-circuit saturation curve
i_q	quadrature-axis armature current
L_{adu}	direct-axis armature to rotor mutual inductance (unsaturated)
L_{aqu}	quadrature-axis armature to rotor mutual inductance (unsaturated)
L_{fkd}	differential leakage inductances proportional to fluxes that link one or more damper windings and the field, but that do not link the armature; $k=1,2,\ldots,n$, where k is a list of the damper windings to which these field fluxes are mutual. In some cases, for example, $k=12$ indicates an equal coupling between the field and both the #1 and the #2 equivalent rotor circuits.
L_{mfkd}	mutual inductance between field and damper circuits, where $k=1,2,n$ as above. For example, $L_{fld} = L_{mfld} - L_{ad}$.
L_l	armature leakage inductance
L_{fd}	field winding leakage inductance
L_{kd}	direct-axis damper winding leakage inductance; $k=1,2,\ldots, n$
L_{kq}	quadrature-axis damper winding leakage inductance; $k=1,2,\ldots,n$
$L_d(s)$	direct-axis operational inductance
$L_q(s)$	quadrature-axis operation inductance
N_a	number of turns on one phase of the armature winding
N_{fd}	number of turns in the field winding/per pole
r_{fd}	field resistance measured directly in physical ohms
R_{fd}	field resistance referred to the armature
R_{kd}	direct-axis damper winding resistance; $k=1,2,\ldots,n$
$s=j\omega$	Laplace operator
v_{arm}	voltage between two energized armature terminals during standstill frequency response tests
$Z_{afo}(s)$	standstill armature to field transfer impedance
$Z_{armd}(s)$	operational impedance measured between two armature terminals during direct-axis tests
$Z_{armq}(s)$	operational impedance measured between two armature terminals during quadrature-axis tests
$Z_d(s)$	direct-axis operational impedance
$Z_q(s)$	quadrature-axis operational impedance
Δ	A small change
ω	electrical frequency in rad/s

$N_{af}(o)$ effective or base turns ratio determined from $Z_{afo}(s)$

N_{af}(base) effective or base turns ratio determined by stator and field current bases (reciprocal system).

NOTE — L_{fd}, L_{fkd}, L_{kq}, R_{kd}, and R_{kq}: These five capitalized symbols represent rotor parameters referred to the armature; values are usually quoted in p.u. on the armature impedance base.

Annex B

(Informative)

Conversion table

Table B-1 —Conversion of SI to English units

Quantity	SI system	to	Equivalent English system
Length	1 meter (m)	=	3.281 ft = 39.37 in
Mass	1 kilogram (kg)	=	2.205 lb (mass)
Force	1 Newton (N)	=	0.225 lb (force)
Torque	1 Newton · meter (N · m)	=	0.738 ft-lb
Energy	1 Joule (J)	=	0.738 ft-lb
Power	1 Watt (W)	=	1.341×10^{-2} hp
Angular velocity	1 rad/s	=	9.549 rev/min
Pressure	1 Pa (1 N/m^2)	=	1.451×10^{-4} lb/in^2
Moment of inertia	1 $kg \cdot m^2$	=	23.7 $lb \cdot ft^2$

Annex C

(Informative)

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C.1 Section 10

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