IEEE Guide for Test Procedures for Synchronous Machines

Part I—Acceptance and Performance Testing

Part II—Test Procedures and Parameter Determination for Dynamic Analysis

115™

IEEE Power & Energy Society

Sponsored by the
Electric Machinery Committee

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Approved 9 December 2009

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

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Introduction

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

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

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

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

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

— Part I, Acceptance and Performance Testing

— Part II, Test Procedures and Parameter Determination for Dynamic Analysis

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Participants

At the time this guide was submitted to the IEEE-SA Standards Board for approval, the Generator Subcommittee's Working Group #7 had the following membership:

Haran C. Karmaker, *Chair*
Innocent Kamwa, *Co-chair*
René Wamkeue, *Secretary*

Michael W. Brimsek
Ron Chu
Joseph D. Hurley
Reinhard Joho
Swam S. Kalsi
Joseph D. Law
Bruce Ledger
Timothy MacDonald
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Chris Mi
Lon Montgomery
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Pouyan Pourbeik
John J. Ready
Shep Salon
Ahmed El Serafi
Manoj Shah
Gregory Snitchler
Nick Stranges
Stephan Umans
John Yagielski

The following members of the individual balloting committee voted on this guide. Balloters may have voted for approval, disapproval, or abstention.

William J. Ackerman
Michael Adams
Ali Al Awazi
William Bartley
Thomas Bishop
William Bloethe
Steven Brockschink
Andrew Brown
Gustavo Brunello
Antonio Cardoso
Weijen Chen
Ian Culbert
Roger Daugherty
Matthew Davis
Gary L. Donner
Donald Dunn
James Dymond
Gary Engmann
Rostyslaw Fostiak
Randall Groves
Gary Heuston
Scott Hietpas
William B. Hopf
David Horvath
James Jones
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Haran C. Karmaker
John Kay
Tanuj Khandelwal
Geoffrey Klempner
J. Koepfinger
Saumen Kundu
Chung-Yiu Lam
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Lawrence Long
O. Malik
Omar Mazzoni
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Howard Penrose
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Douglas Seely
Ahmed El Serafi
Gil Shultz
James E. Smith
David Tepen
S. Thamilarasan
James Timperley
John Vergis
James Wilson
Oren Yuen

When the IEEE-SA Standards Board approved this guide on 9 December 2009, it had the following membership:

Contents

IEEE Guide for Test Procedures for Synchronous Machines

Part I—Acceptance and Performance Testing

1. Overview

1.1 Scope

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

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

1.2 Organization of the guide

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

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

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

1.3 Miscellaneous notes

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

— Added a new subclause (3.16) on vibration testing to recommend procedures for performing vibration tests according to current industry practices.

— Revised 7.3.6 to correct errors in the prevision edition.

— Updated procedures to reflect state-of-the-art practices and technology.

— Reedited all equations to make them flexible to further changes and corrections.

— Added an annex (Annex F) on the load rejection test procedure in Clause 11.

— Updated references and the bibliography.

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

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

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

The International System of Units (SI) or metric system of units has been used in this document. Annex A lists a bibliography, in which references are noted particularly for Clause 5 and for Clause 9 through Clause 12. Annex B lists nomenclature used particularly in Clause 5 and in Clause 9 through Clause 12. Annex C includes discussions on leakage and Potier reactance. Annex D gives an example of calculation of per unit (p.u.) field current. Annex E describes the test procedures for quadrature-axis transient and subtransient reactances and time constants. Annex F includes descriptions on generator load rejection test procedure. Annex G includes discussions on magnetic nonlinearity. Annex H describes an alternative approach to model development.

1.4 Instrumentation

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

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

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

WARNING

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

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

[1] Information on references can be found in Clause 2.

2. Normative references

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

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

IEC 60034-14, Mechanical vibrations of certain machines with shaft heights 56 mm and higher—Measurement, evaluation and limits of vibration severity.[3]

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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[2] ASME publications are available from the American Society of Mechanical Engineers, 22 Law Drive, Fairfield, NJ 07007, USA (http://www.asme.org/).
[3] IEC publications are available from the International Electrotechnical Commission, Case Postale 131, 3, rue de Varembé, CH-1211, Genève 20, Switzerland/Suisse (http://www.iec.ch/). IEC publications are also available in the United States from the American National Standards Institute, 25 West 43rd Street, 4th Floor, New York, NY 10036, USA (http://www.ansi.org/).
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IEEE Std 492™, IEEE Guide for Operation and Maintenance of Hydro-Generators.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

NEMA MG1, Motors and Generators.[7]

[6] ISO/IEC publications are available from the ISO Central Secretariat, Case Postale 56, 1 rue de Varembé, CH-1211, Genève 20, Switzerland/Suisse (http://www.iso.ch/). ISO/IEC publications are also available in the United States from the American National Standards Institute, 25 West 43rd Street, 4th Floor, New York, NY 10036, USA (http://www.ansi.org/).
[7] NEMA publications are available from the National Electrical Manufacturers Association, 1300 N. 17th St., Ste. 1847, Rosslyn, VA 22209, USA (http://www.nema.org/).

3. Miscellaneous tests

3.1 Insulation resistance

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

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

NOTE—While IEEE Std 1095 is written specifically for vertical hydraulic-turbine-driven generators, the procedure is applicable to other types of machines.[8]

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

3.2 Dielectric and partial discharge tests

3.2.1 General

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

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

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

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

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

— Method 1. Alternating-voltage testing at power frequency (see 3.2.3)

— Method 2. Direct-voltage testing of stator windings (see 3.2.4)

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

— Method 4. Partial discharge testing (see 3.2.6)

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

3.2.2 Preparation

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

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

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

3.2.3 Method 1. Alternating-voltage testing at power frequency

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

a) Transformer-voltmeter
b) Sphere gap

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

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

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

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

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

Because this testing can be destructive to the winding, some precautions are advised. It should be noted that the test voltage applied during manufacture testing of new windings is a one-time value. For purposes of maintenance testing in subsequent years, it is advisable to apply only a lesser percentage of the original test value. For suggested values, see EPRI EL-5036 [B20].[9]

3.2.4 Method 2. Direct-voltage testing of stator windings

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

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

[9] The numbers in brackets correspond to the numbers of the bibliography in Annex A.

WARNING

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

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

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

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

3.2.6 Method 4. Partial discharge testing

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

3.3 Resistance measurements

3.3.1 General

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

3.3.2 Correction to specified temperature

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

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

where

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

t_s is the specified temperature, in degrees Celsius

R_t is the test value of winding resistance, in ohms

t_t is the temperature of winding when resistance was measured, in degrees Celsius

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

3.3.3 Reference field resistance

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

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

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

3.3.4 Reference field resistance from a running test

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

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

3.3.5 Field resistance for running temperature tests

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

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

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

3.3.6 Effect of brush voltage drop

To determine the field resistance of a running machine accurately, it is necessary to obtain the voltage drop across the field winding without including the voltage drop of the brushes supplying the field current. This step is especially important when the field current is very small, e.g., when determining the reference resistance value (see 3.3.4). For this purpose, it is desirable to measure the voltage drop directly across the collector rings, using special brushes that are in contact with the collector rings only during voltage measurement. For this purpose, it is possible to use

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

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

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

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

3.4 Tests for short-circuited field turns

3.4.1 General

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

— Method 1. Voltage drop, dc
— Method 2. Voltage drop, ac
— Method 3. DC resistance
— Method 4. Exciting coil for cylindrical rotors
— Method 5. Rotor waveform detection for cylindrical rotors

3.4.2 Method 1. Voltage drop, dc

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

3.4.3 Method 2. Voltage drop, ac

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

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

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

3.4.4 Method 3. DC resistance

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

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

3.4.5 Method 4. Exciting coil for cylindrical rotors

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

3.4.6 Method 5. Rotor waveform detection for cylindrical rotors

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

3.5 Polarity test for field poles

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

3.6 Shaft current and bearing insulation

3.6.1 General

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

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

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

— Method 1. Across end shafts
— Method 2. Across bearing oil film, uninsulated bearings
— Method 3. Across bearing insulation
— Method 4. Bearing insulation—Running test
— Method 5. Bearing insulation—Static test
— Method 6. Double insulation

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

3.6.2 Method 1. Across end shafts

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

3.6.3 Method 2. Across bearing oil film, uninsulated bearings

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

3.6.4 Method 3. Across bearing insulation

Many machines have one or more bearings insulated to eliminate shaft currents. For these methods as described in this subclause as well as 3.6.5 through 3.6.7, it is assumed that insulation is located between the bearing and the frame of the machine. To determine the presence of a voltage that will produce shaft currents in such a machine, a low-resistance conductor is connected from the shaft to the uninsulated bearing in order to short-circuit the oil film, and a low-range ac voltmeter (or a high-range ac ammeter) is connected between the shaft and the frame successively at each insulated bearing. Deflection of the instrument indicates the presence of a voltage that will produce shaft currents if the bearing insulation is not present.

3.6.5 Method 4. Bearing insulation—Running test

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

3.6.6 Method 5. Bearing insulation—Static test

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

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

3.6.7 Method 6. Double insulation

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

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

3.7 Phase sequence

3.7.1 General

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

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

Phase sequence can be tested using the following methods:

— Method 1. Phase-sequence indicators
— Method 2. Indication of differential voltage
— Method 3. Direction of rotation for machines that can be started on a power source

3.7.2 Method 1. Phase-sequence indicators

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

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

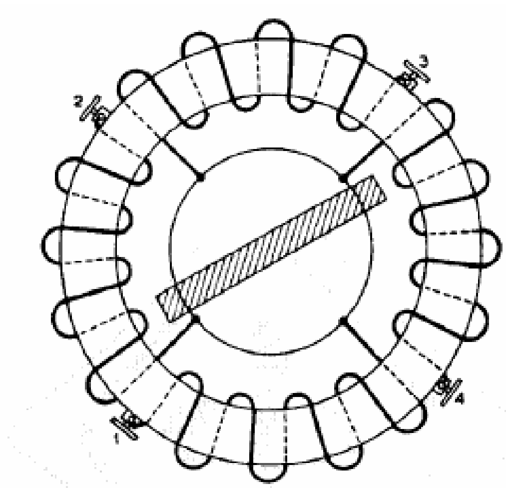


Figure 1—Phase-sequence instrument

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

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

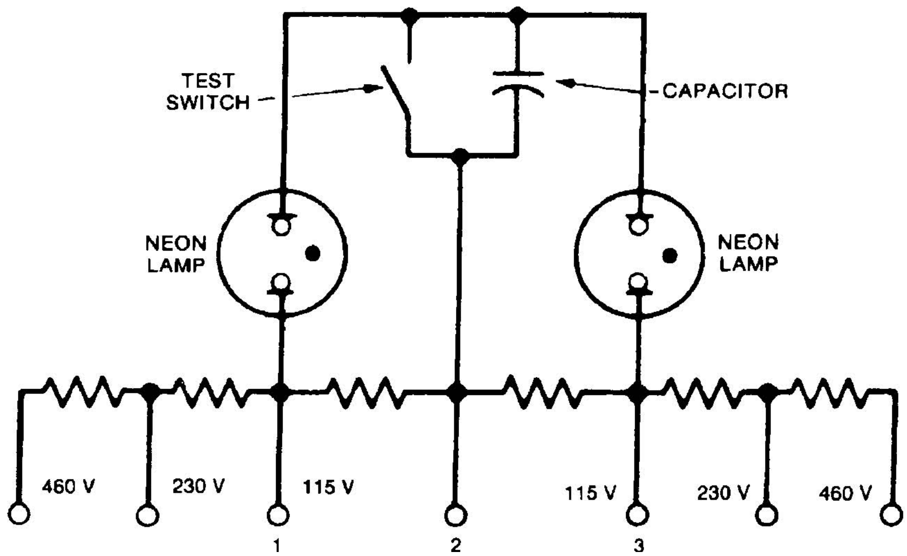


Figure 2—Neon-lamp phase-sequence indicator

3.7.3 Method 2. Indication of differential voltage

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

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

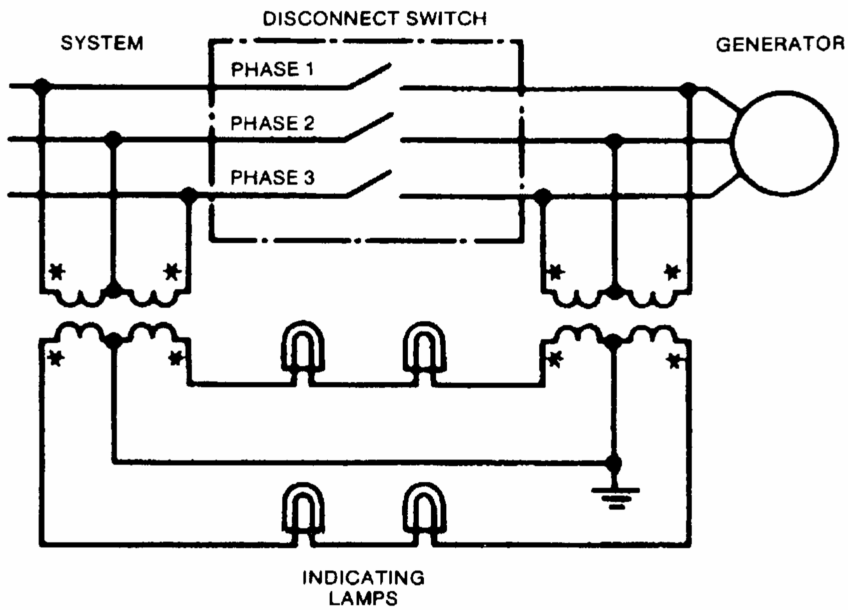


Figure 3—Connection diagram for comparing phase sequence of a generator with that of a system by indicating voltage across an open disconnect switch

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

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

3.8 Telephone-influence factor (TIF)

3.8.1 General

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

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

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

where

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

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

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

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

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

3.8.2 Weighting factors

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

3.8.3 Voltage transformer considerations

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

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

3.9 Balanced TIF

3.9.1 General

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

— Method 1. Line-to-line voltage
— Method 2. Phase voltage

3.9.2 Method 1. Line-to-line voltage

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

3.9.3 Method 2. Phase voltage

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

3.10 Residual-component TIF

3.10.1 General

For the definition of *residual-component telephone-influence factor (TIF)*, see *The IEEE Standards Dictionary* [B29]. The residual-component TIF can be determined by the following test methods:

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

3.10.2 Method 1. Machines that can be connected in delta

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

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

where

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

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

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

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

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

3.10.3 Method 2. Machines that cannot be connected in delta

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

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

3.10.4 Method 3. Line-to-neutral test

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

3.11 Line-to-neutral TIF

3.11.1 General

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

3.11.2 Method of test

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

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

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

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

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

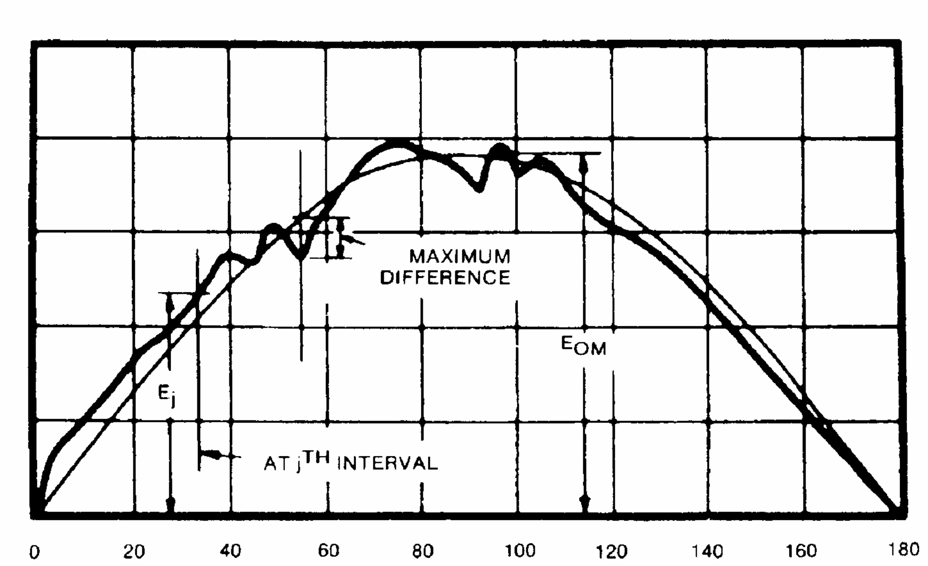


Figure 4—Plot of wave for deviation factor

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

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

where

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

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

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

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

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

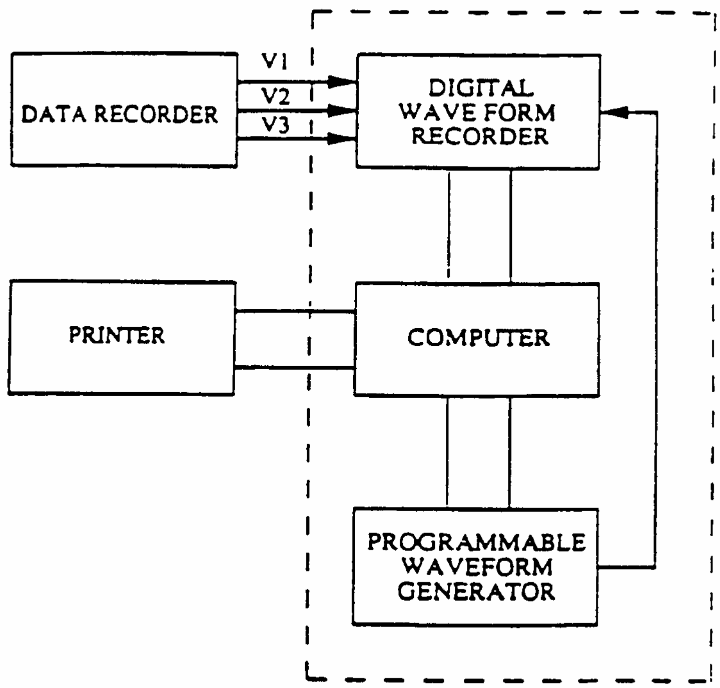


Figure 5—Block diagram of instrumentation used in waveform analysis

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

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

3.12.2 Waveform analysis

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

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

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 step 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 as follows:

$$E_j = E_i - E_O$$

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

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

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

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

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

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

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

3.12.3 Fourier analysis

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

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

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

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

$$\phi_n = \tan^{-1}\left({b_n}/{a_n} \right) \quad a_n > 0$$

$$= \tan^{-1}\left({b_n}/{a_n} \right) + \pi \quad a_n < 0 \tag{3-15}$$

$$n = 1,2,3,...$$

where

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

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

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

where

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

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

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

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 ac voltmeter calibrated with the circuit. A harmonic analyzer can also be used to measure E_n.

3.12.4 Measuring rms value

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

3.13 Overspeed tests

3.13.1 General

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

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

3.13.2 Procedure

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

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

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

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

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

3.14 Line-charging capacity

3.14.1 General

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

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

3.14.2 Method 1. As motor

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

3.14.3 Method 2. As generator

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

3.14.4 Method 3. As generator

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

CAUTION

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

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

3.15 Acoustic noise

3.15.1 General

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

3.15.2 Procedure

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

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

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

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

3.16 Vibration testing

3.16.1 General

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

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

3.16.2 Motors and small generators

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

3.16.3 Large synchronous cylindrical rotor generators—Shaft vibrations

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

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

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

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

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

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

3.16.4 Large synchronous cylindrical rotor generators—Bearing vibrations

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

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

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

3.16.5 Synchronous generators in hydroelectric applications

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

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

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

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

4. Saturation curves, segregated losses, and efficiency

4.1 General

4.1.1 Efficiency

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

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

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

4.1.2 Methods to measure losses

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

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

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

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

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

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

CAUTION

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

4.1.3 Elimination of exciter input

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

4.1.4 Effect of temperature and pressure

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

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

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

4.1.5 Coupled machines

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

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

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

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

4.1.6 Steam turbine overheating

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

4.1.7 Dewatering hydraulic turbine

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

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

4.1.8 Electric starting

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

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

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

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

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

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

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

4.2 Method 1. Separate drive

4.2.1 Driving motor

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

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

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

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

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

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

4.2.2 Procedure

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

4.2.3 Dynamometer as driver

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

$$\text{Power in kilowatts} = \frac{nT}{k} \tag{4-1}$$

where

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

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

4.2.4 Mechanical driver

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

4.2.5 Open-circuit saturation curve

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

a) Six readings should be taken below 60% of rated voltage (1 at zero excitation).

b) From 60% to 110%, readings should be taken, at a minimum, at every 5% increment in terminal voltage (minimum of 10 points). This area is a critical range, and an attempt should be made to obtain as many points as the excitation control resolution will allow.

c) Above 110%, readings should be taken, at a minimum, at two points, including one point at approximately 120% of the rated no-load field current (or at the maximum value recommended by the manufacturer).

d) At rated voltage, readings should be taken of the terminal voltage (line-to-line) of all three phases to check phase balance. These readings should be made under constant conditions of excitation and speed and with the same voltmeter.

CAUTION

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

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

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

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

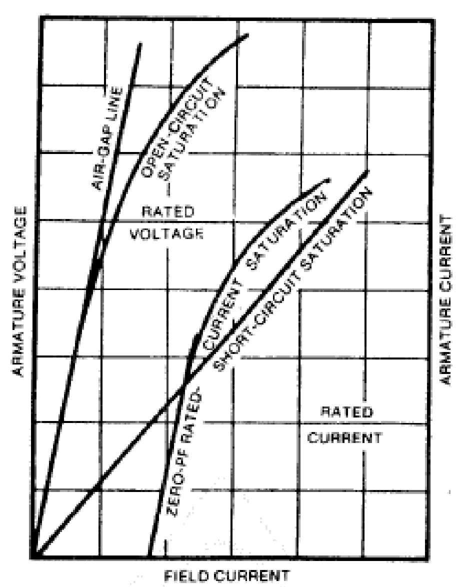


Figure 6—Saturation curves

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

4.2.6 Air-gap line

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

4.2.7 Core loss and friction and windage loss

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

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

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

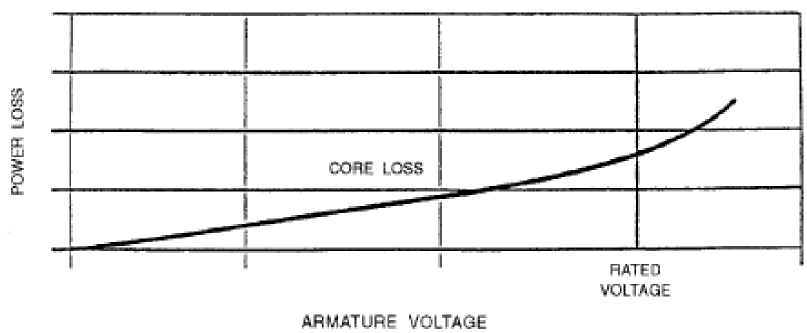


Figure 7—Core loss curve (power loss versus armature voltage)

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

4.2.8 Short-circuit saturation curve

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

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

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

Current readings should be taken with decreasing excitation starting with the value that will produce an armature current equal to the maximum allowable. The highest current point should be taken first so that the winding temperature will be as nearly constant as possible during the run. The results may be plotted as in Figure 6.

4.2.9 Short-circuit loss and stray-load loss

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

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

Short-circuit loss includes the stray-load loss plus the armature I^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 dc resistance corrected to the average temperature of the winding during the test. For high-voltage hydrogen-cooled machines, there may be an appreciable difference between the temperature of the armature conductors and the measured values. In such cases, a correction to the measured temperature can be used to improve the accuracy of determining the armature I^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 8.

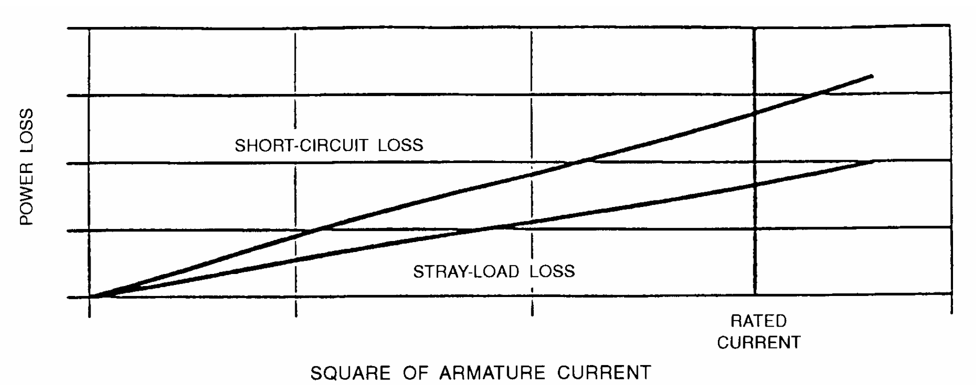


Figure 8—Short-circuit loss and stray-load loss curves

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

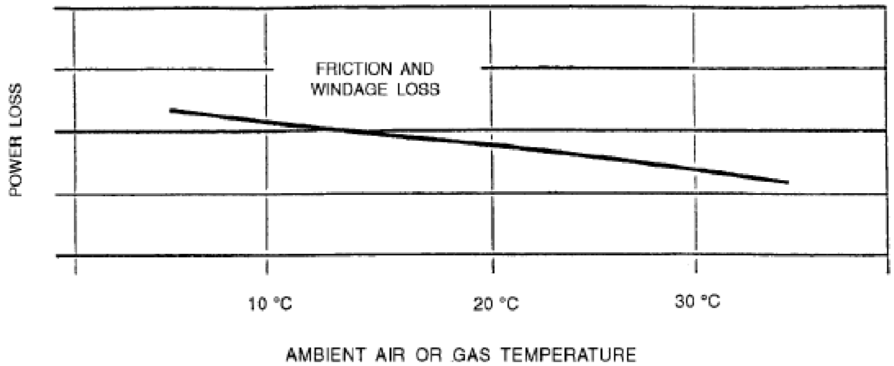


Figure 9—Plot of windage losses against temperature

4.2.10 Zero-power-factor saturation curve

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

4.3 Method 2. Electric input

4.3.1 General

The machine is run as an unloaded synchronous motor from a power supply of adjustable voltage and steady frequency equal to the rated frequency of the machine under test. Power input is measured by wattmeters or 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 complication will make obtaining correct readings of the power input difficult. The use of a driving generator that has a damper winding and is appreciably smaller than the driven machine may be helpful.

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

4.3.2 Instrument transformers

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

4.3.2.1 Current transformers

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

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

4.3.2.2 Voltage transformers

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

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

4.3.3 Voltage on instruments

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

4.3.4 Methods to measure power input

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

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

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

4.3.4.1 Connections of measuring devices

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

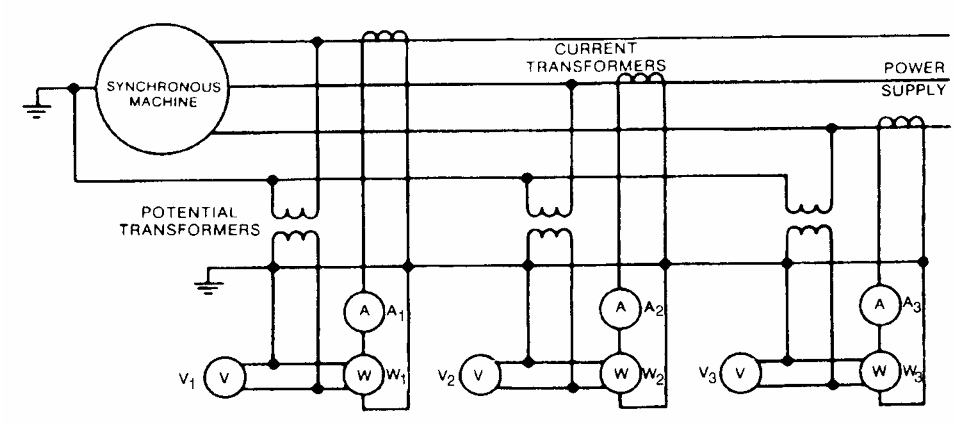


Figure 10—Connection diagram—Three-wattmeter method of measuring power

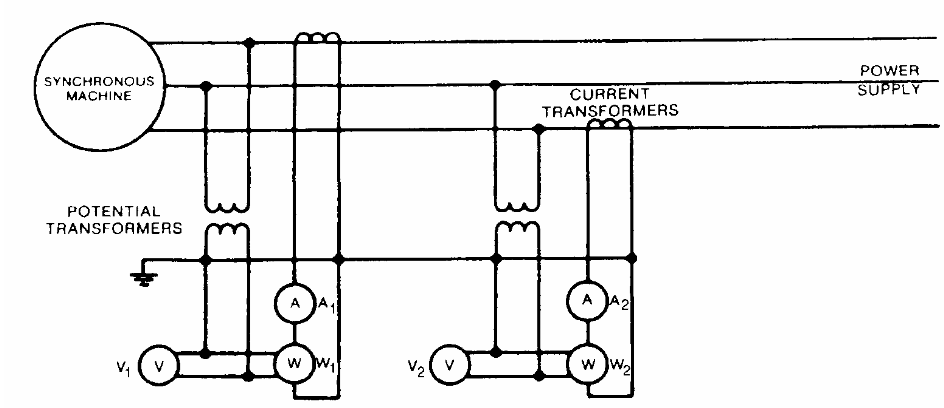


Figure 11—Connection diagram—Two-wattmeter method of measuring power

4.3.4.2 Method 1. Wattmeters

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

4.3.4.3 Method 2. Portable standard watthour meters

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

4.3.4.4 Method 3. Ordinary watthour meters

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 averaging over a suitable number of time periods.

4.3.5 Accuracy

Normally, corrections are required for scale marking of the instruments. For 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.

4.3.6 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 watthour 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.

4.3.7 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 4.2.5 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 using 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 4.1.1). The results may be plotted as shown in Figure 7.

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 12. 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 13, 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 that can be extended to give the intercept on the horizontal axis.

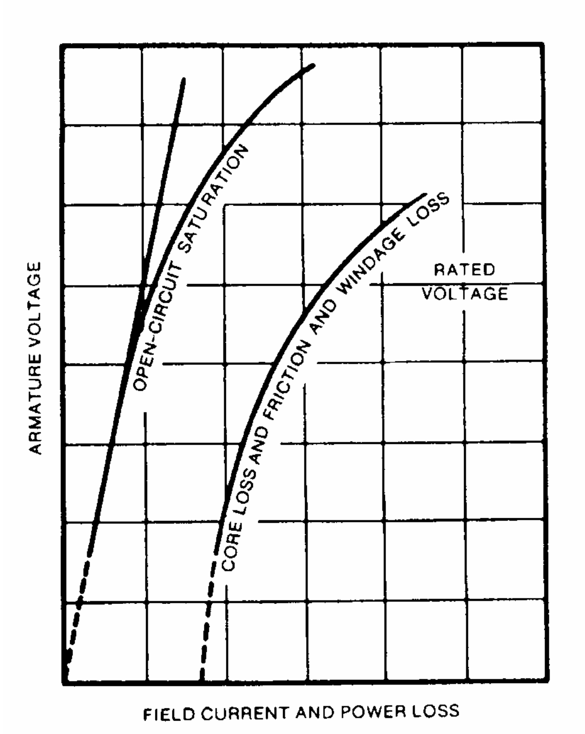


Figure 12—Open-circuit saturation and core loss curves by electric-input method

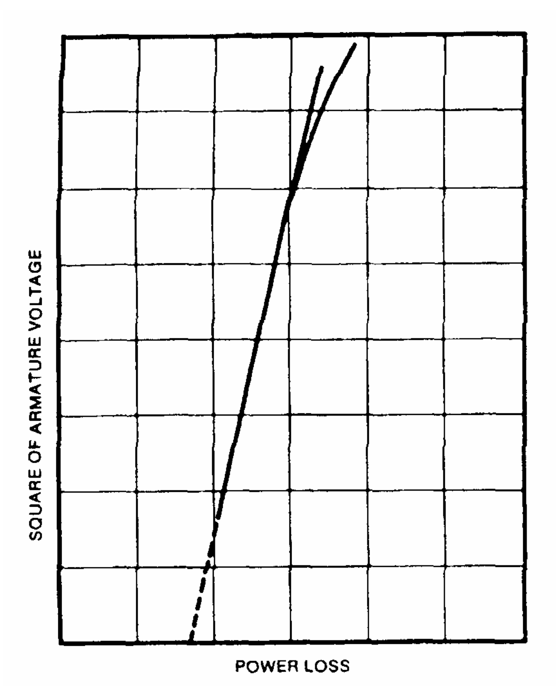


Figure 13—Construction curves for extrapolating loss curves from electric-input method

4.3.8 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 12.

4.3.9 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.

4.3.10 Total loss curve

Figure 14 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 13. 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.

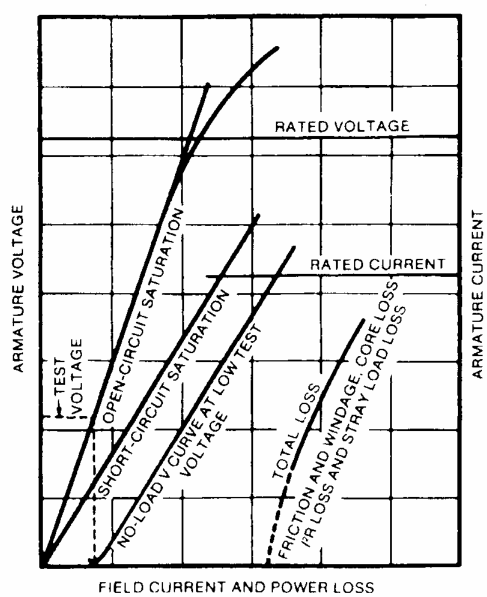


Figure 14—Curves from electric-input method

4.3.11 Short-circuit saturation curve

The curve resulting from the plotting of armature current versus field current as obtained in 4.3.9 and 4.3.10 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 Method 3. Retardation

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). The availability of electronic counters makes this method 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 where 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 Equation (4-2).

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

where

- $(\pi/30)$ is the conversion from revolutions per minute to radians per second
- n is the rotational speed, in revolutions per minute
- dn/dt is the rate of deceleration as determined from the slope of speed-time curve at n, in revolutions per minute per second
- J is the moment of inertia of rotating parts, in kilogram square meters

Procedures will be given for obtaining speed-time curves (see 4.4.9.1), determining deceleration rates (see 4.4.9), and obtaining the moment of inertia (J) of the rotating parts (see 4.4.11). 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 because 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 approach 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 that 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 step is not possible, it should be dewatered (see 4.1.7 and 4.1.8). The unit is then brought to approximately 10% overspeed, 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. Speed and time are measured in ways so that the deceleration rate can be determined at rated speed.

When testing hydraulic-turbine-driven generators, it is common practice 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 ac source, the losses should be calculated at several speeds below normal up to as near normal as possible for each condition of excitation. 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 s to 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 buildup of the field is 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 to determine deceleration

Three methods to determine deceleration are covered in this guide:

- Method 1. Speed-time
- Method 2. DC generator
- Method 3. 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 procedures can be used for recording speed-time relations.

a) *Tachometer.* Using a tachometer is especially applicable to machines of large inertia.

b) *Speed recorder.* An appropriate instrument is used to record speed versus time.

A series of speed-time curves should be plotted from the test data. Figure 15 shows typical retardation curves. For each curve, the loss at any speed may be calculated by means of Equation (4-2).

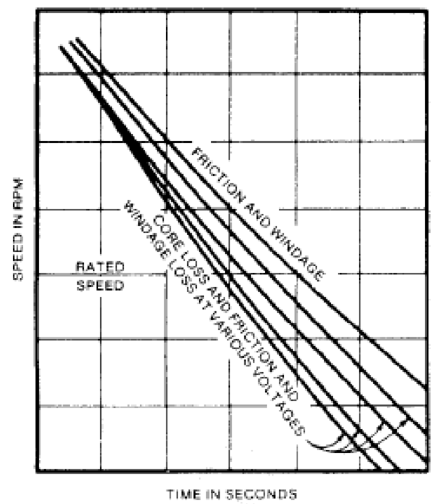


Figure 15—Typical retardation curves

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 rpm, respectively, above and below rated speed, n_s (where $n_1 = n_8 + A$, and $n_2 = n_s - A$). The speed-time curve should be reasonably straight between speeds n_1 and n_2. The values of time t_1 and t_2, in seconds, are read from the speed-time curve, respectively, at n_1 and n_2. The loss is then calculated using Equation (4-3).

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

where

$(\pi/30)$	is the conversion from revolutions per minute to radians per second
n_S	is the synchronous speed, in revolutions per minute
A	is the speed increment above and below n_s, in revolutions per minute
$t_2 - t_1$	is the time, in seconds, as determined from the speed-time curve to decelerate from $(n_s + A)$ to $(n_s - A)$
J	is the moment of inertia of rotating parts, in kilogram square meters

4.4.9.2 Method 2. DC 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 dc 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 dc generator will be opposed to the voltage of a second battery (No. 2). (See Figure 16 for a typical diagram of connections.)

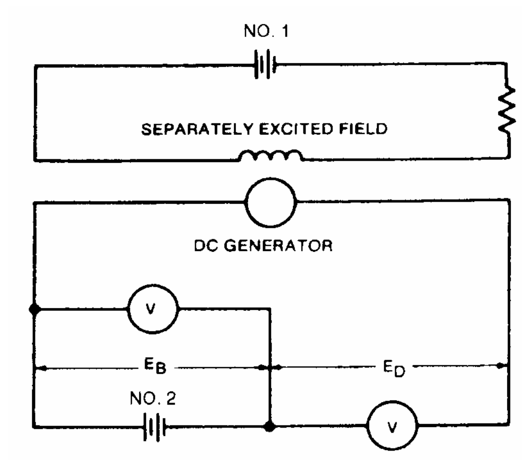


Figure 16—Speed measurement by dc generator

Battery No. 1 should have an output voltage about 1/10 or less of the rated voltage of the field circuit of the dc 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 No. 2 at approximately full scale and the other, with about 1/5 this range, to read the difference between the voltages of battery No. 2 and the dc generator. The voltage of battery No. 2 should be such that the differential voltage between it and the dc 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	is the proportionality factor relating speed to voltage (it is not actually necessary to evaluate K)
E_B	is the voltage of battery No. 2

E_D is the differential voltage

n_c is the known speed (in revolutions per minute) at which losses are to be determined (usually rated speed)

E_{DC} is the differential voltage at speed n_c

n_c is $K(E_{DC} + E_B)$ or $K = \dfrac{n_c}{E_{DC} + E_B}$

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

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

$\dfrac{dE_D}{dt}$ is the rate or decrease of differential voltage, in volts per second

$\dfrac{dn}{dt}$ is the rate of deceleration, in revolutions per minute per second

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 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).

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

where

$\pi/30$ is the conversion from revolutions per minute to radians per second
J is the moment of inertia of rotating parts, in kilogram square meters

The voltage of battery No. 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 the voltages. A useful check after making the open-circuit core loss test (see 4.4.3) is to plot E_D against the ac 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 ac generator voltage. This check should always be made if a belted exciter or belted dc 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 ac 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 revolutions of the rotor of the machine under test. 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 Equation (4-5) and Equation (4-6).

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

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

where

n is the speed, in revolutions per minute
dn/dt is the angular deceleration, in revolutions per minute per second
t_1 is the time for the first group of n_r revolutions of the rotor, in seconds
t_3 is the time for the third group of, n_r revolutions of the rotor, in seconds
n_r is the number of revolutions of the rotor in each of the intervals t_1 and 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_5 and t_7, would be obtained by substituting t_5 and t_7 for t_1 and t_3 in Equation (4-5) and Equation (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, 4.3.8, and 4.3.9). The open-circuit saturation curve can be checked by data from the open-circuit retardation tests (see 4.4.3) using readings of armature voltage, field current, and speed. The voltage readings for each test are plotted versus 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). However, 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, and this constant nature eliminates the need for correcting the armature currents to rated-speed values for use in the saturation curve.

4.4.11 Methods to determine rotor polar moment of inertia (*J*)

The following methods exist to determine J, the polar moment of inertia of the rotor:

— Method 1. Manufacturer
— Method 2. Speed retardation without excitation
— Method 3. Speed retardation with excitation
— Method 4. Speed retardation with direct-connected exciter
— Method 5. Physical pendulum

4.4.11.1 Method 1. Manufacturer

The value of J of the rotor is customarily obtained from the manufacturer, which can calculate the value.

4.4.11.2 Method 2. Speed retardation without excitation

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 speed retardation curve of the unexcited machine and the known value of friction and windage loss using Equation (4-2).

4.4.11.3 Method 3. Speed retardation with excitation

The machine is run as an unloaded synchronous motor at normal speed at approximately unity power factor (see 4.3.7). The power input is measured; this power input includes friction and windage, core, and copper losses. The copper loss should be subtracted to obtain the loss that 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 data to be substituted in Equation (4-1) with the known losses to obtain the J.

4.4.11.4 Method 4. Speed retardation with direct-connected exciter

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 and with constant power output. From the measured load and the known exciter losses, the value of J can be calculated from the two retardation curves.

4.4.11.5 Method 5. Physical pendulum

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 should be used for increased accuracy.

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 R_g in SI units may then be calculated by means of the following equation:

$$R_g = R_2 \sqrt{\frac{gt^2}{4\pi^2 (R_1 - R_2)} - 1} \tag{4-7}$$

where

R_g 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 m/(s)^2

then

$$J = M \left(R_g\right)^2 \tag{4-8}$$

where

M is the mass of the rotor, in kilograms

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 value of J may then be calculated by using Equation (4-9).

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

where

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

4.5 Method 4. Heat transfer

4.5.1 Machines with water coolers

This method of measuring losses 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. Equation (4-10) measures the loss absorbed by the water.

$$\text{Loss in kilowatts} = 4.187\,(t_h - t_c)Q \tag{4-10}$$

where

t_h	is the temperature of water leaving cooler, in degrees Celsius
t_c	is the temperature of water entering cooler, in degrees Celsius
Q	is the rate of water flow, in liters per second

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:

$$\text{Loss in kilowatts} = 4.187\ \mathrm{c_p}\,GQ\,(t_h - t_c) \tag{4-11}$$

where

$\mathrm{c_p}$	is specific heat of the oil (relative to water)
G	is specific gravity of the oil (relative to water); heat and gravity evaluated at the average temperatures t_h and t_c
t_h	is temperature of oil leaving bearing, in degrees Celsius

t_c is temperature of oil entering bearing, in degrees Celsius
Q is rate of oil flow, liters per second

Because the difference between t_h and t_c is usually small, it is 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 to cancel any difference in thermometers.

The rate of flow of water can be measured by a calibrated flow meter, or, if an appropriate flow meter 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 per unit area of exposed surface may be estimated by the following approximate equation:

$$\text{Loss} = 0.5\times 10^{-6}\,(t_r - t_a)\ \text{W/m}^2 \tag{4-12}$$

where

t_r is the average temperature of the entire radiating surface, in degrees Celsius
t_a is the ambient temperature, in degrees Celsius

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

Efficiency can be measured by the following methods:

— Method 1. Segregated losses

— Method 2. Input-output

4.6.1 Method 1. Segregated losses

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

— For a generator:

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

— For a motor:

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

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 IEEE C50 standard series and NEMA MG1.

4.6.2 Method 2. Input-output

The efficiency from the input-output method is determined as shown in Equation (4-15).

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

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 Equation (4-16).

$$\text{Power in kilowatts} = \frac{nT}{k} \tag{4-16}$$

where

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

For the correction of dynamometer, coupling windage, and bearing loss, see IEEE Std 112. The electric input to the motor or output of the generator should be carefully measured. The leads to the voltage transformers should be connected to the terminals of the machine under test to eliminate 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 voltage transformers.

If a dynamometer is not available, the test machine may be driven by or loaded by an ac or dc 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

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 in this clause. 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 also described in this clause. In some cases, the manufacturer may supply the machine constants and the open-circuit saturation curve.

5.2 Test methods

Some of the following methods are part of the parameter requirements for excitation calculations and are more fully described in other subclauses.

— Open-circuit saturation curve (see 4.2.5)

— Armature resistance, R_a (see 3.3)

— Direct-axis unsaturated synchronous reactance, X_{du} (see 10.3)

— Quadrature-axis unsaturated synchronous reactance, X_{qu} (see 10.4 and 10.4.1)

5.2.1 Determining armature leakage reactance, X_l

There are no specific tests for directly determining X_l. (Subclauses 12.3.1 and 12.5.4 give 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 *The IEEE Standards Dictionary* [B29]). 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 “zigzag” 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 Methods to determine Potier reactance

5.2.2.1 Method 1. Zero power factor

The Potier reactance is determined from the open-circuit saturation curve and from the rated current zero-power-factor overexcited saturation curve (see 4.2.5 and 4.2.10). Typical curves are plotted in Figure 17.

The intersection of the zero-power-factor saturation curve with the rated-voltage ordinate locates the point *d*, as shown in Figure 17. 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 value is equal to line *a'd'* on Figure 17.

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

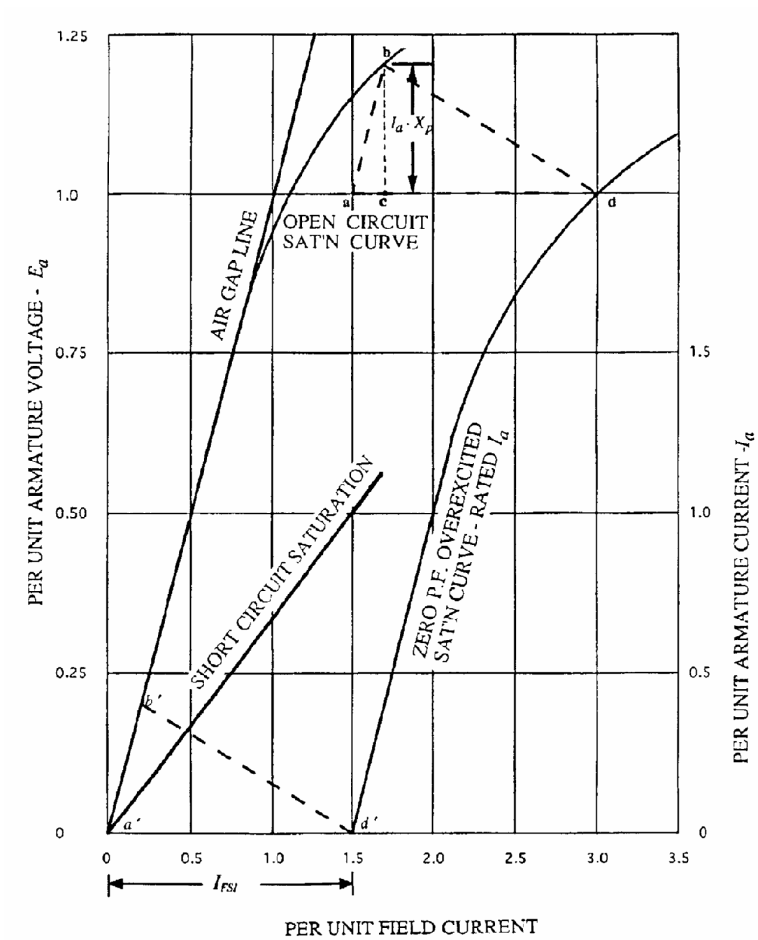


Figure 17—Determination of Potier reactance voltage

5.2.2.2 Method 2. 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 p.u. 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, the quadrature-axis synchronous reactance, X_{qu}, must also be known.

a) Calculate a p.u. value of excitation or p.u. value of field current, I_{FU}, as described in 5.3.2.2 or 5.3.2.3.

b) Determine the p.u. value of the *measured* field current I_{FU} by dividing the measured field current by the base value of field current corresponding to 1.0 p.u. 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 20 in 5.3.2.3).

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 20. This figure 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 18 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 p.u. magnitude of the phasor $E_p - E_a$ can now be determined by Equation (5-1).

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

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

NOTE 1—Strictly speaking, the $I_a X_p$ term in the figure should be an impedance voltage drop. However, in machines larger than 100 kW to 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 *overexcited* 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.*

NOTE 2—For *overexcited* conditions in a generator, the armature current, I_a, lags the terminal voltage, E_a, in phase, and the power-factor angle, ϕ, 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 to Figure 18. The convention for positive angle in these phasor diagrams is that phase *rotation* is counterclockwise.

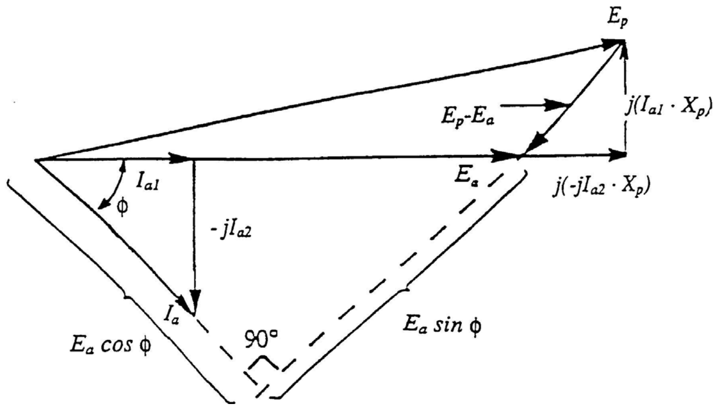


Figure 18—Calculation of magnitude of $E_p - E_a$

Theoretically, the leakage and Potier reactances should be the same value. However, because of saturation phenomena, they often differ. Annex C 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 the following methods:

— Method 1. Specified operation conditions
— Method 2. Phasor diagram analysis
— Method 3. Potier reactance and without machine saliency

These methods are all empirical, but seem to give relatively close agreement with measured values of field current.

5.3.1 Method 1. 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 Method 2. Phasor diagram analysis

5.3.2.1 Terminology and definitions

The following terminology is used in 5.3.2.2 and 5.3.2.3, which describe the steps in the phasor diagram analysis:

- E_a is the machine terminal voltage (or kilovolts), in per unit
- I_a is the machine armature current, in per unit
- E_{QD} is the 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} is the generated voltage back of X_{du}, in per unit
- I_{FU} is the field current (usually in amperes or sometimes in per unit) required to induce a voltage E_{GU} on the air-gap line (see Figure 20)
- E_p is the voltage back of Potier reactance, X_p, in per unit
- R_1 is the positive sequence resistance (see 10.7) and generally assumed to be equal to R_a, the stator resistance per phase
- I_{FG} is the 1.0 p.u. field amperes corresponding to 1.0 p.u. E_a on the air-gap line

5.3.2.2 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 19. The following procedures are used for salient-pole machines for generators and motors

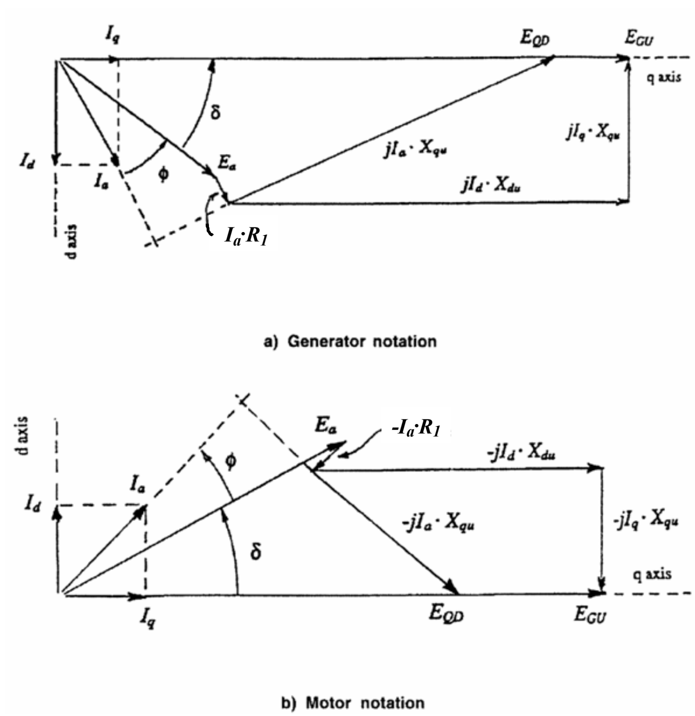


Figure 19—Phasor diagrams for calculation of E_{GU} for salient pole machines

NOTE—For generator notation, the plus sign should be used when a plus-or-minus sign is encountered; conversely, the minus 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, in the denominator the plus sign changes to a minus sign, and the minus sign changes to a plus sign.

a) $$\delta = \tan^{-1}\left\{\frac{|I_a|R_1\sin\phi + |I_a|X_{qu}\cos\phi}{|E_a| + R_1|I_a|\cos\phi - |I_a|X_{qu}\sin\phi}\right\} \tag{5-3}$$

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

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

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) $$E_{GU} = E_a + I_a R_1 + jI_q X_{qu} + jI_d X_{du} \tag{5-6}$$

d) Determine I_{FU} by locating I_{GU} on the air-gap line (Figure 20 is illustrative).

e) Calculate the voltage back of E_p.

$$E_p = E_a + I_a R_1 + jI_a X_p \tag{5-7}$$

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

f) Find the saturation increment, I_{FU}, the *difference* between the field current value required to induce E_p on the air-gap line and the value of field current corresponding to E_p on the open-circuit saturation curve (see Figure 20).

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 D.

5.3.2.3 Cylindrical rotor machines

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

a) Calculate the unsaturated generated voltage.

$$E_{GU} = E_a + I_a R_1 + jI_a X_{du} \tag{5-8}$$

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.

$$E_p = E_a + I_a R_1 + jI_a X_p \tag{5-9}$$

d) Find the incremental field current, I_{FS}, to account for saturation (see Figure 20).

e) Calculate the overall field current, which, as in 5.3.2.2, is equal total sum of I_{FU} and I_{FS}.

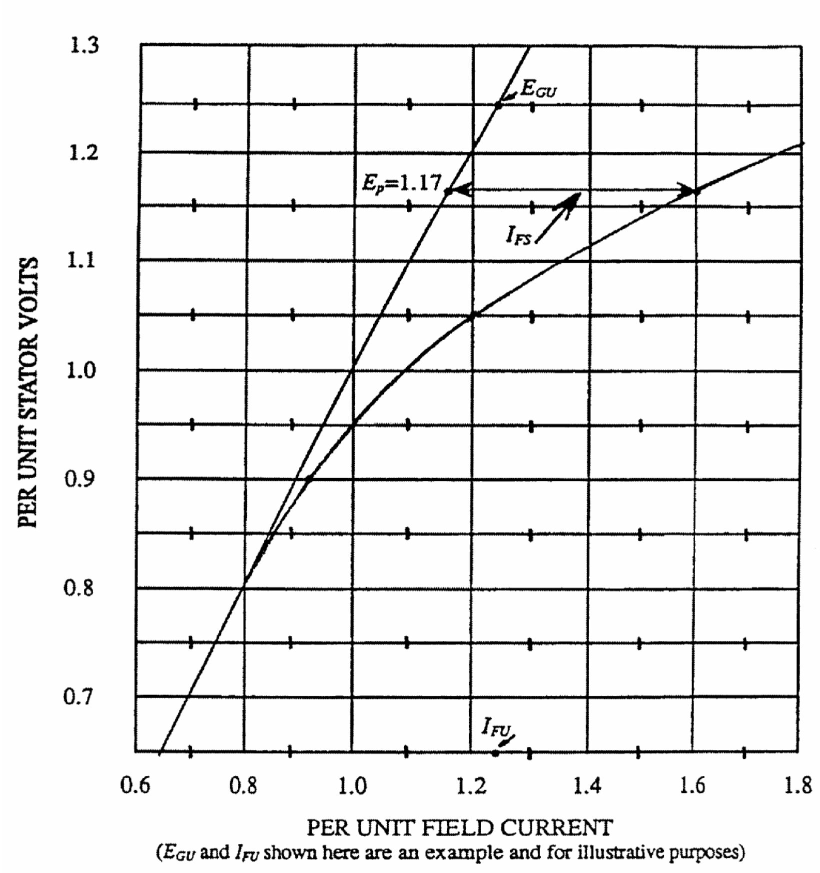


Figure 20—Typical open-circuit saturation curve for a 2400 kVA generator

5.3.3 Method 3. Potier reactance 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 21.

The values may be laid out to scale, laying off $I_a R_1$ to the right for a generator and to the left for a motor and laying off $I_a X_p$ vertically upward as shown. For an overexcited machine, the power-factor angle, ϕ, is positive and drawn above the horizontal. For an underexcited 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.

$$E_p = \sqrt{\left(E_a \cos\phi \pm I_a R_1\right)^2 + \left(E_a \sin\phi + I_a X_p\right)^2} \quad \text{p.u.} \tag{5-10}$$

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 are unavailable.
ϕ is the power-factor angle, positive for overexcited operation, negative for underexcited operation
I_aR_1 is positive for a generator and negative for a motor

NOTE—The sign convention for ϕ, the power-factor angle, as used in Equation (5-10) and Equation (5-11) is *opposite* to that used in the phasor diagram analysis of 5.3.2.2. The usage in 5.3.2.2 is common today in stability and excitation analysis of synchronous machines. This subclause, 5.3.3, has been repeated from 5.3.5 in the 1983 edition of IEEE Std 115 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.

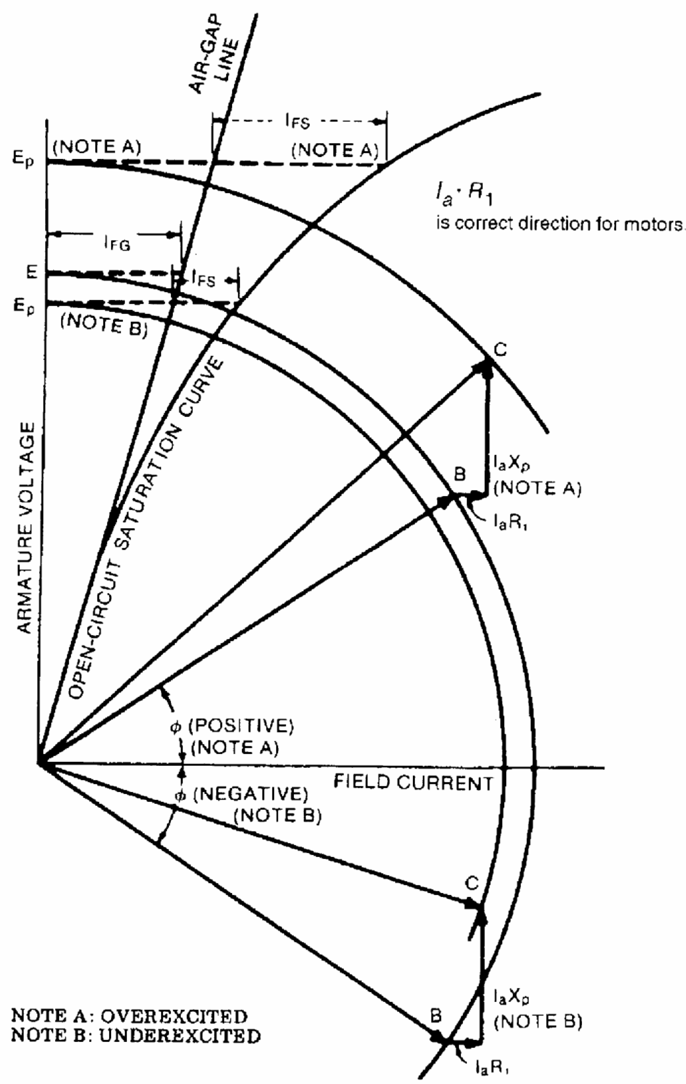


Figure 21—Diagram for voltage back of Potier reactance for synchronous generator

See the note before this figure regarding the atypical convention for the sign of ϕ, the power-factor angle.

The load field current for a specified armature current, power factor, and voltage may be obtained as shown in Figure 22 and Figure 23. 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 underexcited 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 Figure 22 and Figure 23 are shown for generator operation. The diagrams for motor operation would be mirror images of those shown in these figures and with a negative electrical angle, δ, between I_{FG} and I_{FL}.

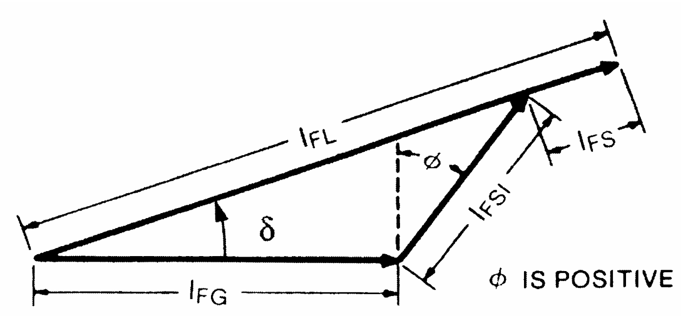


Figure 22—Determination of load field current overexcited operation (motor or generator)

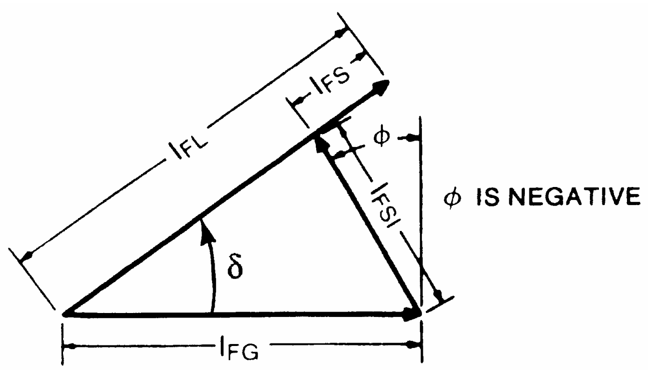


Figure 23—Determination of load field current underexcited operation (motor or generator)

The value of I_{FL}, the load field current, can also be determined by Equation (5-11).

$$I_{FL} = I_{FS} + \sqrt{\left(I_{FG} + I_{FSI} \times \sin\phi\right)^2 + \left(I_{FSI}\cos\phi\right)^2} \tag{5-11}$$

where

- ϕ is the power-factor angle, positive for overexcited operation and negative for underexcited 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 17 or Figure 20)
- 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 21)

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

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 guide; they are also treated in more detail in IEEE Std 1110.

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 values are used in calculating machine electrical torques (T_e) as shown by Equation (5-12).

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

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 IEEE Std 1110 for further discussion of synchronous machine electrical torques.

The direct, quadrature, and zero (d-q-0) axis synchronous machine model concepts of R. H. Park have been adopted in most present-day computer simulation programs. Establishing the widely accepted direct-axis and quadrature-axis model is, at present, considered basic to time-domain stability simulation and analysis 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} 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 24 depicts the load excitation calculation process. From this figure, the basic equation for field excitation is, in per unit, is shown in Equation (5-13).

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

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 $\Delta X_{adu} \times I_{fd}$. This value is the difference between the value of field excitation from the air-gap line and another value from the open-circuit curve, all at a voltage E'_q. (See IEEE Std 1110 for more detail.) $\Delta X_{adu} \times I_{fd}$ is added to E_I to give a total excitation. Field excitation E_I in per unit is based on the nonreciprocal system.

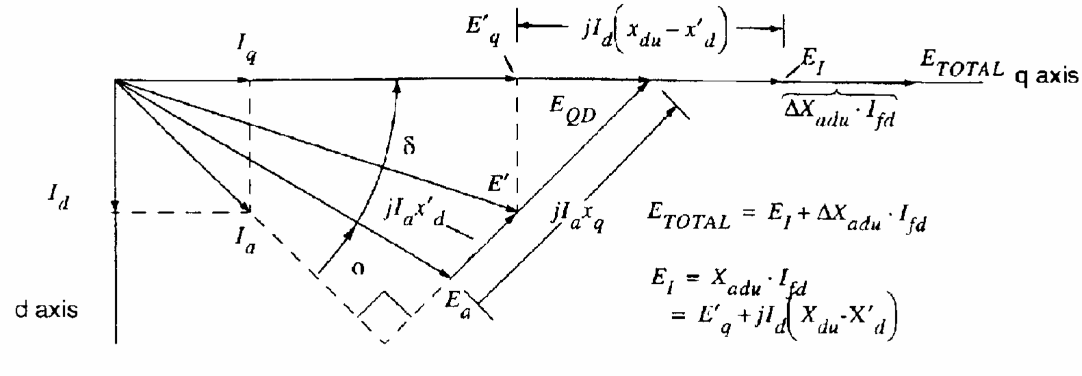


Figure 24—Phasor diagram for calculating $X_{adu} I_{fd}$ (=E_I)

In the second approach, described in IEEE Std 1110, 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 direct axis and quadrature axis. Such model networks consist of inductances and resistances (see IEEE Std 1110). 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 25. Thus,

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

Field current i_{fd} in per unit is calculated directly and is based on the reciprocal system (see Rankin [B42]). X_{ads} equals X_{adu} divided by the saturation factor K_d ($X_{ds} = X_{ads} + X_l$). (See Figure 26.) A similar factor K_q may be calculated for the quadrature axis, using a quadrature-axis saturation curve (if available). See IEEE Std 1110 for more detail, including the derivation of a quadrature-axis curve from measurements of machine terminal conditions and internal angle δ.

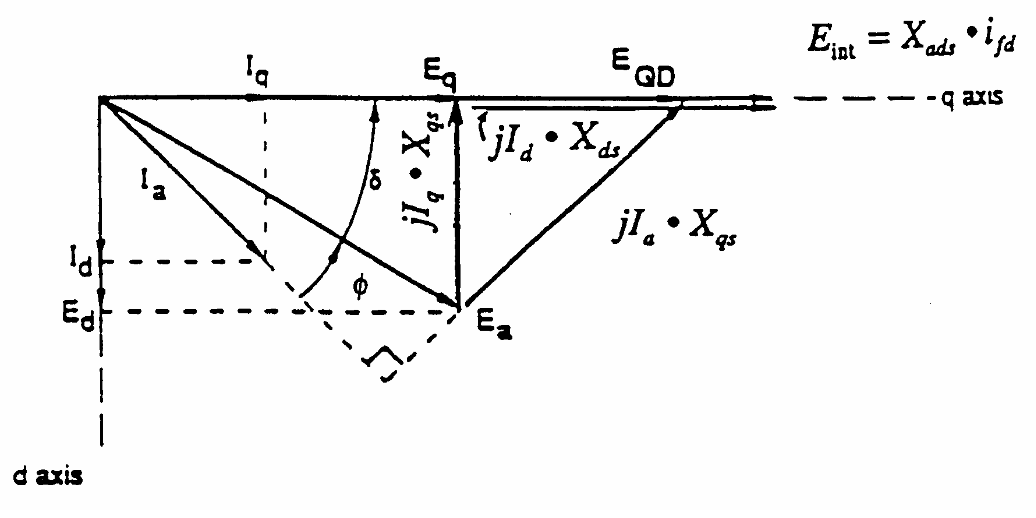


Figure 25—Phasor diagram for calculating $X_{ads} i_{fd}$

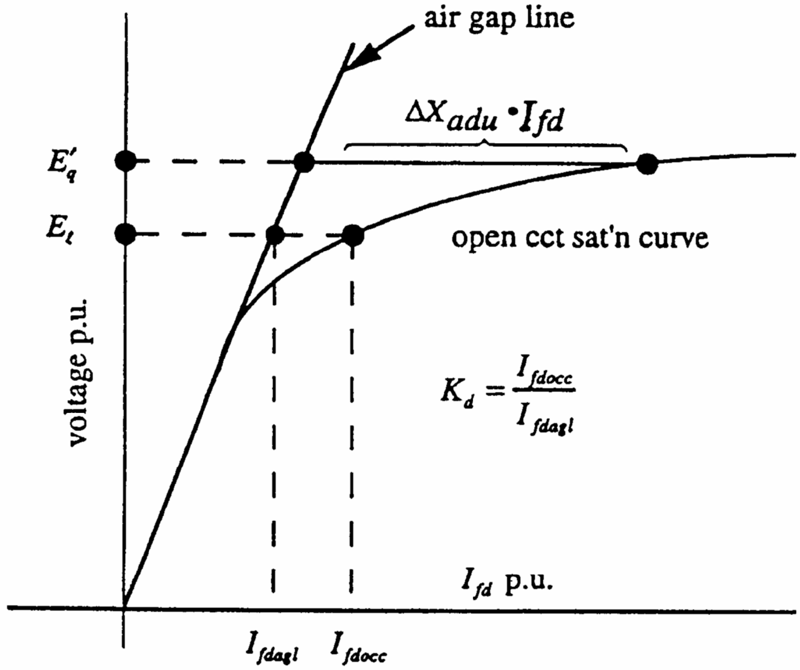


Figure 26—Calculation of saturation functions for adjustments to Equation (5-13) and Equation (5-14)

K_d is obtained from points on the air-gap line or open-circuit saturation curve 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 quadrature-axis "air-gap line" and a derived quadrature-axis curve, as described also in IEEE Std 1110.

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 that is usually 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 methods are most commonly used for temperature testing:

- Method 1. Conventional loading
- Method 2. Synchronous feedback
- Method 3. Zero power factor
- Method 4. Open-circuit and short-circuit loading

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 and to take 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 (in square megavoltamperes) rather than armature per unit (in square amperes) against temperature rise, the latter being shown in Figure 27. Use of per unit (in square megavoltamperes) has some limitations because certain machine designs *may* have unequal voltage-related or current-related losses. The recommendations for carrying out method 1 test are summarized in the following:

a) Maintain, where possible, machine terminal voltage within ± 2% of rated during the tests. Plot data as in Figure 27.

b) Perform a series of tests at various voltage levels near rated and interpolate the results using, for example, linear regression methods. Plot data as in Figure 27.

NOTE—Figure 28 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 plots are not part of method 1.

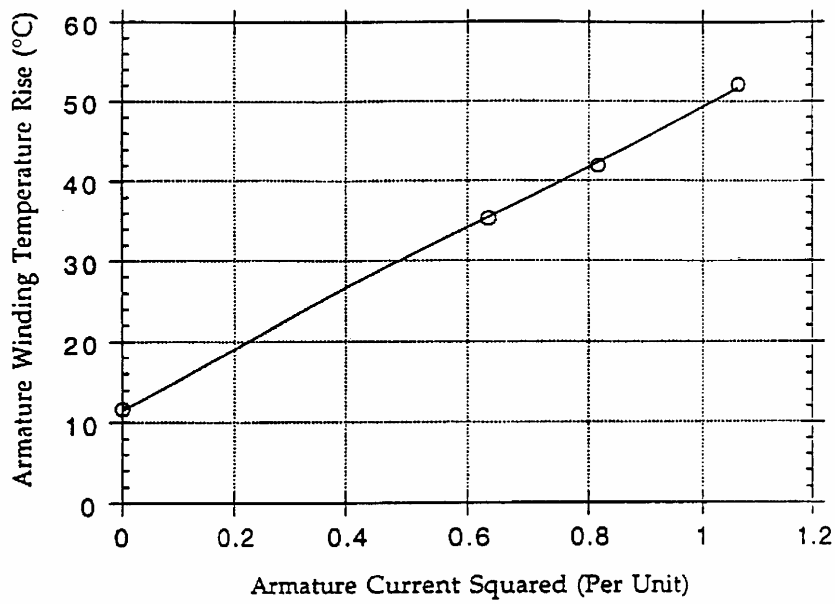


Figure 27—Typical plot of armature winding temperature rise versus armature current squared

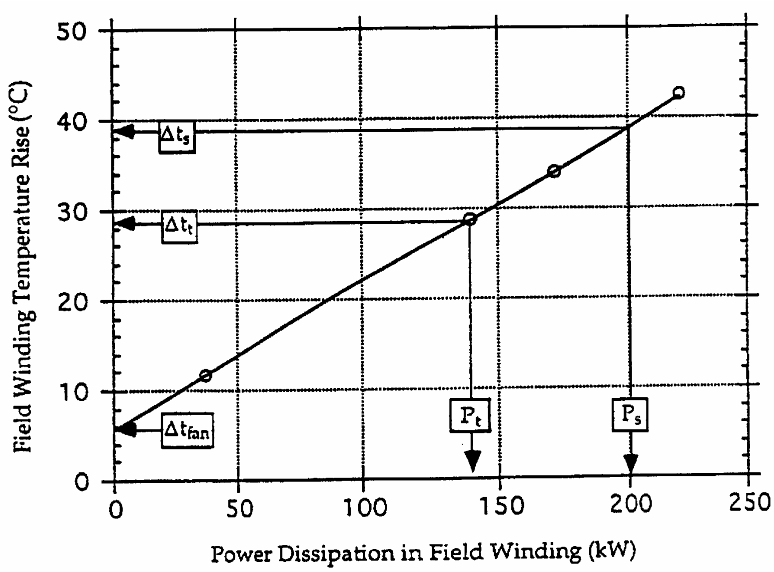


Figure 28—Typical curve of field temperature versus field power

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 under 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 (in kilovoltamperes) 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 and 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 that is the same as the voltage back of Potier reactance at rated load conditions. The voltage back of Potier reactance may be calculated by Equation (5-10) using either a measured or calculated value of reactance. This voltage may also be calculated by Equation (5-7) using I_aX_p as determined from 5.2.2.1 or 5.2.2.2, thus using either a measured or calculated value of Potier reactance X_p. The resulting armature temperature rises will be nearly the same as if the machine had been loaded at rated conditions. A typical curve is shown in Figure 27. It is sometimes impractical to use a variable voltage power supply for testing large machines in this manner. Refer to 6.2.3.2 if the armature voltage cannot be adjusted in accordance with this subclause.

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 Equation (6-5) and Equation (6-8). There are elements of approximation in both equations.

As seen in Figure 28, 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 value 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), this linear relationship can be expressed as shown in Equation (6-1).

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

where

β is the slope of the temperature rise, which can be determined empirically using Equation (6-2)

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

Equation (6-1) and Equation (6-2) can be combined to form Equation (6-3).

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

where

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

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

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

Otherwise, one must account for the temperature effect on resistance in Equation (3-1) (see 3.3.2) by using Equation (6-6).

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

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 Equation (6-7).

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

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 Equation (6-8) for the specified temperature rise as a function of specified field current.

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

where

Δt_s is the temperature rise (in degrees Celsius) 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 (in degrees Celsius) for specified field current $I_{f,s}$
$t_{c,t}$ is the reference coolant temperature (in degrees Celsius) obtained during measurement of temperature rise Δt_t
Δt_t is the temperature rise (in degrees Celsius) for test field current $I_{f,t}$
Δt_{fan} is the temperature rise (in degrees Celsius) through fan (or blower)
$I_{f,t}$ is the field current, in amperes, under test conditions
$I_{f,s}$ is the field current, in amperes, corresponding to a specified load
P_s are the field current losses at a specified load
P_t are the field current losses at the test load

6.2.3.2 Power factor larger than 0.9

For generators and motors rated at power factors above 0.9 (and particularly machines 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 of which element 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 about 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 7) for the machine under test be determined prior to the temperature tests. Armature overcurrent due to an underexcitation (possibly even a negative excitation) and the rotor field overcurrent are selected in such a way that satisfies the following conditions:

$$P_A \Delta t_R = \sum_{t_1}^{t_2} \left(P_v + P_I\right)_o \Delta t_o + \sum_{t_1}^{t_2} \left(P_v + P_I\right)_M \Delta t_u \tag{6-9}$$

$$P_F \Delta t_R = \sum_{t_1}^{t_2} P_{F\,o} \Delta t_o + \sum_{t_1}^{t_2} P_{Fu} \Delta t_u \tag{6-10}$$

where

P_A is the total armature loss at the specified load, in kilowatts
P_F is the total field loss at the specified load, in kilowatts

Δt_R is the time interval of test = ($t_2 - t_1$), in seconds
P_{Fo} is the field loss during overexcitation, in kilowatts
P_{Fu} is the field loss during underexcitation, in kilowatts
P_I is the current dependent armature loss, in kilowatts
P_V is the voltage dependent armature loss, in kilowatts
t_1 is the time at start of test, in seconds
t_2 is the time at finish of test, in seconds
Δt_o is the test time interval for overexcitation, in seconds
Δt_u is the test time interval for underexcitation, in seconds

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-circuits 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 dependent only 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 the variables subscripted with “u” are referred to the short-circuit excitation. In most cases, discharging 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 29). 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 hydro generators in the 50–370 MVA range shows that method 4 can give calculated temperature rises that on occasion may be as much as 7 °C lower than method 1. Method 1 is the preferred method of making these tests.

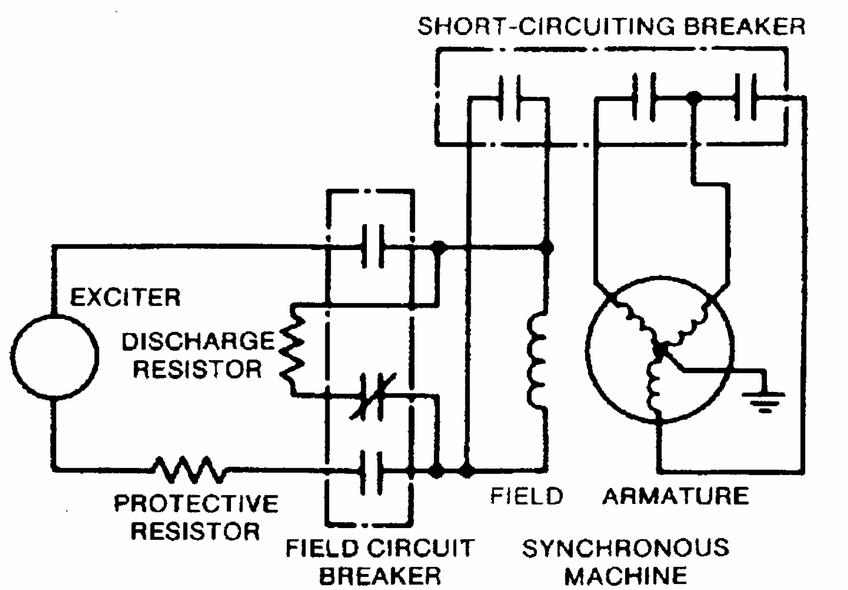


Figure 29—Field winding circuit for open-circuit and short-circuit loading (method 4)

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 to measure temperature

6.4.1 General

Temperatures may be measured using the following methods:

- Method 1. Resistance thermometer or thermocouples
- Method 2. Embedded detector
- Method 3. Winding resistance
- Method 4. Local temperature detector

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

6.4.2 Method 1. Resistance thermometer or thermocouples

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

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 IEEE Std C50.13 or NEMA MG1.

6.4.4 Method 3. Winding 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 Equation (6-11).

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

where

t_t is the total temperature of winding when R_t was measured, in degrees Celsius
R_t is the resistance measured during test, in ohms (see 3.3)
R_b is the reference value of resistance previously measured at known temperature, t_b, in ohms (see 3.3)
t_b is the temperature of winding when reference value of resistance R_b was measured, in degrees Celsius
k is 234.5 for pure copper, in degrees Celsius
k is 225 for aluminum based on a volume conductivity of 62% of pure copper, in degrees Celsius

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.

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

where

R_0 is the calculated total resistance of the winding at 0 °C, in ohms

R_{Oa} is the calculated resistance of the aluminum portion of the winding at 0 °C, in ohms

R_{Oc} is the calculated resistance of the copper portion of the winding at 0 °C, in 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, in degrees Celsius

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 devices 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 methods, the temperatures so measured should not be interpreted in relation to standards written in terms of the 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 appropriate 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 machine 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 machines

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 step is not done. A 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, halfway up the machine in the area from which cooling air is drawn. They should be placed so 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 referenced to an air temperature that 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 referenced 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 that 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 that enters at each temperature.

6.6.5 Machines cooled by other means

Machines cooled by means other than discussed in 6.6.2 through 6.6.4 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 readings 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 in the cylinder 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 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 methods 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, which should be measured in at least four places

b) Armature core, which should be measured in at least four places

c) Field, which 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 can be significant.

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 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 of 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 Table 1.

Table 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	See NOTE
NOTE—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 Table 1, 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 on 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 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 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 Table 1, 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 device indicating the highest temperature.

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 2, refer to *The IEEE Standards Dictionary* [B29].

Table 2—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 asynchronous 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 important, especially 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 voltage 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 performed 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 with 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 rapidly; therefore, 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 along with key temperatures in both the stator and the rotor.

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 varies directly 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 versus voltage that may be extrapolated to give the current at the specified voltage. Locked-rotor current can be measured by the following methods:

— Method 1. Torque by scale and beam
— Method 2. Torque by electric input

The armature current to be plotted is the average of all phases. The data from the tests are plotted as shown in Figure 30.

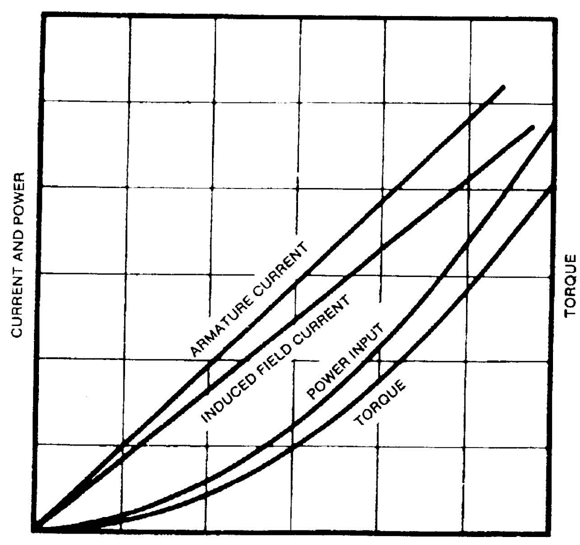


Figure 30—Torque characteristics with locked rotor

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 Equation (7-1) and Equation (7-2).

$$T_g = \frac{T_t}{T_n} \quad p.u. \tag{7-1}$$

where

T_g	is the air-gap torque at test conditions, in per unit on output base
T_t	is $F \times l$ = mechanical output torque of motor at test condition, in newton meters
F	is the net force, in newtons
l	is the length of lever arm, in meters
T_n	is the base mechanical output torque of motor, in newton meters
T_n	is $\dfrac{1000 \times P_{MN}}{\frac{2\pi}{60} n_s}$ (7-2)
n_s	is the synchronous speed, in revolutions per minute
P_{MN}	is the rated output of motor being tested, in kilowatts

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 4.2.9, 4.3.9, and 4.4.4) at the test current from the test power input.

For machines that have part-winding starting or for 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 method 1 or method 2 may be adjusted to a value corresponding to specified voltage by Equation (7-3).

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

where

T_{LR}	is the locked-rotor torque corresponding to specified voltage, in per unit on output base
T_g	is the air-gap torque at test conditions, in per unit
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 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

The following methods may be used to determine sufficient data to plot a speed-torque curve for a motor:

- Method 1. Measured output
- Method 2. Acceleration
- Method 3. Input
- Method 4. Direct measurement

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.

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

From the results of the following tests, adjusted to specified voltage, curves of p.u. torque, p.u. armature current, and induced field current, in amperes, should be plotted versus 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 while 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, i.e., 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 along with armature voltage, 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).

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

where

P_{GO} is the output of dc generator, in kilowatts
P_{GL} is the losses of dc generator (including friction and windage), in kilowatts
T_{FW} is $\dfrac{\left(P_{FW}\right) n_s}{P_{MN}\, n}$
T_{FW} is the motor friction and windage torque, in 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), in kilowatts
n_s is the synchronous speed of motor, in revolutions per minute
n is the test speed of motor, in revolutions per minute (if directly coupled, n=n_s)
P_{MN} is the rated output of motor being tested, in kilowatts

At the speed for the test point, the torque of the motor T, adjusted to specified voltage E, is obtained from Equation (7-8) or Equation (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 ac 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 to plot 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 versus time should be made. Recording instrumentation is preferred over 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 be taken ordinarily 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 only a 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, e.g., *5, 10, 15,* instead of merely stating *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 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.

7.3.3.1 Calculating air-gap torque, T_g, at each speed

Air-gap torque, T_g, at each speed is calculated from the acceleration using Equation (7-5).

$$T_g = \left(\frac{\left(\frac{\pi}{30}\right)^2 J N_S \left(dn/dt\right)}{1000 P_{MN}} \right) + T_{FW} \text{ p.u. on output base} \tag{7-5}$$

where

N_S is the synchronous speed, in revolutions per minute
dn/dt is the acceleration at each speed, in revolutions per minute per second
T_{FW} is the torque due to friction and windage at each speed [see Equation (7-4)], per unit on output base
J is the moment of inertia of rotating parts, in kilogram square meters
P_{MN} is the rated output of motor being tested, in kilowatts

At the speed for the test point, the torque of the motor *T,* adjusted to specified voltage *E,* is obtained from Equation (7-8) or Equation (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 readings called for in 7.3.3 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 (see 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).

$$T_g = \frac{P_{Si} - P_{SC} - P_C}{P_{MN}} \text{ p.u. on output base} \tag{7-6}$$

where

- P_{si} is the input power to stator, in kilowatts
- P_{sc} is the short-circuit loss at test current (see 4.2.8, 4.3.10, and 4.4.4), in kilowatts
- P_c is the open-circuit core loss at test voltage, in kilowatts
- P_{MN} is the rated output of motor being tested, in kilowatts

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 Equation (7-8) or Equation (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).

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

where

- T_t is the mechanical output torque of motor at test condition
- 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)], in per unit on output base

At the speed for the test point, the torque of the motor T, adjusted to specified voltage E, is obtained from Equation (7-8) or Equation (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 the specified voltage E, is obtained by correcting a tested quantity using Equation (7-8) and Equation (7-9) as appropriate.

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

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

where

- E_t is the line-to-line voltage of the motor at the test point, in per unit
- T_g is the air-gap torque at test point corresponding to voltage E_t, in per unit on output base
- T_{FW} is the torque due to motor friction and windage at speed for the test point [see Equation (7-4)], in per unit on output base
- I_t is the armature current at test point corresponding to voltage E_t, in per unit

K_1 is $\dfrac{\log_{10}\left(\dfrac{T_1}{T_2}\right)}{\log_{10}\left(\dfrac{E_1}{E_2}\right)}$, the torque exponent of voltage ratio ($K_1 = 2$, neglecting saturation effects) (7-10)

K_2 is $\dfrac{\log_{10}\left(\dfrac{I_1}{I_2}\right)}{\log_{10}\left(\dfrac{E_1}{E_2}\right)}$, the current exponent of voltage ratio ($K_2 = 1$, neglecting saturation effects) (7-11)

- E_1 is the convenient line voltage at which T_1 and I_1 were measured, in per unit
- E_2 is the convenient line voltage at which T_2 and I_2 were measured, in per unit
- T_1 is the air-gap torque measured at line voltage E_1, in per unit on output base
- T_2 is the air-gap torque measured at line voltage E_2, in per unit on output base
- I_1 is the armature current measured at line voltage E_1, in per unit
- I_2 is the armature current measured at line voltage E_2, in per unit

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 log-log paper. A straight line is drawn through each set of test points. Such plots, as shown in Figure 31, provide a convenient means of extrapolation to any specified voltage up to 120% of the rated voltage. When using this method, the value of K_1 is found from the slope of the line of best fit for the straight line plotted through the three torque points. The value of K_2 is found from the slope of the line of best fit for the straight line plotted through the current points.

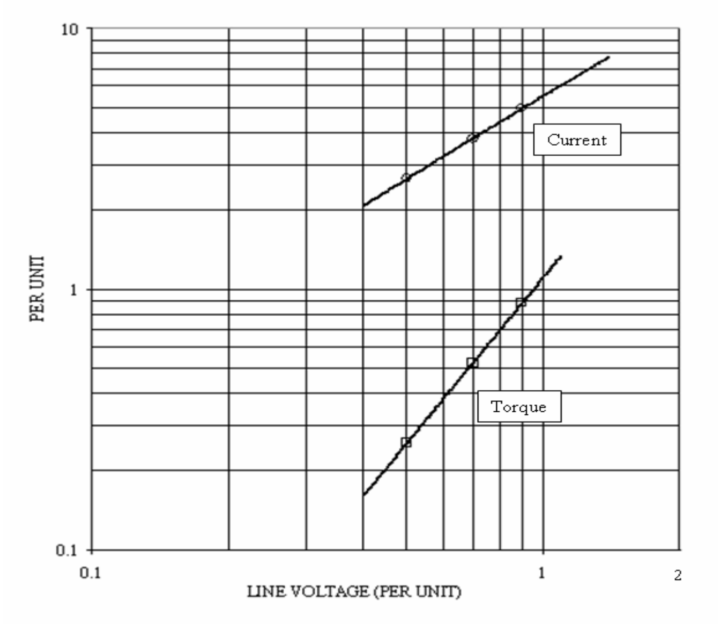


Figure 31—Correction for voltage effects

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, Equation (7-4), Equation (7-5), and Equation (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 the armature current adjustment. For greater accuracy, the adjusted values of torque, armature current, and induced field current obtained from Equation (7-8) and Equation (7-9) 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 General

Pull-out torque can be measured by the following methods:

— Method 1. Direct measurement
— Method 2. Calculation from machine constants

7.4.2 Method 1. Direct measurement

The motor is operated and the load is increased while 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 p.u. pull-out torque. This method is usually not practicable for large machines.

7.4.3 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 Equation (7-12).

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

where

T_{PO} is the pull-out torque, in per unit of base mechanical output torque
E_s is the specified terminal voltage, in per unit
I_{FL} is the specified field current, in amperes or per unit
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, in per unit

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.

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

where

X_{ds} is the direct-axis saturated synchronous reactance, in per unit
X_{qs} is the quadrature-axis saturated synchronous reactance, in per unit
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 omission 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 verify the mechanical integrity 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, due to faults on the power system (or industrial system) or due to full load rejection, or subject to 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 capability of the machine is measured in a qualitative manner.

Before performing tests for mechanical integrity, the manufacturer should be consulted. The machine must 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 tightened to the applicable specification. The rotor must 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 and IEEE Std 43.

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 high current flows, particularly on large machines, result in great forces on the test conductors. To prevent damage 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. This setup minimizes the risk of 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 recording devices.

All protective relays that 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 (SSFR) testing. Those factors, which experience has shown should be at least recognized, are spelled out in Clause 12 on SSFR testing.

IEEE Guide for Test Procedures for Synchronous Machines

Part II—Test Procedures and 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 by using analog (of network) computers, starting in the 1930s and 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 practice 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 modeling 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 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-axis and quadrature-axis representation became the norm. While second-order models were used extensively from 1945 to 1965, third-order (or higher order) models appeared to be required for some types of excitation-system studies. These requirements led to IEEE Std 115A (incorporated in the 1995 edition of the guide) for describing SSFR testing. This supplement dealt with testing of turbo alternators, particularly for parameter determination and third-order direct-axis and quadrature-axis model development.

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

Procedures for testing and parameter determination methods for short-circuit tests are given in Clause 11, while similar tests and stability model development through SSFR methods are given in Clause 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 Clause 5. 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 is discussed in Clause 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 IEEE Std 1110.

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 Clause 10, Clause 11, or Clause 12.

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

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

9.2 P.U. quantities

9.2.1 Comments

Subsequent clauses of this guide provide methods for determining machine reactances and resistances in per unit because this form is the most often desired by the user and may constitute 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 p.u. quantities, care should be used in defining clearly the p.u. 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 base three-phase power, $S_{N\Delta}$, base line-to-line 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 p.u. quantity expressed on one base can be converted to another base by multiplying by the old base quantity and dividing by the new.

P.U. quantities may be expressed in either peak or rms values. In this guide, rms values are normally used.

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 megavoltamperes 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).

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

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).

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

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 p.u. 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). For wye-connected machines, a p.u. base current for one phase of the wye winding denoted by I_N would be as expressed in Equation (9-3).

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

where

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

$E_{N\Delta}$ is the base line-to-line voltage, in volts
E_N is the base line-to-neutral voltage, in 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, in megavoltamperes
$E_{N\Delta}$ is the base line-to-line voltage, in 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 rms currents and voltages. If this practice is followed, the usual relations between instantaneous, average, and rms currents or voltages will apply regardless of whether the results are expressed in physical values or in p.u. values.

9.2.4 Base impedance

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

The base impedance is the value of impedance that 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 Equation (9-2) and Equation (9-3) into Equation (9-6), as shown by Equation (9-7).

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

where the quantities are expressed in the same units as in Equation (9-3).

The same base shall be used regardless of 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 *p.u.* voltage is E_a, and the nomenclature for stator *p.u.* current is I_a. This practice corresponds to the nomenclature used in IEEE Std 1110. It is also used in 5.2.2.1 of this guide. Note also that base voltage is expressed 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 given in Equation (9-8).

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

where

$E_{N\Delta}$ is the machine stator terminal base, in kilovolts, line to line
$S_{N\Delta}$ is the three-phase of the machine, in megavoltamperes
Z_N can also be expressed in a single phase basis as follows:

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

where

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

The base impedance Z_N is in terms of single phase, line-to-neutral ohms. This practice 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 Clause 12, the field circuit base, in ohms, referred to the stator is given as shown in Equation (9-10).

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

where

E_N and I_N are as defined in Equation (9-2) and Equation (9-3)

The i_{fdbase} is the field current excitation, in amperes, required to induce a p.u. voltage E_a on the open-circuit air-gap line of the machine equal to $I_a\, X_{adu}$. E_a is in per unit of $E_{N\Delta}$ or E_N kV. I_a is 1.0 p.u. 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 p.u. values as viewed from the stator terminals. In so doing, direct-axis 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 relationship was originally discussed by Rankin [B42] in great detail. Rankin designated the i_{fdbase} as the reciprocal system. Rankin developed this system by indicating that the stator-to-field and field-to-stator p.u. mutual inductances were equal or reciprocal in value. For a discussion of an alternate (nonreciprocal) I_{fdbase}, see Canay [B8]. This nonreciprocal base field current, in amperes, is that required to induce 1.0 p.u. V (or kV), E_a, on the open-circuit air-gap line.

The relationship between the two field current bases is shown in Equation (9-11).

$$i_{fdbase} = I_{fdbase}\left(X_{adu}\right) \tag{9-11}$$

where

X_{adu} is the unsaturated p.u. value of the direct-axis magnetizing reactance

The Equation (9-11) relationship is also shown graphically in Figure 32 and Figure 33. This conversion from the reciprocal system to the nonreciprocal system is also discussed more fully, with numerical examples, in IEEE Std 1110.

9.2.5 Base frequency

The base frequency is regularly selected as equal to the rated frequency. From this value, the base electrical angular velocity, ω_N, and the base time constant, t_N, if needed, are obtained by Equation (9-12).

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

A time constant, 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.

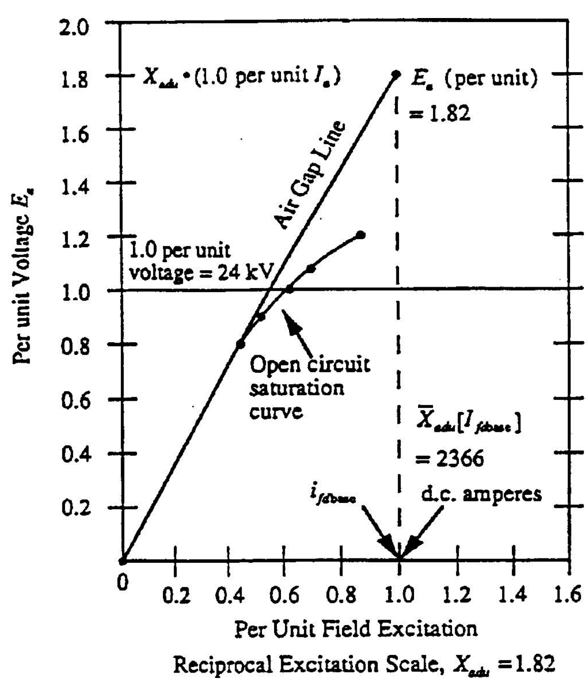


Figure 32—P.U. field excitation reciprocal excitation scale, X_{adu} = 1.82

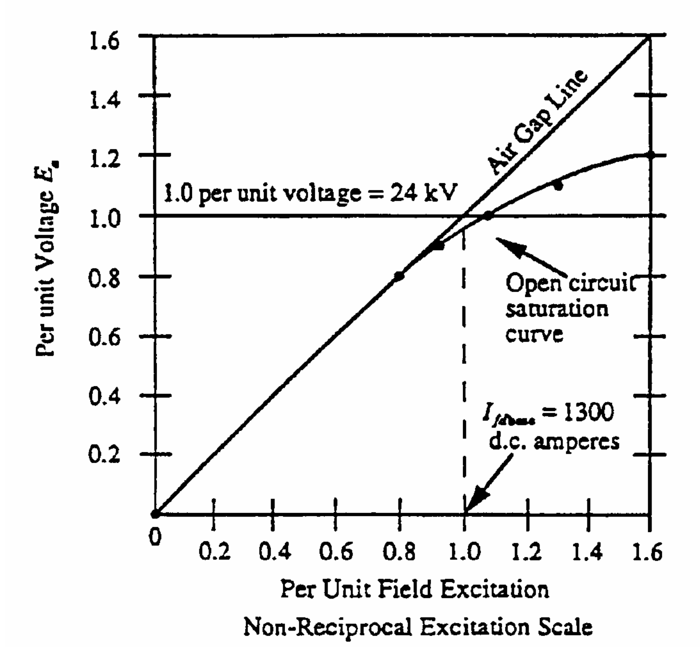


Figure 33—P.U. field excitation nonreciprocal excitation scale

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

10.1 Purpose

Some of the steady-state tests suggested in this clause are required for analyzing the performance of a synchronous machine under normal operating conditions. Under such conditions, changes in megavoltampere 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 guide. 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 clause 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 also *The IEEE Standards Dictionary* [B29]).

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 megavoltampere rating 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_{qu} Unsaturated 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 resistance, as defined 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 *The IEEE Standards Dictionary* [B29]. 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 17 (see 5.2.2.1), synchronous reactance can be calculated using Equation (10-1). In Figure 17, base values are plotted as 1.0 p.u. Figure 17 can also be plotted with base values in actual amperes or volts.

$$X_{du} = \frac{I_{FSI}}{I_{FG}} \text{ p.u.} \tag{10-1}$$

where

X_{du} is the unsaturated synchronous reactance

I_{FSI} is the field current corresponding to the 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 Clause 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 *The IEEE Standards Dictionary* [B29]. 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 the portion of X_q subject to saturation, similar to the practice in 10.3.

As a corollary, $X_{qu} = X_{aqu} + X_l$.

Similar assumptions regarding X_{qs} are that it equals $X_{aqu} + X_l$.

Quadrature-axis synchronous reactance can be determined by the following methods:

— Method 1. Slip test
— Method 2. Maximum lagging current
— Method 3. Empirical function
— Method 4. Load angle

10.4.2 Method 1. Slip test

The slip test is conducted by driving the rotor at a speed 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 34 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 with 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.

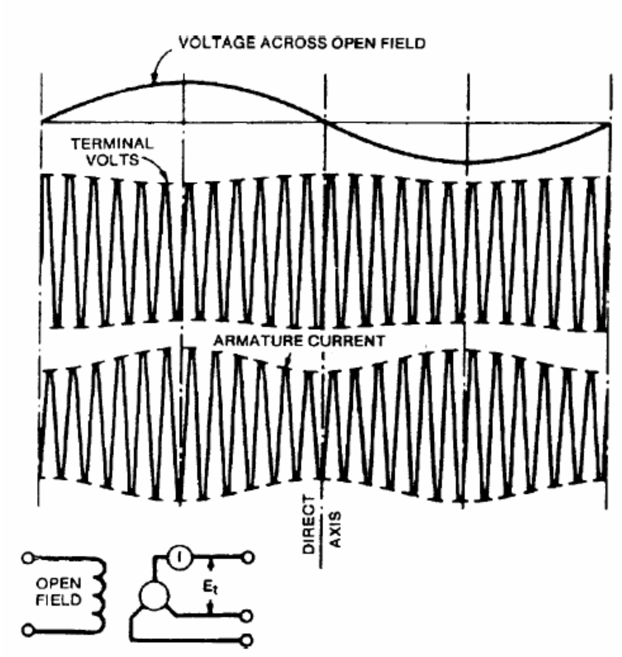


Figure 34—Slip method of obtaining quadrature-axis synchronous reactance

10.4.2.1 Precautions

It is sometimes 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 continuing with three or more tests at progressively greater slips. The manufacturer should be consulted before performing these tests.

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 verified 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 minimize the risk of dangerously increasing the voltage across the instruments.

If the slip is sufficiently low and the speed is 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.

10.4.2.2 Determination of X_{qu} using method 1

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 Equation (10-2) and Equation (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) and to obtain the quadrature-axis synchronous reactance by Equation (10-4) or Equation (10-5).

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

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

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

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

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 34.

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 under test 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 to cause 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 process gives a saturated value, X_{qs}.

10.4.3.1 Determination of X_{qs} using method 2

The quadrature-axis synchronous reactance is obtained as shown in Equation (10-6).

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

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 function

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), 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 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 Determining negative-sequence reactance, X_2

For the definition of *negative-sequence reactance*, see *The IEEE Standards Dictionary* [B29].

Negative-sequence reactance can be determined by the following methods:

- Method 1. Applied negative-sequence current (see 10.5.1.3)
- Method 2. Applied negative-sequence voltage (see 10.5.1.4)
- Method 3. Applied single-phase line-to-line sustained short circuit (see 10.5.1.5)
- Method 4. Applied single-phase line-to-line sudden short circuit (see 10.5.1.6)
- Method 5. Applied single-phase voltage (see 10.5.1.7)

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 adjacent 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 10.5.1.3), 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 that depend upon a knowledge of the direct-axis subtransient reactance, X''_d, determined for comparable conditions by the short-circuit tests given in Clause 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 Duesterhoeft [B18].

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 method 1 through method 3.

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

10.5.1.3 Method 1. Applied negative-sequence current

The machine under test 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 under test 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 per unit. If either the currents or voltages contain harmonics of more than a few percentage points, waveforms measurements of steady-state currents and voltages should be made. This step may require that the test currents be applied for several seconds before the waveforms are recorded. The waveform 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 percentage points greater than that of the fundamental, the test will be subject to appreciable error.

10.5.1.3.1 Parameter determination using method 1

The negative-sequence reactance for this test is obtained from Equation (10-7), Equation (10-8), and Equation (10-9).

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

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

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

where

E is the average of rms values of fundamental component of the three line-to-line voltages, in per unit
I is the average of rms values of fundamental component of the three line currents, in 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 10.5.2.)

10.5.1.4 Method 2. Applied negative-sequence voltage

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 under test will be substantially sinusoidal. The procedure is the same as for method 1 with waveform 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 10.5.1.4.1.

From an analysis of the waveforms of current, the average of the rms values of the fundamental component of the three line currents, in per unit, is used for I in Equation (10-7) and Equation (10-8). From analysis of the voltage waveforms, 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, in per unit, 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.

10.5.1.4.1 Correction for method 2 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).

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

where

X_{2t} is the negative-sequence test reactance obtained by using Equation (10-9), in per unit
X''_d is the direct-axis subtransient reactance, in per unit

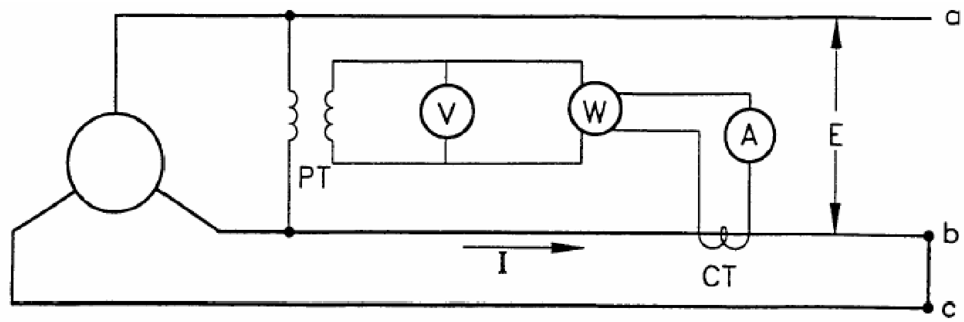
To make this correction, the direct-axis subtransient reactance should be known for approximately the same conditions. (To correct the rated-current value of X_{2t}, the rated current value of X''_d should be used.) (See 11.8.4.)

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.

10.5.1.5 Method 3. Applied single-phase line-to-line sustained short circuit

10.5.1.5.1 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 35. A voltage 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 35—Diagram for determining negative-sequence impedance using 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.

10.5.1.5.2 Parameter determination using method 3

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

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

where

E is the fundamental component of voltage, in per unit of base line-to-line voltage
I is the fundamental component of short-circuit current, in per unit of base line current

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

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

where

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

If both the voltage and current contain significant third-harmonic components, the procedure of 10.5.1.5.3 c) should be followed.

10.5.1.5.3 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) The defined negative-sequence reactance for sinusoidal negative-sequence current is obtained from the value obtained during a line-to-line short circuit.

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

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 waveforms in addition to meter readings and use the waveforms 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).

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

where

P'_{v-a} is the adjusted value of wattmeter reading
P_{v-a} is the actual wattmeter reading, in per unit of base *single-phase* power used in Equation (10-12)
E_3 is the rms third-harmonic voltage, in per unit of base line-to-line voltage
I_3 is the rms third-harmonic current, in per unit of base line current

10.5.1.6 Method 4. Applied single-phase line-to-line sudden short circuit

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

10.5.1.7 Method 5. Applied single-phase voltage

This method is described more fully in Clause 11 since, even though the particular tests are sustained or steady state, they are a complementary procedure to the sudden short-circuit tests for determining the parameters X''_d and X''_q. These tests are detailed in 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 that of the negative-sequence current under normal operating conditions. If the effects of rotor-current frequency on negative-sequence reactance are appreciable, this method 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).

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

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.

10.5.2 Determining negative-sequence resistance, R_2

For the definition of *negative-sequence resistance*, see *The IEEE Standards Dictionary* [B29].

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.

Negative-sequence resistance can be determined by the following methods:

— Method 1. Applied negative-sequence current

— Method 2. Single-phase line-to-line sustained short circuit

10.5.2.1 Method 1. Applied negative-sequence current

An applied sinusoidal negative-sequence current test is made in accordance with 10.5.1.3. 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.

10.5.2.2 Method 2. Single-phase line-to-line sustained short circuit

A sustained single-phase short-circuit test is made in accordance with 10.5.1.5. From this test, values of impedance, Z_2, and reactance, X_2, are obtained (see 10.5.1.5). 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 Determining zero-sequence reactance, X_0

For the definition of *zero-sequence reactance*, see *The IEEE Standards Dictionary* [B29]. The zero-sequence reactance has significance only for a wye-connected machine with accessible neutral.

10.6.1.1 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.

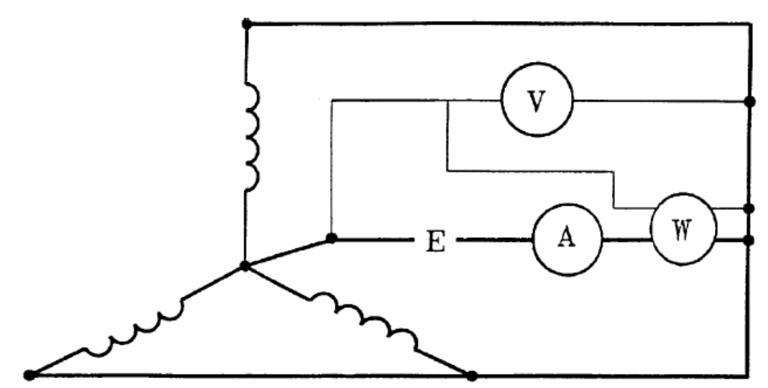
Zero-sequence reactance can be determined by the following methods:

— Method 1. Parallel circuit
— Method 2. Series circuit
— Method 3. Sustained short circuit

10.6.1.2 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 36).

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 36—Test setup for Z_0 measurement using 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.

10.6.1.2.1 Parameter determination using method 1

The zero-sequence impedance is obtained by Equation (10-17).

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

where

- E is the test voltage, in per unit of base *line-to-neutral* voltage
- I is the total test current, in per unit 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.

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

where

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

10.6.1.3 Method 2. Series circuit

In this method, the windings of the three phases are connected in series, as shown in Figure 37. 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 10.6.1.2). 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.

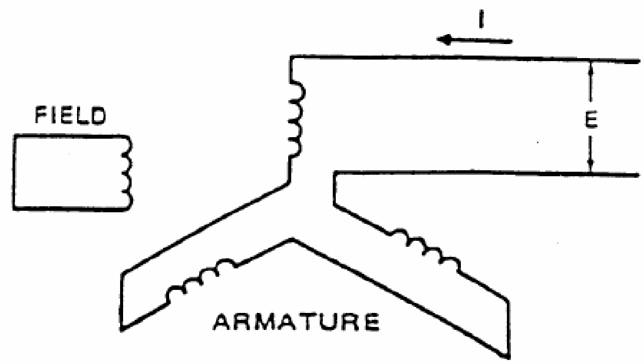


Figure 37—Diagram for determining zero-sequence reactance using method 2

10.6.1.3.1 Parameter determination using method 2

The zero-sequence impedance for the series circuit connection is obtained by Equation (10-19).

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

where

E is the voltage, in per unit of base *line-to-neutral* voltage
I is the current, in per unit 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.

10.6.1.4 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 38. 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.

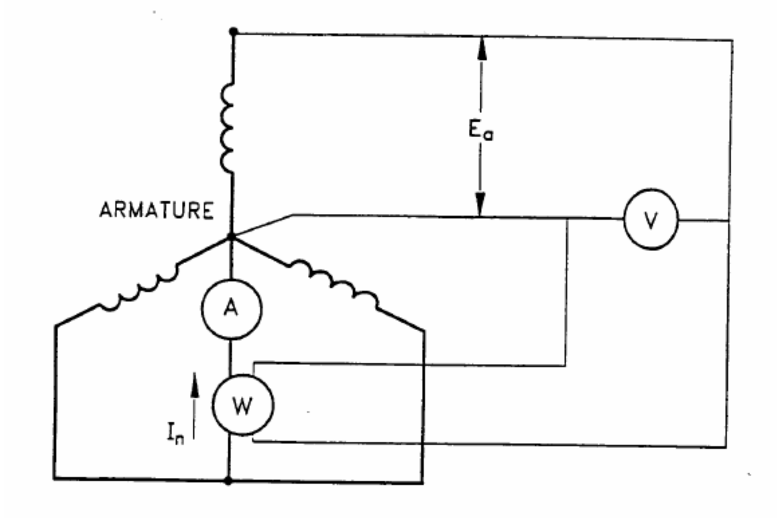


Figure 38—Diagram for determining zero-sequence reactance and resistance using method 3

10.6.1.4.1 Parameter determination using method 3

The zero-sequence impedance is obtained by Equation (10-20).

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

where

E_a is the line-to-neutral voltage of the open phase, in per unit of base *line-to-neutral* voltage
I_n is the neutral current, in per unit 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).

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

where

P_{an} is the wattmeter reading, 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.

10.6.1.4.2 Additional comments on parameter determination using method 3

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 37 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.

10.6.2 Determining zero-sequence resistance, R_0

For the definition of *zero-sequence resistance*, see *The IEEE Standards Dictionary* [B29]. 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.

Zero-sequence resistance can be measured by the following methods:

— Method 1. Parallel circuit
— Method 2. Series circuit
— Method 3. Sustained short circuit

10.6.2.1 Method 1. Parallel circuit

When making a test for zero-sequence reactance in accordance with 10.6.1.2.1, the power input, *P,* is measured by a single-phase wattmeter. The zero-sequence resistance is determined by Equation (10-22).

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

where

P is the test power input, in per unit of base *single-phase* power, S_N
I is the total test current, in per unit of base line current

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

10.6.2.2 Method 2. Series circuit

When making a test for zero-sequence reactance in accordance with 10.6.1.3, the power input, *P,* is measured be a single-phase wattmeter. The zero-sequence resistance is determined by Equation (10-23).

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

where

P is the test power input, in per unit of base *single-phase* power, S_N
I is the test current, in per unit of base line current

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

10.6.2.3 Method 3. Sustained short circuit

When making a test for zero-sequence reactance in accordance with 10.6.1.4, 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 shown in Equation (10-24).

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

where

P_{an} is the wattmeter reading, in per unit of base *single-phase* power S_N (see 9.2.2)
I_n is the neutral current, in per unit 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 Clause 12 when discussing the determination of operational quantities as viewed from the machine stator terminals.

For the definition of *positive-sequence resistance*, see *The IEEE Standards Dictionary* [B29].

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).

The stray-load loss, W_{LO}, 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).

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

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

where

R_a is the armature resistance per phase corrected to specified temperature, in ohms
W_{LO} is the stray-load loss at base line current, in kilowatts
I_N is the base line current, in amperes (see 9.2.3)
Z_N is the base armature impedance, in ohms (see 9.2.4)

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)

10.8.1.1 General

The test procedures required for determining the SCR are similar to the procedures described in 10.3 for calculating the direct-axis synchronous reactance. These procedures are detailed in 4.2.4 and 4.2.7.

Although the SCR is not used in stability calculations (as is the direct-axis synchronous reactance, X_{du} or X_{ds}), 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 (SCR)*, see *The IEEE Standards Dictionary* [B29].

10.8.1.2 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 SCR, in accordance with Equation (10-27). (See Figure 17 in 5.2.2.1.)

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

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, *δ*

10.8.2.1 General

The definition of internal load angle, δ, is the angular displacement, at a specified load, of the resultant magnetic field (due to the vector sum of the rotor field winding mmf and the armature reaction mmf along with saturation effects) from that of the no-load magnetic field. This general definition is rigorous and also accounts for the no-load magnetic axis being different from the geometric axis specifically for some generators that have the trailing edge field slots moved closer to the direct axis to reduce peak flux under load.

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

This issue is discussed in more detail in IEEE Std 1110, where different saturation effects occurring in the direct axis of the machine, compared to the quadrature axis, are covered. An examination of a phasor diagram (see Figure 39) will assist in a better grasp of the definition given at the beginning of this subclause.

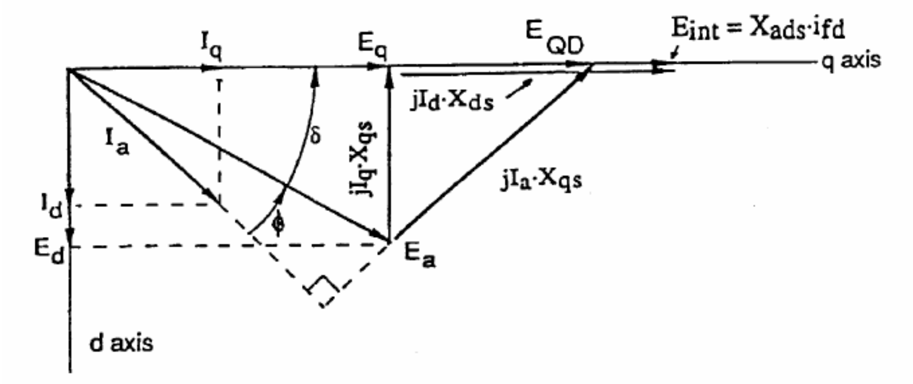


Figure 39—Phasor diagram for a synchronous machine

Figure 39 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 $X_{ads} \times i_{fd}$ (product) corresponds to the internal field excitation in the Rankin reciprocal p.u. system, and this phasor is located on the quadrature axis. If δ is known from some type of measurement (see description below), certain quotients in the form of phasor magnitudes shown in Figure 39 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 IEEE Std 1110 for more detail.)

The internal load angle can be calculated by the following additional methods:

— Method 1. Equation (10-28)

— Method 2. Optical measurement

— Method 3. Electronic measurement

10.8.2.2 Method 1. Equation (10-28)

A method of calculating δ may be approximated in accordance with Equation (10-28).

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

Referring again to Figure 39, 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.

10.8.2.3 Method 2. Optical measurement

The stroboscopic method can still be used, but has been replaced, for turbo generators especially, by the electronic processing techniques described in 10.8.2.4.

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 no-load, 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 shown in Equation (10-29).

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

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 point applies in particular to shafts of hydro generators.

10.8.2.4 Method 3. Electronic measurement

All of the preceding terminal quantities shown in the phasor diagram in Figure 39 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 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 per 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 the no-load setting as that used and obtained at the actual power angle measurement condition at some 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 tests with sudden changes to 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 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 can be devised so that relays may 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 has been of interest. Original analysis of short-circuit currents by machine designers, commencing about 75 years ago, indicated that there are basically two periods during which the rates of current decay may be easily identified. The initial and shorter period is named the *subtransient* regime. The subsequent and much longer period is called the *transient* regime. Such regimes of time can 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 $1/e$, or 0.368, of its original value.

11.3 Methodology for 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 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 E for special quadrature-axis test descriptions.

There is a theoretical justification for developing short-circuit equations, which give results matching the short-circuit test values. This justification 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

Before conducting a short-circuit test, the manufacturer of the machine under test should be consulted.

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 nonsimultaneous 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 for machines that are wye-connected or delta-connected.

11.4.4 Interpretation of test data

11.4.4.1 General

When currents and voltages are 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 per unit 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.

11.4.4.2 Allowances for distortion in test oscillographic results

If oscillograms from single-phase line-to-line, single-phase line-to-neutral, or two-phase line-to-neutral short circuits are used for evaluation of impedances, waveform distortion may render the method of 11.4.4.1 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 rapid, the accepted methods of harmonic analysis will not give accurate results, and the separation of the wave into components can be only approximated. If the measurements are calibrated by steady-state data, the wave distortion effect is eliminated.

11.4.4.3 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 11.4.4.1). If the current contains even harmonics of appreciable magnitude, the line representing the dc component is not midway between the envelopes and can be located only by waveform 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 dissymmetry are discussed in 11.12.1, which covers the general subject of computerized analyses of current decrement wave forms. It also relates to the recording procedures of 11.7.1.2.1 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 subclauses) 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 automatic voltage regulator (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 values may be obtained by continuing the recording until steady state has been reached. Because the final decay of armature current is 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 recording 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 are provided in Clause 8. Those recommendations cover both the mechanical and electrical integrity of the machine.

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 that 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 step 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 in the test is at least as great as capacity of the exciter used in normal service and if 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 the quantities measured during short-circuit tests.

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

The synchronous reactance (X_d), transient reactance (X'_d), subtransient reactance (X''_d), transient short-circuit time constant (τ'_d), and subtransient short-circuit time constant (τ''_d) are used to describe the machine's behavior on sudden short circuit. This calculation can be done in accordance with Equation (11-1) for the ac rms components of current following a three-phase short circuit from no load when neglecting armature-circuit resistances and assuming constant exciter voltage. Details on the calculation method can be found in Harrigton and Whittlesey [B22] and Kilgore [B36].

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

where

$I(t)$	is the ac rms short-circuit current, in per unit
E	is the ac rms voltage before short circuit, in per unit
t	is the time, in seconds, measured from the instant of short circuit
e	is the exponential function

NOTE—Reactances must be in per unit on the machine power 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 *The IEEE Standards Dictionary* [B29].

X''_d and τ''_d are also defined in *The IEEE Standards Dictionary*.

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 much faster than the second. By subtracting the first (constant) term and plotting the remainder on semilogarithmic 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 semilogarithmic 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 semilogarithmic plot is established as a minimum at 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 IEEE Std 1110). Special tests for open-circuit values of τ'_{do} and τ''_{do} are discussed later in this clause (see 11.10).

11.7 Tests for transient and subtransient direct-axis parameters (reactance values)

11.7.1 Parameter determination by sudden short circuit or voltage recovery

Direct-axis parameters can be determined by the following methods:

— Method 1. Envelope of ac component from sudden short circuit

— Method 2. DC component from sudden short circuit

— Method 3. Voltage recovery

11.7.1.1 Method 1. Envelope of ac component from sudden short circuit

The direct-axis *transient* reactance is determined from the current waves of a three-phase short-circuit suddenly applied to the machine operating on open circuit 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 when neglecting the rapid variation of current during the first few cycles. Figure 40 and Figure 41 illustrate this method of determining the direct-axis transient reactance.

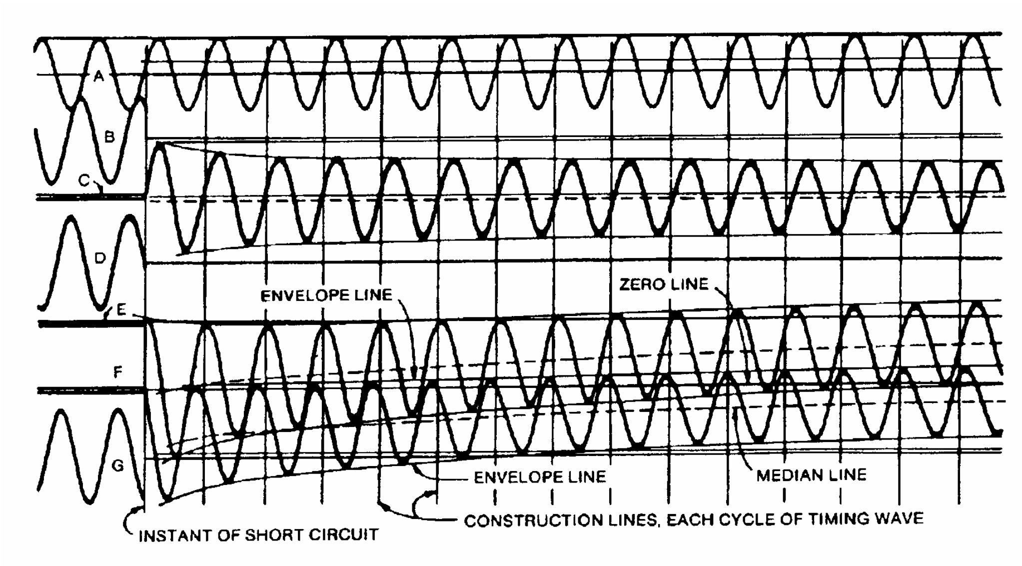


**Figure 40—Oscillogram of three-phase sudden short circuit:
1) Timing wave—Trace A;
2) Armature current—Traces C, E, and F;
3) Armature voltage—Traces B, D, and G**

For each test run, oscillograms should be taken, as described in 11.4.2 through 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 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 determining 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 this subclause are plotted as curve A (on the same sheet) to give the subtransient component of the short-circuit current as shown in Figure 41. The result is expected to be 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''.

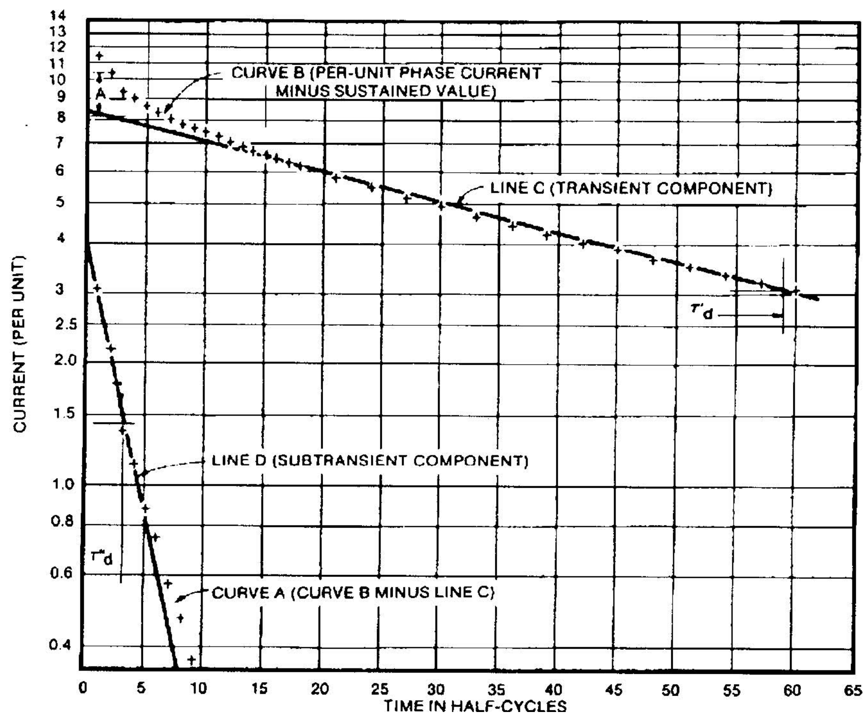


Figure 41—Analysis of ac component of short-circuit current (for one of three phrases)

11.7.1.2 Method 2. DC component from sudden short circuit

A 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 nearly the same instant, preferably within five electrical degrees. (Method 1 is preferred as it is a more direct test.) The p.u. magnitude of the dc component for each phase is determined as described in 11.4.4.3 for several values of time. The values of the dc component for each phase may now be plotted on a semilogarithmic plot similar to that used for the ac components (see Figure 44 in 11.8.4.2). The initial values of the dc component for the three phases are obtained by extrapolating the plotted curves of current back to zero time.

11.7.1.2.1 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 11.7.1.2.2).

The envelopes of the current waves are drawn as shown in Figure 40. 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 11.4.4.1 and 11.4.4.2. 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 semilogarithmic paper, with current on the logarithmic scale, as a function of time. These curves will be similar to curve B in Figure 41. The current should decrease rapidly during the first few cycles and 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 clauses 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 generalization applies especially to the calculation of transient reactances and time constants.

11.7.1.2.2 Description of method 2 for determining 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 situation 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 and may result in a significantly different field current after steady state is reached from the field current that 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 that decays according to the transient time constant is larger than for method 1 (see 11.8.2).

Figure 42 shows the connections that 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.

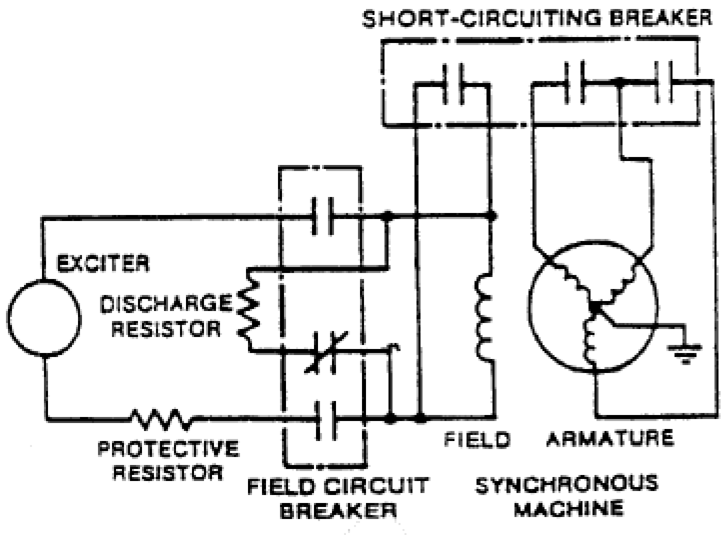


Figure 42—Diagram for sudden short-circuit test for direct-axis transient reactance using method 2

11.7.1.3 Method 3. Voltage recovery

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 using instruments. The differential voltage, E_{Δ}, 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 semilogarithmic plot of the differential voltage is made versus time with the differential voltage on the logarithmic axis (see curve B of Figure 43). 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 while neglecting the first few cycles of rapid change (see line C of Figure 43). The time-zero value of this transient differential voltage is denoted by $E'_{\Delta 0}$, as shown in the figure.

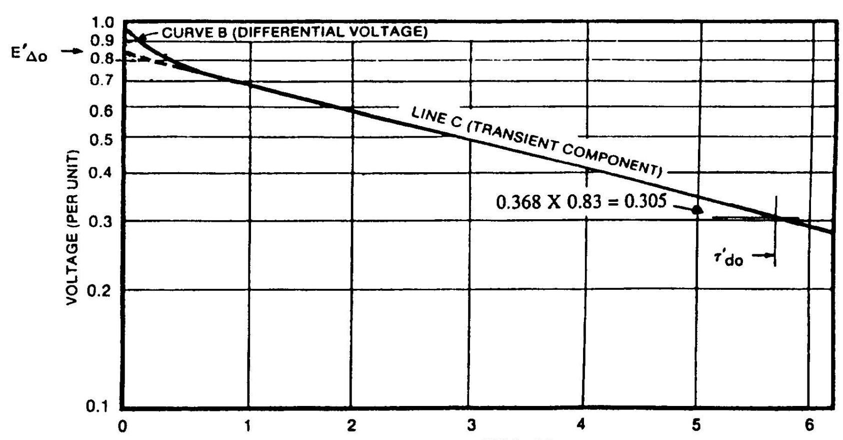


Figure 43—Voltage recovery test for transient reactance and time constant

11.8 Determination of transient and subtransient reactance values based on method 1, method 2, and method 3 in 11.7

11.8.1 Method 1. Three-phase sudden short circuit

The reader should refer back to the end of 11.7.1.2.1. 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 3).

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

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 11.7.1.2.1 (see Figure 41 and Table 3)

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 an 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 a quantity necessary to provide the required information.

Table 3—Example of determining 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 per unit.

11.8.2 Method 2. Combined short circuit of armature and field

Equation (11-1) would be considered to apply to the current in this test if two of the terms of the formula (E/X_{ds}) are eliminated. This follows because there is zero steady-state armature current. Therefore, the portion of the current that 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 semilogarithmic plot of Figure 41, 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 Method 3. Voltage recovery

The direct-axis transient reactance, X'_d, is obtained as shown in Equation (11-3).

$$X'_d = \frac{E_\infty - E'_{\Delta 0}}{I} \text{ p.u., reactance} \tag{11-3}$$

where

- $E'_{\Delta 0}$ is the initial transient component of differential voltage, in per unit
- E_∞ is the steady-state voltage, in per unit
- I is the armature current before opening the circuit, in per unit

Refer again to Figure 43.

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.

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

$$E_{\infty c} = E_\infty \frac{n_R}{n_\infty} \tag{11-5}$$

The steps in this correction process are as follows:

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 43 is then drawn and projected back to zero time to obtain a speed-corrected value of $E'_{\Delta 0}$, now called $E'_{\Delta 0C}$. This plot is semilogarithmic.

Then X'_d corrected for speed changes is shown in Equation (11-6).

$$X'_d = \frac{E_{\infty c} - E'_{\Delta 0}}{I} \text{ p.u., reactance} \tag{11-6}$$

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 per unit

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 Determining subtransient reactance parameter

11.8.4.1 Method 1. Envelope of ac component from sudden short circuit

Referring to 11.7.1, the values of I'' determined in that way are generally more accurate than the values 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 shown in Equation (11-7) (see Table 3).

$$X''_d = \frac{E}{I''} \ \text{p.u.} \tag{11-7}$$

where

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

I'' is the p.u. initial ac component of short-circuit current, as determined in 11.7.1.1 (see Figure 41 and Table 3)

11.8.4.2 Method 2. DC component from sudden short circuit

Referring to 11.7.1.2, the *absolute* values of the initial dc components, in per unit, are designated (a), (b), and (c), where (a) is the largest value and (b) and (c) are smaller. Table 3 gives an example, and Figure 44 should be examined.

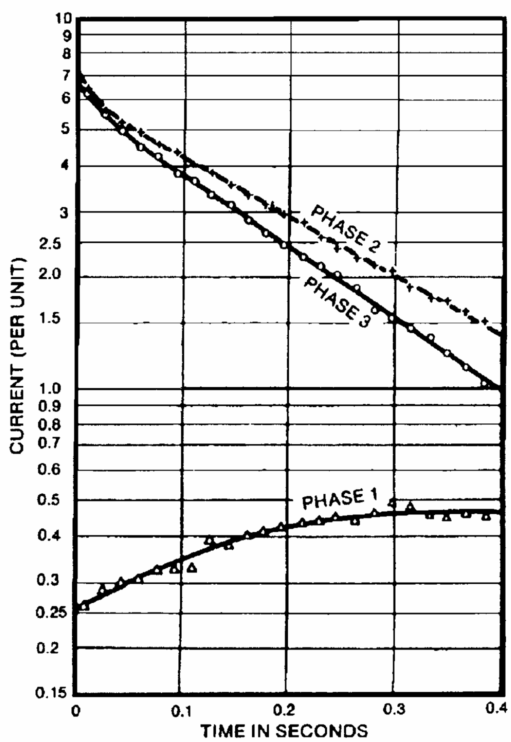


Figure 44—DC components of phase currents

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 Equation (11-8), Equation (11-9), and Equation (11-10).

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

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

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

If the three values of I'' differ, a weighted average should be used while 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 value determined by Equation (11-11).

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

I'', the weighted average, is substituted in Equation (11-12).

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

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

11.9 Tests for direct-axis transient and subtransient short-circuit time constants

11.9.1 Determining direct-axis transient short-circuit time constant, τ'_d

11.9.1.1 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 41, line C) to decrease to $1/e$, or 0.368, times its initial value. The determination of direct-axis transient short-circuit time constant is shown in Figure 41.

A rated-current value of this 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. A rated-voltage value 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 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.

11.9.1.2 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_f. The direct-axis transient short-circuit time constant can be corrected to specified temperature by using Equation (11-13).

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

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, in degrees Celsius
t_s	is the specified temperature, in degrees Celsius
k	is the factor defined in 6.4.4, which depends on current conducting material (copper, aluminum, etc.)

11.9.2 Determining direct-axis subtransient short-circuit time constant, τ''_d

11.9.2.1 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 (see method 1 in 11.8.4.1). It is the time, in seconds, required for the subtransient alternating component of the short-circuit current (see Figure 41, line D) to decrease to 1/*e*, or 0.368, times its initial value.

The determination of this time constant is shown in Figure 41.

The rated-current value of the direct-axis subtransient 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 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 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 Tests for direct-axis transient and subtransient open-circuit time constants

11.10.1 Determining direct-axis transient open-circuit time constant, τ'_{do}

For the definition of *direct-axis transient open-circuit time constant,* see *The IEEE Standards Dictionary* [B29]. Direct-axis transient open-circuit time constant can be determined by the following methods:

- Method 1. Field short circuit (see 11.10.1.1)
- Method 2. Discharge resistor connection (see 11.10.1.2)
- Method 3. Field current (see 11.10.4)
- Method 4. Voltage recovery (see 11.10.5)

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 45. 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. The 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.

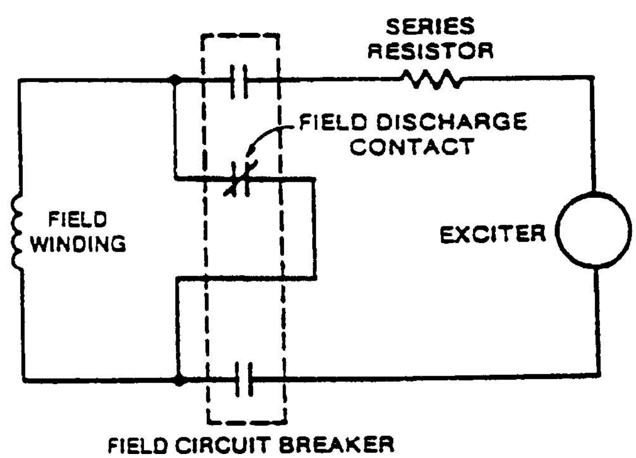


Figure 45—Field-winding circuit for direct-axis transient open-circuit time constant using method 1

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 46 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 that 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.

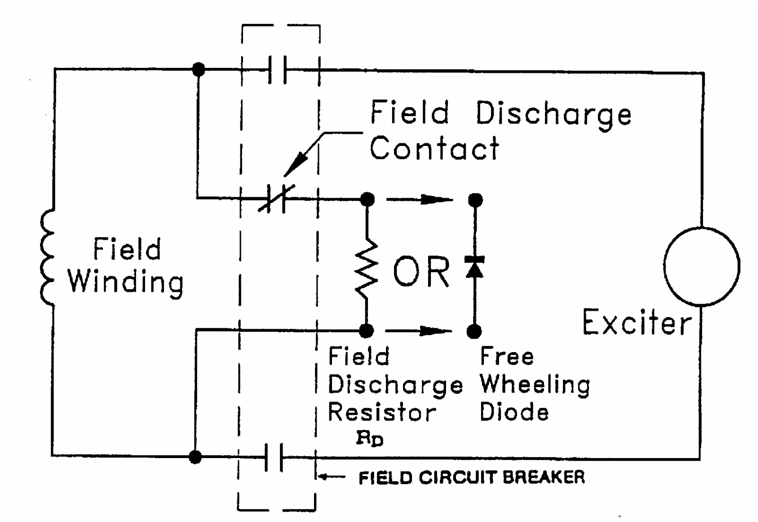


Figure 46—Field-winding circuit for direct-axis transient open-circuit time constant using method 2

Substitution of a suitable semiconductor diode in place of the discharge resistor may be made. In this case, R_D may be 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.

11.10.2 Parameter determination using method 1

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 47. Normally, the curve is approximately a straight line if the few initial points of rapid decay are neglected. Extrapolation of the curve, while 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 $1/e$, or 0.368, times the effective initial voltage is the transient open-circuit time constant, τ'_{d0}.

The time constant, τ'_{d0}, can be corrected to a specified temperature, t_s, using Equation (11-14).

$$\tau'_{d0} = \tau'_{d0t}\left(\frac{k+t_t}{k+t_s}\right)\text{ s} \tag{11-14}$$

where

τ'_{d0t} is the direct-axis transient open-circuit time constant from tests, in seconds
t_t is the field winding temperature during test (obtained according to 6.4.4), in degrees Celsuis
t_s is the specified temperature, in degrees Celsius
k is the factor defined in 6.4.4 (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).

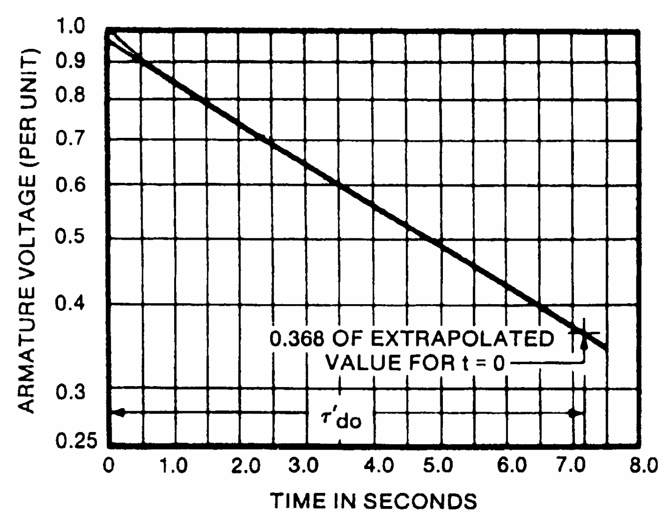


Figure 47—Determination of direct-axis transient open-circuit time constant

11.10.3 Parameter determination using method 2

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 $1/e$, or 0.368, of its effective initial value while 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.

Next the modified time constant should 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).

The apparent direct-axis transient open-circuit time constant, corrected to the specified temperature, is calculated using Equation (11-15).

$$\tau'_{d0A} = \tau'_{d0R}\left(\frac{R_{fd} + R_D}{R_{fds}}\right) \text{ s} \tag{11-15}$$

where

τ'_{d0A} is the apparent direct-axis transient open-circuit time constant (which has been corrected to eliminate the resistive effect of the discharge resistor), in seconds
τ'_{d0R} is the modified time constant obtained from semilogarithmic plot (which includes resistive effect of the discharge resistor), in seconds
R_{fd} is the measured field resistance, in ohms
R_{fds} is the field resistance at a specified temperature, in ohms
R_D is the median resistance of discharge resistor during the period of analysis, in ohms

11.10.3.1 Corrections to allow for discharge resistor using method 2

The discharge resistor in Figure 46 may have an effect that cannot be completely accounted for by the method of 11.10.3. This situation 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 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 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 method 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 method 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 method 2), and one of the latter methods should be used as the test result.

11.10.5 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 $1/e$, 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 Equation (11-14)].

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

For the definition of *direct-axis subtransient open-circuit time constant*, see *The IEEE Standards Dictionary* [B29].

The direct-axis subtransient open-circuit time constant is determined from the voltage-recovery test data used to determine the direct-axis transient reactance (see method 3 in 11.7.1.3). The subtransient voltage (curve A of Figure 48) 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 43 to obtain a better time scale. A semilogarithmic plot of the subtransient voltage versus time is made, with the voltage on the logarithmic axis.

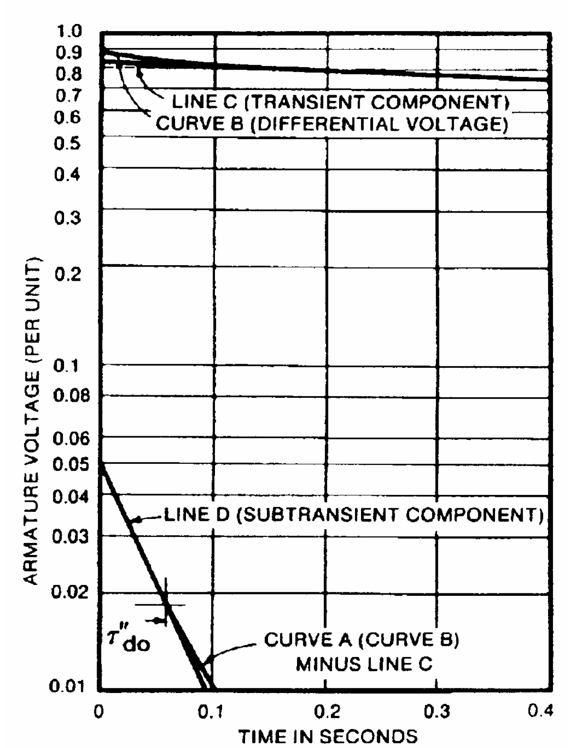


Figure 48—Voltage recovery test for direct-axis subtransient open-circuit time constant

A straight line (line D of Figure 48) is fitted to this plot, and preference is given 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/*e*, or 0.368, times the ordinate of the line at the instant of opening the circuit.

11.11 Determining short-circuit armature time constant, τ_a

11.11.1 General

For the definition of *short-circuit time constant of the armature winding*, see *The IEEE Standards Dictionary* [B29].

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

— Method 1. Resolved dc component

— Method 2. DC components of phase currents

— Method 3. Field current response

11.11.2 Method 1. Resolved dc component

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 per unit, is calculated for each value of time using Equation (11-16) (see Harrigton and Whittlesey [B22] and Kamwa et al. [B33]).

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

where

- a is the largest value of dc component of the three phase currents at the selected time, in per unit (see 11.4.4.3)
- b is the second largest value of dc component, in per unit
- c is the smallest value of dc component, in per unit

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/*e*, or 0.368, times its initial value.

11.11.3 Method 2. DC components of phase currents

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/*e*, 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 44). Method 1 is preferred because it makes better use of the data.

11.11.4 Method 3. Field current response

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/*e*, 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 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 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 Equation (11-17).

$$\tau_a = \tau_{at}\left(\frac{k+t_t}{k+t_s}\right)\ \mathrm{s} \tag{11-17}$$

where

τ_{at} is the short-circuit armature time constant at test temperature, in seconds
t_t is the temperature of armature winding by detector before the test, in degrees Celsius
t_s is the specified temperature, in degrees Celsius
k is as defined in 6.4.4 for field winding material

11.12 Computerized implementation of the general procedures noted in 11.7 through 11.11

11.12.1 General

This automated procedure is based primarily on IEEE papers listed as examples in Annex A (see Harrigton and Whittlesey [B22], Marxsen and Morsztyn [B38], and Kamwa et al. [B33]). The transient and subtransient reactances discussed in previous subclauses are based essentially on much-used graphical methods. The same applies to transient and subtransient time constants that are derived in 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 are stored digitally in kiloampere values, along with the nominal nameplate specifications of the machine V_{nom} (phase-to-phase rms in kilovolts) and I_n (rms phase current in kiloamperes). These values 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 short-circuit armature time constant. However, this new equation excludes any subtransient saliency and ignores any possible second-harmonic terms in the current waveforms.

11.12.2 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_{up}, I_{app}) and (T_{low}, I_{low}) are determined for the total window length of N_f cycles. Time and current are in seconds and kiloamperes, respectively.

11.12.3 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: polynomial fitting and spline interpolation.

11.12.3.1 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 shown in Equation (11-18) and Equation (11-19).

$$P_{upp}(t) = A_{upp0} + A_{upp1}t + \cdots + A_{upp10}t^{10} \tag{11-18}$$

$$P_{low}(t) = A_{low0} + A_{low1}t + \cdots + A_{low10}t^{10} \tag{11-19}$$

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 $P_{total}(t) = P_{upp}(t) + P_{low}(t)$, which yields Equation (11-20).

$$\begin{aligned} P_{total}(T_{upp}) = {} & (A_{upp0} + A_{low0}) + (A_{upp1} + A_{low1})T_{upp} + \\ & \cdots + (A_{upp10} + A_{low10})T_{upp}^{10} \end{aligned} \tag{11-20}$$

The dc (P_{dc}) and symmetrical (P_{sym_ac}) components at a given time, t, are expressed as shown in Equation (11-21) and Equation (11-22), respectively.

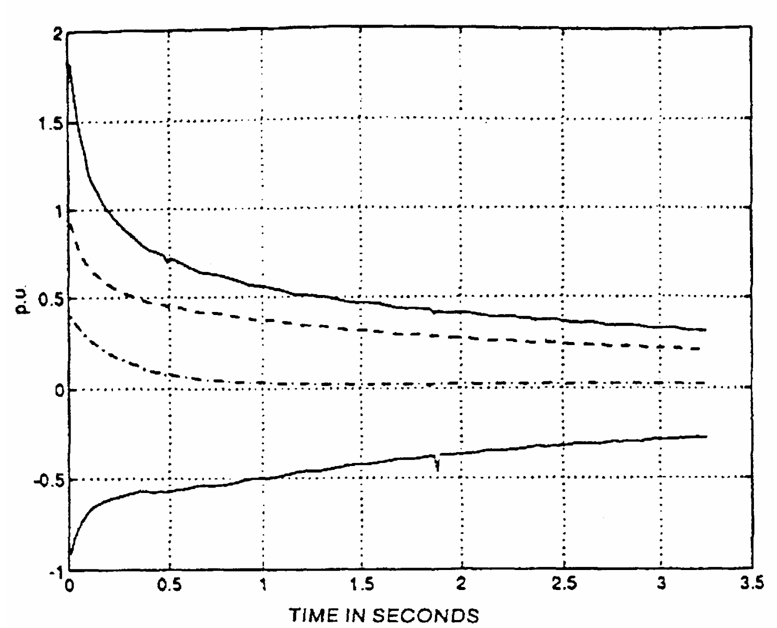
$$P_{dc}(t) = (P_{upp}(t) + P_{low}(t))/2 \tag{11-21}$$

$$P_{sym\_ac}(t) = (P_{upp}(t) - P_{low}(t))/2 \tag{11-22}$$

11.12.3.2 Application of spline interpolation

Spline functions yield smooth interpolating curves that are less likely to exhibit the large oscillations characteristic of high-degree polynomials (see de Boor [B14]). Briefly speaking, a cubic spline consists of cubic polynomials pieced together so that their values and the values 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 49.



—— Upper and lower envelopes
------ Symmetrical component
— · — DC component

Figure 49—Component data for automatic analysis

11.12.4 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 Equation (11-23).

$$i(t) = \frac{[I_{upp}(t) - I_{low}(t)]}{2\sqrt{2}I_n} - \frac{I_{ss}}{I_n} \text{ p.u.} \tag{11-23}$$

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 shown in Equation (11-24).

$$i_{dc}(t) = \frac{[I_{upp}(t) + I_{low}(t)]}{2\sqrt{2}I_n} \text{ p.u.} \tag{11-24}$$

The factor $\sqrt{2}$ converts the peak amplitude into rms value. Symmetrical and dc components obtained from spline interpolation of Equation (11-18) and Equation (11-19) are illustrated in Figure 49.

11.12.5 Transient straight-line representation

In addition to the hypotheses used in the second paragraph of 11.12.1, assume that after about 10 to 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, e.g., 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 these data using standard polynomial-regression procedures as shown in Equation (11-25).

$$\ln \Delta i'(t) = \ln\ i(t) = A't + B' \tag{11-25}$$

for t in the range beyond 20 cycles.

Note that *ln* is a natural logarithm to the base e, where e = 2.71828. Applying this model to the data in Figure 49, between 10 cycles and about 160 cycles, the following parameters are obtained:

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 50(a).

The actual transient parameters can be determined using Equation (11-26), Equation (11-27), and Equation (11-28) (see Kamwa et al. [B33]).

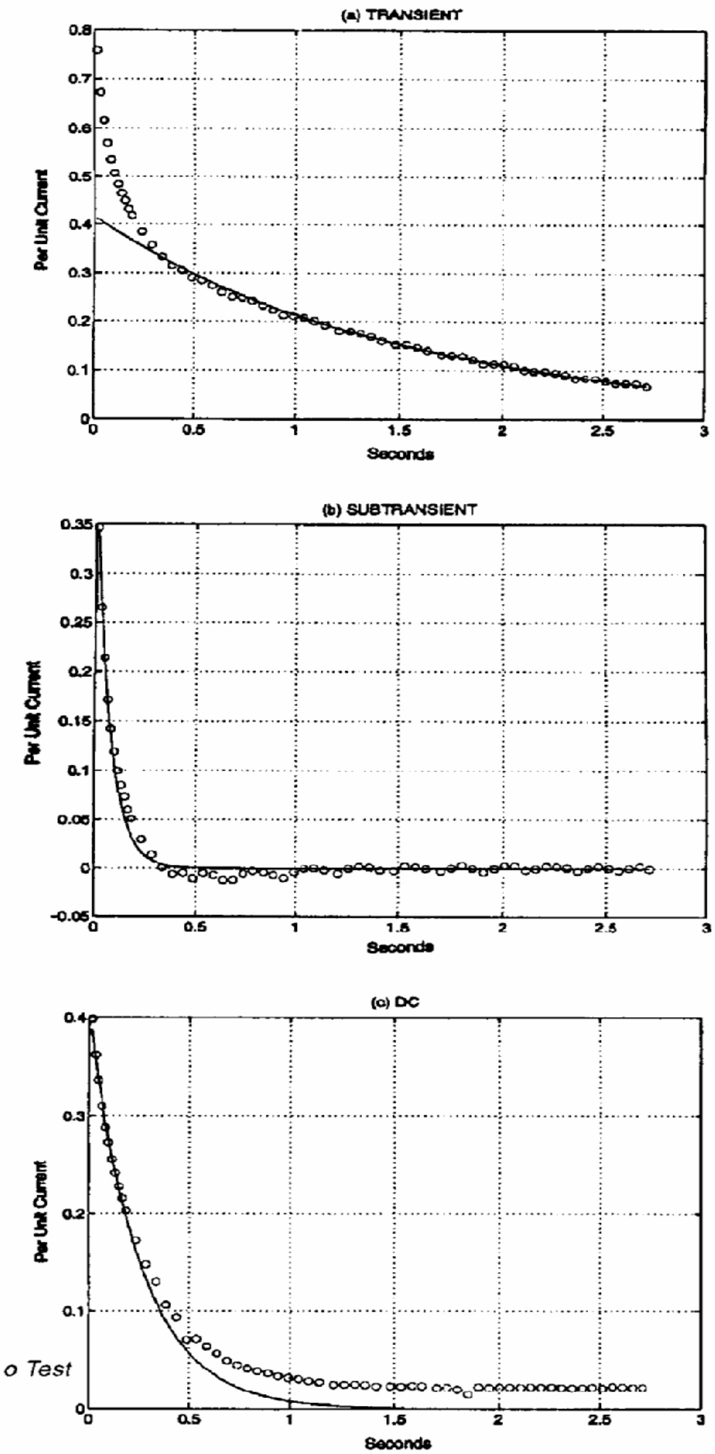
$$\tau'_d = -\frac{1}{A'} \quad \text{s} \tag{11-26}$$

$$\Delta i'(0) = e^{B'} \ \text{p.u.} \tag{11-27}$$

$$X'_d(t) = \frac{V_0/V_n}{\left[\Delta i'(0) + I_{ss}/I_n\right]} \ \text{p.u.} \tag{11-28}$$

where

V_0 is the terminal phase-voltage prior to the short-circuit, in rms kilovolts



a) Transient data:
$\Delta i'(t)$

b) Subtransient data:
$\Delta i''(t)$

c) Direct current data:
abs[$i_{dc}(t)$].____*Model. o Test*

Figure 50—Decoupled time-scales analysis

11.12.6 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 shown in Equation (11-29).

$$\Delta i''(t) = i(t) - \Delta i'(t) = i(t) - e^{(A't+B')} \tag{11-29}$$

Assuming that the subtransient effects predominate over the armature dc offset effects for the first few (e.g., 3 to 4) cycles, a single time-constant model can be fitted to $\Delta i''(t)$ as shown in Equation (11-30).

$$\ln \Delta i''(t) = A''t + B'' \tag{11-30}$$

for t in the range from zero to 3 to 4 cycles. For example, in the envelope data in Figure 49, 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 50(b).

The actual subtransient parameters are then derived, in per unit and seconds, using Equation (11-31), Equation (11-32), and Equation (11-33).

$$\tau''_d = -\frac{1}{A''} \quad \text{s} \tag{11-31}$$

$$\Delta i''(0) = e^{B''} \quad \text{p.u.} \tag{11-32}$$

$$X''_d(t) = \frac{V_0/V_n}{\left[\Delta i''(0) + \Delta i'(0) + I_{ss}/I_n\right]} \quad \text{p.u.} \tag{11-33}$$

11.12.7 DC component straight-line representation

Having assumed that the subtransient and transient effect dominate, respectively, in the ranges of 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 cycles and 20 cycles. It follows that a single time-constant model can be fitted to $i_{dc}(t)$, in the linear logarithmic form shown in Equation (11-34).

$$\ln abs(i_{dc}(t)) = A_{dc}t + B_{dc} \tag{11-34}$$

for t in the range 4 cycles to about 20 cycles. For the i_{dc} data in Figure 49, the statistical analysis leads to $A_{dc} = -3.9532$ and $B_{dc} = -0.8961$. From Figure 50(c), this single-exponential model compares well with the original data in the same interval. The dc parameters, in per unit and seconds, are finally computed from Equation (11-35) and Equation (11-36).

$$\tau_a = -\frac{1}{A_{dc}} \quad \text{s} \tag{11-35}$$

$$i_{dc}(0) = e^{(B_{dc})} \quad \text{p.u. A} \tag{11-36}$$

11.12.8 Averaging

Steps 11.12.2 to 11.12.7 are applied to each phase current and lead 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 Method 3. Applied voltage

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, and the third is isolated. The connections are shown in Figure 51. 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 Equation (11-37).

$$X = \frac{E}{I} \quad \text{p.u.} \tag{11-37}$$

where

- E is the applied line-to-line voltage, in per unit of base *line-to-neutral* voltage
- I is the line current, in per unit 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 (11-37). 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.

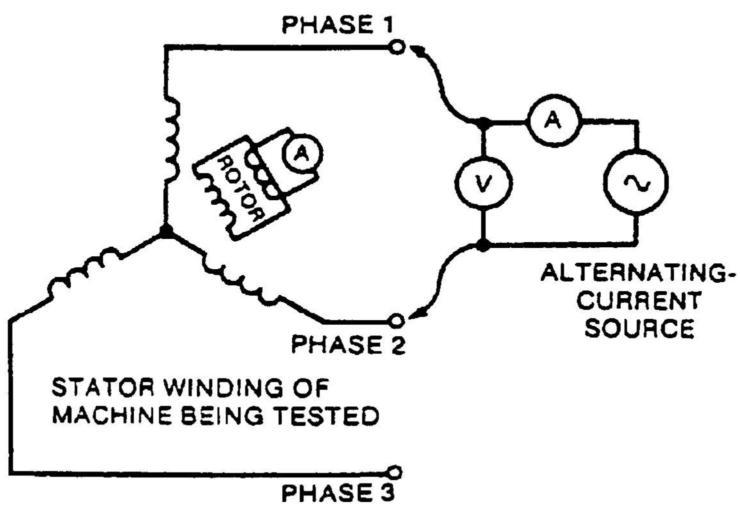


Figure 51—Diagram for determining direct-axis subtransient reactance by method 3

11.13.1.2 Parameter determination using 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 Equation (11-38).

$$K = \frac{X + Y + Z}{3} \tag{11-38}$$

The amplitude of the sinusoidal component of voltage reactance variation is given by Equation (11-39).

$$M = +\sqrt{(Y - K)^2 + \frac{(Z - X)^2}{3}} \tag{11-39}$$

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 (11-40). Usually, the direct-axis reactance corresponds to the smallest possible stationary-rotor reactance. For this case, the use of the negative sign in Equation (11-40) is suggested.

$$X''_d = \frac{K \pm M}{2} \text{ p.u.} \tag{11-40}$$

For solid-steel cylindrical-rotor machines under certain conditions, the direct-axis reactance may correspond to the maximum stationary-rotor reactance. In such cases, 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 (11-40).

NOTE—This situation 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 Method 4. Indirect method for determining X''_d

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 nearly equal to the negative-sequence reactance, X_2, and may be taken equal to the negative-sequence reactance as determined by 10.5.1.5.

11.13.3 Rated-current and rated-voltage values—saturation effects 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' in 11.7.1.2.1) has rated value. The corresponding total ac component (see I'' in 11.7.1.1) including the subtransient component would, therefore, be somewhat greater. In method 1 and method 2 (see 11.8.4), the direct-axis subtransient reactance is determined from the same tests that are used for determining 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 method 2).

When method 3 or method 4 is used, there is no 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 method 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 IEEE Std 1110. 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.

For safety reasons, methods 3 or 4 likely cannot 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 from 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, on open circuit, and at rated speed.

11.13.4.2 Determining parameter X_2

The open-circuit voltage, E, in per unit of rated voltage, is measured before the short circuit, and the rms value of the initial ac component of armature current, I'', in per unit 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 as shown in Equation (11-36).

$$X'_{2LL} = \frac{\sqrt{3}E}{I''} - X''_d \quad \text{p.u.} \tag{11-36}$$

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 10.5.1.5.3.

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 Determining quadrature-axis subtransient reactance, X''_q

11.13.5.1 General

For the definition of *quadrature-axis subtransient reactance*, see *The IEEE Standards Dictionary* [B29].

Quadrature-axis subtransient reactance can be determined by the following methods:

— Method 1. Applied voltage
— Method 2. Sudden short circuit

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.

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 (see 11.13.1.1). 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.

$$X''_q = \frac{K \pm M}{2} \quad \text{p.u.} \tag{11-37}$$

where

K and M are determined from Equation (11-33) and Equation (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. In such cases, 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 determining 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 the values 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 Equation (11-38).

$$X_{LL} = \frac{\sqrt{3}E}{I''} \quad \text{p.u.} \tag{11-38}$$

The quadrature-axis subtransient reactance is obtained using Equation (11-39).

$$X''_q = \frac{(X_{LL} - X''_{d3})^2}{X''_{d3}} \quad \text{p.u.} \tag{11-39}$$

11.13.6 Determining rated current or rated voltage values of X''_q—Saturation effects

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 method can be considered only as an approximation to the rated voltage value, but a more precise method has not been investigated.

12. Standstill frequency response (SSFR) testing

12.1 General considerations and basic theory

12.1.1 Purpose of this form of testing

In Clause 8 and in the introduction to Clause 11, the reasons for short-circuit tests are 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 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 reactances, transient and subtransient, and their corresponding short-circuit time constants have historically been determined from the short-circuit testing procedures described in Clause 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 E. It is widely accepted that present-day stability studies require both direct-axis and quadrature-axis synchronous machine characteristics for adequate simulation of power system dynamic responses.

An alternative exists to the above tests covered in Clause 11, and these alternate procedures are called *standstill frequency response (SSFR) testing*. An IEEE Committee Report [B27] 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 SSFR 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 about why SSFR testing has become an acceptable alternative to short-circuit testing is that identification of field responses is possible. This possibility is described more fully in the two-port direct-axis concept discussed further in 12.1.3.

Another specific advantage of SSFR test methods is that they can be performed, and at 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 setup and without resorting to special short-circuit and/or low-voltage tests.

However, although SSFR tests are easy to implement with present-day technology (see IEEE PES WG 12 Report [B28], Bortoni and Jardini [B6], and Aliprantis et al. [B2]), they are usually, of necessity, conducted with the machine operating under nonstandard conditions (e.g., running with the magnetization current at levels different from those specified for the rated air-gap voltage). For this reason, the analysis of SSFR test data usually yields models requiring further adjustments to correct for the overly low magnetizing currents that tend to occur during test. Canay [B10] relied on the ac component of the field-current during a sudden short-circuit test to enhance the capability of the standstill-based transfer functions to predict dynamic phenomena, such as out-of-step operation subsequent to a close-up fault. Based again on short-circuit results, some unexpected and innovative ways of improving synchronous machine models by including operational effects and leakage saturation have been reported in Auckland et al. [B4]. Even after the emergence of proven standstill procedures, a niche will still exist for other tests such as the short-circuit test (see Clause 11) to help describe the normal operational behavior of the machine better. In an early comparison of models derived independently from SSFR and short-circuit tests on the same 500 MW machine (see Diggle and Dineley [B17]), it was reported that the latter was superior in predicting dynamic phenomena, which suggests that adjustment of the SSFR-based model using short-circuit data could be beneficial, at least in the case of some turbine generators. The adjustment could also be carried out using on-line frequency responses or small signal responses recorded during transient disturbances (see Dandeno et al. [B13]).

The best single test to effectively complement standstill tests is the sudden short-circuit test, which still is the basis of the IEC and IEEE standards used for contract purposes at many utilities (see Kamwa et al. [B35]) where it is applied for commissioning and retrofitting all facilities of 10 MW and greater. Even in the foreseeable future, when finite-element methods have developed to such an extent that certain tests can be avoided, it seems reasonable to envisage calculations being performed in two different ways, using SSFR and short-circuit simulations, which complement each other.

12.1.3 Theoretical background

The IEEE Committee Report [B27] published in 1980 provided the basic theory for SSFR 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

$$\begin{aligned} \Delta\psi_d(s) &= G(s)\Delta e_{fd}(s) - L_d(s)\times\Delta i_d(s) \\ \Delta\psi_q(s) &= \qquad\qquad\quad - L_q(s)\times\Delta i_q(s) \end{aligned} \tag{12-1}$$

where

ψ_d and ψ_q	are direct-axis 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 52 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.

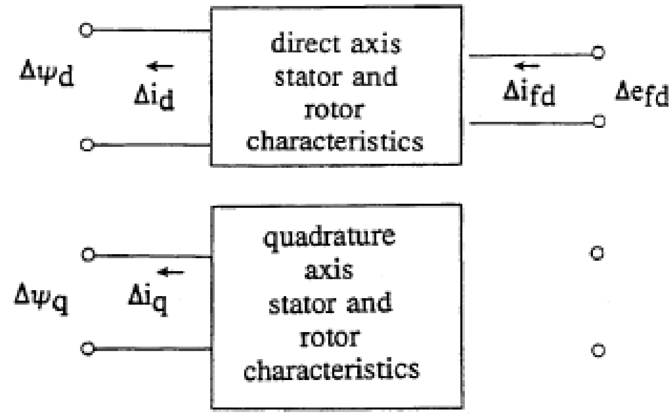


Figure 52—Two-port direct-axis and quadrature-axis representation based on Equation (12-1)

12.1.3.1 Definition of operational parameters for direct and quadrature axes

The definitions below are the principal ones that power system analysts have found convenient when describing the response of synchronous machines (see IEEE Committee Report [B27]). Note that functions of s are complex quantities, where $s = j\omega = j2\pi f$ rad/s.

- $L_d(s)$ is *direct-axis operational inductance*, which 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
- $L_q(s)$ is *quadrature-axis operational inductance*, which is the Laplace transform of the ratio of the quadrature-axis armature flux linkages to the quadrature-axis current
- $G(s)$ is *armature flux to field transfer function*, which 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 is as follows:

- $sG(s)$ is *armature current to field transfer function*, which 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 as follows:

- $Z_{afo}(s)$ 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

Canay [B9] describes how the above-noted transfer functions may be developed into specific models. Second-order models are chosen, and a closed form set of equations is listed that describes the rotor model elements of Figure 53. Although the values of L_{ad} and L_{aq} in Figure 53 can be derived from measurements described in Clause 10, they are often taken from generator design data. L_l is generally taken from design data.

Note that in Figure 53, on the direct axis, an additional inductance, L_{fld}, is shown. This inductance has been identified in recent literature as a differential leakage inductance. It was shown in Rusche et al. [B43] 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 hydro generators, the opposite is true, and L_{fld} often has a negative value.

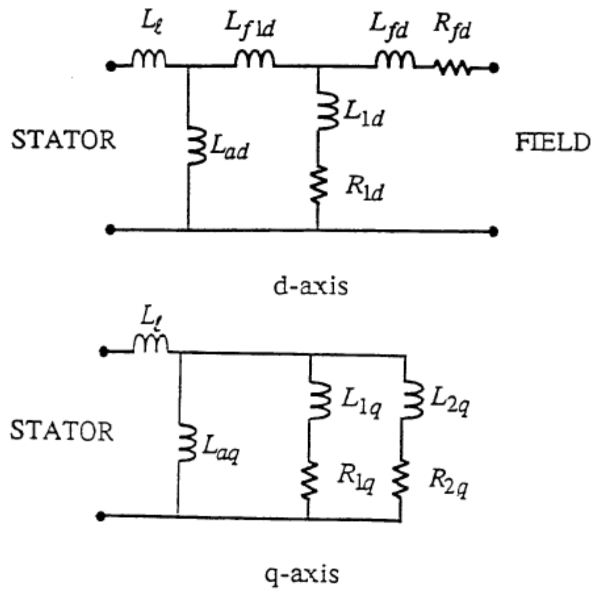


Figure 53—Complete direct-axis equivalent and quadrature-axis equivalent (second-order model)

Canay [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 only stator responses to generator transient conditions are 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 forms are discussed in IEEE Std 1110.

12.1.5 Additional comments on applying operational methods to synchronous machines

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 quadrature axis and a two-port network in the direct axis. Some implications of this equivalency are as follows:

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, no pressing need exists for matching $Z_{afo}(s)$ in the higher frequency ranges beyond 1 Hz to 10 Hz. The use of $Z_{afo}(s)$ in determining the effective stator-to-rotor-turns ratio is important and is discussed in 12.5.

c) In the quadrature axis, just one transfer function, $L_q(s)$, is sufficient to fully characterize the machine stator terminal behavior.

The SSFR test described in following subclauses 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 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 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 follow. See Canay [B10] for a detailed exposition of the above comments.

Aspects of SSFR testing that are different from short-circuit current testing procedures in Clause 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 likely that on-line or open-circuit rated speed, SSFR 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.

Rusche et al. [B43], EPRI EL-1424 [B19], Dandeno et al. [B13], and Hurley and Schwenk [B25] discuss the theory of developing SSFR models, and some of the applications of such models to turbo generator dynamic performance.

As reported in an IEEE PES WG 12 Report [B28], these techniques have been applied with a similar success to machines of salient pole construction. However, 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 direct-axis and quadrature-axis test for various pole positions (see Bortoni and Jardini [B6]).

12.2 Testing conditions for SSFR procedures and instrumentation requirements

12.2.1 Machine conditions for SSFR 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 step 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 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 step is most easily done by hand-cranking the turning gear. If this method 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 SSFR 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

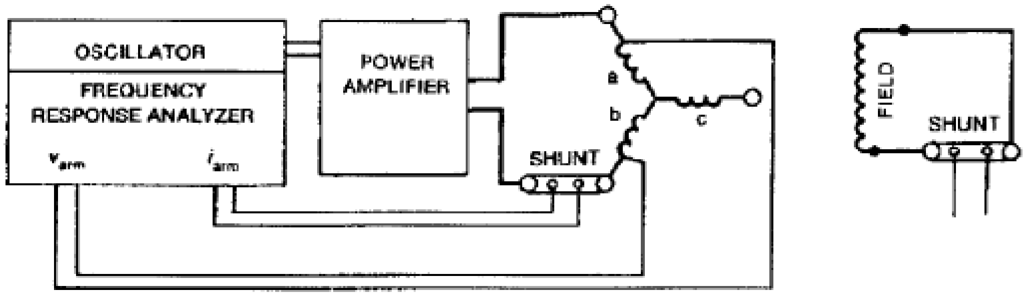
The relationship between the *measured* quantities and the *desired* variables is given in 12.2.6. An oscillator, sometimes an integral part of the above-mentioned analyzer, provides the test signal. This signal goes to a power amplifier, the output of which is connected to two terminals of the generator armature winding. The metering error of any measured transfer function should not exceed 1% at any point in the frequency range. Refer also to 12.3.1. Several variations in the testing procedures are shown in Figure 54.

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).

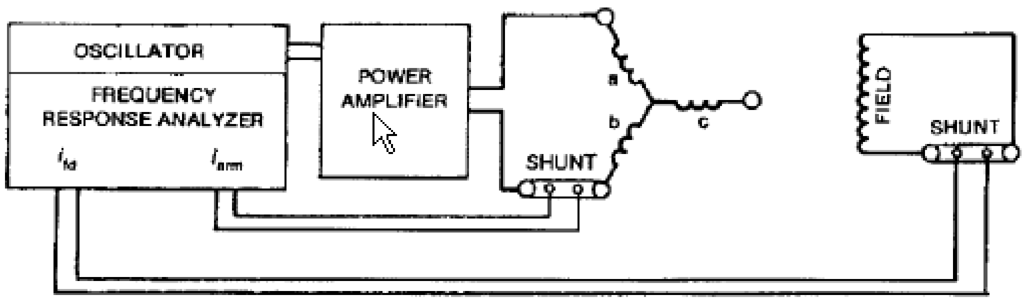
Normal precautions to avoid overloading inputs and outputs of instruments should be observed. The impedance measured at the armature terminals at very low frequencies will be approximately twice the armature phase resistance. The maximum measured impedance will be approximately $2(R_2 + j\omega L_2)$ 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.

12.2.4 Measurement accuracy

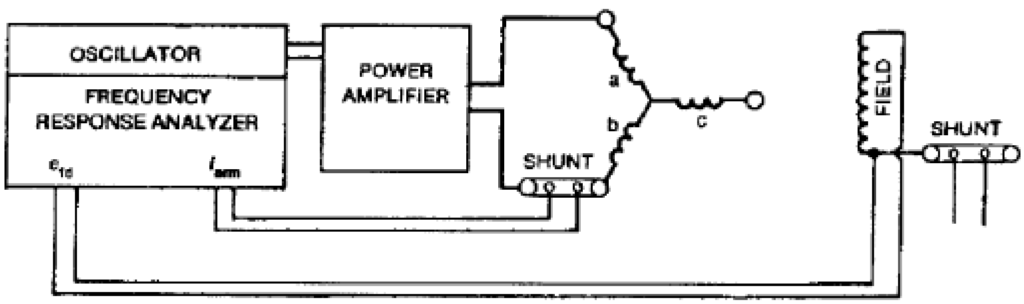
Reducing or eliminating the effect of contact resistances is important to the accuracy of the measurements, particularly on the armature winding. The current metering shunt for the armature should be bolted directly to the conductor in the isolated phase bus and as close to the generator terminals as 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 55 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 56 are appropriate.



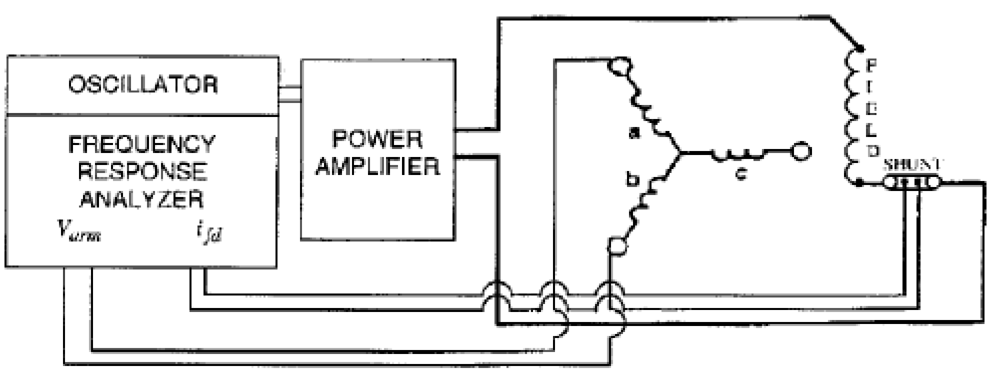
a) Measurement of $Z_d(s)$



b) Measurement of $\Delta i_{fd}/\Delta i_{arm}$



c) Measurement of $\Delta e_{fd}/\Delta i_{arm}$



d) Measurement of $\dfrac{\Delta v_{arm}}{\Delta i_{fd}}$

Figure 54—Test setup for direct-axis measurements

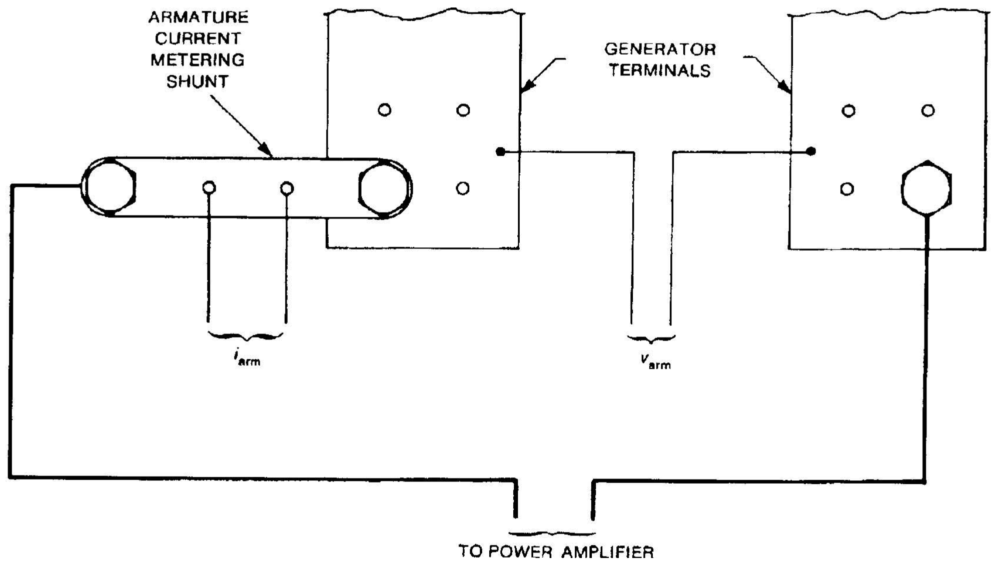


Figure 55—Connections for differential inputs

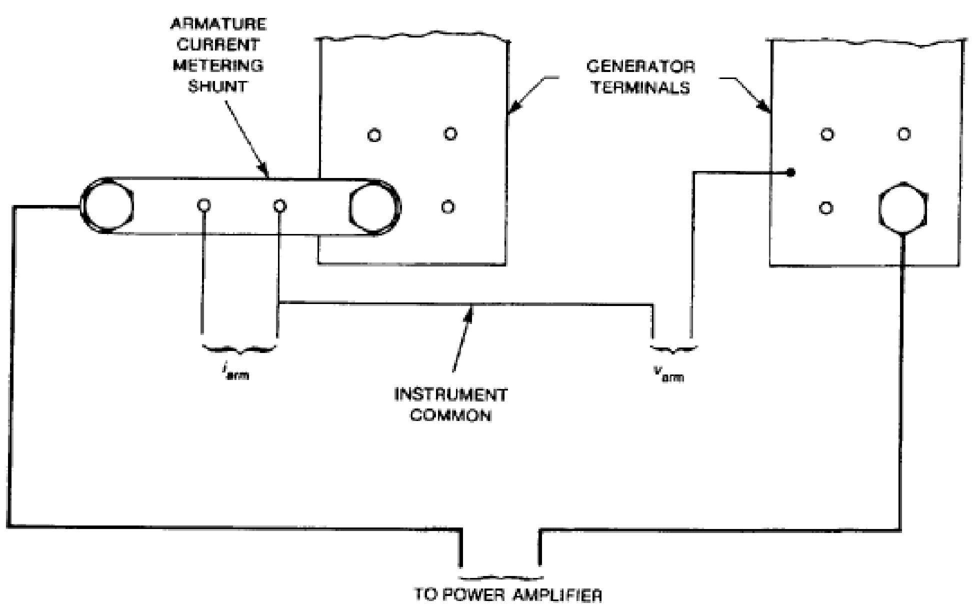


Figure 56—Connections for single-ended inputs

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

$$\sqrt{3}i_s\left({I_{fd}(base)}\big/{i_a(base)}\right)$$

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 amperes.

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.

12.2.5 Precautions and ancillary matters relating to machine safety

It shall be recognized that during SSFR 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 minimize the risk of damage to either stator or rotor components. This goal 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 five operational quantities (in 12.1.3.1) have been found useful in developing transfer functions or equivalent direct-axis or quadrature-axis models for synchronous machines. These quantities can be obtained from other measurable parameters with the machine at standstill. Early works and discussions on the concepts of rotating machine operational impedances and, by implication, operational inductances were authored by Adkins and Harley [B1] and Concordia [B11] among others.

The principal parameters noted below relate to the 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 12.5.4.1, its contribution to the total impedance is only significant at low frequencies.

   Also,

$$Z_d(s) = -\left.\frac{\Delta e_d(s)}{\Delta i_d(s)}\right|_{\Delta e_{fd}=0} \Omega \tag{12-2}$$

   $Z_d(s)$ 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 Equation (12-3) through Equation (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.

b) $Z_q(s)$. 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. See Equation (12-3).

$$Z_q(s) = -\frac{\Delta e_q(s)}{\Delta i_q(s)}\bigg|\ \Omega \tag{12-3}$$

c) A third machine quantity is given by the relation shown in Equation (12-4).

$$G(s) = \frac{\Delta e_d(s)}{s\Delta e_{fd}(s)}\bigg|_{\Delta i_d = 0} \tag{12-4}$$

An alternative method of measuring this parameter is suggested as shown in Equation (12-5).

$$sG(s) = \frac{\Delta i_{fd}(s)}{\Delta i_d(s)}\bigg|_{\Delta e_{fd} = 0} \tag{12-5}$$

The advantage of the form of measurement in Equation (12-5) is that it can be measured at the same time as $Z_d(s)$.

d) A fourth measurable synchronous machine parameter at standstill is the armature-to-field transfer impedance as shown in Equation (12-6).

$$Z_{afo}(s) = \frac{\Delta e_{fd}(s)}{\Delta i_d(s)}\bigg|_{\Delta i_{fd} = 0}\ \Omega \tag{12-6}$$

e) 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 De Mello et al. [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 the frequency corresponding to the transient open-circuit time constant of the generator as shown in Equation (12-8).

$$f_{\min} = \frac{0.016}{T'_{do}} \tag{12-8}$$

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, ten steps per decade will provide adequate resolution in the range of 0.01 Hz to 200 Hz. However, for the low-frequency response measurements in the range 0.01 Hz down to 0.001 Hz, a measurement resolution of 40 steps per decade is preferable. Nevertheless, 15 steps per decade is deemed sufficient when a heavy averaging is performed to minimize the noise at each step (see Table 4).

Table 4—Typical SSFR configuration for transfer function measurement using modern LabView-controlled spectrum analyzer

Frequency range	Number of measurement points	Integration or averaging time (in cycles of frequency under test)	Test duration
0.001 Hz to 1 Hz	45	5 cycles	10 h
1 Hz to 1000 Hz	60	10 cycles	1.5 min

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 per decade is required to achieve an accurate measurement of the effective stator resistance, R_a, at the time of the SSFR test.

The mutual inductance between the field and armature windings, L_{afd}, shall also be measured, as shown in Equation (12-9).

$$L_{afd} = \frac{3}{2}\frac{1}{s}\lim_{s\to 0}\left[Z_{afo}(s)\right] \tag{12-9}$$

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}. The expression r_{fd} is the total resistance in the field winding circuit during the measurement of $\Delta i_{fd}(s)/\Delta i_d(s)$, namely the field resistance plus metering shunt plus connecting lead and contact resistances.

12.3.2 Positioning the rotor for direct-axis tests

Positioning the rotor is accomplished by temporarily connecting the power amplifier as in Figure 57. 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 zeroed. 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.

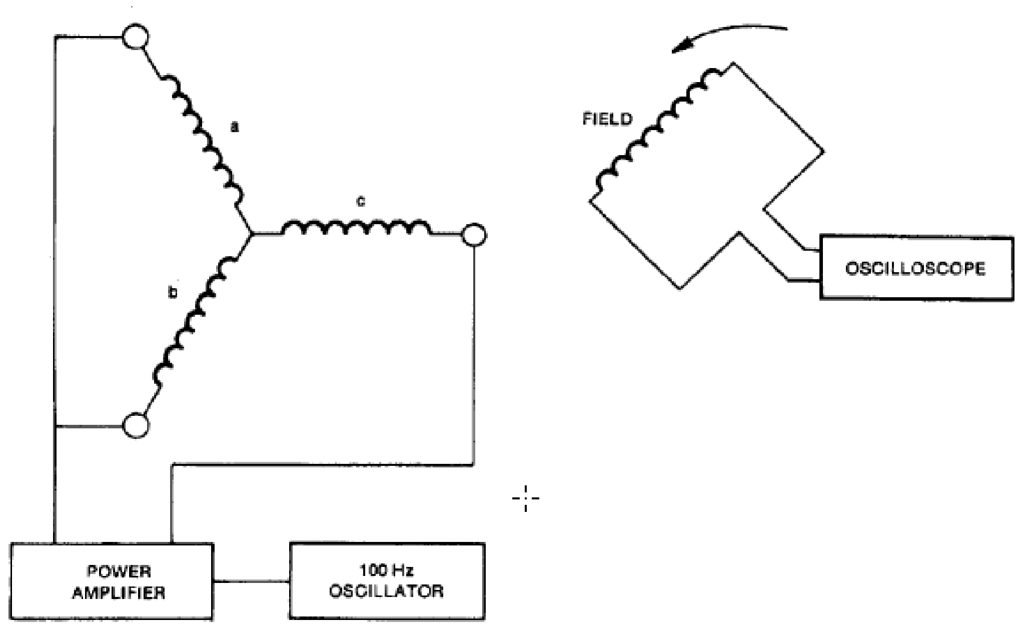


Figure 57—Positioning of rotor for direct-axis tests

12.3.3 Direct-axis tests

12.3.3.1 Measurement of $Z_d(s)$ and stator resistance, R_a

Referring to Figure 54(a), connect the power amplifier to terminals *a* and *b* of the armature winding through the metering shunt. Short the field winding through a noninductive metering shunt to make solid connections to the field winding. This step 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 in Figure 54. The following notations are used to distinguish between the mathematical quotients in Equation (12-2) through Equation (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 of 0.001 Hz to 200 Hz.

Instrument readings obtained from the test setup of Figure 54(a) permit the stator direct-axis operational impedance and stator resistance to be obtained as shown in Equation (12-10) and Equation (12-11).

$$Z_d(s) = \frac{1}{2} Z_{armd}(s) \quad \Omega \tag{12-10}$$

$$R_a = \frac{1}{2}\left\{\lim_{s \to 0}\left[Z_{armd}(s)\right]\right\} \quad \Omega \tag{12-11}$$

$Z_d(s)$ quantities are plotted in Figure 58 and Figure 59.

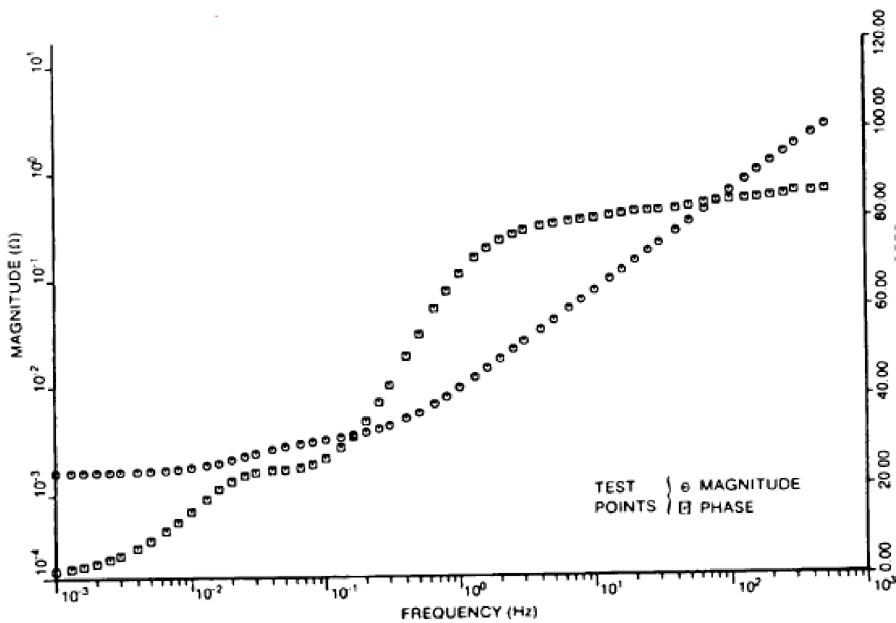


Figure 58—Direct-axis impedance (field-shorted)

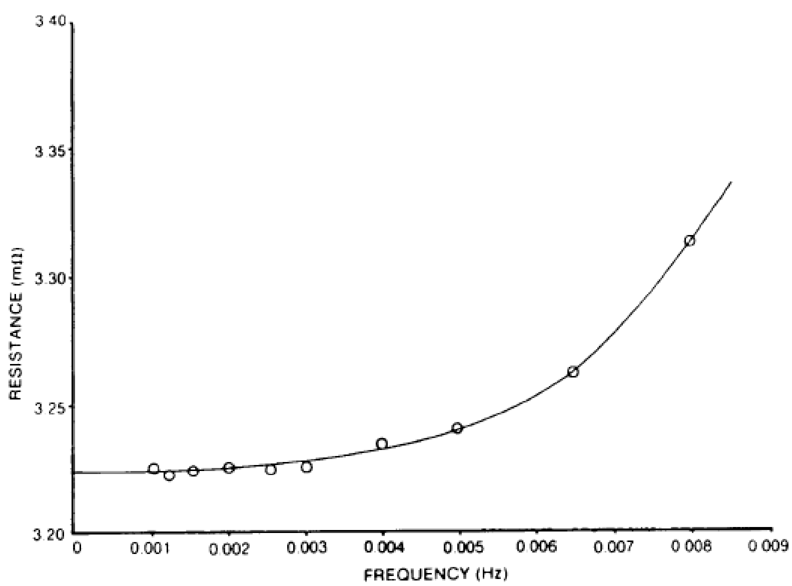


Figure 59—Resistive component of $Z_{armd}(s)$

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 level of accuracy, 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 $L_d(s)$ as shown in Equation (12-12).

$$L_d(s) = \frac{Z_d(s) - R_a}{s} \text{ H} \tag{12-12}$$

The variable s is defined in 12.1.3.1.

Interpretation and utilization of $L_d(s)$ data, which are plotted in Figure 60, are considered in 12.5.

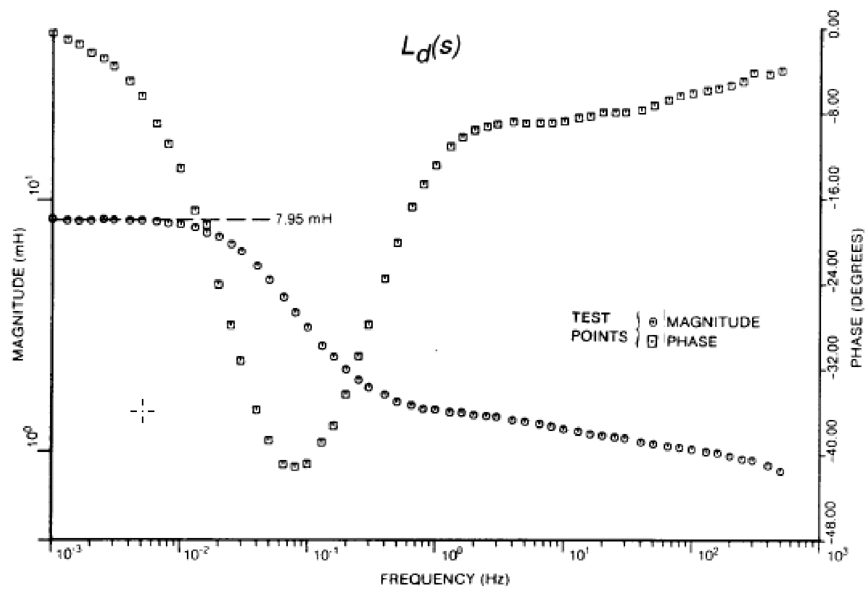


Figure 60—Direct-axis operational inductance (field-shorted)

12.3.3.2 Measurement of *sG*(*s*)

Now, connect the instrument to the i_{fd} and V_{arm} signal leads, Figure 54(b), 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, solving Equation (12-13)

$$\frac{\Delta i_{fd}(s)}{\Delta i_d(s)} = \frac{\Delta i_{fd}(s)}{\Delta i_{arm}(s)/\cos(30^o)} = \sqrt{\frac{3}{4}} \frac{\Delta i_{fd}(s)}{\Delta i_{arm}(s)} \tag{12-13}$$

will lead to a plot similar to Figure 61. The cosine 30° factor in Equation (12-13), Equation (12-14), and Equation (12-15) recognizes the physical or electrical phase displacement between the field (as aligned in 12.3.2) and either phase b or c.

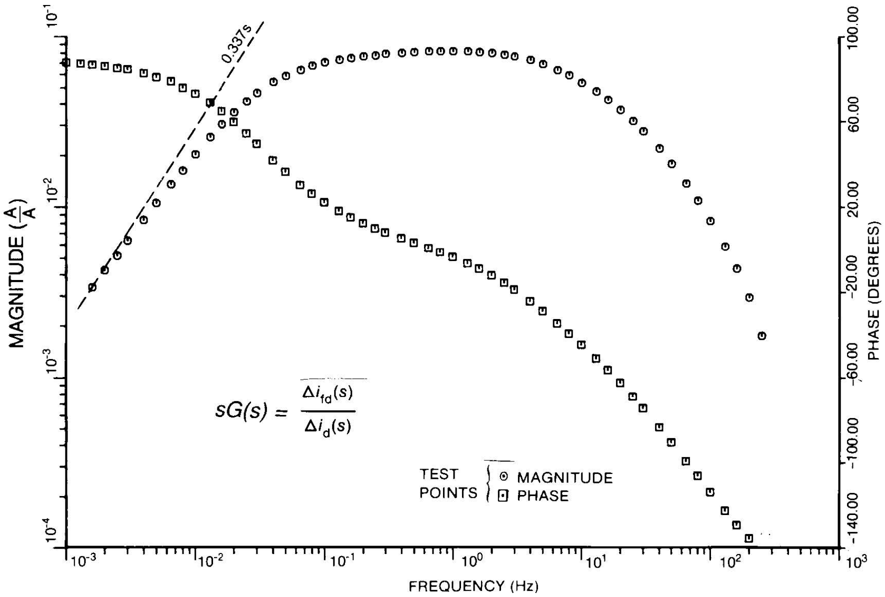


Figure 61—Standstill armature to field transfer function with field shorted = *sG*(*s*)

12.3.3.3 Measurement of $Z_{afo}(s)$

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 54(c). 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

$$Z_{afo}(s) = \frac{\Delta e_{fd}(s)}{\Delta i_d(s)} = \frac{\Delta e_{fd}(s)}{\Delta i_{arm}(s)/\cos(30^\circ)} = \sqrt{\frac{3}{4}}\frac{\Delta e_{fd}(s)}{\Delta i_{arm}(s)}\Omega \tag{12-14}$$

When plotted, these points will be similar to Figure 62. This completes those direct-axis tests that are usually performed.

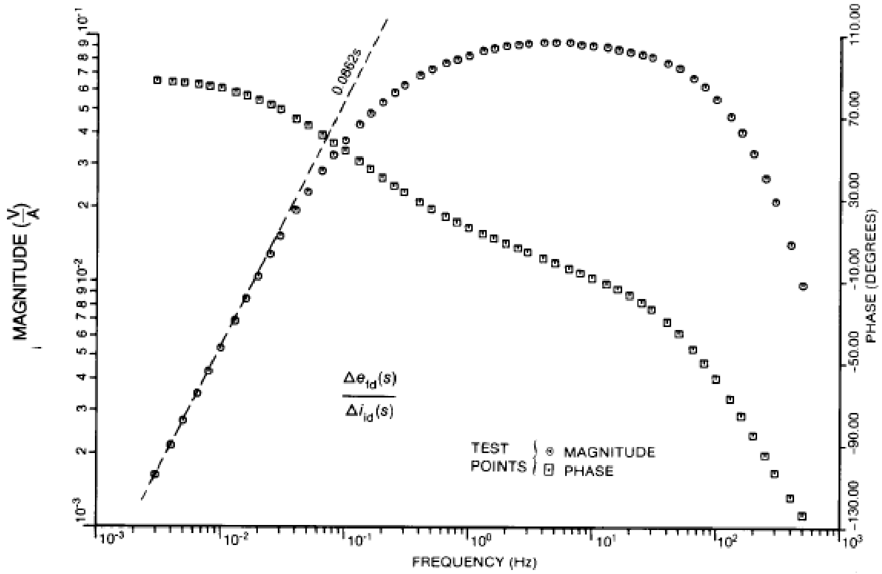


Figure 62—Standstill armature to field transfer impedance with field open = $Z_{afo}(s)$

12.3.3.4 Measurement of $Z_{fao}(s)$

This measurement of field-to-stator transfer impedance is occasionally required. For this value, the test setup of Figure 54(c) can be modified to that of Figure 54(d). The i_{arm} leads would then be connected to the field shunt. The e_{fd} leads of Figure 54(c) 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, as shown in Figure 54(d). Then $Z_{fao}(s)$ is determined as shown in Equation (12-15).

$$Z_{fao}(s) = \frac{\Delta e_d(s)}{\Delta i_{fd}(s)} = \frac{1}{2}\left\{\frac{\Delta v_{arm}(s)/\cos(30^\circ)}{\Delta i_{fd}(s)}\right\} = \sqrt{\frac{1}{3}}\,\frac{\Delta v_{arm}(s)}{\Delta i_{fd}(s)}\ \Omega \tag{12-15}$$

When the $Z_{fao}(s)$ measurement is not required, the quadrature-axis tests may now be performed by aligning the rotor with phase *a* as described in 12.3.4.

12.3.4 Positioning the rotor for quadrature-axis tests

Connect the power amplifiers across phases *a* and *b* as in Figure 54 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 54(a).

Instrument readings over the complete frequency range obtained from the new test setup of Figure 54(a) permit the stator quadrature-axis operational impedance and stator resistance to be obtained as shown in Equation (12-16) and Equation (12-17).

$$Z_q(s) = \frac{1}{2} Z_{armq}(s) \quad \Omega \tag{12-16}$$

$$R_a = \frac{1}{2}\left\{\lim_{s \to 0}\left[Z_{armq}(s)\right]\right\} \quad \Omega \tag{12-17}$$

$Z_q(s)$ quantities are plotted in Figure 63.

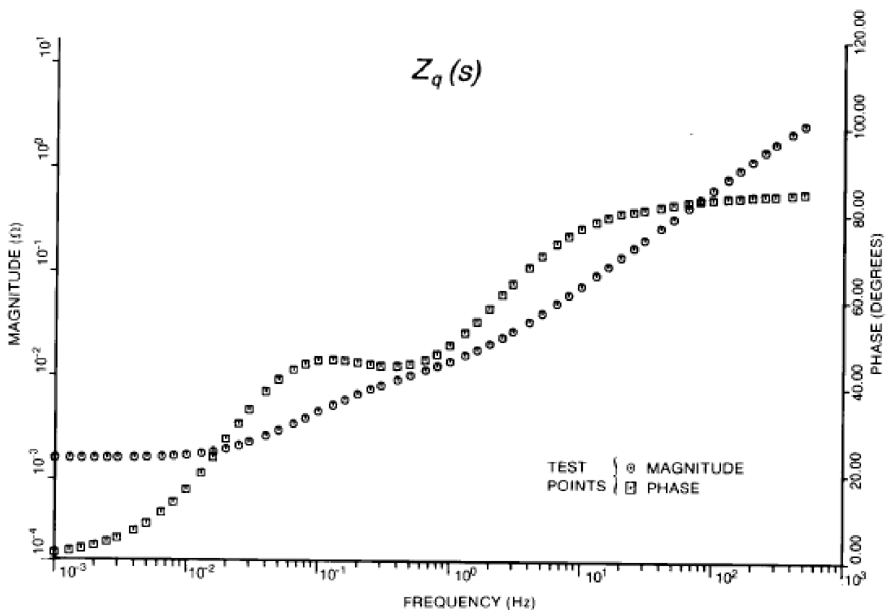


Figure 63—Quadrature-axis impedance

Note that the dc resistance of one phase of the armature winding, R_a, 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 quadrature-axis data and the techniques in 12.3.3.1 in case a change in the winding temperature has altered its value since the direct-axis tests.

$Z_q(s)$ and R_a will be used to calculate $L_q(s)$ as shown in Equation (12-18).

$$L_q(s) = \frac{Z_q(s) - R_a}{s} \ \text{H} \tag{12-18}$$

where s was defined in 12.1.3.1. Interpretation and utilization of $L_q(s)$ data, which are plotted in Figure 64, are considered in detail in 12.5.

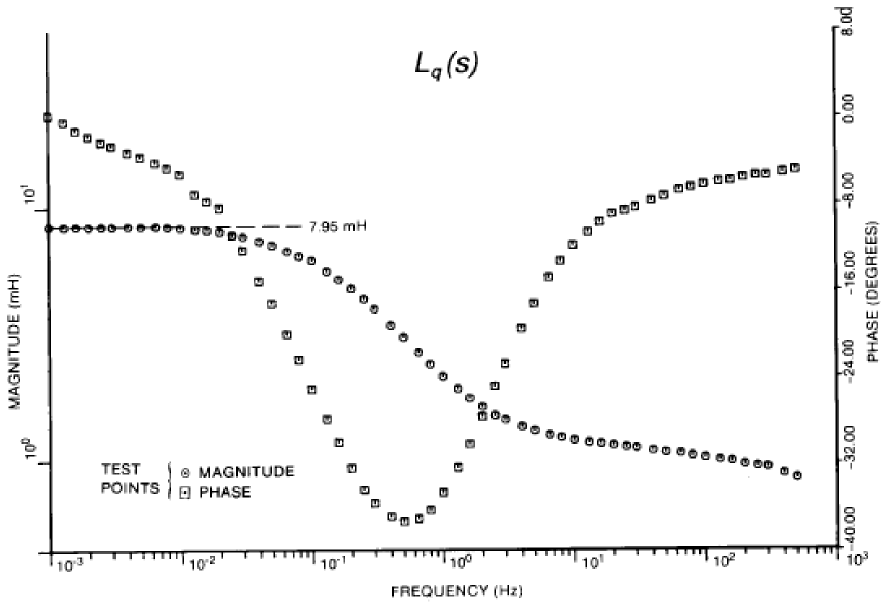


Figure 64—Quadrature-axis operational inductance

12.4 Interpretation of test data

Interpretation of test data 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 case might be true infrequently, but recent experience by users indicates that several issues may be involved in the fitting process. Some of these issues are listed below:

a) *Structure*: For the direct-axis network, it is possible to choose between the structures proposed by IEEE Std 1110. The models in Figure 65 for the direct axis and in Figure 66 for the quadrature axis are representative of commonly used models for fitting SSFR test data, as recommended in IEEE Std 1110.

   For each of the direct-axis models in Figure 65, whether first, second, or third order, the test data must be interpreted as a complete set. The same rule applies to the quadrature-axis models of Figure 66. For consistency, if a third-order model is chosen for the direct axis, a third-order model is also recommended for the quadrature axis.

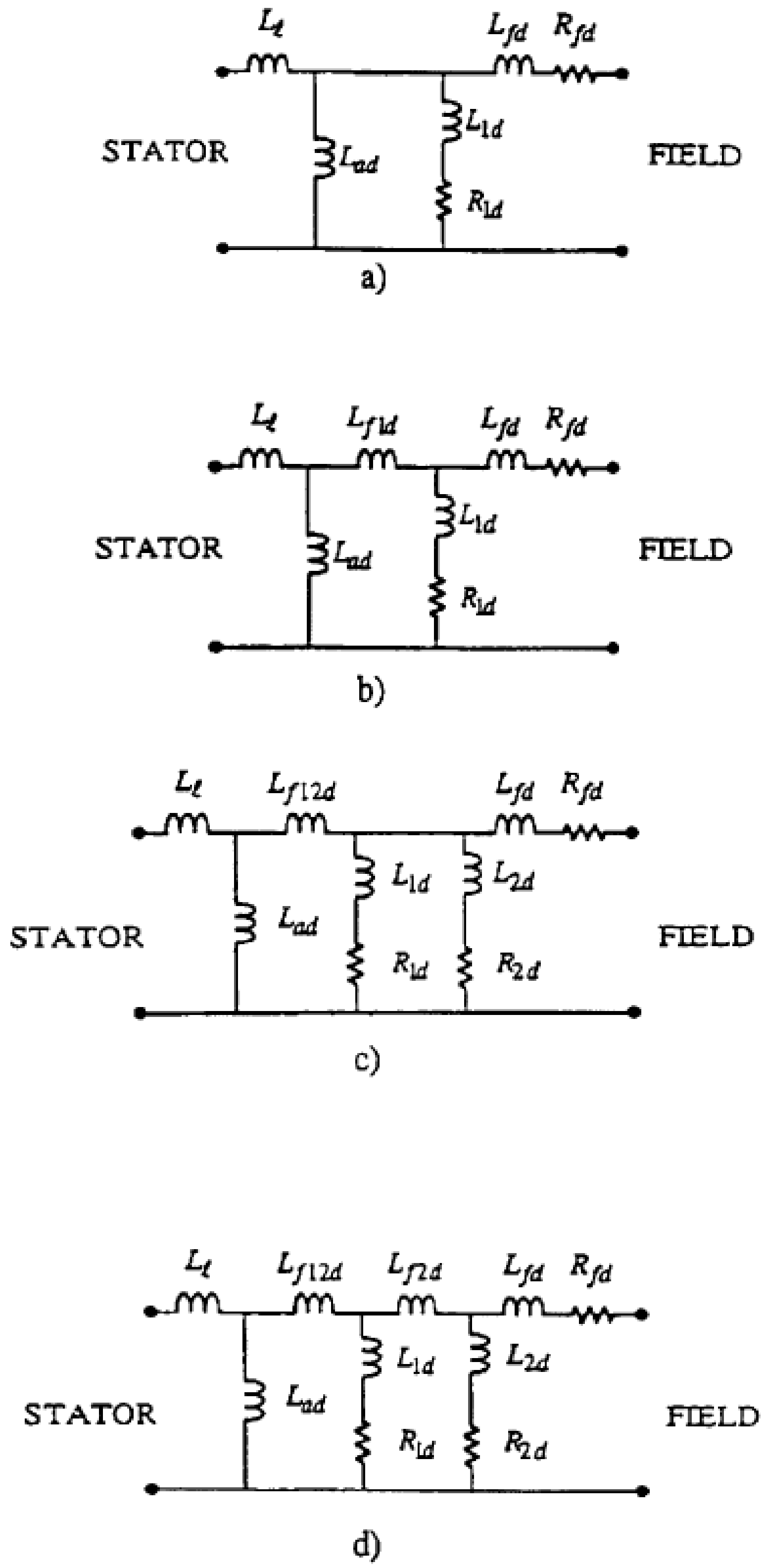


Figure 65—Direct-axis equivalent circuits

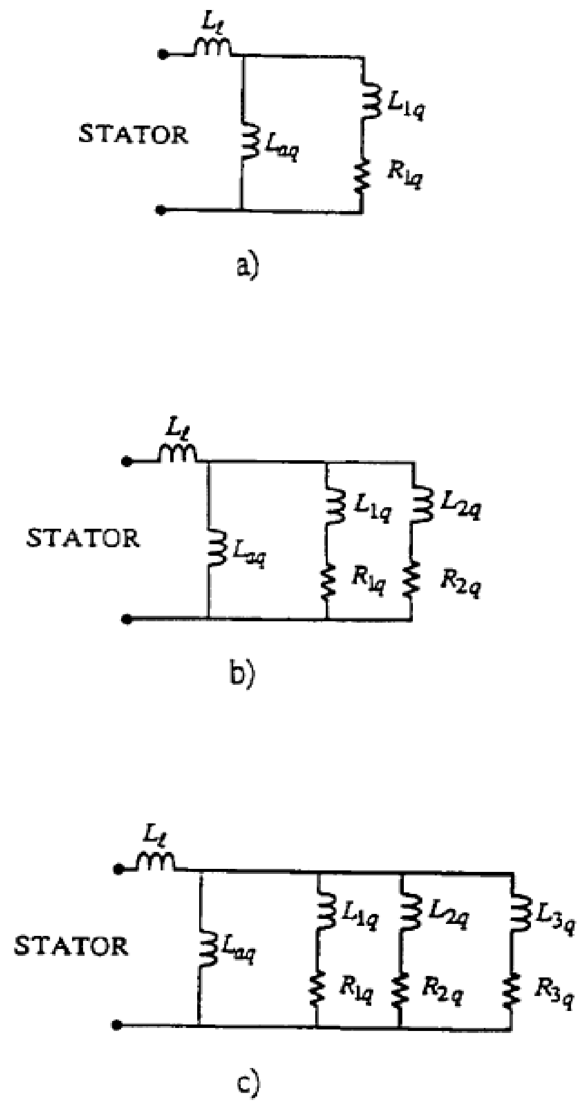


Figure 66—Quadrature-axis equivalent circuits

b) *P.U. 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_{f1d}, L_{f12d}, or L_{f2d} can be constructed for the same machine (see IEEE Std 1110).

c) *Incomplete modeling*: Since the machine's direct 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.

To summarize, the direct fitting of equivalent circuits (even though this process involves possible solutions that 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 (see Aliprantis et al. [B2]) 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 the IEEE Committee Report [B27] published in 1980, the suggestions for modeling based on SSFR testing proposed that a specific stability model be assumed for both the direct axis and quadrature axis of a turbo generator. This approach to modeling was in contrast to the long-accepted reactance and time constant approach used, for example, in Clause 11 of this guide. Around that time, it was pointed out in Umans et al. [B45] that other approaches to using the test data were available. An alternate approach to fitting SSFR data was later described in 1993 (see Canay [B10]). 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 versus 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.

The IEEE Committee Report [B27] showed 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 proposed in IEEE Std 1110 or in Figure 65 of this guide 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 direct axis. When the state-space model of the direct and quadrature axes 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 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 SSFR 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 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 route 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

12.5.2.1 Direct axis

The steps for the direct axis are as follows:

a) Assume the best available estimate for the stator leakage inductance, L_l. Typically, it could be the value supplied by the manufacturer.

b) $L_d(o)$ is the low-frequency limit of $L_d(s)$.

$$L_{ad}(o) = L_d(o) - L_l \ \mathrm{H} \tag{12-19}$$

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 value is further discussed in Annex H.

c) When the information in step 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 shown in Equation (12-20).

$$N_{af}(o) = \left\{ \frac{1}{sL_{ad}(o)} \lim_{s\to 0} \left[\frac{\Delta e_{fd}(s)}{\Delta i_d(s)} \right] \right\} \tag{12-20}$$

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 [B42] noted that the physical turns ratio must be adjusted by several factors. Among these factors are the armature winding pitch and distribution factors and the field flux form factor. These factors 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 as shown in Equation (12-21).

$$\frac{P \cdot N_{fd}}{N_a}[K] = \frac{3}{2}\frac{i_a(base)}{i_{fd}(base)} = N_{af}(base) \tag{12-21}$$

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, in amperes
i_{fd}(base) is I_{fd}(base) × (L_{adu}), where I_{fd}(base) is the excitation, in amperes (dc), to produce rated armature volts on the air-gap line, and L_{adu} is in per unit

It should be noted that $N_{af}(o)$ and N_{af}(base) are usually close to each other in value. In the following direct-axis model development, $N_{af}(o)$ will be used. The use of both $N_{af}(o)$ and N_{af}(base) is discussed in Annex H.

d) The field resistance, referred to the armature winding, is shown in Equation (12-22).

$$R_{fd} = \frac{sL_{ad}(o)}{\lim\limits_{s \to 0}\left\{\frac{\Delta i_{fd}(s)}{\Delta i_d(s)}\right\}\frac{2}{3}\left[N_{af}(o)\right]} \quad \Omega \tag{12-22}$$

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 step b) to its unsaturated value L_{adu} (see Annex H).

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:

$$R_{fd} \text{ at } 100^o C = \left[\frac{234.5+100}{234.5+T_f}\right]\left[r_{fd}\right]\left[\frac{3}{2}\right]\left[\frac{1}{N_{af}(o)}\right]^2 \quad \Omega \tag{12-23}$$

where

r_{fd} is the field resistance measured at the field terminals
T_f is the average field winding temperature, in degrees Celsius, 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 (see Rankin [B42]), refer back to Equation (12-21).

$$i_{fd}(base) = \frac{3}{2} i_a(base)\left[\frac{1}{N_{af}(o)}\right] \text{ A (dc)} \tag{12-24}$$

Note the use of $N_{af}(o)$ in place of N_{af}(base).

12.5.2.2 Quadrature axis

The steps for the quadrature axis are as follows:

a) Assume the same value for the armature leakage inductance that was used in the direct axis.

b) $L_q(o)$ is the low-frequency limit of $L_q(s)$.

$$L_{aq}(o) = L_q(o) - L_l \text{ H} \tag{12-25}$$

Again, this value is correct for the test conditions, but may be different at operating flux densities.

c) Choose an equivalent circuit structure for the quadrature axis.

d) 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 at this point.

e) Convert $L_{aq}(o)$ to its unsaturated value L_{aqu} (see Annex H).

f) 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 SSFR 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 in the operational form for the dependent variable, for example,

$$L_q(s) = L_q(o)\frac{(1+sT_1)(1+sT_2)(1+sT_3)}{(1+sT_4)(1+sT_5)(1+sT_6)} \tag{12-26}$$

for the quadrature axis or the actual equivalent circuit elements [see Figure 66(c) for example].

Some analysts tend to assign, for example, quadrature-axis time constants to the quantities in Equation (12-26) (see Aliprantis et al. [B2]). Thus T_1 would be considered to be representative of T'_q, 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 E, but they are not identical. Similar comments apply to transfer functions developed from direct-axis test data. The direct axis transfer function expressions are not identical in time constant values to the values developed in Clause 11 from various short-circuit or voltage recovery tests, such as T'_d, T''_d, or T'_{do}.

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-axis and quadrature-axis functions. Programs or procedures that could be suitable for curve-fitting the results are described in The Mathworks [B39]. Refer also to Annex H.

One approach is to use a pattern-search technique (see Hooke and Jeeves [B24]). Briefly, the pattern-search technique is a general method for linear and nonlinear 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 as shown in Equation (12-27).

$$\Gamma_0 = \Big[j\omega L_l \quad j\omega L_{aq}(o) \quad j\omega L_{1q} \quad R_{1q} \quad \ldots \quad j\omega L_{ad}(o) \quad j\omega L_{f12d} \quad j\omega L_{1d} \quad R_{1d} \quad \ldots \quad j\omega L_{fd} \quad R_{fd} \quad \frac{1}{N_{af}(o)} \Big] \tag{12-27}$$

The letter (o) refers to the low-frequency limit of each respective variable.

$$\Gamma_o = [\gamma_1 \quad \gamma_2 \quad \ldots \quad \gamma_n] \tag{12-28}$$

where

n is the number of elements in the vector

$$e_{ij} = \omega_i \omega_j \left[FR_{idata}(\omega = 2\pi f_j) - FR_{icalc}\left\{(\omega = 2\pi f_j), \Gamma_0\right\}\right]^2 \tag{12-29}$$

Each frequency point, 2 πf_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, [e.g., $L_d(s)$, $sG(s)$, and $L_q(s)$] 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 shown in Equation (12-30).

$$e_0 = \sum_{\forall ij} e_{ij} \tag{12-30}$$

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 nonfixed 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 process 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. and X_l = 0.178 p.u.

$$\text{Armature base impedance} \quad = \frac{(18)(18)}{192.3} = 1.685\Omega$$

$$\text{Armature base inductance} \quad = \frac{1.685}{120\pi} = 4.469\,mH$$

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:

$$Z_d(s); \quad \frac{\Delta e_{fd}(s)}{\Delta i_d(s)}; \quad \frac{\Delta i_{fd}(s)}{\Delta i_d(s)}; \quad Z_q(s)$$

The functions are shown in Figure 58, Figure 62, Figure 61, and Figure 63, respectively. Figure 59 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 59, R_a = 0.001612 Ω 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, $Z_d = 0.003370\,|30.6°\Omega$.

The corresponding operational inductance for this particular frequency is

$$L_d = \frac{0.003370\underline{|30.6^o} - 0.001612}{j(0.13)(2\pi)} \quad H$$
$$= 0.002627\underline{|-36.9^o} \quad H$$

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 60. The quadrature-axis operational inductance, $L_q(s)$, plotted in Figure 64, is obtained in the same way from $Z_q(s)$.

12.5.4.1 Direct axis

Beginning with the direct axis and following the steps in 12.5.2.1:

a) L_l = 0.795 mH = 0.178 p.u. given a base inductance of 4.469 mH

b) From Figure 60
$L_d(o)$ = 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 62

$$N_{af}(o) = \left\{ \frac{1}{sL_{ad}(o)} \lim_{s\to 0} \left[\frac{\Delta e_{fd}(s)}{\Delta i_d(s)} \right] \right\} = \frac{1}{s\left(0.007155\right)} \{0.0862s\}$$

Then $N_{af}(o) = \dfrac{0.0862}{0.007155} = 12.05$

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 61. This function is, in the limit, Ks as $s(=j\omega)$ approaches zero. This result is the straight dotted line $(0.0862)s$ in Figure 62. 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 60

$$R_{fd} = \frac{sL_{ad}(o)}{\lim_{s\to 0} \left\{ \dfrac{\Delta i_{fd}(s)}{\Delta i_d(s)} \right\} \dfrac{2}{3} \left[N_{af}(o) \right]} = \frac{s\left(0.007155\right)}{\left(0.3375s\right)\left(\dfrac{2}{3}\right)\left(12.05\right)} \quad \Omega$$

$$R_{fd} = \frac{0.007155}{2.70233} = 0.002643 \quad \Omega$$

Thus, a value of R_{fd} can be obtained directly from the standstill test data (at 20 °C). This process is an alternative method of obtaining the field resistance.

e) The equivalent circuit structure in Figure 65(d) 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
$R_{1d} = 0.0263\ \Omega$
$L_{2d} = 2.282$ mH
$R_{2d} = 0.006574\ \Omega$
$L_{fd} = 0.726$ mH

g) At rated armature voltage on the air-gap line of the open-circuit saturation curve, $I_{fd}(\text{base}) =$ 590 A dc

$$L_{adu} = \left[\frac{3}{2}\right]\left[\frac{1}{12.05}\right]\left[\frac{18000\sqrt{2}}{\sqrt{3}\left(120\pi\right)\left(590\right)}\right] = 8.225\ mH \text{ referred to the armature}$$

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,

$$r_{fd} = \left[\frac{234.5+100}{234.5+20}\right]\left[0.2045\right] = 0.2688 \quad \Omega$$

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 step f) 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

$$L_l = \frac{0.795}{4.469} = 0.178\ p.u.$$

$$L_{adu} = \frac{8.225}{4.469} = 1.840\ p.u.$$

$$L_{f12d} = \frac{0.267}{4.469} = 0.060\ p.u.$$

$$L_{1d} = \frac{0}{4.469} = 0\ p.u.$$

$$R_{1d} = \frac{0.0263}{1.685} = 0.0156\ p.u.$$

$$L_{f2d} = \frac{0}{4.469} = 0\ p.u.$$

$$L_{2d} = \frac{2.282}{4.469} = 0.511\ p.u.$$

$$R_{2d} = \frac{0.006574}{1.685} = 0.00390\ p.u.$$

$$L_{fd} = \frac{0.726}{4.469} = 0.162\ p.u.$$

$$R_{fd} = \frac{0.002777}{1.685} = 0.00165\ p.u.$$

j) The base peak armature current and the base field currents will now be established to check the value of N_{af}(base).

$$\text{Base peak armature current } i_a(\text{base}) = \left(\frac{192.3\ MVA}{18\sqrt{3}}\right)\sqrt{2} = 8722.9\,A$$

(Use Equation (12-21), but substitute the value of 12.05 for $N_{af}(o)$ determined from step c), rather than using N_{af}(base). A value of base field current can be closely approximated.)

$$i_{fd}(\text{base}) = \frac{3}{2}(8772.9)\left[\frac{1}{12.05}\right] = 1086\ A\ \text{dc}$$

k) Knowing i_{fd}(base) and i_a(base), a cross-check on N_{af}(base) may be obtained from Equation (12-21):

$$N_{af}\,(base) = \frac{3}{2}\frac{(8722.9)}{1086} = 12.05$$

$N_{af}(o)$ 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) × L_{adu} where I_{fd}(base) = 590 A dc. Therefore, i_{fd}(base) = 590 × 1.84 = 1086 A

Z_{base} for the field,

$$\text{referred to the stator } = \frac{\text{Rated machine voltamperes}}{\left[i_{fd}\,(\text{base})\right]^2} = \frac{192.3\times10^6}{(1086)^2} = 163.05\ \Omega$$

$$\text{Again } R_{fd}\ \text{p.u.} = \frac{r_{fd}\,(corrected\ to\ 100^0 C)}{163.05} = \frac{0.2688}{163.05} = 0.00165\ p.u.$$

which agrees closely with the calculation in step i).

12.5.4.2 Quadrature axis

The quadrature axis is considered next.

a) L_l = 0.795 mH

b) From Figure 63
$L_q(o)$ = 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 noteworthy. 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 66(c); L_l and $L_{aq}(o)$ are known at this point.

d) An iterative procedure, identical to that described above, fitted to the quadrature-axis operational inductance gave the following model element values:

$$L_{1q} = 6.045\ mH$$
$$R_{1q} = 0.01355\ \Omega$$
$$L_{2q} = 0.735\ mH$$
$$R_{2q} = 0.01525\ \Omega$$
$$L_{3q} = 0.453\ mH$$
$$R_{3q} = 0.1578\ \Omega$$

$$L_{aq}(o) = L_{qu}\left(\frac{8.225}{7.155}\right)$$
$$= 7.155\left(\frac{8.225}{7.155}\right)$$
$$= 8.225\ mH$$

e) Converting to p.u. values,

$$L_l = \frac{0.795}{4.469} = 0.178\ p.u.$$
$$L_{aqu} = \frac{8.225}{4.469} = 1.840\ p.u.$$
$$L_{1q} = \frac{6.045}{4.469} = 1.353\ p.u.$$
$$R_{1q} = \frac{0.01355}{1.685} = 0.00804\ p.u.$$
$$L_{2q} = \frac{0.735}{4.469} = 0.1645\ p.u.$$
$$R_{2q} = \frac{0.01525}{1.685} = 0.00905\ p.u.$$
$$L_{3q} = \frac{0.453}{4.469} = 0.101\ p.u.$$
$$R_{3q} = \frac{0.1578}{1.685} = 0.0936\ p.u.$$

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 Figure 65(d) and Figure 66(c). 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 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-axis or quadrature-axis tests. This alignment is done to simplify the transformation of stator and field measurements of three-phase synchronous machine to the appropriate direct-axis and quadrature-axis quantities. The mathematical transformations and other expressions for such direct-axis and quadrature-axis quantities are detailed in Coultes and Watson [B12].

This reference also relates the measurements derived from the preceding equations [see Equation (12-8) through Equation (12-17)] to a particular complexity level of the model. As indicated in 12.5.1, as well as in Coultes and Watson [B12], other direct-axis and quadrature-axis model structures can also be chosen (see IEEE Std 1110) of higher or lower order (see Aliprantis et al. [B2]).

Annex A

(informative)

Bibliography

[B1] Adkins, B., and Harley, R.G., *The General Theory of Alternating Current Machines: Application to Practical Problems*. London: Chapman & Hill, 1975.

[B2] Aliprantis, D. C., Sudhoff, S. D., and Kuhn, B. T., "Experimental Characterization Procedure for a Synchronous Machine Model with Saturation and Arbitrary Rotor Network Representation," *IEEE Transactions on Energy Conversion,* vol. EC-20, no. 3, pp. 595–603, Sept. 2005.

[B3] ANSI S1.6, Preferred frequencies, frequency levels, and band numbers for acoustical measurements.[10]

[B4] Auckland, D. W., Kabir, S. M. L., and Shuttleworth, R., "Generator Model for Power System Studies," *IEE Proceedings C*, 137, pp. 333–390, Nov. 1990.

[B5] Beckwith, Sterling, "Approximating Potier Reactance," *AIEE Transactions,* vol. 56, pp. 813–818, July 1937.

[B6] Bortoni, E. C., and Jardini, J. A., "Experience with standstill frequency response (SSFR) testing and analysis of salient pole synchronous machines," *IEEE Transactions on Energy Conversion,* vol. EC-19, no. 4, pp. 687–691, Dec. 2004.

[B7] Bortoni, E. D. C., and Jardini, J. A., "Synchronous Machines Parameter Identification Using Load Rejection Test Data," *IEEE Transactions on Energy Conversion*, vol. 17, no. 2, pp. 242–247, June 2002.

[B8] Canay, I. M., "A new method of determining q-axis quantities of a synchronous machine," *ETZ A*, vol. 86, pp. 561–568, 1965.

[B9] Canay, I. M., "Causes of Discrepancies on Calculation of Rotor Quantities and Exact Equivalent Diagrams of the Synchronous Machine," *IEEE Transactions on Power Apparatus and Systems,* vol. PAS-88, pp. 1114–1120, July 1969.

[B10] Canay, I. M., "Determination of Model Parameters of Machines from the Reactance Operators xd(js), xq(js)" and "Modeling of Alternating-Current Machines Having Multiple Rotor Circuits," *IEEE Transactions on Energy Conversion,* vol. EC-8, no. 2, pp. 272–279 and pp. 280–296, June 1993.

[B11] Concordia, C., *Synchronous Machines – Theory and Performance*. New York: John Wiley, 1951.

[B12] Coultes, M. E., and Watson, W., "Synchronous Machine Models by Standstill Frequency Response Tests," *IEEE Transactions on Power Apparatus and Systems,* vol. PAS-100, no. 4, pp. 1480–1489, Apr. 1981.

[B13] Dandeno, P. L., Kundur, P., Poray, A. T., and Coultes, M. E., "Validation of Turbogenerator Stability Models by Comparison with Power Systems Tests," *IEEE Transactions on Power Apparatus and Systems,* vol. PAS-100, no. 4, pp. 1637–1645, Apr. 1981.

[10] ANSI publications are available from the American National Standards Institute, 25 West 43rd Street, 4th Floor, New York, NY 10036, USA (http://www.ansi.org/).

[B14] de Boor, C., *A Practical Guide to Splines*. New York: Springer-Verlag, 1978.

NOTE—FORTRAN programs included in this book are now available in Matlab Spline Toolbox [B39].

[B15] De Mello, F. P., and Hannett, L. N., "Validation of Synchronous Machine Models and Derivation of Model Parameters from Tests," *IEEE Trans. on Power Apparatus and Systems*, vol. PAS-100, no. 2, pp. 662–672, Feb. 1981.

[B16] De Mello, F. P., Hannett, L. N., and Willis, J. R., "Determination of Synchronous Machine Stator and Field Leakage Inductances from SSFR Tests," *IEEE Transactions,* PWRS vol. 3, no. 4, pp. 1625–1632, Nov. 1988.

[B17] Diggle, R., and Dineley, J. L., "Generator Works Testing: Sudden-Short-Circuit or Standstill Variable-Frequency-Response Method," *IEE Proceedings C*, 128(4), pp.177–182, July 1981.

[B18] Duesterhoeft, W. C., "The Negative-Sequence Reactance of an Ideal Synchronous Machine," *AIEE Transactions,* vol. 68, part 1, pp. 510–514, and discussion by W. A. Lewis, pp. 513, 514, 1947.

[B19] EPRI Report EL-1424, "Determination of Synchronous Machine Stability Study Constants," vol. 1, Sept. 1980, Westinghouse Electric Corporation, and vol. 2, Dec. 1980, Ontario Hydro. [Two of four reports on EPRI Project 997] [11]

[B20] EPRI Report EL-5036, 1982, Electric Generator—Vol. 1.

[B21] EPRI Report EL-5736, Confirmation of Test Methods for Synchronous Machine Dynamic Performance Models, 1988.

[B22] Harrigton, D., and Whittlesey, J. I., "The Analysis of Sudden Short-Circuit Oscillograms of Steam Turbine Generators," *AIEE Transactions*, vols.78 and 79, pp. 551–565, 1959.

[B23] Hirayama, K., "Practical Detailed Model for Generators," *IEEE Transactions on Energy Conversion*, vol. 10, no. 1, pp. 105–110, Mar. 1995.

[B24] Hooke, R., and Jeeves, T., "Direct Search Solution of Numerical and Statistical Problems," *J. Assoc. Comput,* vol. 8, no. 2, Apr. 1961.

NOTE—Such a procedure is now available in Matlab [B39].

[B25] Hurley, J. D., and Schwenk, H. R., "Standstill Frequency Response Modeling and Evaluation by Field Tests on a 645 MVA Turbine Generator," *IEEE Transactions on Power Apparatus and Systems,* vol. PAS-100, no. 2, pp. 828–836, Feb. 1981.

[B26] IEC 60034-4:1985, Rotating electrical machines—Part 4: Methods for determining synchronous machine quantities from tests. [12]

[B27] IEEE Committee Report (P. L. Dandeno, Chair) "Supplementary Definitions and Associated Test Methods for Obtaining Parameters for Synchronous Machine Stability Study Simulations." *IEEE Transactions on Power Apparatus and Systems,* vol. PAS-99, no. 4, pp. 1625–1633, July–Aug. 1980. [13]

[11] EPRI publications are available from the Electric Power Research Institute (http://www.epri.com).
[12] IEC publications are available from the International Electrotechnical Commission, Case Postale 131, 3, rue de Varembé, CH-1211, Genève 20, Switzerland/Suisse (http://www.iec.ch/). IEC publications are also available in the United States from the American National Standards Institute, 25 West 43rd Street, 4th Floor, New York, NY 10036, USA (http://www.ansi.org/).
[13] IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, Piscataway, NJ 08854, USA (http://standards.ieee.org/).

[B28] IEEE PES WG 12 Report (P. L. Dandeno, Chair), "Experience with standstill frequency response (SSFR) testing and analysis of salient pole synchronous machines," *IEEE Trans. Energy Conversion.*, vol. 14, no. 4, pp. 1209–1217, Dec. 1999.

[B29] *The IEEE Standards Dictionary: Glossary of Terms & Definitions*.

[B30] IEEE Std C50.12™, IEEE Standard for Salient-Pole 50 Hz and 60 Hz Synchronous Generators and Generator/Motors for Hydraulic Turbine Applications Rated 5 MVA and Above.[14]

[B31] IEEE Std 1™, IEEE Recommended Practice—General Principles for Temperature Limits in the Rating of Electrical Equipment and for the Evaluation of Electrical Insulation.

[B32] IEEE Std 1255™, IEEE Guide for Evaluation of Torque Pulsation During Starting of Synchronous Motors.

[B33] Kamwa, I., Pilote, M., Carle H., Viarouge, P., Mpanda-Mabwe B., and Crappe, R., "Computer Software to Automate the Graphical Analysis of Sudden-Short-Circuit Oscillograms of Large Synchronous Machines," *IEEE Transactions on Energy Conversion,* vol. 10, no. 3, pp. 399–405, Sept. 1995.

[B34] Kamwa, I., Viarouge, P., and Dickinson, J., "Identification of Generalized Models of Synchronous Machines from Time-Domain Tests," *IEE Proceedings C,* 138(6), pp. 485–498, Nov. 1991.

[B35] Kamwa, I., Viarouge, P., and Mahfoudi, R., "Phenomenological Models of Large Synchronous Machines from Short-Circuit Tests During Commissioning—A Classical/Modern Approach," *IEEE Transactions on Energy Conversion,* vol. EC-9, no. 1, pp. 85–97, Mar. 1994.

[B36] Kilgore, L. A., "Calculation of Synchronous Machine Constants," *AIEE Transactions,* vol. 50, pp. 1201–1213, Dec. 1931.

[B37] March, L. A., and Crary, S. B., "Armature Leakage Reactance of Synchronous Machines," *AIEE Transactions,* vol. 54, pp. 378–381, April 1935.

[B38] Marxsen, A. L., and Morsztyn, K., "Analysis of Synchronous Machine Transient Tests Using a Microcomputer," *IEE Proceedings,* 124(4), pp. 377–380, 1977.

[B39] The MathWorks, Version R2007b, Matlab & Simulink Software.[15]

[B40] Minnich, S. H., "Small Signals, Large Signals and Saturation in Generator Modeling," *IEEE Transactions on Energy Conversion,* vol. EC-1, pp. 94–102, Mar. 1986.

[B41] Mohamed, A., Hussain, A., Zali, S. M., and Ariffin, A., "A Systemic Approach in Estimating the Generator Parameters," *Electric Power Components and Systems*, vol. 30, pp. 301–313, 2002.

[B42] Rankin, A. W., "Per unit Impedance of Synchronous Machines," *AIEE Transactions,* vol. 64, pp. 569–572 and pp. 839–841, Aug. 1945.

[B43] Rusche, P. A. E., Brock, G. J., Hannett, L. N., and Willis, J. R., "Test and Simulations of Network Dynamic Response Using SSFR and RTDR Derived Synchronous Machine Models," *IEEE Transactions on Energy Conversion*, vol. 5, no.1, pp. 145–155, Mar. 1990.

[B44] Shackshaft, G., "Implementation of New Approach to the Determination of Synchronous-Machine Parameters from Test," *IEE Proceedings*, vol. 124, no. 12, pp. 1170–1177, 1977.

[14] The IEEE standards or products referred to in this clause are trademarks of the Institute of Electrical and Electronics Engineers, Inc.
[15] This software is available from http://www.mathworks.com.

[B45] Umans, S. D., Mallick, J. A., and Wilson, G. L., "Modeling of Solid Rotor Turbogenerators—Parts I and II," *IEEE Transactions,* PAS-97, pp. 269–291, Jan./Feb. 1978.

[B46] Wamkeue, R., Baetscher, F., and Kamwa, I., ''Hybrid State Model Based Time-domain Identification of Synchronous Machine Parameters from Saturated Load Rejection Test Records,'' *IEEE Transactions on Energy Conversion*, vol. 23, no. 1, pp. 68–77, Mar. 2008.

Annex B

(normative)

Nomenclature

This nomenclature pertains to Clause 3 through Clause 7 and Clause 9 through Clause 12.

k, K	local variables defined in associated clauses or subclauses
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, L_{fkd} 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}	$= L_{mf1d} - L_{ad}$ mutual inductance between field and damper circuits, where $k=1,2,n$ as above
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 operational 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 SSFR 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 per unit on the armature impedance base.

Annex C

(informative)

Discussion on leakage and Potier reactances

Subclause 5.2.2.1 pointed out that *theoretically,* the Potier reactance and the leakage reactance are one and the same. However, in practice, they are seldom identical. 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 5.3.2.2 or 5.3.2.3. A problem arises when one has both the leakage and Potier reactances available.

Potier reactance has been described as a fictitious (or nonconstant) reactance 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 5.2.2.1) 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 to a generator (or motor) zero power factor overexcited, with rated (1.0 p.u.) armature current.

Beckwith [B5] 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, a less than normal armature current (and corresponding field current) 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.

March and Crary [B37] discuss 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).

March and Crary [B37] also noted that the Potier reactance of turbo generators does not vary as much as that of hydro generators for the above-described conditions. Another of their conclusions 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. Kilgore [B36] extends and confirms the armature leakage flux calculations of March and Crary.

In summary, March and Crary recommend 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 have several variations involving the machine inductances and currents. Two of the approaches are described generally in IEEE Std 1110.

Annex D

(informative)

Example of calculation of p.u. field current (I_F)

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

a) Calculation of internal angle δ using Equation (5-3) or alternatively:

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

δ = 18.47° [See also Figure 19(a)].

b) $I_d = 0.909 \sin [18.47° - (-25.8°)] \underline{/18.47° - 90°}$ [see Equation (5-4)]
$= 0.6345 \underline{/-77.53°}$
$I_q = 0.909 \cos [18.47° - (-25.8\ °)] \underline{/18.47°}$ [see Equation (5-5)]
$= 0.6909 \underline{/18.47°}$

c) $E_{GU} = E_a + I_a R_a + jI_a \times X_{du} + jI_q \times X_{qu}$
$= 1.5414 + j\ 0.5150$
$= 1.6252\underline{/18.47°}$

d) I_{GU} = 1.625 for E_{GU} = 1.625 on air-gap line (see Figure 20)

e) $E_p = E_a + I_a \times R_a + jI_a \times X_p = 1.1675 + j\ 0.1071 = 1.1675\underline{/5.26°}$

f) For E_p = 1.167 on air-gap line, and on open-circuit saturation curve
$I_{FS} = 1.59 - 1.167 = 0.423$ p.u.

$I_F = I_{FU} + I_{FS}$ = 1.625 + 0.423 = 2.048 p.u.

NOTE 1—Neglecting resistance $E_{QD}\underline{/\delta} = 1.3898 \underline{/18.75°}$
$E_P = 1.1592 \underline{/5.51°}$

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

Annex E

(informative)

Quadrature-axis transient or subtransient tests

E.1 General

As noted in 11.1 through 11.3, 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 60034-4:1985 [B26] be noted here. The ones briefly described here are used in determining transient and subtransient *quadrature*-axis synchronous machine characteristic values—both reactances and time constants (see Canay [B8]). IEC 60034-4:1985 describes such tests as *unconfirmed* test methods for determining synchronous machine quantities.

E.2 Description of tests for quadrature-axis values

The methodology for the transient and subtransient quadrature-axis characteristic values involves operating the synchronous machine at a low voltage, at low power, while connected synchronously (or asynchronously) to a power system source. Three procedures (two of them related) are summarized below in the interests of brevity, but are intended to generally indicate the methodology:

- Method 1. Disconnection applied low armature voltage during very low slip
- Method 2. Disconnecting applied low armature voltage with machine running asynchronously on load
- Method 3. Suddenly short-circuiting machine while running on load at low voltage

E.2.1 Method 1. Disconnecting applied low armature voltage during very low slip

The test method of suddenly disconnecting the applied low armature voltage during a low slip 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, armature 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 quadrature axis with the required accuracy.

NOTE—In many types of machines, it is difficult to segregate transient and subtransient voltage components along the quadrature axis because the high decrement components may not be clearly separated from the remainder.

E.2.2 Method 2. Disconnecting applied low armature voltage with machine running asynchronously on load

The test method of disconnecting applied low armature voltage with 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 with the excitation winding short-circuited.

By positioning signals on the shaft, the direct-axis 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 quadrature-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 quadrature-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 quadrature-axis signal while 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.

E.2.3 Method 3. Suddenly short-circuiting machine while running on load at low voltage

The test method of 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 must be taken in choosing the proper voltage to be able to load the machine up to 90 ± 20 electrical degrees and also to minimize the risk of damage 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 E.2.2. The quadrature-axis current is measured using the current in phase 3 at the time of the quadrature-axis signal. The direct-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 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 semilogarithmic scale.

E.3 Terminology and definitions for quadrature-axis transient and subtransient reactances

E.3.1 Description of tests for reactances

The definitions listed in Annex A of IEC 60034-4:1985 [B26] for quadrature-axis transient reactance, X'_q, and quadrature-axis subtransient reactance, X''_q, are essentially the same as, and conform in principle and theory, to those listed in *The IEEE Standards Dictionary* [B29].

The test-derived descriptions of X'_q and X''_q in Annex A of IEC 60034-4:1985 are, for practical purposes, as follows:

a) X'_q —The quotient of the initial value of a sudden change in the fundamental ac component of armature voltage that 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, with the machine running at rated speed and high-decrement components during the first cycles being excluded.

b) X''_q —The same value as described in item a) except that the high-decrement components during the first cycles are included.

NOTE—See E.2.3 for actual methodology.

E.3.2 Parameter determination from tests

Parameter determination for X'_q and X''_q is based on the test procedures detailed in E.2.3.

a) $$X'_q(t) = \frac{E_d(0)}{\left[I_q(0) + \Delta I'_q(0)\right]} \text{ (all quantities in per unit)}$$

where

$E_d(0)$ and $E_q(0)$ are the components of the voltage and current at the time of short circuit

b) $$X''_q(t) = \frac{E_d(0)}{\left[I_q(0) + \Delta I'_q(0) + \Delta I''_q(0)\right]} \text{ (all quantities in per unit)}$$

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 E.2.1 and E.2.2 are not detailed in this annex, but can be found in Annex A of IEC 60034-4:1985 [B26]. The above derivation is given as a typical example.

E.4 Terminology and definitions for quadrature-axis transient and subtransient short-circuit time constant

The quadrature-axis transient short-circuit time constant, τ'_q, is summarized as follows: 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 $1/e$, or 0.368, of its initial values, with the machine running at rated speed.

The quadrature-axis subtransient short-circuit time constant, τ''_q, is summarized as follows: 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 $1/e$, or 0.368, of its initial value, with the machine running at rated speed.

The above two quantities can also be derived following the test procedures described in E.2.3.

E.5 Terminology and definitions for quadrature-axis transient and subtransient open-circuit time constant (τ'_{qo} and τ''_{qo})

E.5.1 Quadrature-axis transient open-circuit time constant

The quadrature-axis transient open-circuit time constant, τ'_{qo}, is summarized as follows: The time required for the slowly changing component of 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/*e*, or 0.368, of its initial value, with the machine running at rated speed.

E.5.2 Quadrature-axis subtransient open-circuit time constant

The quadrature-axis subtransient open-circuit time constant, τ''_{qo}, is summarized as follows: 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/*e*, or 0.368, of its initial value, with the machine running at rated speed.

Annex F

(informative)

Generator load rejection tests

The load rejection test (i.e., opening the generator main breaker while the generator is initially carrying some reactive and/or real power) is a particular type of decrement test, while the field voltage is kept constant (see Shackshaft [B44]), for determining generator parameters (see De Mello and Hannett [B15] and Rusche et al. [B43]). EPRI Project EL-5736 [B21] performed rotating time-domain response (RTDR) tests including the load rejection test to compute machine parameters. Comparisons between load rejection and SSFR models can be found in Rusche et al. [B43]. Hirayama [B23] discusses the impacts of the AVR on recorder data following a load rejection test. In Bortoni and Jardini [B7] and Mohamed et al. [B41], modern identification techniques based on the arbitrary axis load rejection test are proposed to compute direct-axis and quadrature-axis transient and subtransient reactance and open-circuit time constants. A graphical approach to compute generator parameters from a direct-axis load rejection test is proposed in IEEE Std 1110. In Wamkeue et al. [B46], a method to predict the load rejection test from a so-called hybrid model using equivalent-circuit parameters is proposed and applied for the parameters determination.

F.1 Load rejection test procedure

The convenient time to perform the load rejection test is when the machine is being taken out of service or for an outage.

F.1.1 Operational considerations for load rejection tests

The following operational considerations apply to load rejection tests:

— The first event for the test should be the isolation of the synchronous machine from the power system. Ideally, then the test should be initiated by opening the generator main breaker (circuit breaker connecting the machine to the system). It is typically not desirable to have the turbine or the excitation system automatically transfer-trip once the generator main breaker has been opened as this event will skew the results of the test. For example, when performing the reactive power rejection test (with minimal real power, i.e., machine flux is primarily on the direct axis), it is undesirable to transfer-trip the turbine and exciter because ideally field voltage and generator speed should be kept constant throughout the test. A load rejection initiated by a turbine trip usually is not suitable since typically the turbine valves must close before the generator main breaker opens. A turbine trip causes undesirable changes in the initial operating point of the synchronous machine. Another practical reason for avoiding a turbine trip is that in the case of large steam turbine generators, a turbine trip may subsequently lead to a boiler trip. If a boiler trip should occur, it may take several hours to bring the unit back to full-speed no-load and thus ready for any subsequent tests.

— To eliminate the effects of the voltage regulator on the machine's terminal voltage following load rejection, the voltage regulator should be placed in manual control (i.e., to control field voltage) prior to initiating the trip.

— Excitation must be maintained following load rejection. However, it is common to have relaying schemes trip the field breaker once they sense that the generator main breaker has opened. This automatic transfer trip should be temporarily disabled.

— Load rejection tests must be performed at relatively low real-power levels (e.g., 10% of units rating) to reduce the potential for adverse effects on the equipment. Large load rejections would also likely result in overspeed conditions or other large changes in prime mover variables.

The direct-axis load rejection test is performed by rejecting reactive power. The generator phase voltages, field voltage, and field current are typically recorded. For direct-axis load rejection, the active power should be maintained around zero (P = 0 p.u.) and reactive power Q chosen in the interval of –0.10 p.u. to –0.40 p.u. (absorbing reactive power from the system).

F.1.2 Technical problems for load rejection tests

The following technical problems may be incurred for load rejection tests:

— For the quadrature-axis load rejection test, the rotor positioning must be such that the rotor angle and the load angle are opposite ($\delta_0 = -\phi$). This condition is difficult to obtain if a power angle indicator is unavailable.

— One practical consideration in performing the load rejection test is to keep the field voltage constant during the test.[16] This condition is not possible for excitation systems whose source is fed from the generator terminals. In this case, the dynamics of the field voltage should be taken into account in the parameter derivation process. Also, by design, some excitation systems control field current and not field voltage when placed in manual control. This situation results in a field voltage transient following load rejection and needs to be taken into account for the parameter derivation process. Finally, for rotating brushless exciters, it is not possible to measure the field voltage; therefore, the field voltage of the exciter should be used in the analysis.

— For the reactive power rejection test, the generator terminal voltage will decay considerably and may result in interruption of auxiliary load if it is fed from the generator terminals. Therefore, unit auxiliaries (e.g., feed water pumps) that may typically feed from the generator terminals must be transferred to other station transformers.

F.2 Theoretical background for load rejection test

F.2.1 Terminal voltage in terms of transient reactance and time constants after load rejection test

The direct-axis and quadrature-axis armature fluxes $\Delta\psi_d(t)$ and $\Delta\psi_q(t)$ in the transient state can be computed from the generator operational relationships [see Equation (12-1)] in Equation (F-1).

$$\begin{aligned} \Delta\psi_d(s) &= G(s)\Delta v_f(s) - x_d(s)\Delta i_d(s) \\ \Delta\psi_q(s) &= -x_q(s)\Delta i_q(s) \end{aligned} \tag{F-1}$$

Considering the machine model with one damping winding in each axis of Figure F.1 yields the corresponding direct-axis and quadrature-axis operational reactances as shown in Equation (F-2).

$$\begin{aligned} x_d(s) &= x_d \frac{(1+sT_d')(1+sT_d'')}{(1+sT_{d0}')(1+sT_{d0}'')} = x_d + (x_d' - x_d)\frac{sT_{d0}'}{1+sT_{d0}'} + (x_d'' - x_d')\frac{sT_{d0}''}{1+sT_{d0}''} \\ x_q(s) &= x_q \frac{(1+sT_q')}{(1+sT_{q0}')} = x_q + (x_q' - x_q)\frac{sT_{q0}'}{1+sT_{q0}'} \end{aligned} \tag{F-2}$$

[16] The discussion here pertains to estimating generator parameters. Once the generators parameters have been derived, the same load rejection test may be used to derive parameters for the excitation system if the exciter is kept in automatic voltage regulation mode; in this case, field voltage will vary.

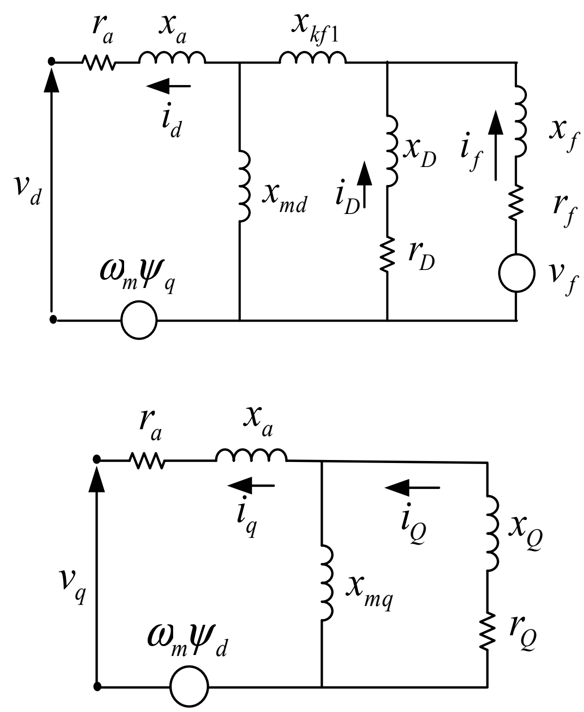


Figure F.1—Equivalent circuits of synchronous generator

$\Delta i_d(s) = \frac{I_d}{s}$ and $\Delta i_q(s) = \frac{I_q}{s}$ since the field voltage is maintained constant during the whole load rejection test ($\Delta v_f(s) = 0$). The armature flux transients given by Equation (F-1) are given in time domain by Equation (F-3).

$$\begin{aligned}\Delta\psi_d(t) &= x_d I_d + I_d(x'_d - x_d)e^{\left(-\frac{t}{T'_{d0}}\right)} + I_d(x''_d - x'_d)e^{\left(-\frac{t}{T''_{d0}}\right)} \\ \Delta\psi_q(t) &= x_q I_q + I_q(x'_q - x_q)e^{\left(-\frac{t}{T'_{q0}}\right)}\end{aligned} \tag{F-3}$$

I_d and I_q are steady-state currents before the load rejection obtained from Figure 39 (see 10.8.2). See Equation (F-4).

$$E_d = E_a \sin\delta_0 \qquad E_q = E_a \cos\delta_0 \tag{F-4}$$

$$I_d = I_a \sin(\delta_0 + \phi) \qquad I_q = I_a \cos(\delta_0 + \phi) \tag{F-5}$$

Armature flux transients previously computed illustrate that the load rejection test of the generator is the superposition of direct-axis and quadrature-axis separated load rejection tests. Accordingly, direct-axis load rejection test is performed when the direct-axis parameters are required since the direct-axis armature flux ψ_d contains only direct-axis parameters of the generator as shown previously. Similarly, the quadrature-axis armature flux ψ_q contains only quadrature-axis generator parameters. The quadrature-axis load rejection test provides parameters of the quadrature axis.

For given phase voltages (abc), the direct-axis and quadrature-axis armature voltages are computed from Equation (F-8) and Equation (F-9). θ is the rotor angle (Equivalent Park angle).

$$\psi_d(t) = \Psi_d + \Delta\psi_d(t) = E_q + \Delta\psi_d(t) \tag{F-6}$$

$$\psi_q(t) = \Psi_q + \Delta\psi_q(t) = -E_d + \Delta\psi_q(t) \tag{F-7}$$

$$v_d(t) = -\omega(t)\psi_q(t) = \frac{2}{3}\left[v_a(t)\cos\theta + v_b(t)\cos\left(\theta - \frac{2\pi}{3}\right) + v_c(t)\cos\left(\theta + \frac{2\pi}{3}\right)\right] \tag{F-8}$$

$$v_q(t) = \omega(t)\psi_d(t) = -\frac{2}{3}\left[v_a(t)\sin\theta + v_b(t)\sin\left(\theta - \frac{2\pi}{3}\right) + v_c(t)\sin\left(\theta + \frac{2\pi}{3}\right)\right] \tag{F-9}$$

F.2.2 Purely direct-axis load rejection test

For the direct-axis load rejection test, the generator terminal flux is on direct-axis $\delta_0 = 0$ and P = 0 p.u. The rotor speed is constant $\omega(t) = \omega_0 = 1$ (in per unit) during the direct-axis load rejection test. Since $\phi = -\frac{\pi}{2}$, the direct-axis current defined by Equation (F-5) becomes $I_d = -I_a$ and $E_q = E_a$ in Equation (F-4). Accordingly, Equation (F-8) and Equation (F-9) lead to Equation (F-10) and Equation (F-11).

$$v_d(t) = -\omega(t)\psi_q(t) = 0$$

$$\begin{aligned} v_q(t) = v(t) = \psi_d(t) &= -\frac{2}{3}\left[v_a(t)\sin(\omega_b t) + v_b(t)\sin\left(\omega_b t - \frac{2\pi}{3}\right) + v_c(t)\sin\left(\omega_b t + \frac{2\pi}{3}\right)\right] \\ &= E_a - x_d I_a - I_a(x'_d - x_d)e^{\left(-\frac{t}{T'_{d0}}\right)} - I_a(x''_d - x'_d)e^{\left(-\frac{t}{T''_{d0}}\right)} \end{aligned} \tag{F-10}$$

$$v_a(t) = v_q(t)\sin(\omega_b t) \tag{F-11}$$

The graphical method defined in 11.12.1 can be used to compute generator direct-axis parameters in Equation (F-10).

F.3 Determination of direct-axis parameters and open-circuit time constants from purely direct-axis load rejection test

The terminal voltage following the purely direct-axis load rejection test can be written from Equation (F-10) as follows:

$$v(t) = V_{q\infty} + V'_{q0}e^{\left(-\frac{t}{T'_{d0}}\right)} + V''_{q0}e^{\left(-\frac{t}{T''_{d0}}\right)} = V_{q\infty} + v'_q(t) + v''_q(t) \tag{F-12}$$

with

$$
\begin{aligned}
V_{q\infty} &= E_a - x_d I_a \\
V'_{q0} &= I_a (x_d - x'_d) \\
V''_{q0} &= I_a (x'_d - x''_d)
\end{aligned}
\tag{F-13}
$$

The direct-axis reactance, transient and subtransient reactances are defined by Equation (F-14).

$$
\begin{aligned}
x_d &= \frac{E_a - V_{q\infty}}{I_a} \\
x'_d &= x_d - \frac{V'_{q0}}{I_a} \\
x''_d &= x'_d - \frac{V''_{q0}}{I_a}
\end{aligned}
\tag{F-14}
$$

Figure F.2 illustrates the terminal voltage of the load rejection test of a purely capacitive load performed on a small laboratory 208 V, 1.5 kVA, four-pole, 60 Hz, synchronous turbine generator. The steady-state terminal voltage and current prior to the load rejection are $E_a = 0.5232$ p.u. and $I_a = 0.16$ p.u. with the total reactive power of $Q = -0.083712$ p.u.

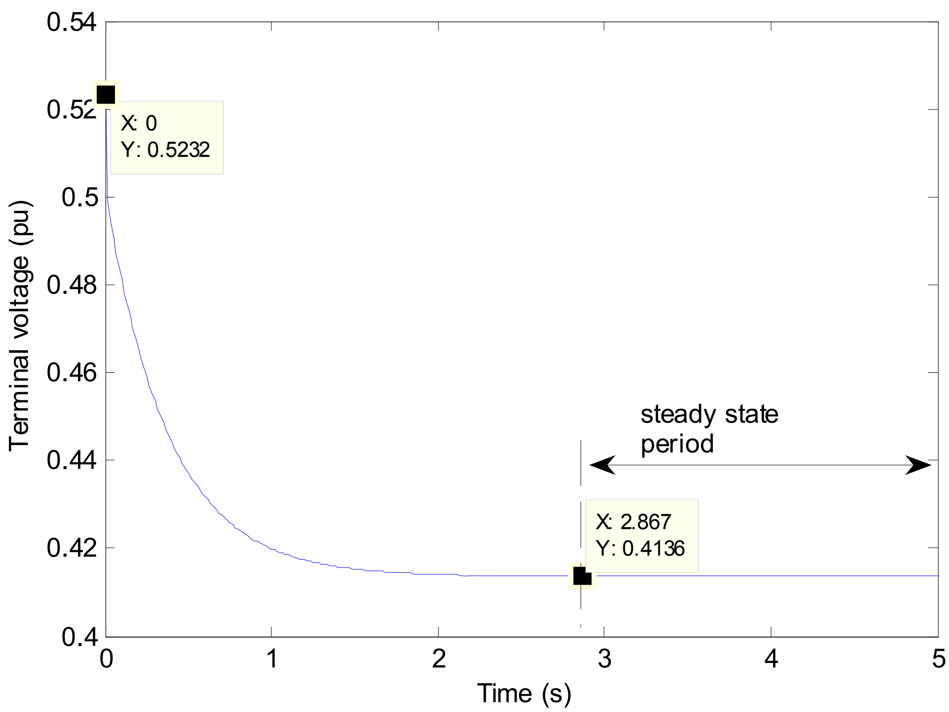


Figure F.2—Terminal voltage following load rejection of purely capacitive load

From Figure F.2, $V_{q\infty} = 0.4136$ p.u. The direct-axis reactance is computed from Equation (F-14) by the following:

$$x_d = \frac{E_a - V_{q\infty}}{I_a} = \frac{0.5232 - 0.4136}{0.16} = 0.685 \text{ p.u.}$$

From Equation (F-12) and Figure F.3,

$$v'_q(0) + v''_q(0) = V'_{q0} + V''_{q0} = v_t(0) - V_{q\infty} = E_a - V_{q\infty} = 0.5232 - 0.4136 = 0.1096 \text{ p.u.}$$

The transient and subtransient reactance are then computed from Figure F.3 by the following:

$$x'_d = x_d - \frac{V'_{q0}}{I_a} = 0.685 - \frac{0.087}{0.16} = 0.141 \text{ p.u.}$$

$$x''_d = x'_d - \frac{V''_{q0}}{I_a} = 0.141 - \frac{0.1096 - 0.092}{0.16} = 0.031 \text{ p.u.}$$

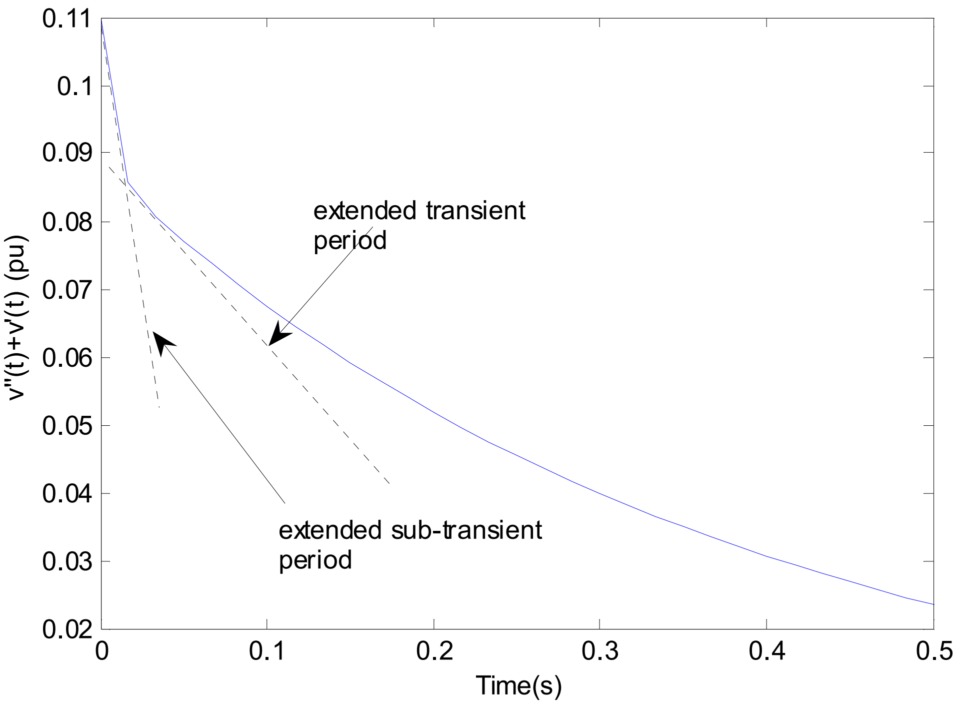


Figure F.3—Transient and subtransient terminal voltage

In general, T''_{d0} is smaller than T'_{d0} for $t > 3T'_{d0}$. The subtransient can then be neglected, and the transient period is given by Equation (F-15).

$$v'_q(t) = v_t(t) - V_{q\infty} - V''_{q0}e^{\left(-\frac{t}{T''_{d0}}\right)} \approx v_t(t) - V_{q\infty} = V'_{q0}e^{\left(-\frac{t}{T'_{d0}}\right)} \tag{F-15}$$

T'_{d0} is graphically evaluated from semilogarithmic plots of the transient formulation given in Equation (F-16). From Figure F.4, $T'_{d0} = 0.3667 \approx 0.68\ s$.

$$\ln(v'_q(t)) = \ln\left(v_t(t) - V_{q\infty}\right) = \ln\left(V'_{q0} e^{\left(-\frac{t}{T'_{d0}}\right)}\right) = \ln(V'_{q0}) - \frac{t}{T'_{d0}} \tag{F-16}$$

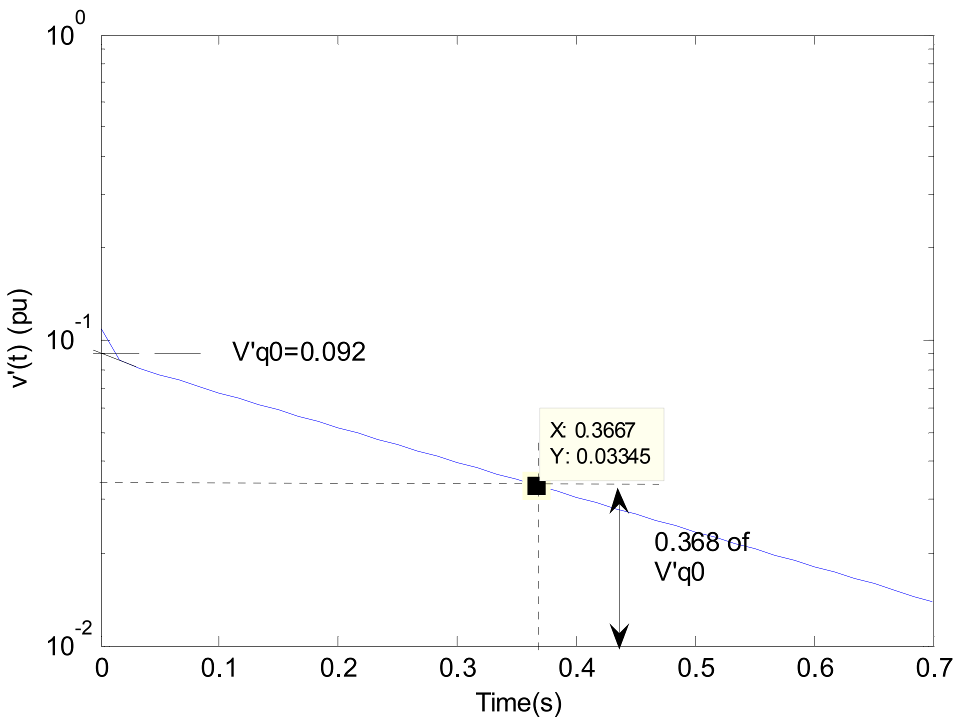


Figure F.4—Semilogarithmic plot of transient terminal voltage $v'_q(t)$ as a function of time

Similarly, for the subtransient terminal voltage, Equation (F-17) is true.

$$\ln(v''_q(t)) = \ln\left(v_t(t) - V_{q\infty} - v'_{q0}(t)\right) = \ln\left(V''_{q0} e^{\left(-\frac{t}{T''_{d0}}\right)}\right) = \ln(V''_{q0}) - \frac{t}{T''_{d0}} \tag{F-17}$$

and $T''_{d0} = 0.065\ s$.

Finally, the terminal voltage can be written as follows:

$$v_q(t) = 0.4136 + 0.087 e^{\left(\frac{-t}{0.37}\right)} + 0.0176 e^{\left(\frac{-t}{0.065}\right)} \text{ (p.u.)}$$

Figure F.5 compares model and actual data.

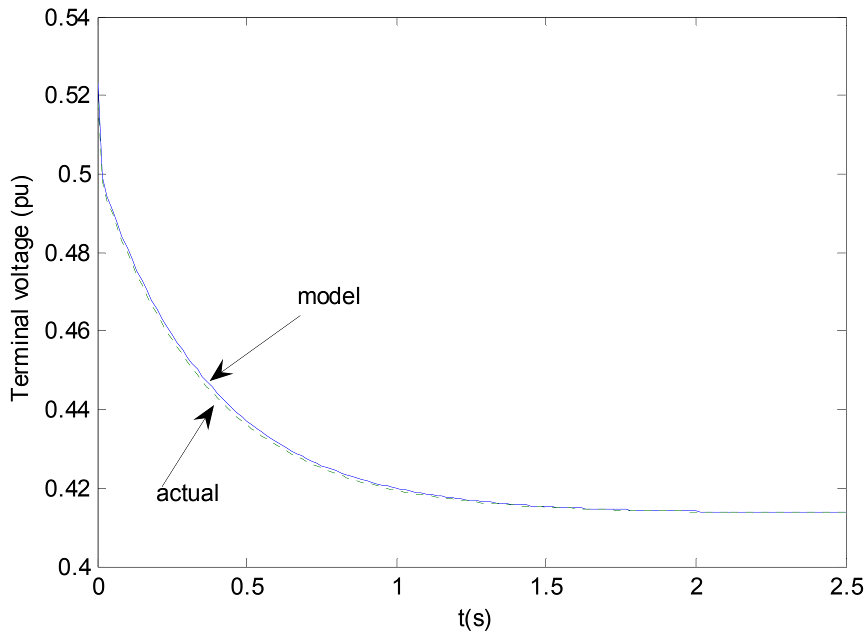


Figure F.5—Comparison between model and actual data

Annex G

(informative)

Magnetic nonlinearity

There are a number of ways to define inductance starting 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, which is illustrated in Figure G.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 is often used 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. The normal magnetization curve of Figure G.2 shows that the permeability is defined as given in Equation (G-1).

$$\mu = \frac{B}{H} \tag{G-1}$$

where

μ is permeability
B is magnetic flux density, in teslas
H is magnetic field intensity, in amperes per meter

The permeability, μ, is small for low values of flux density, and it 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* and is given in Equation (G-2).

$$\mu_{inc} = \frac{\partial B}{\partial H} \tag{G-2}$$

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 reach a maximum somewhere in between.

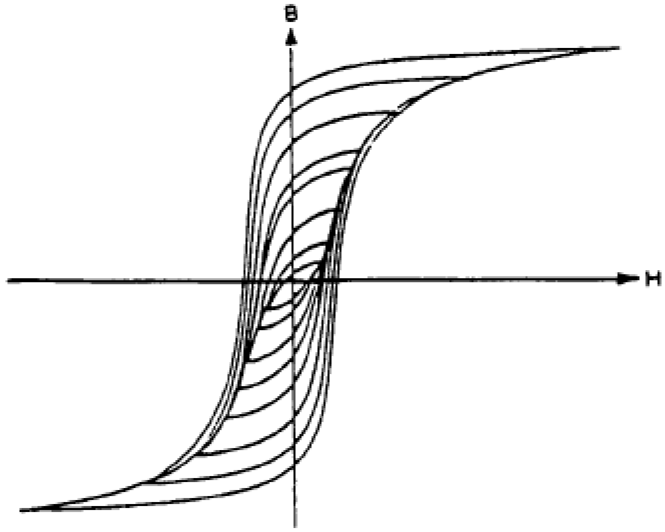


Figure G.1—Magnetic nonlinearity of iron—B-H loops

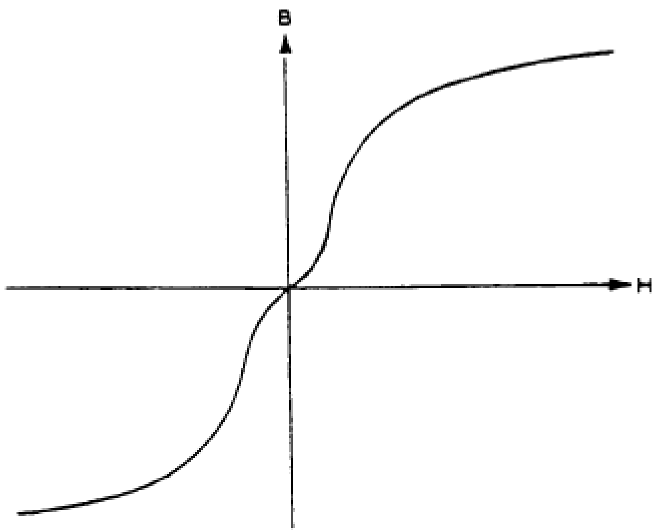


Figure G.2—Magnetic nonlinearity of iron—locus of tip of B-H loops

Since SSFR 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 SSFR 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 SSFR test data need to be adjusted upward to achieve an unsaturated model for the machine. Generally, 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 Minnich [B40].

An unsaturated value for L_{ad}, in henries, can be calculated from the rated-speed open-circuit saturation curve [see step g) in 12.5.4.1] as shown in Equation (G-3).

$$L_{adu} = \left(\frac{3}{2}\right)\left(\frac{1}{N_{af}(o)}\right)\left(\frac{V_t}{\omega_n I_{fd}}\right)\text{H} \quad \text{referred to the stator} \tag{G-3}$$

The value of $N_{af}(o)$ can be determined as shown in step c) of the example in 12.5.4.1. 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 amperes dc. L_{adu} is substituted for $L_{ad}(o)$ determined in step b) of 12.5.2.1 in the direct-axis equivalent circuit. Similarly, in the quadrature-axis equivalent circuit, $L_{aq}(o)$, as determined in 12.5.2.2, 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.

Annex H

(informative)

Alternative approach to model development

H.1 Introduction

In the general remarks in 12.4.1, it is stated that the suggested procedure for developing a third-order model was one of many possible routes. This statement applied in particular for turbo generator 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. The example is based on work by Kamwa et al. [B34]. The machine chosen for analysis is an alternative one but identical in megavoltampere rating, power factor, and terminal voltage to one of the eight similar machines referred to in Coultes and Watson [B12]. The rotor amortisseur details in the machine being analyzed in this annex are much simpler than the original machine reported on and analyzed by Coultes and Watson.

H.2 Machine technical details

The machine constants required to initiate an analysis of the SSFR data are as follows:

Machine rating: 588 MVA, 22 kV, 60 Hz

MVA (base) = 588 = ($S_{N\Delta}$) kV (base) = 22 = ($E_{N\Delta}$)

$$Z_{base}(\text{armature}) = \frac{\left(E_{N\Delta}\right)^2}{S_{N\Delta}} = 0.8231 \quad \Omega \tag{H-1}$$

$$i_a\,(\text{base})\text{ peak stator} = \frac{588\times10^6\sqrt{2}}{22\times10^3\sqrt{3}} = 2182.3\text{ A} \tag{H-2}$$

I_{fd}(base) = the 1001 A dc required to induce 22 kV line to line on the open-circuit air-gap line

L_{du} = the 2.348 p.u. by sustained short-circuit test

L_l = 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 $L_d(s)$ magnitude, in ohms (as well as in decibels), and phase angles, in degrees, at each test point. The armature-to-field-transfer function data, $sG(s)$, are given from test as amperes/amperes, and the armature-to-field-transfer impedance, $Z_{afo}(s)$, [of the transfer inductance, $L_{afo}(s)$] is given as volts/amperes.

An extract of the data available for analysis is shown in Table H.1.

Table H.1—Samples of SSFR data for 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

H.3 Establishing 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 [B42]. The approach is centered on determining the base field amperes in the Rankin (or reciprocal) system.

Thus, Equation (H-3) is true.

$$i_{fd}(base) = I_{fd}(base) \times L_{adu} = 1001(2.158) = 2160\ A\,dc \tag{H-3}$$

N_{af}(base) is taken from Equation (12-21) and shown in Equation (H-4).

$$\begin{aligned} N_{af}(base) &= \frac{1.5\left[i_a(base)\ peak\ amperes\right]}{i_{fd}(base)} \\ &= \frac{1.5(2182.3)}{2160} = 15.155 \end{aligned} \tag{H-4}$$

H.4 Approach to model development

In the present example, only the direct-axis network is considered 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:

a) 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, for example, 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.

b) Keep L_d(o), $N_{af}(o)$, and R_{fd} fixed. By varying the remaining network parameters (see 12.5.3) 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 200 Hz. Although the data, as illustrated in Table H.1, are given in ohms, a step suggested here is to use the $L_d(s)$ magnitudes in decibels. Some transfer function analyzers print such information in either decibels or ohms. $sG(s)$ and $Z_{afo}(s)$ data are measured as noted in Table H.1.

As opposed to the model chosen in the example of 12.5.4.1, a third-order direct-axis model is chosen with just one differential leakage inductance, L_{f12d}, as shown in Figure 65(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 12.5.3) is seldom necessary since magnitude and phase errors are well distributed from low to high frequencies. However, transfer function weighting is still useful (ω_i in 12.5.3) 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 H.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.), and 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 H.2—Initial network parameters (in per unit)

$L_l = 0.19$	$L_{ad} = 1.853$	$L_{1d} = 0.110$	$R_{1d} = 0.090$
$L_{fd} = 0.154$	$R_{fd} = 0.00097$	$L_{2d} = 0.110$	$R_{2d} = 0.38$
$L_{f12d} = 0.0$	$L_{f2d} = 0.0$	$N_{af}(o) = N_{af}(\text{base}) = 15.173$	

H.5 First stage of fitting

In the first fitting stage, the data of the three transfer functions [$L_d(s)$, $sG(s)$, $Z_{afo}(s)$] between 0.0016 Hz and 0.3548 Hz are used simultaneously, and the unknown parameters shown in Equation (H-5) are adjusted to minimize the sum of squared errors on the magnitude (in decibels) and phase (in degrees).

$$\Gamma = \left[R_{1d} \quad R_{2d} \quad L_{1d} \quad L_{2d} \qquad L_{2d} \quad R_{fd} \quad L_{f12d}\, L_{ad}(o) \quad N_{af}(o) \right] \tag{H-5}$$

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 as follows:

$L_{ad}(o) = 1.9273$ p.u.; $\qquad N_{af}(o) = 15.111$; $\qquad R_{fd} = 0.0011435$ 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, 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 the example in 12.5.4, a subset of unknown parameters is then adjusted iteratively as shown in Equation (H-6).

$$\Gamma = \left[R_{1d} \quad R_{2d} \quad L_{fd} \quad L_{1d} \quad L_{2d} \quad L_{f12d} \right] \tag{H-6}$$

The optimum parameters obtained at convergence of the fitting process are given in Table H.3. Least-squares statistical inference performed on the corresponding residuals gives rough, usually pessimistic, bounds on the estimated network parameters in Table H.3.

Table H.3—Final network parameters based on a measured Rankin "X_{ad}-base" (L_l = 0.19 p.u.)[a]

Resistances and inductances on machine rating (p.u.)	
L_{fd} = 0.15152 ± 0.009 (5.9%)	R_{fd} = 0.0011435 ± 0.00004 (3.9%)
L_{1d} = 1.2672 ± 0.20 (15%)	R_{1d} = 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%)

[a] Field resistance not yet corrected for rated temperature.

H.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 shown in Equation (H-7).

$$\Gamma_o = \left[R_{fd} \quad R_{1d} \quad R_{2d} \quad L_{fd}\, L_{1d} \quad L_{2d} \quad L_{ad}(o) \quad L_{f12d} \right] \tag{H-7}$$

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 H.4.

Table H.4—Final network parameters based on rated Rankin "X_{ad}-base"[a]

Resistances and inductances on machine rating (p.u.)			
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	$N_{af}(o) = N_{af}$(base) = 15.173	

[a] Field resistance not yet corrected for rated temperature.

To illustrate the performance achieved by the various models of the 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 H.2): 6922
- Final model with measured "X_{ad}-base" (Table H.3): 841.3
- Final model with rated "X_{ad}-base" (Table H.4): 774.1

It is observed that the model with the best performance from an engineering point of view (Table H.3) is not necessarily the one giving the lowest sum of residual errors. In fact, the model in Table H.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 Figure H.1 and Figure H.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 Figure H.1 and Figure H.2.

H.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 H.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 step h) in 12.5.4].

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, both obtained from the analyses outlined in H.3 through H.6.

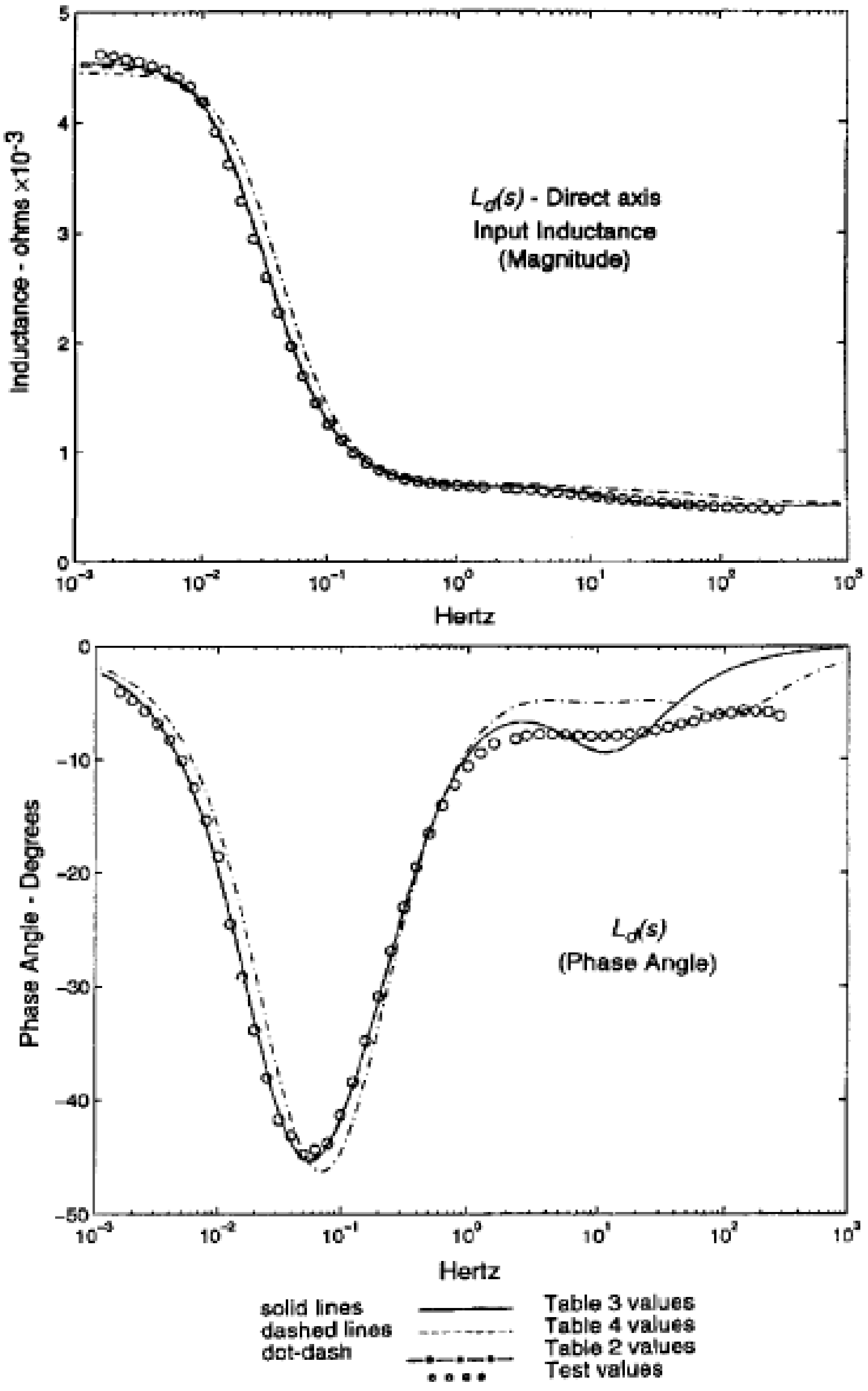


Figure H.1—Plots of magnitude and phase angle of direct-axis operational inductance for 588 MVA turbine generator

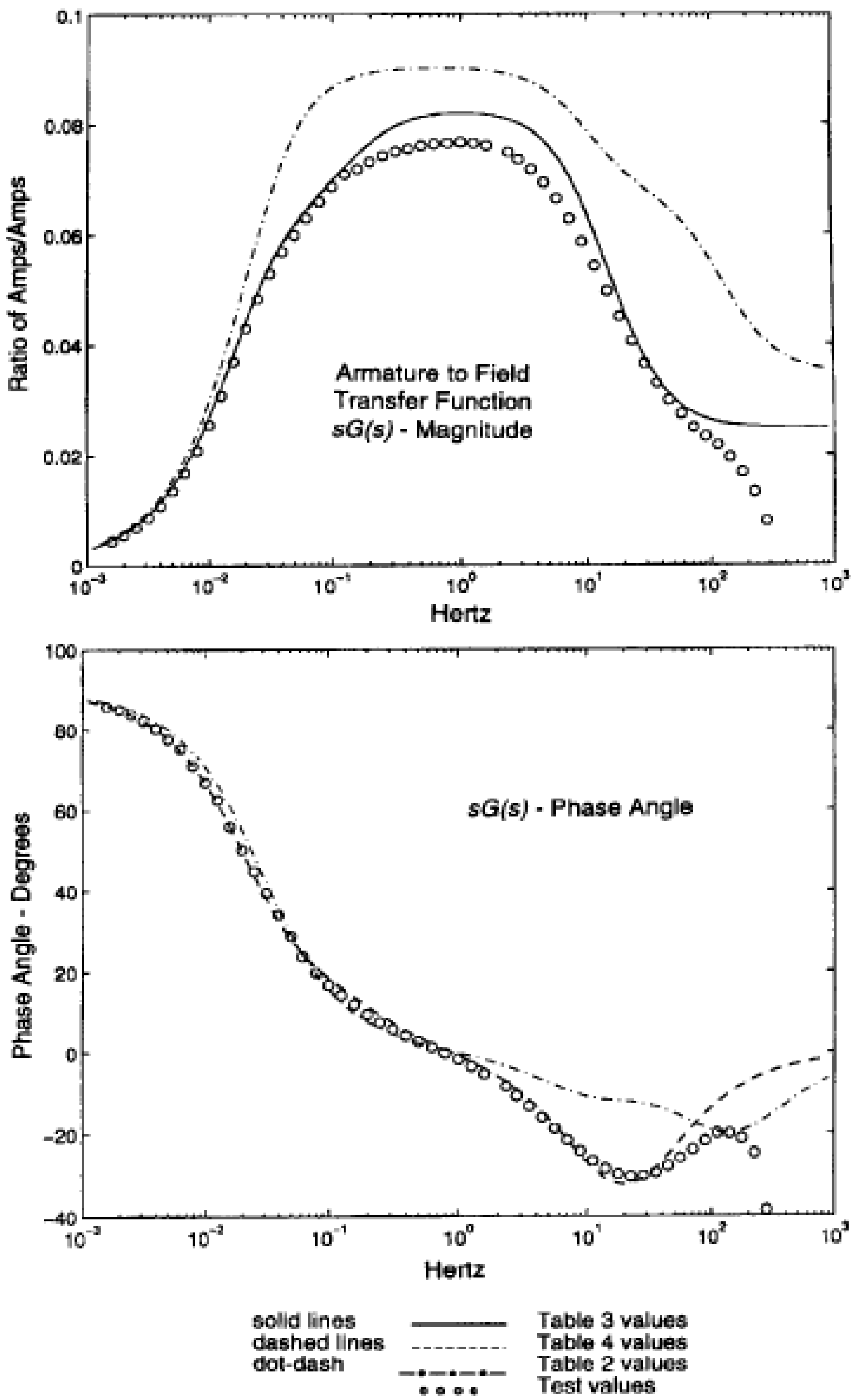


Figure H.2—Plots of magnitude and phase angle of armature-to-field transfer function for 588 MVA turbine generator