IEEE SA
STANDARDS
ASSOCIATION

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

IEEE Power and Energy Society

Developed by the
Electric Machinery Committee

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

STANDARDS

IEEE

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

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

Developed by the

Electric Machinery Committee
of the
IEEE Power and Energy Society

Approved 7 November 2019

IEEE SA Standards Board

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

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

The Institute of Electrical and Electronics Engineers, Inc.
3 Park Avenue, New York, NY 10016-5997, USA

PDF: ISBN 978-1-5044-6347-8 STD23999
Print: ISBN 978-1-5044-6348-5 STDPD23999

Important Notices and Disclaimers Concerning IEEE Standards Documents

IEEE documents are made available for use subject to important notices and legal disclaimers. These notices and disclaimers, or a reference to this page, appear in all standards and may be found under the heading "Important Notices and Disclaimers Concerning IEEE Standards Documents." They can also be obtained on request from IEEE or viewed at http://standards.ieee.org/ipr/disclaimers.html.

Notice and Disclaimer of Liability Concerning the Use of IEEE Standards Documents

IEEE Standards documents (standards, recommended practices, and guides), both full-use and trial-use, are developed within IEEE Societies and the Standards Coordinating Committees of the IEEE Standards Association ("IEEE SA") Standards Board. IEEE ("the Institute") develops its standards through a consensus development process, approved by the American National Standards Institute ("ANSI"), which brings together volunteers representing varied viewpoints and interests to achieve the final product. IEEE Standards are documents developed through scientific, academic, and industry-based technical working groups. Volunteers in IEEE working groups are not necessarily members of the Institute and participate without compensation from IEEE. While IEEE administers the process and establishes rules to promote fairness in the consensus development process, IEEE does not independently evaluate, test, or verify the accuracy of any of the information or the soundness of any judgments contained in its standards.

IEEE Standards do not guarantee or ensure safety, security, health, or environmental protection, or ensure against interference with or from other devices or networks. Implementers and users of IEEE Standards documents are responsible for determining and complying with all appropriate safety, security, environmental, health, and interference protection practices and all applicable laws and regulations.

IEEE does not warrant or represent the accuracy or content of the material contained in its standards, and expressly disclaims all warranties (express, implied and statutory) not included in this or any other document relating to the standard, including, but not limited to, the warranties of: merchantability; fitness for a particular purpose; non-infringement; and quality, accuracy, effectiveness, currency, or completeness of material. In addition, IEEE disclaims any and all conditions relating to: results; and workmanlike effort. IEEE standards documents are supplied "AS IS" and "WITH ALL FAULTS."

Use of an IEEE standard is wholly voluntary. The existence of an IEEE standard does not imply that there are no other ways to produce, test, measure, purchase, market, or provide other goods and services related to the scope of the IEEE standard. Furthermore, the viewpoint expressed at the time a standard is approved and issued is subject to change brought about through developments in the state of the art and comments received from users of the standard.

In publishing and making its standards available, IEEE is not suggesting or rendering professional or other services for, or on behalf of, any person or entity nor is IEEE undertaking to perform any duty owed by any other person or entity to another. Any person utilizing any IEEE Standards document, should rely upon his or her own independent judgment in the exercise of reasonable care in any given circumstances or, as appropriate, seek the advice of a competent professional in determining the appropriateness of a given IEEE standard.

IN NO EVENT SHALL IEEE BE LIABLE FOR ANY DIRECT, INDIRECT, INCIDENTAL, SPECIAL, EXEMPLARY, OR CONSEQUENTIAL DAMAGES (INCLUDING, BUT NOT LIMITED TO: PROCUREMENT OF SUBSTITUTE GOODS OR SERVICES; LOSS OF USE, DATA, OR PROFITS; OR BUSINESS INTERRUPTION) HOWEVER CAUSED AND ON ANY THEORY OF LIABILITY, WHETHER IN CONTRACT, STRICT LIABILITY, OR TORT (INCLUDING NEGLIGENCE OR OTHERWISE) ARISING IN ANY WAY OUT OF THE PUBLICATION, USE OF, OR RELIANCE

Translations

The IEEE consensus development process involves the review of documents in English only. In the event that an IEEE standard is translated, only the English version published by IEEE should be considered the approved IEEE standard.

Official statements

A statement, written or oral, that is not processed in accordance with the IEEE SA Standards Board Operations Manual shall not be considered or inferred to be the official position of IEEE or any of its committees and shall not be considered to be, or be relied upon as, a formal position of IEEE. At lectures, symposia, seminars, or educational courses, an individual presenting information on IEEE standards shall make it clear that his or her views should be considered the personal views of that individual rather than the formal position of IEEE.

Comments on standards

Comments for revision of IEEE Standards documents are welcome from any interested party, regardless of membership affiliation with IEEE. However, IEEE does not provide consulting information or advice pertaining to IEEE Standards documents. Suggestions for changes in documents should be in the form of a proposed change of text, together with appropriate supporting comments. Since IEEE standards represent a consensus of concerned interests, it is important that any responses to comments and questions also receive the concurrence of a balance of interests. For this reason, IEEE and the members of its societies and Standards Coordinating Committees are not able to provide an instant response to comments or questions except in those cases where the matter has previously been addressed. For the same reason, IEEE does not respond to interpretation requests. Any person who would like to participate in revisions to an IEEE standard is welcome to join the relevant IEEE working group.

Comments on standards should be submitted to the following address:

Secretary, IEEE SA Standards Board
445 Hoes Lane
Piscataway, NJ 08854 USA

Laws and regulations

Users of IEEE Standards documents should consult all applicable laws and regulations. Compliance with the provisions of any IEEE Standards document does not imply compliance to any applicable regulatory requirements. Implementers of the standard are responsible for observing or referring to the applicable regulatory requirements. IEEE does not, by the publication of its standards, intend to urge action that is not in compliance with applicable laws, and these documents may not be construed as doing so.

Copyrights

IEEE draft and approved standards are copyrighted by IEEE under US and international copyright laws. They are made available by IEEE and are adopted for a wide variety of both public and private uses. These include both use, by reference, in laws and regulations, and use in private self-regulation, standardization, and the promotion of engineering practices and methods. By making these documents available for use and adoption by public authorities and private users, IEEE does not waive any rights in copyright to the documents.

Photocopies

Subject to payment of the appropriate fee, IEEE will grant users a limited, non-exclusive license to photocopy portions of any individual standard for company or organizational internal use or individual, non-commercial use only. To arrange for payment of licensing fees, please contact Copyright Clearance Center, Customer Service, 222 Rosewood Drive, Danvers, MA 01923 USA; +1 978 750 8400. Permission to photocopy portions of any individual standard for educational classroom use can also be obtained through the Copyright Clearance Center.

Updating of IEEE Standards documents

Users of IEEE Standards documents should be aware that these documents may be superseded at any time by the issuance of new editions or may be amended from time to time through the issuance of amendments, corrigenda, or errata. An official IEEE document at any point in time consists of the current edition of the document together with any amendments, corrigenda, or errata then in effect.

Every IEEE standard is subjected to review at least every 10 years. When a document is more than 10 years old and has not undergone a revision process, it is reasonable to conclude that its contents, although still of some value, do not wholly reflect the present state of the art. Users are cautioned to check to determine that they have the latest edition of any IEEE standard.

In order to determine whether a given document is the current edition and whether it has been amended through the issuance of amendments, corrigenda, or errata, visit IEEE Xplore at http://ieeexplore.ieee.org/ or contact IEEE at the address listed previously. For more information about the IEEE SA or IEEE's standards development process, visit the IEEE SA Website at http://standards.ieee.org.

Errata

Errata, if any, for IEEE standards can be accessed via https://standards.ieee.org/standard/index.html. Search for standard number and year of approval to access the web page of the published standard. Errata links are located under the Additional Resources Details section. Errata are also available in IEEE Xplore: https://ieeexplore.ieee.org/browse/standards/collection/ieee/. Users are encouraged to periodically check for errata.

Patents

Attention is called to the possibility that implementation of this standard may require use of subject matter covered by patent rights. By publication of this standard, no position is taken by the IEEE with respect to the existence or validity of any patent rights in connection therewith. If a patent holder or patent applicant has filed a statement of assurance via an Accepted Letter of Assurance, then the statement is listed on the IEEE SA Website at http://standards.ieee.org/about/sasb/patcom/patents.html. Letters of Assurance may indicate whether the Submitter is willing or unwilling to grant licenses under patent rights without compensation or under reasonable rates, with reasonable terms and conditions that are demonstrably free of any unfair discrimination to applicants desiring to obtain such licenses.

Essential Patent Claims may exist for which a Letter of Assurance has not been received. The IEEE is not responsible for identifying Essential Patent Claims for which a license may be required, for conducting inquiries into the legal validity or scope of Patents Claims, or determining whether any licensing terms or conditions provided in connection with submission of a Letter of Assurance, if any, or in any licensing agreements are reasonable or non-discriminatory. Users of this standard are expressly advised that determination of the validity of any patent rights, and the risk of infringement of such rights, is entirely their own responsibility. Further information may be obtained from the IEEE Standards Association.

Participants

At the time this guide was completed, the Test Procedure for Synchronous Machines Working Group had the following membership:

Haran C. Karmaker, *Chair*
Innocent Kamwa, *Vice Chair*
Robert F. Gray, *Secretary*

Jemimah C. Akiror
William Bloethe
Abdelghafour Belqorchi
Stefano Bomben
Edson C. Bortoni
Douglas J. Conley
Mohammed El Kahel
Ahmed El Serafi
Swarn S. Kalsi
Travis Kittleson
Jim F. Lau
Leonardo Lima
Kevin Mayor
Arezki Merkhouf
Robert Messel
Ali Moeini
Nils E. Nilsson
Edward L. Owen
Roberto Siniscalchi
Nick Stranges
Ernest Tchuisse
Robert Thornton-Jones
Stephen Umans
Rene Wamkeue
John Yagielski

The working group recognizes the contributions made by Prof. Ahmed El Serafi to the standard since 1992. Prof. El Serafi passed away on 9 April 2018.

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

Thomas Bishop
William Bloethe
Stefano Bomben
Demetrio Bucaneg Jr
Paul Cardinal
Luis Coronado
Scott Cotner
Edson da Costa Bortoni
Roger Daugherty
Gary Donner
Donald Dunn
Rostyslaw Fostiak
Alexander Glaninger-Katschnig
J. Travis Griffith
Randall Groves
Paul Hamer
Werner Hoelzl
Geza Joos
Innocent Kamwa
Haran C. Karmaker
John Kay
Isidoro Kerszenbaum
Chung-Yiu Lam
Mario Lanaro
Leonardo Lima
William Lockley
Lawrenc Long
O. Malik
Kevin Mayor
James Michalec
Ali Moeini
William Newman
Lorraine Padden
Shawn Patterson
Iulian Profir
Bartien Sayogo
Gary Smullin
Kris Sommerstad
Gary Stoedter
Nick Stranges
K. Stump
David Tepen
Michael Thompson
Wayne Timm
John Vergis
Lisa Ward
Iain Wright
Dean Yager
John Yagielski
Oren Yuen
Hugh Zhu

When the IEEE SA Standards Board approved this guide on 7 November 2019, it had the following membership:

Introduction

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

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

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

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

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

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

Contents

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

1. Overview

1.1 Scope

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

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

1.2 Organization of the guide

The guide consists of 12 clauses. Each clause is organized into subclauses.

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

This guide is intended to provide sufficient instructions for performing normally required tests. Throughout this guide, cross-references to subclauses have been used frequently to call attention to pertinent related material. When reference is made to a subclause, it is intended that the reference includes 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 IEEE Std 115-2009 and contains the following updates:

- Updated the procedures to reflect state-of-the-art practices and technology.
- Redrawn some figures to make them more legible and clear.
- Updated references and bibliography.
- Added a definitions clause (see Clause 3) to define the significant terms used in this guide.
- Deleted Clause 8 of the 2009 version and included the contents in Clause 11.
- The testing methods for telephone-influence factor (TIF) have been moved from the main body to Annex C.

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

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

The International System of Units (SI) or metric system of units has been used in this guide. Annex A lists a bibliography, in which the non-normative references cited in the guide are listed. Annex B lists the nomenclature of main symbols. Annex C discusses the telephone influence factor (TIF). Annex D includes the same discussions on leakage and Potier reactance as in Annex C of the 2009 version. Annex E updates the example of calculation of per unit (p.u.) field current of Annex D of the 2009 version. Annex F includes the details on mathematical background for the equations in Clause 11. Annex G includes same discussions on magnetic nonlinearity as in the 2009 version. Annex H includes a new example of standstill frequency response (SSFR) test data analysis for a large synchronous machine. Clause 12 has been updated to include an example of SSFR testing on a large salient-pole machine.

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.

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

Calibrated high-accuracy instrumentation and accessory equipment should be used. When suitable automatic data acquisition systems or high-speed recorders are available, they should 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 help minimize the risk of damage to the machine or operators, it is recommended that all tests be performed either under the manufacturer's supervision or in accordance with the manufacturer's recommendations.

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

2. Normative references

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

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

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

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 for High-Voltage Testing Techniques.

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

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

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

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

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

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

---

[2] ASME publications are available from the American Society of Mechanical Engineers (http://www.asme.org/).
[3] IEC publications are available from the International Electrotechnical Commission (http://www.iec.ch/). IEC publications are also available in the United States from the American National Standards Institute (http://www.ansi.org/).
[4] IEEE publications are available from The Institute of Electrical and Electronics Engineers (http://standards.ieee.org/).
[5] The IEEE standards or products referred to in this clause are trademarks of The Institute of Electrical and Electronics Engineers, Inc.

IEEE Std 95™, IEEE Recommended Practice for Insulation Testing of 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 Guide for Electrical Measurements in Power Circuits.

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

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

IEEE Std 519™, IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems.

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

IEEE Std 1110™, IEEE Guide for Synchronous Generator Modeling Practices and Applications in Power System Stability Analyses.

IEEE Std 1434™, IEEE Guide for the Measurement of Partial Discharges in AC Electric Machinery.

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

ISO 20816-1, Mechanical vibration—Measurement and evaluation of machine vibration—Part 1: General guidelines.

ISO 20816-2, Mechanical vibration—Measurement and evaluation of machine vibration—Part 2: Land-based gas turbines, steam turbine and generators in excess of 40 MW, with fluid-film bearings and rated speeds of 1500 r/min, 1800 r/min, 3000 r/min and 3600 r/min.

ISO 20816-4, Mechanical vibration—Measurement and evaluation of machine vibration—Part 4: Gas turbines in excess of 3 MW, with fluid-film bearings.

ISO 20816-5, Mechanical vibration—Measurement and evaluation of machine vibration—Part 5: Machine sets in hydraulic power generating and pump-storage plants.

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

ISO 9614, Acoustics—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 International Organization for Standardization (http://www.iso.ch/). ISO/IEC publications are also available in the United States from the American National Standards Institute (http://www.ansi.org/).
[7] NEMA publications are available from the National Electrical Manufacturers Association (http://www.nema.org/).

3. Definitions

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

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

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

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

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

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

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

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

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

[8] *IEEE Standards Dictionary Online* is available at http://dictionary.ieee.org.

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

operational impedance: A representation in which the impedance of a system is expressed as a function of the Heaviside operator $p = d/dt$ or the Laplace operator $s = j\omega$. In the modeling of synchronous machines, the Park transformed stator flux linkages per second are often expressed in terms of impedances $Xq(p)$ and $Xd(p)$, termed the quadrature-axis and direct-axis operational impedances, respectively. Using these expressions, the dynamics of the rotor windings are represented within the operational impedances; therefore, the rotor of a synchronous machine can be considered as either a distributed or lumped parameter system.

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

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

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

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

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

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

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

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

4. Miscellaneous tests

4.1 Insulation resistance

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

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

NOTE—While IEEE Std 1095 is written specifically for vertical hydraulic-turbine-driven generators, the procedure is applicable to other types of machines.[9]

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

4.2 Dielectric and partial discharge tests

4.2.1 General

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

WARNING

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

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

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

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

— Method 1. Alternating-voltage testing at power frequency (see 4.2.3)
— Method 2. Direct-voltage testing of stator windings (see 4.2.4)
— Method 3. Very low frequency testing of stator windings (see 4.2.5)
— Method 4. Partial discharge testing (see 4.2.6)

[9] Notes to text, tables, and figures are for information only and do not contain requirements needed to implement the standard.

4.2.2 Preparation

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

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

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

4.2.3 Method 1. Alternating-voltage testing at power frequency

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

- Transformer-voltmeter
- Sphere gap

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

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

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

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

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

Because this testing can be destructive to the winding, some precautions are advised. It should be noted that the test voltage applied during manufacture testing of new windings is a one-time value. For purposes of maintenance testing in subsequent years, it is advisable to apply only a lesser percentage of the original test value. For suggested values, see EPRI EL-5036 [B19].[10]

4.2.4 Method 2. Direct-voltage testing of stator windings

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

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

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

WARNING

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

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

4.2.5 Method 3. Very low frequency testing of stator windings

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

4.2.6 Method 4. Partial discharge testing

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

4.3 Resistance measurements

4.3.1 General

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

4.3.2 Correction to specified temperature

When the resistance, R_t, 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 using Equation (1).

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

where

R_s	is the winding resistance, corrected to specified temperature, t_s, in ohms
t_s	is the specified temperature, in °C
R_t	is the test value of winding resistance, in ohms
t_t	is the temperature of winding when resistance was measured, in °C
k	is the characteristic constant for the winding material (see 7.4.4)

4.3.3 Reference field resistance

The resistance of the field winding is commonly measured at standstill in order to obtain a reference value (R_b) from which to determine field temperature during running tests by the method of 7.4.4. 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.

4.3.4 Reference field resistance from a running test

Although it is preferable to obtain the reference value of field resistance at standstill because both the resistance and temperature can be determined more accurately, it is often advantageous to obtain or verify the reference value by a test made at or near normal speed using the drop-of-potential method. For conductor-cooled rotors, winding temperature may change too rapidly to make this method practicable. The making or relieving of turn-to-turn short circuits in the field winding may cause the measured resistance of the field circuit to differ substantially from the standstill value and thus provide a possible incidental check for short-circuited turns (see 4.4).

Immediately after the machine has been brought up to speed, starting with the rotor at a known uniform temperature, a dc voltage is applied to the field in as small a value as will permit accurate current and voltage measurements. As soon as the current has become constant, the voltage drop across the collector rings should be measured. Since the voltage drop of the normal brushes may be a substantial fraction of the impressed voltage in this test, it is essential that the brush voltage drop be eliminated from the voltage measurement or reduced by special methods of voltage measurement or special test procedures (see 4.3.6).

4.3.5 Field resistance for running temperature tests

To determine the field temperature under specified or desired load conditions, the field resistance should be measured by the drop-of-potential method after the machine has been operated at the required field current and as near as practicable to the required loading conditions long enough for a uniform temperature to be reached. The temperature of the field winding is then determined in accordance with 7.4.4. The resistance obtained from this test is called R_t in Equation (59).

Including brush voltage drop in the measured field voltage may introduce a substantial error in the temperature determination; therefore, it is highly desirable to eliminate or reduce its effect in this test (see 4.3.6).

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

4.3.6 Effect of brush voltage drop

To determine the field resistance of a running machine accurately, it is necessary to obtain the voltage drop across the field winding without including the voltage drop of the brushes supplying the field current. This step is especially important when the field current is very small, e.g., when determining the reference resistance value (see 4.3.4). For this purpose, it is desirable to measure the voltage drop directly across the collector rings, using special brushes that are in contact with the collector rings only during voltage measurement. For this purpose, it is possible to use the following:

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

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

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

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

4.4 Tests for short-circuited field turns

4.4.1 General

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

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

4.4.2 Method 1. Voltage drop, dc

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

4.4.3 Method 2. Voltage drop, ac

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

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

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

4.4.4 Method 3. DC resistance

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

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

4.4.5 Method 4. Exciting coil for cylindrical rotors

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

4.4.6 Method 5. Rotor waveform detection for cylindrical rotors

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

4.5 Polarity test for field poles

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

4.6 Shaft current and bearing insulation

4.6.1 General

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

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

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

— Method 1. Across end shafts (see 4.6.2)
— Method 2. Across bearing oil film, uninsulated bearings (see 4.6.3)

- Method 3. Across bearing insulation (see 4.6.4)
- Method 4. Bearing insulation—Running test (see 4.6.5)
- Method 5. Bearing insulation—Static test (see 4.6.6)
- Method 6. Double insulation (see 4.6.7)

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

4.6.2 Method 1. Across end shafts

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

4.6.3 Method 2. Across bearing oil film, uninsulated bearings

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

4.6.4 Method 3. Across bearing insulation

Many machines have one or more bearings insulated to eliminate shaft currents. For these methods as described in this subclause as well as 4.6.5 through 4.6.7, it is assumed that insulation is located between the bearing and the frame of the machine. To determine the presence of a voltage that will produce shaft currents in such a machine, a low-resistance conductor is connected from the shaft to the uninsulated bearing in order to short-circuit the oil film, and a low-range ac voltmeter (or a high-range ac ammeter) is connected between the shaft and the frame successively at each insulated bearing. Deflection of the instrument indicates the presence of a voltage that will produce shaft currents if the bearing insulation is not present.

4.6.5 Method 4. Bearing insulation—running test

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

4.6.6 Method 5. Bearing insulation—static test

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

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

4.6.7 Method 6. Double insulation

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

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

4.7 Phase sequence

4.7.1 General

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

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

Phase sequence can be tested using the following methods:

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

4.7.2 Method 1. Phase-sequence indicators

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

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

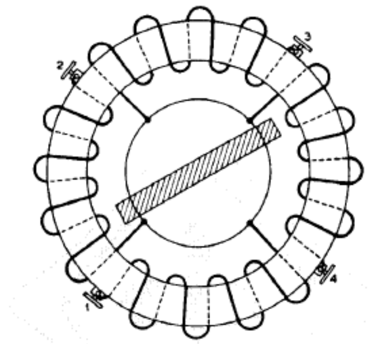


Figure 1—Phase-sequence instrument

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

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

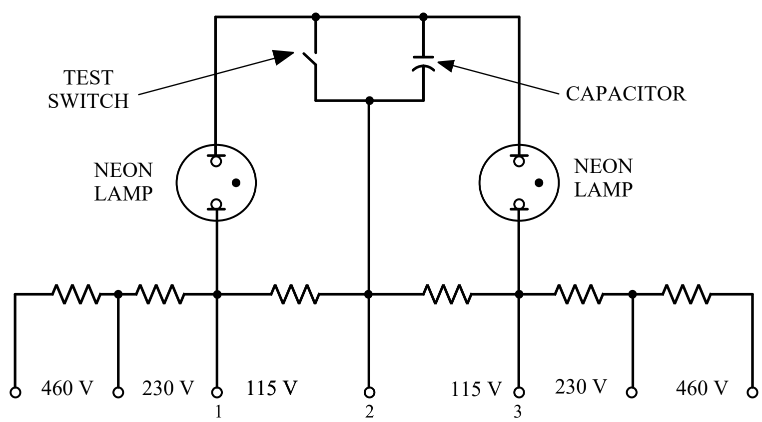


Figure 2—Neon-lamp phase-sequence indicator

4.7.3 Method 2. Indication of differential voltage

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

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

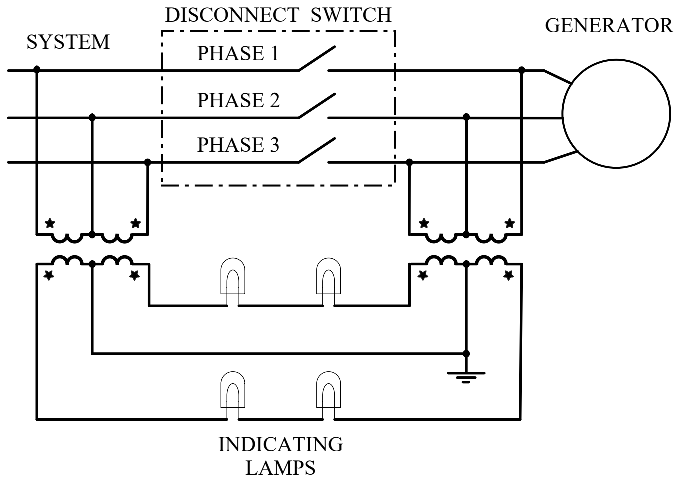


Figure 3—Connection diagram for comparing phase sequence of a generator with that of a system by indicating voltage across an open disconnect switch

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

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

4.8 Stator terminal voltage—waveform deviation and distortion factors

4.8.1 Procedure for testing

For the definition of *deviation and distortion factor*, see the *IEEE Standards Dictionary Online*. 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. 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).

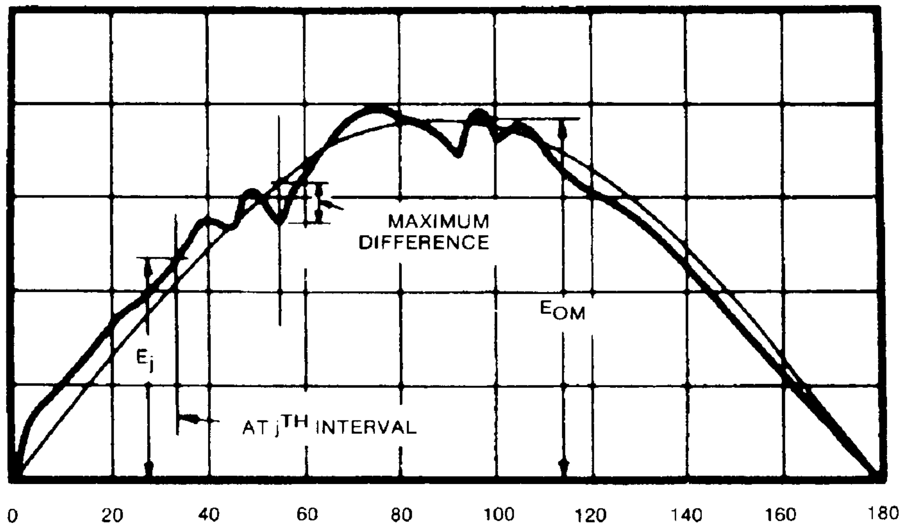


Figure 4—Plot of wave for deviation factor

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 (2).

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

where

E_j is the 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.

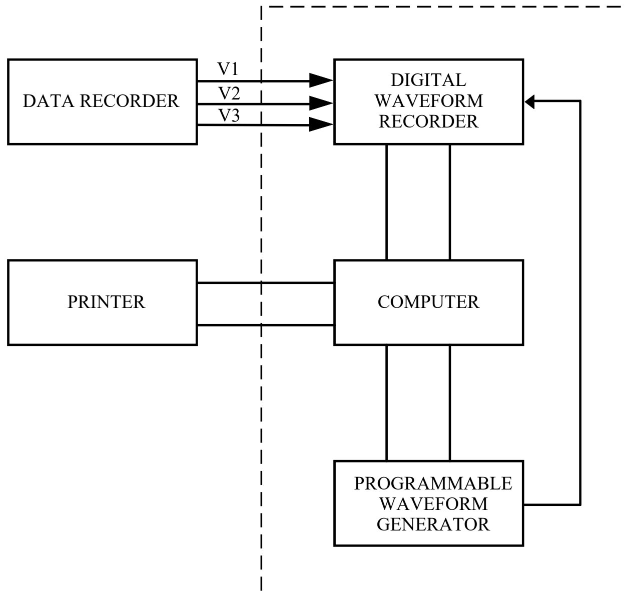


Figure 5—Block diagram of instrumentation used in waveform analysis

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 4.8.2.

4.8.2 Waveform analysis

The maximum value of the deviation between the two waves, when located as described in 4.8.1, may be designated by ΔE . Then the deviation factor, F_{DEV} , is given by Equation (3).

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

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:

$$E_0 = \frac{\sum_{i=1}^{N} E_i}{N} \tag{4}$$

where

E_0 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 E_0 calculated in Equation (4) should then be subtracted from each the sample data points, E_i, in the waveform. The rms value of the input waveform is then calculated by Equation (5).

$$E_{RMS} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(E_i - E_0)^2} \tag{5}$$

Therefore, the zero-to-peak amplitude of the equivalent sine wave, E_{OM}, is as shown in Equation (6).

$$E_{OM} = \sqrt{2}E_{RMS} \tag{6}$$

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 (7).

$$\Delta E = \max\left(\left|E_j - E_{OM}\sin 2\pi\frac{j}{N}\right|\right) \qquad j = 1, 2, \ldots, N \tag{7}$$

4.8.3 Fourier analysis

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

$$a_n = \frac{2}{N}\sum_{j=1}^{N} E_j \cos 2\pi\frac{nj}{N} \qquad n = 1, 2, 3, \ldots \tag{8}$$

$$b_n = \frac{2}{N}\sum_{j=1}^{N} E_j \sin 2\pi \frac{nj}{N} \qquad n = 1,2,3,\ldots \tag{9}$$

$$E_n = \sqrt{a_n^2 + b_n^2} \qquad n = 1,2,3,\ldots \tag{10}$$

$$\phi_n = \begin{cases} \tan^{-1}\dfrac{b_n}{a_n} & a_n > 0 \\ \pi + \tan^{-1}\dfrac{b_n}{a_n} & a_n < 0 \end{cases} \qquad n = 1,2,3,\ldots \tag{11}$$

where

- n is the order of the harmonic component
- a_n is the cosine term of the n^{th} harmonic
- b_n is the sine term of the n^{th} harmonic
- E_n is the rms magnitude of the n^{th} harmonic
- ϕ_n is the relative phase angle of the n^{th} harmonic

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 (12).

$$F_{Di} = \frac{\sqrt{\sum_{n=2}^{K} E_n^2}}{E_{rms}} \tag{12}$$

where E_n is defined in Equation (10) and E_{RMS} is defined in Equation (5).

By digital method, after obtaining the magnitudes of the harmonics, the distortion factor, F_{Di}, can be calculated as shown in Equation (13).

$$F_{Di} = \frac{\sqrt{\sum_{n=2}^{K} E_n^2}}{E_{OM}} \tag{13}$$

where E_n is defined in Equation (10).

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.

4.8.4 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.)

4.9 Overspeed tests

4.9.1 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.

4.9.2 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 4.12 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.

4.10 Line-charging capacity

4.10.1 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 4.10.4.) Line-charging capacity can be measured by the following test methods:

- Method 1. As motor (see 4.10.2)
- Method 2. As generator (see 4.10.3)
- Method 3. As generator (see 4.10.4)

4.10.2 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.

4.10.3 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.

4.10.4 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.

4.11 Acoustic noise

4.11.1 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 workday for various noise levels are set in the United States by the Occupational Safety and Health Administration (OSHA).

4.11.2 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.

4.12 Vibration testing

4.12.1 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.

4.12.2 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.

4.12.3 Large synchronous cylindrical rotor generators—shaft and bearing vibrations

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

Measurements should be made at rated speed per ISO 20816-1. Relative or absolute displacements may be measured, based on the judgment and normal practice of the manufacturer. As a minimum, the magnitude of broadband vibration should be measured and recorded.

Unless specified otherwise by the customer, the machine should be at rated speed under steady-state operating conditions.

Acceptance criteria will be per agreement between buyer and seller, with typical criteria provided in ISO 20816-2 for steam turbine applications and ISO 20816-4 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.

4.12.4 Synchronous generators in hydroelectric applications

4.12.4.1 Shaft and bearing vibrations testing

For synchronous generators used in hydroelectric applications, see ISO 20816-1 for general guidelines and ISO 20816-5 for shaft and bearing vibration testing procedures for hydraulic power generating and pump storage plants. Acceptance criteria will be per agreement between customer and manufacturer, with typical criteria provided in ISO 20816-5 for hydro-generators.

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.

4.12.4.2 Stator core and frame vibrations testing

On synchronous generators in hydroelectric applications, some customers request stator core and stator frame structural vibration assessment as part of their orders. Nowadays, it is important to determine the core and the frame of the stator hydro-generator vibration limits.

An important aging mechanism is vibration or relative movement between laminations of the stator core. Vibration measurement is one way to evaluate whether the core is likely being subjected to mechanical aging and wear.

This guide excludes winding ends vibration limits as available sensors are not widely available and their installation is quite invasive for an acceptance and performance testing.

The vibration measurement methods should be in accordance to the methods described with in ISO 20816-5 and ISO 20816-1. It is difficult to determine a specific vibration limit to apply to the stator and frame; however, this aspect related to the limit of the vibration is well discussed in IEEE Std 62.2. Stator core and frame should not be treated as a monolithic body; results from an inappropriate number of sensors could be a wrong indicator of maximal vibration level.

The vibration on the stator core or on the stator frame could be measured simply at rated condition and sometimes at different power factor by using an accelerometer or velocity probe reading. Vibration amplitude (RMS or 0-peak or peak-to-peak) and predominant frequencies (hertz) should be noted.

Acceleration (or velocity) probes should be immune to magnetic field, shaft currents, dust, and oil vapor as well as residual shaft magnetism and false signals caused by variable shaft material composition or shaft electromagnetic properties. The probe frequency response should cover the bandwidth of 3 Hz to 10 000 Hz. Operating temperature of the probe should be at least 60 °C.

5. Saturation curves, segregated losses, and efficiency

5.1 Saturation curves

5.1.1 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 are distributed approximately as follows:

a) Six readings taken below 60% of rated voltage (1 at zero excitation).
b) From 60% to 110%, readings are 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 are 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 are 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 should be reduced to zero and then increased carefully to the desired value to remove the effects of hysteresis in the results.

The machines need to 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.

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.

5.1.2 Air-gap line

The air-gap line consists of a line that passes through the origin and best approximates the linear, lower portion of the saturation curve and that extends past the point at which the saturation curve ceases to appear to be linear. See Figure 6.

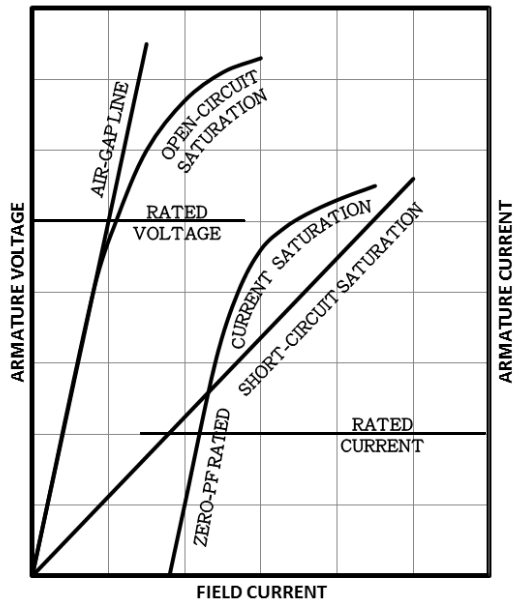


Figure 6—Saturation curves

5.1.3 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 are 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 is checked for each phase.

Current readings are taken with decreasing excitation starting with the value that will produce an armature current equal to the maximum allowable. The highest current point is normally 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.

5.1.4 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 6.2.2). 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.

5.2 General considerations in segregated loss measurements

5.2.1 Elimination of exciter input

If a direct-connected or belted exciter is used for excitation during the loss tests, its power input is deducted from the total input when determining friction and windage loss, core loss, and stray-load loss (see also 5.3.2.6).

5.2.2 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 is 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 need to be considered in establishing conditions of tests for losses for machines where temperature can be adjusted.

5.2.3 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 can 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.

5.2.4 Steam turbine overheating

Occasionally, steam-turbine-driven generators are tested for losses without steam on the turbine blades. During such tests, precautions need 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.

5.2.5 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. It is advisable to obtain the turbine manufacturer’s approval should be obtained before doing 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.

5.2.6 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 are normally 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.

5.3 Methods to measure losses

5.3.1 General

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

— Method 1. Separate drive (see 5.3.2)
— Method 2. Electric input (see 5.3.3)
— Method 3. Retardation (see 5.3.4)
— Method 4. Heat transfer (see 5.3.5)

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.

5.3.2 Method 1. Separate drive

5.3.2.1 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 is chosen 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 needs to be available.

The driving motor needs to 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 will normally either have variable-frequency power for starting or 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 are 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.

5.3.2.2 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.

5.3.2.3 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 (14).

$$P = \frac{nT}{k} \tag{14}$$

where

P	is the power, in kW
n	is the rotational speed, in revolutions per minute (rpm)
T	is the torque, in N·m
k	scaling factor equal to 30 000/π if the torque is in N·m and the power is in kW

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

5.3.2.4 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.

5.3.2.5 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 have been determined previously) from the power input to the driving motor (see 5.2.1).

The friction and windage loss is obtained as the power input to the machine under test, with zero excitation (see 5.3.2.6). The voltage at the machine terminals should be checked, and if any appreciable residual voltage appears, the field may need to 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.

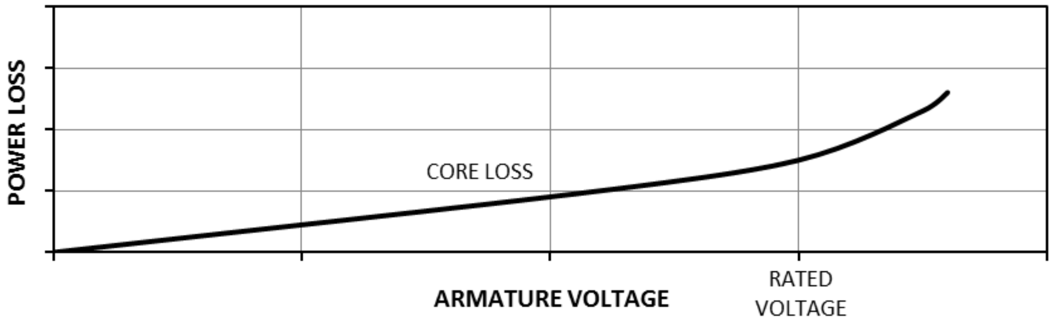


Figure 7—Core loss curve (power loss versus armature voltage)

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.

5.3.2.6 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 5.1.3). At each value of armature current, the power input to the driving motor is measured as described in 5.3.2.5. The driving-motor loss is subtracted from the measured power input to obtain the loss of the machine under test. (See also 5.2.1.) The friction and windage loss, determined as in 5.3.2.5, is subtracted from the loss of the machine to obtain the short-circuit loss.

The temperature of the armature winding can 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.

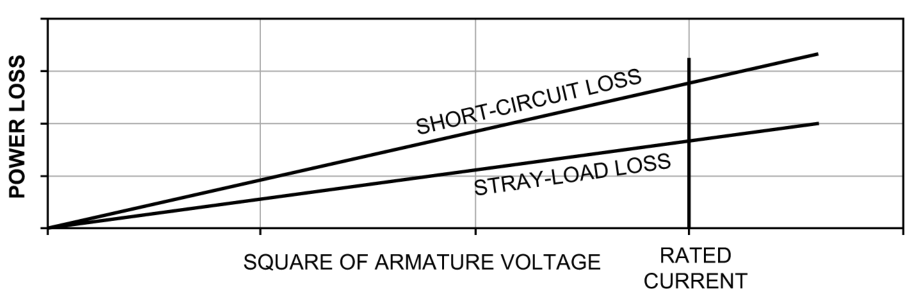


Figure 8—Short-circuit loss and stray-load loss curves

5.3.3 Method 2. Electric input

5.3.3.1 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.

5.3.3.2 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.

5.3.3.2.1 Current transformers

The primary current rating of the current transformers used to test for open-circuit characteristics are usually 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.

5.3.3.2.2 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 normally has 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 5.3.3.8). Since the test is done near zero power factor, highburden voltage transformers are used to reduce the phase angle errors to the high-accuracy, low-burden digital instruments.

5.3.3.3 Voltage on instruments

For low-voltage points and points near normal voltage in the test for open-circuit characteristics, the voltage transformers used 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.

5.3.3.4 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 5.3.3.4.2)
- Method 2. Portable standard watthour meters (see 5.3.3.4.3)
- Method 3. Ordinary watthour meters (see 5.3.3.4.4)

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.

5.3.3.4.1 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 9 is 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 9, or the two wattmeter connection for measuring three-phase power, Figure 10, 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 10, 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 9 and Figure 10. A polyphase wattmeter may also be used.

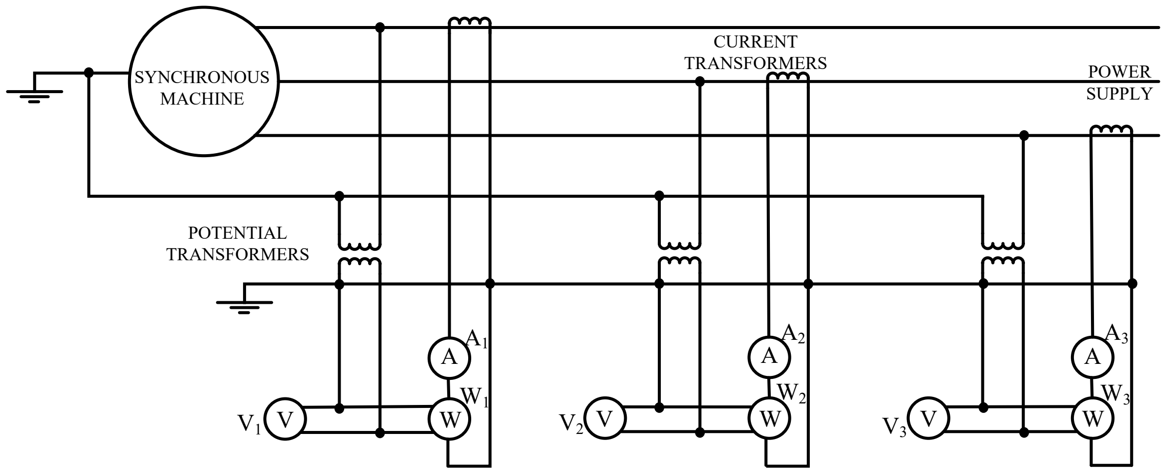


Figure 9—Connection diagram for three-wattmeter method of measuring power

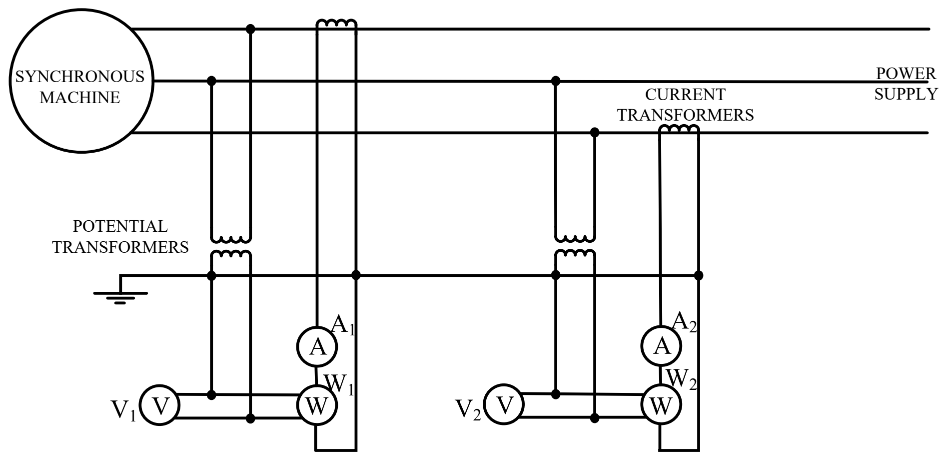


Figure 10—Connection diagram for two-wattmeter method of measuring power

5.3.3.4.2 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.

5.3.3.4.3 Method 2. Portable standard watthour meters

Portable standard watthour meters are connected according to the requirements given in 5.3.3.4.1. 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.

5.3.3.4.4 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.

5.3.3.5 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.

5.3.3.6 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.

5.3.3.7 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 5.1.1 as possible. Readings are 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 5.4). 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 11. 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 12, 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.

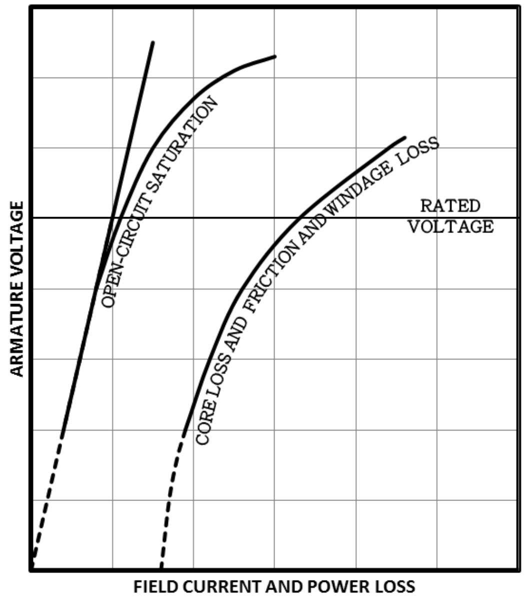


Figure 11—Open-circuit saturation and core loss curves by electric-input method

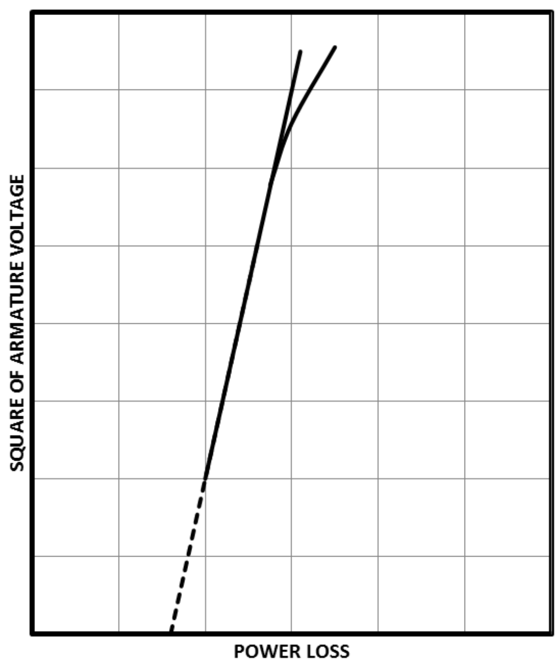


Figure 12—Construction curves for extrapolating loss curves from electric-input method

NOTE—Regarding 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 11.

5.3.3.8 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 is 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 are normally 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 are taken. The temperature of the stator conductors are taken by thermometers located in several places on the end windings or by embedded detectors in machines so equipped.

5.3.3.9 Total loss curve

Figure 13 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-circuits 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 12. 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.

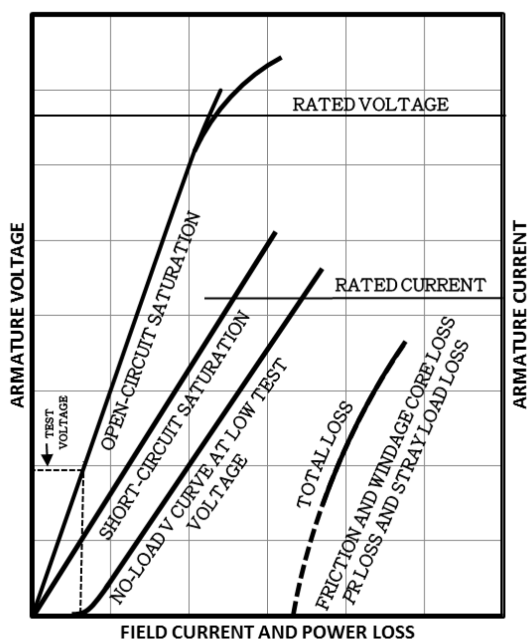


Figure 13—Curves from electric-input method

NOTE—Regarding short-circuit saturation curve, the curve resulting from the plotting of armature current versus field current as obtained in 5.3.3.8 and 5.3.3.9 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.

5.3.4 Method 3. Retardation

5.3.4.1 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 should be made for any apparatus connected to the machine during these tests.

Knowing the rate of deceleration, the loss can be determined by Equation (15).

$$P_{loss} = \left(\frac{\pi}{30}\right)^2 \frac{nJ}{1000}\frac{dn}{dt} \tag{15}$$

where

P_{loss} is the power loss, in kW
$\pi/30$ is the conversion factor from rpm to rd/s
n is the rotational speed in rpm
dn/dt is the rate of deceleration as determined from the slope of speed-time curve at n, in rpm/s
J is the moment of inertia of rotating parts, in kg.m^2

Procedures will be given for obtaining speed-time curves (see 5.3.4.7.1), determining deceleration rates (see 5.3.4.7), and obtaining the moment of inertia (J) of the rotating parts (see 5.3.4.8). Refer to 5.2 for general comments applicable to this method of loss determination.

5.3.4.2 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 may need to be demagnetized by applying field current in alternate directions with successively smaller magnitude.

5.3.4.3 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 is 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 5.3.4.2) from the total open-circuit loss for each test, the open-circuit core loss is obtained.

5.3.4.4 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 is 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 5.3.4.2), 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.

5.3.4.5 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.

5.3.4.5.1 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.

5.3.4.5.2 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 needs to be adjusted continuously to maintain constant excitation on the machine under test, and its power input should be deducted in calculating the results.

5.3.4.5.3 Other mechanically connected apparatus

The inertia, J, of the prime mover and any other mechanically connected apparatus is 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, is multiplied by the square of the ratio of its speed to the machine speed before adding it to the machine inertia.

5.3.4.6 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 is normally uncoupled, but if this step is not possible, it should be dewatered (see 5.2.5 and 5.2.6). 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 can 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.

5.3.4.6.1 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 are 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.

5.3.4.6.2 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 needs to 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.

5.3.4.7 Methods to determine deceleration

Three methods to determine deceleration are covered in this guide:

- Method 1. Speed-time (see 5.3.4.7.1)
- Method 2. DC generator (see 5.3.4.7.2)
- Method 3. Electronic counter (see 5.3.4.7.3)

5.3.4.7.1 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 are plotted from the test data. Figure 14 shows typical retardation curves. For each curve, the loss at any speed may be calculated by means of Equation (15).

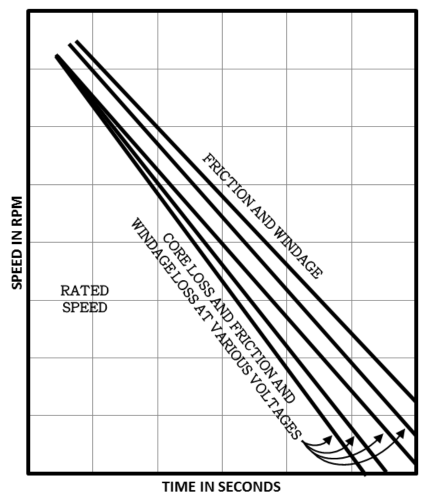


Figure 14—Typical retardation curves

The loss may be determined from several points on the speed-time curve and the slope of a tangent at each point using Equation (15). 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 (15) 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 (15) 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 $n_1 = n_s + A$, and $n_1 = n_s + A$). 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 (16).

$$P_{loss} = \left(\frac{\pi}{30}\right)^2 \frac{n_s J}{1000} \frac{2A}{t_2 - t_1} \tag{16}$$

where

- P_{loss} is the calculated power losses, in kW
- $\pi/30$ is the conversion factor from rpm to rd/s
- n_s is the synchronous speed in rpm
- A is the speed increment above and below n_s, in rpm, that define the time instants t_1 and t_2
- $t_2 - t_1$ 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 kg.m^2

5.3.4.7.2 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 can 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 are made so that the voltage of the dc generator will be opposed to the voltage of a second battery (NO. 2). (See Figure 15 for a typical diagram of connections.)

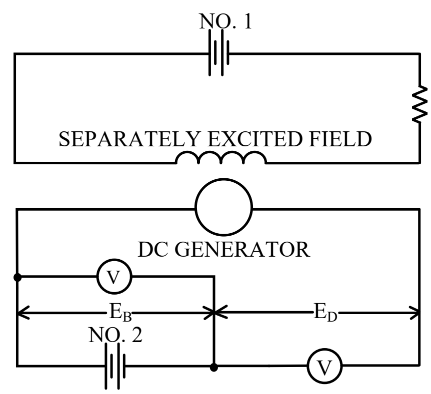


Figure 15—Speed measurement by dc generator

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 are 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 shown in Equation (17).

$$n = K(E_D + E_B) \tag{17}$$

where

- n is the speed at the test point, in rpm

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

and, similarly, see Equation (18).

$$n_C = K(E_{DC} + E_B) \quad \Leftrightarrow \quad K = \frac{n_C}{E_{DC} + E_B} \tag{18}$$

where

n_C is the known speed, in rpm, at which losses are to be determined (usually rated speed)
E_{DC} is the differential voltage at speed n_C

Then, considering that the battery voltage E_B is constant, see Equation (19).

$$\frac{dn}{dt} = K\frac{dE_D}{dt} = \frac{n_C}{E_{DC} + E_B}\frac{dE_D}{dt} \tag{19}$$

where

dn/dt is the rate of deceleration, in rpm/s
dE_D/dt is the rate of decrease of differential voltage, in volts 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 is 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 (20).

$$P_{loss} = \left(\frac{\pi}{30}\right)^2 \frac{J}{1000}\frac{n_C^2}{E_{DC} + E_B}\frac{dE_D}{dt} \tag{20}$$

where

P_{loss} is the calculated power losses, in kW
$\pi/30$ is the conversion factor from rpm to rd/s
J is the moment of inertia of rotating parts, in kg.m^2

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 help 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 5.3.4.3) 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 help 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.

5.3.4.7.3 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 (21) and Equation (22).

$$n = \frac{30n_r(t_1 + t_3)}{t_1 t_3} \tag{21}$$

$$\frac{dn}{dt} = \frac{60n_r(t_3 - t_1)}{t_1 t_3 (t_1 + t_3)} \tag{22}$$

where

- n is the speed, in rpm
- dn/dt is the angular deceleration, in rpm/s
- 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 time intervals t_1 and t_3 and also 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 (21) and Equation (22).

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 (15) determines the loss.

NOTE—Regarding open-circuit and short-circuit saturation curves: Saturation curves should be obtained while driving the unit at rated speed if possible (see 5.3.2.4, 5.3.2.5, 5.1.3, and 5.3.3.8). The open-circuit saturation curve can be checked by data from the open-circuit retardation tests (see 5.3.4.3) 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 5.3.4.4). 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.

5.3.4.8 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 (see 5.3.4.8.1)

- Method 2. Speed retardation without excitation (see 5.3.4.8.2)
- Method 3. Speed retardation with excitation (see 5.3.4.8.3)
- Method 4. Speed retardation with direct-connected exciter (see 5.3.4.8.4)
- Method 5. Physical pendulum (see 5.3.4.8.5)

5.3.4.8.1 Method 1. Manufacturer

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

5.3.4.8.2 Method 2. Speed retardation without excitation

The friction and windage loss is first determined by the separate-driving-motor method (see 5.3.2.5). 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 (15).

5.3.4.8.3 Method 3. Speed retardation with excitation

The machine is run as an unloaded synchronous motor at normal speed at approximately unity power factor (see 5.3.3.7). The power input is measured; this power input includes friction and windage, core, and copper losses. The copper loss is 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 (14) with the known losses to obtain the J.

5.3.4.8.4 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.

5.3.4.8.5 Method 5. Physical pendulum

When the value of J is to be utilized for the determination of losses (see 5.3.4) or the determination of torque (see 8.3.3), the physical pendulum method can 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 is displaced and allowed to rock freely in the bearings, and the time required to make several oscillations is accurately measured with a stopwatch. The radius of gyration, R_g, in SI units, may then be calculated by means of Equation (23).

$$R_g = R_2\sqrt{\frac{gt^2}{4\pi^2(R_1 - R_2)} - 1} \tag{23}$$

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 constant due to gravity (9.807 m/s^2)

Then, see Equation (24).

$$J = MR_g^2 \tag{24}$$

where

M is the mass of the rotor, in kg

Alternatively, a balanced rotor of known weight, supported by its shaft resting on two horizontal rails in such a way that its axis is level, becomes a physical (compound) pendulum when an unbalance is rigidly attached to its perimeter. In case the two journals are not the same diameter, it is necessary to equip the small journal with a close-fitting bushing to build it up to the size of the larger. When the geometry, mass, and position of such unbalance are known, the period of oscillation is accurately measured, and the value of J may then be calculated by using Equation (25).

$$J = \frac{g}{4\pi^2} t^2 Ub - Ma^2 - U(b-a)^2 \tag{25}$$

where

J is the moment of inertia (gravity) of rotating parts, in kg.m^2
g is the acceleration constant 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 the added unbalance, in kg
M is the mas of the balanced rotor, in kg

5.3.5 Method 4. Heat transfer

5.3.5.1 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 (26) measures the loss absorbed by the water.

$$P_{loss} = 4.187(t_h - t_c)Q \tag{26}$$

where

P_{loss} is the calculated power losses, in kW
t_h is the temperature of water leaving cooler, in °C
t_c is the temperature of water entering cooler, in °C
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 is 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 (26) or from the quantity of circulated oil and oil temperature rise as shown in Equation (27).

$$P_{loss} = 4.187\, c_p\, G\, Q (t_h - t_c) \tag{27}$$

where

P_{loss}	is the calculated power losses, in kW
c_p	is the specific heat of the oil (relative to water)
G	is the specific gravity of the oil (relative to water); heat and gravity evaluated at the average temperatures t_h and t_c
t_h	is the temperature of water leaving cooler, in °C
t_c	is the temperature of water entering cooler, in °C
Q	is the rate of oil flow, in 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 help 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:

$$P_{loss} = 12.4 (t_r - t_a) \tag{28}$$

where

P_{loss}	is the calculated heat loss per unit area, in watts per square meters
t_r	is the average temperature of the entire radiating surface, in °C
t_a	is the ambient temperature, in °C

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

5.4 Efficiency

5.4.1 Introduction

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 5.4.2).

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 4.3.1 and 4.3.2)
e) Field I^2R_f loss using the field current (see Clause 6) and the field resistance corrected to a specified temperature (see 4.3)

Efficiency can be measured by the following methods:

— Method 1. Segregated losses (see 5.4.2)
— Method 2. Input-output (see 5.4.3)

5.4.2 Method 1. Segregated losses

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

— For a generator:

$$\text{efficiency (\%)} = 100 - 100\frac{P_{loss}}{P_{output} + P_{loss}} = 100\left(\frac{P_{output}}{P_{output} + P_{loss}}\right) \tag{29}$$

— For a motor:

$$\text{efficiency (\%)} = 100 - 100\frac{P_{loss}}{P_{input}} = 100\left(\frac{P_{input} - P_{losses}}{P_{input}}\right) \tag{30}$$

where

P_{loss} is the calculated segregated losses
P_{output} is the measured generator electrical power output
P_{input} is the measured motor electrical power input

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.

5.4.3 Method 2. Input-output

The efficiency from the input-output method is determined as shown in Equation (31).

$$\text{efficiency (\%)} = 100\frac{P_{output}}{P_{input}} \tag{31}$$

where

P_{output} is the power output of the machine
P_{input} is the power input of the machine

The power output and input are expressed in the same units.

The preferable method of measuring either mechanical input to a generator or mechanical output of a motor is to use a dynamometer.

Mechanical power input (generator) or output (motor) is obtained from Equation (32).

$$P_{mech} = \frac{nT}{k} \tag{32}$$

where

P_{mech} is the mechanical power (input of a generator, output of a motor), in kW
n is the rotational speed, in rpm
T is the measured torque, in units consistent with scaling factor, k
k is the scaling factor, for example, equal to 30,000/π if the torque, T, is in N·m

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 is 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.

6. Load excitation

6.1 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.

6.2 Test methods

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

a) Open-circuit saturation curve (see 5.1.1)
b) Armature resistance, R_a (see 4.3)
c) Unsaturated direct-axis synchronous reactance, X_{du} (see 10.3)
d) Unsaturated quadrature-axis synchronous reactance, X_{qu} (see 10.4)

6.2.1 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, $X_\ell = X_{du} - X_{adu}$.)

The inductance, 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 Clause 3). 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.

6.2.2 Methods to determine Potier reactance

6.2.2.1 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 5.1.1 and 5.1.4). Typical curves are plotted in Figure 16.

The intersection of the zero-power-factor saturation curve with the rated-voltage ordinate locates the point *d*, as shown in Figure 16. 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 16.

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, in per unit, is equal to the product of the rated per unit armature current and per unit 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.

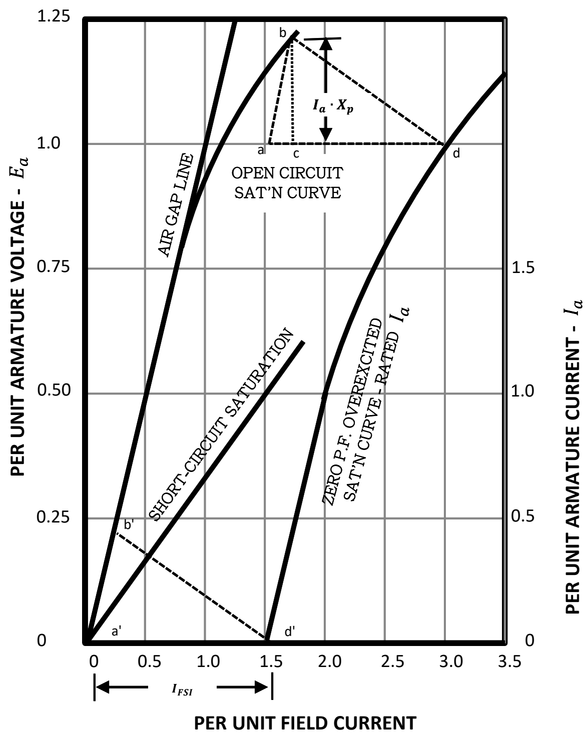


Figure 16—Determination of Potier reactance voltage

6.2.2.2 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 per unit value of X_P. The unsaturated direct-axis synchronous reactance, 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 per unit value of excitation or per unit value of field current, I_{FU}, as described in 6.3.2.2 or 6.3.2.3.
b) Determine the per unit 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 19 in 6.3.2.3).
c) Determine $I_{FS} = I_F - I_{FU}$.

d) Using any desired fitting process, determine the per unit value of E_P (the voltage behind Potier reactance) on the ordinate of, for example, Figure 19. 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 17 indicates the actual phase relationship between E_a, in per unit, and I_a, in per unit. The power-factor angle, ϕ, is also shown. The magnitude of E_P has been determined in step d).

f) The per unit magnitude of the phasor $E_P - E_a$ can now be determined by Equation (33).

$$\left|E_P - E_a\right| = \sqrt{E_P^2 - (E_a \cos\phi \pm I_a R_1)^2} - E_a \sin\phi \tag{33}$$

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,

$$X_P = \frac{\left|E_P - E_a\right|}{\left|I_a\right|} \tag{34}$$

where

I_a is the per unit 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 5.1.4, 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 17. The convention for positive angle in these phasor diagrams is that phase *rotation* is counterclockwise.

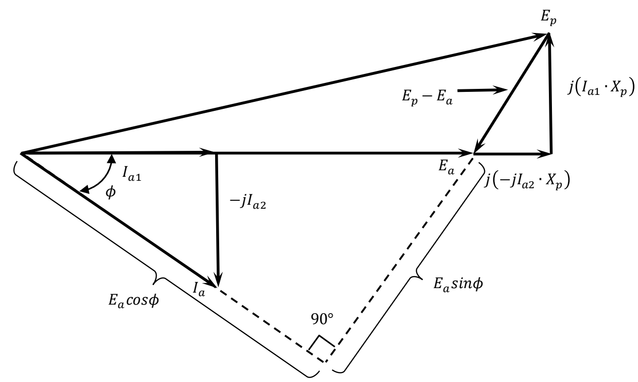


Figure 17—Calculation of magnitude of E_P - E_a

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

6.3 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 (see 6.3.1)
— Method 2. Phasor diagram analysis (see 6.3.2)
— Method 3. Potier reactance without machine saliency (see 6.3.3)

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

6.3.1 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 7.2.2).

6.3.2 Method 2. Phasor diagram analysis

6.3.2.1 Terminology and definitions

The following terminology is used in 6.3.2.2 and 6.3.2.3, 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 19).

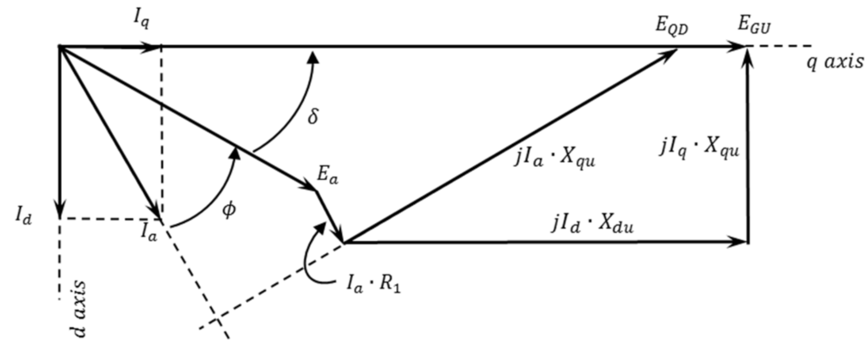
E_P is the voltage back of Potier reactance, X_P, in per unit.

R_1 is the positive sequence resistance (see 10.7) and generally assumed to be equal to R_a, the stator resistance per phase.

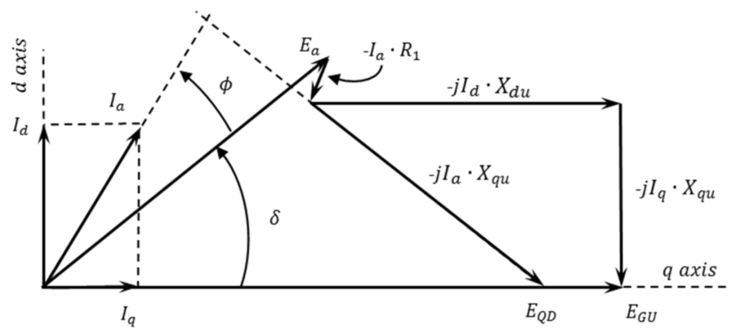
I_{FG} is the 1.0 p.u. field amperes corresponding to $E_a = 1.0$ p.u. on the air-gap line.

6.3.2.2 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 18. The following procedures are used for salient-pole machines for generators and motors.



a) Generator notation



b) Motor notation

Figure 18—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, and the minus sign should be used when a minus-or-plus sign is encountered. Conversely, for motor notation, the minus sign should be used when a plus-or-minus sign is encountered, and the plus sign should be used when a minus-or-plus sign is encountered.

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) Calculate the phasor E_{QD} and determine the phase angle δ between the phasors E_a and E_{QD}.

$$\begin{aligned} E_{QD} &= E_a \pm (R_1 + jX_{qu})I_a = |E_a| \pm (R_1 + jX_{qu})|I_a|(\cos\phi + j\sin\phi) \\ &= |E_a| \pm |I_a|(R_1\cos\phi - X_{qu}\sin\phi) \pm j|I_a|(R_1\sin\phi + X_{qu}\cos\phi) \end{aligned} \tag{35}$$

$$\delta = \tan^{-1}\frac{\pm|I_a|(R_1\sin\phi + X_{qu}\cos\phi)}{|E_a| \pm |I_a|(R_1\cos\phi - X_{qu}\sin\phi)} \tag{36}$$

b) Once the angle δ is determined, the terminal current, I_a, can be expressed in terms of components in phase with the phasor E_{QD} (i.e., a component in the direction of the *quadrature* axis) and in quadrature with the phasor E_{QD} (i.e., a component in the direction of the *direct* axis).

$$I_d = |I_a| \sin(\delta - \phi) \underline{/\delta - 90} \quad (37)$$

$$I_q = |I_a| \cos(\delta - \phi) \underline{/\delta} \quad (38)$$

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) Calculate the phasor E_{GU}.

$$E_{GU} = E_a + R_1 I_a + jI_q X_{qu} + jI_d X_{du} \quad (39)$$

d) Determine I_{FU} by locating E_{GU} on the air gap line (Figure 19 is illustrative).

e) Calculate E_P, the voltage behind the Potier reactance, X_P.

$$E_P = E_a + I_a (R_1 + jX_P) \quad (40)$$

For motor notation, all the plus signs in Equation (39) and Equation (40) become minus signs.

f) Find the saturation increment, I_{FS}, the difference between the field current value required to induce E_P on the air-gap line and value of field current corresponding to E_P on the open-circuit saturation curve (see Figure 19).

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

A numerical example is given in Annex E.

6.3.2.3 Cylindrical rotor machines

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

a) Calculate the unsaturated generated voltage.

$$E_{GU} = E_a + I_a (R_1 + jX_{du}) \quad (41)$$

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

c) Calculate E_P, the voltage behind the Potier reactance.

$$E_P = E_a + I_a (R_1 + jX_P) \quad (42)$$

d) Find the incremental field current, I_{FS}, to account for saturation (see Figure 19).

e) Calculate the overall field current, which, as in 6.3.2.2, is equal to the sum of I_{FU} and I_{FS}.

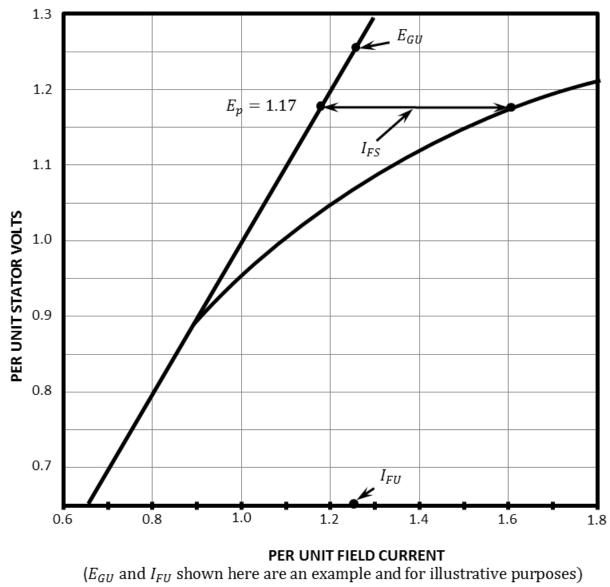


Figure 19—Typical open-circuit saturation curve for a 2400 kVA generator

6.3.3 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, behind the Potier reactance as shown in Equation (43) and Figure 20.

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.

$$E_P = \sqrt{(E_a \cos\phi \pm I_a R_1)^2 + (E_a \sin\phi \pm I_a X_P)^2} \tag{43}$$

where

- E_P is the voltage behind the Potier reactance, in per unit
- X_P is the Potier reactance, in per unit
- E_a is the specified armature (terminal) voltage, in per unit
- I_a is the specified armature (terminal) current, in per unit
- R_1 is the positive-sequence resistance of the armature, in per unit. The armature resistance, 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
- $I_a R_1$ is the voltage drop for the armature resistance and is positive for a generator and negative for a motor

NOTE—The sign convention for ϕ , the power-factor angle, as used in Equation (43) and Equation (44) is opposite to that used in the phasor diagram analysis of 6.3.2.2. The usage in 6.3.2.2 is common today in stability and excitation analysis of synchronous machines. This subclause, 6.3.3, 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.

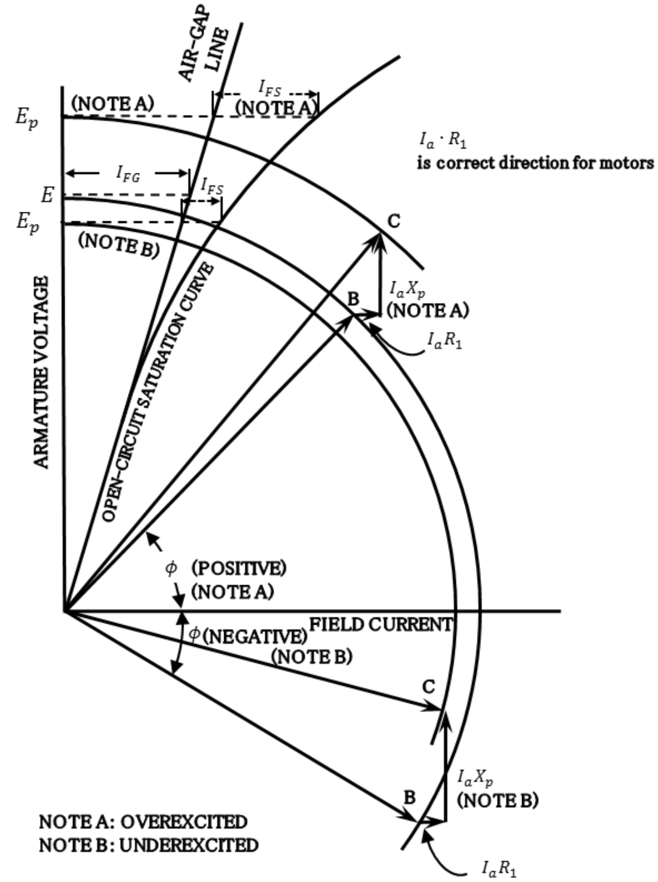


Figure 20—Diagram for voltage behind the Potier reactance for synchronous generator

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 21 and Figure 22. 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 21 and Figure 22 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} .

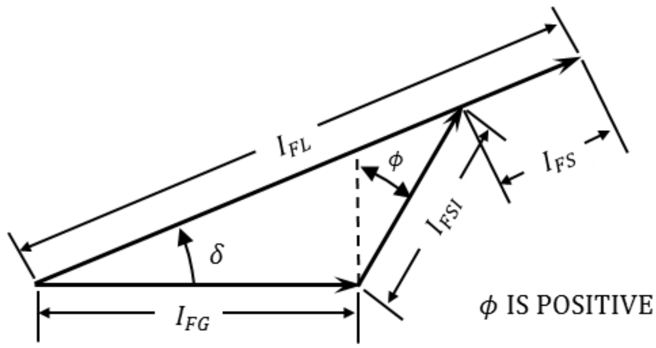


Figure 21—Determination of load field current overexcited operation (motor or generator)

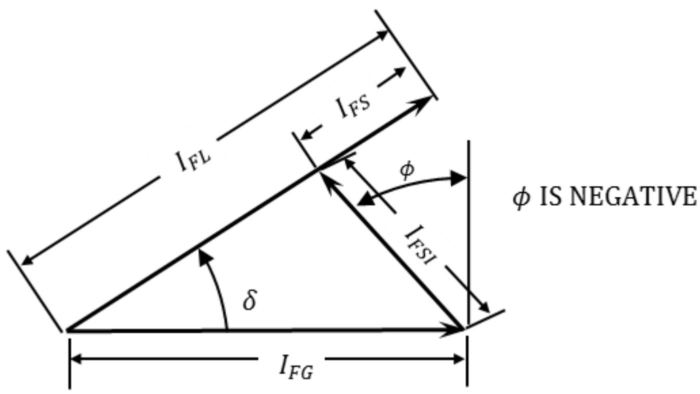


Figure 22—Determination of load field current underexcited operation (motor or generator)

The value of I_{FL}, the load field current, can also be determined by Equation (44).

$$I_{FL} = I_{FS} + \sqrt{(I_{FG} + I_{FSI}\sin\phi)^2 + (I_{FSI}\cos\phi)^2} \tag{44}$$

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 5.1.1 and Figure 16 and Figure 19)
- I_{FSI} is the field current corresponding to the specified armature current on the short-circuit saturation curve (see 5.3.2.5)
- 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 20)

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

6.4 Excitation calculation methods used in stability computer programs

There are many methods available for calculating load excitation (or per unit 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 (45).

$$T_e = \psi_d i_q - \psi_q i_d \tag{45}$$

All the quantities in Equation (45) 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 23 depicts the load excitation calculation process. From this figure, the basic equation for field excitation is, in per unit, is shown in Equation (46).

$$E_I = X_{adu} i_{fd} = E'_q + j(X_{du} - X'_d) I_d \tag{46}$$

An open-circuit saturation curve is used to determine the saturation increment function. In this case, the voltage behind the subtransient reactance X'', disregarding subtransient saliency effects, E'', (rather than E_P or E_I) is used to calculate an increment $\Delta(X_{adu}\ i_{fd})$. This increment 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''. (See IEEE Std 1110 for more detail.) $\Delta(X_{adu}\ i_{fd})$ is added to E_I to give a total excitation. Field excitation E_I, in per unit, is based on the nonreciprocal base for the per unit system (see 9.2.5.2).

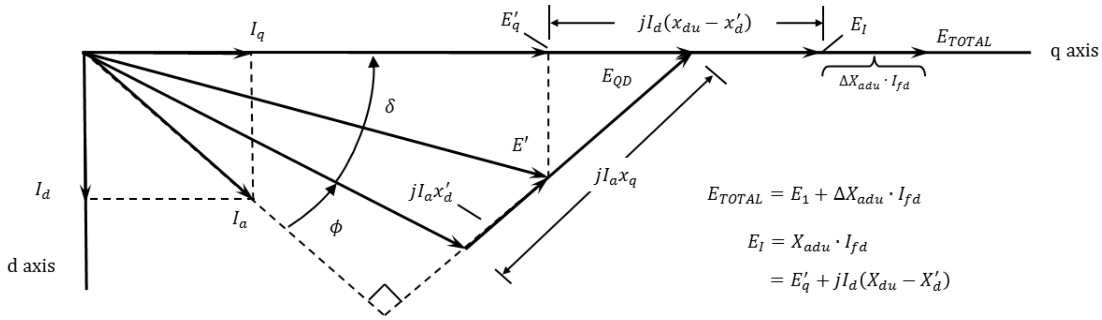


Figure 23—Phasor diagram for calculating $X_{adu}\, i_{fd} (=E_i)$

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 equivalent circuit 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 (46)] 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 24. Thus, see Equation (47).

$$X_{ads} i_{fd} = E_q + jX_{ds} I_d \tag{47}$$

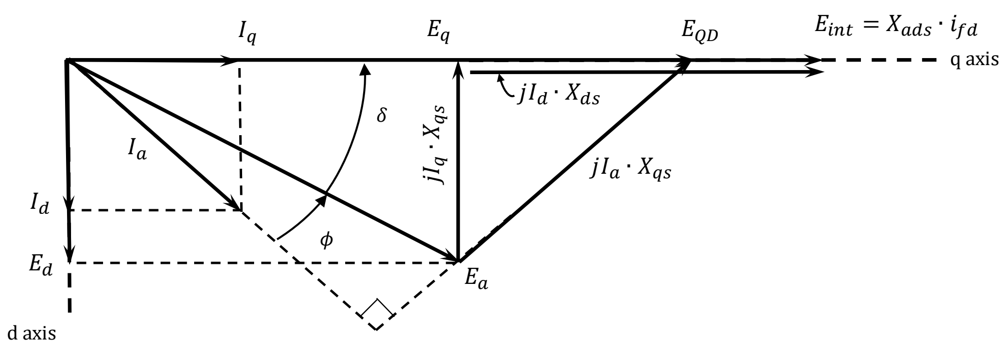


Figure 24—Phasor diagram for calculating $X_{ads}\, i_{fd}$

Field current, i_{fd}, in per unit, is calculated directly and is based on the reciprocal system (see Rankin [B40] and IEEE Std 1110). X_{ads} equals X_{adu} divided by the saturation factor, K_d ($X_{ds} = X_{ads} + X_\ell$; see Figure 25.) 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.

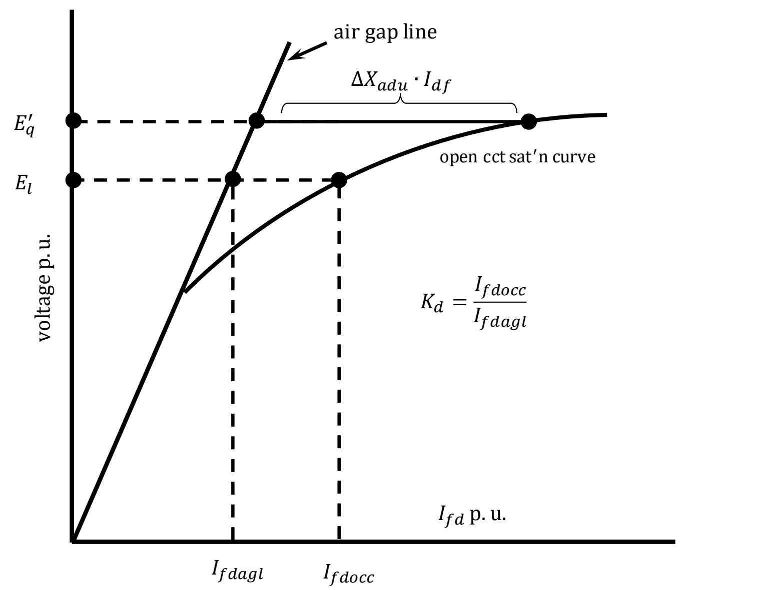


Figure 25—Calculation of saturation functions for adjustments to Equation (46) and Equation (47)

The saturation factor, 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, see Equation (48).

$$K_d = \frac{I_{fdocc}}{I_{fdag\ell}} \tag{48}$$

A similar procedure can be used for calculating K_q, using a quadrature-axis "air-gap line" and a derived quadrature-axis saturation curve, as described also in IEEE Std 1110.

7. Temperature tests

7.1 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.

7.2 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 (see 7.2.1)
- Method 2. Synchronous feedback (see 7.2.2)
- Method 3. Zero power factor (see 7.2.3)
- Method 4. Open-circuit and short-circuit loading (see 7.2.4)

7.2.1 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, disable it 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 26. 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 26.
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 26.

NOTE—Figure 27 shows a plot of temperature rise against field losses. Similar plots of armature and stray load losses may be performed as shown in 5.3.2. These plots are not part of Method 1.

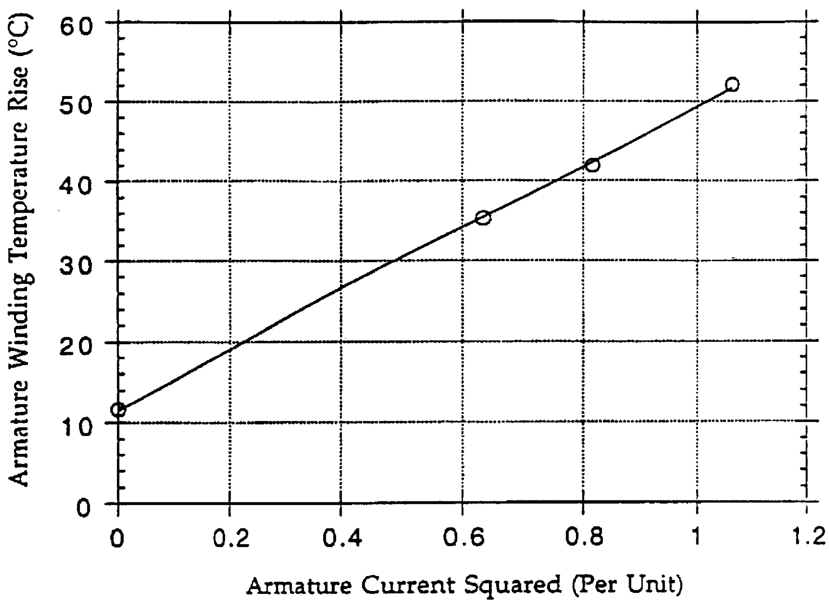


Figure 26—Typical plot of armature winding temperature rise versus armature current squared

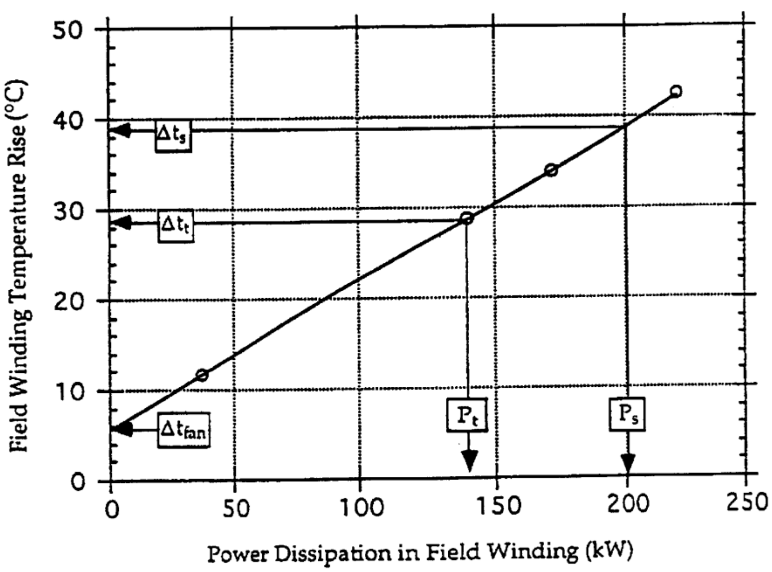


Figure 27—Typical curve of field temperature versus field power

7.2.2 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 reduce 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 4.7) 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. Measure either frequency or speed. 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.

7.2.3 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.

7.2.3.1 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 (43) using either a measured or calculated value of reactance. This voltage may also be calculated by Equation (40) using $I_a X_P$ as determined from 6.2.2.1 or 6.2.2.2, 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 26. It is sometimes impractical to use a variable voltage power supply for testing large machines in this manner. Refer to 7.2.3.2 if the armature voltage cannot be adjusted in accordance with this subclause.

The field-winding losses differ considerably from those of normal operating conditions. Correct the observed temperature rises of the field to correspond to the specified field current. Two equations have been used to make this correction. They appear below as Equation (53) and Equation (56). There are elements of approximation in both equations.

As seen in Figure 27, 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 (56), this linear relationship can be expressed as shown in Equation (49).

$$\Delta t_s + t_{c,s} = (\Delta t_{fan} + t_{c,s}) + \beta P_s \tag{49}$$

where

β is the slope of the temperature rise, which can be determined empirically using Equation (50)

$$\beta = \frac{(\Delta t_t + t_{c,t}) - (\Delta t_{fan} + t_{c,t})}{P_t - 0} = \frac{(\Delta t_t - \Delta t_{fan})}{P_t} \tag{50}$$

Equation (49) and Equation (50) can be combined to form Equation (51).

$$\Delta t_s = \Delta t_{fan} + \frac{P_s}{P_t}(\Delta t_t - \Delta t_{fan}) \tag{51}$$

where

$$\frac{P_s}{P_t} = \left(\frac{P_{f,s}}{I_{f,r}}\right)^2 \frac{R_s}{R_t} \tag{52}$$

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

$$\Delta t_s = \Delta t_{fan} + \left(\frac{I_{f,s}}{I_{f,r}}\right)^2 (\Delta t_t - \Delta t_{fan}) \tag{53}$$

Otherwise, one must account for the temperature effect on resistance in Equation (49) (see 4.3.2) by using Equation (54).

$$\frac{R_s}{R_t} = \frac{k + t_{c,s} + \Delta t_s}{k + t_{c,t} + \Delta t_t} \tag{54}$$

Successive substitution of Equation (54) for R_s / R_t in Equation (52) and then Equation (52) for P_s / P_t in Equation (51) yields Equation (55),

$$\Delta t_s = \Delta t_{fan} + \left(\frac{I_{f,s}}{I_{f,t}}\right)^2 \left(\frac{k + t_{c,s} + \Delta t_s}{k + t_{c,t} + \Delta t_t}\right)(\Delta t_t - \Delta t_{fan}) \tag{55}$$

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 (56) for the specified temperature rise as a function of specified field current.

$$\Delta t_s = \Delta t_{fan} + \left(\frac{I_{f,s}}{I_{f,t}}\right)^2 (\Delta t_t - \Delta t_{fan})\left[\frac{k + t_{c,s} + \Delta t_{fan}}{k + t_{c,t} + \Delta t_t - \left(\frac{I_{f,s}}{I_{f,t}}\right)^2 (\Delta t_t - \Delta t_{fan})}\right] \tag{56}$$

where

Δt_s is the temperature rise, in °C, corrected to correspond to a field current, $I_{f,s}$, for a specified load
k is the constant of the field winding material (see 7.4.4)
$t_{c,s}$ is the specified coolant temperature, in °C, for specified field current, $I_{f,s}$
$t_{c,t}$ is the reference coolant temperature, in °C, obtained during measurement of temperature rise, Δt_t
Δt_t is the temperature rise, in °C, for test field current, $I_{f,t}$
Δt_{fan} is the temperature rise, in °C, 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

7.2.3.2 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 7.2.3.1 because of field heating limits. In such cases, the armature current or the terminal voltage must be reduced. The choice of which element to reduce 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, correct the field temperature as shown in Equation (56). 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:

$$P_A \Delta t_R = \sum_{t_1}^{t_2} (P_V + P_I)_o \Delta t_o + \sum_{t_1}^{t_2} (P_V + P_I)_M \Delta t_u \tag{57}$$

$$P_F \Delta t_R = \sum_{t_1}^{t_2} P_{Fo} \Delta t_o + \sum_{t_1}^{t_2} P_{Fu} \Delta t_u \tag{58}$$

where

P_A is the total armature losses at the specified load, in kW
P_F is the total field losses at the specified load, in kW
Δt_R is the time interval of the test ($t_2 - t_1$), in seconds
P_{Fo} is the field losses during overexcitation, in kW
P_{Fu} is the field losses during underexcitation, in kW
P_I is the current-dependent armature loss, in kW

P_V is the voltage-dependent armature loss, in kW
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.

This method is limited to continuous duty machines due to its imperfect simulation of the loss energy dissipation rates (see 7.3.1).

7.2.4 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. It is strongly recommended that manufacturer's approval 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 7.2.3.2. 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 28). 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.

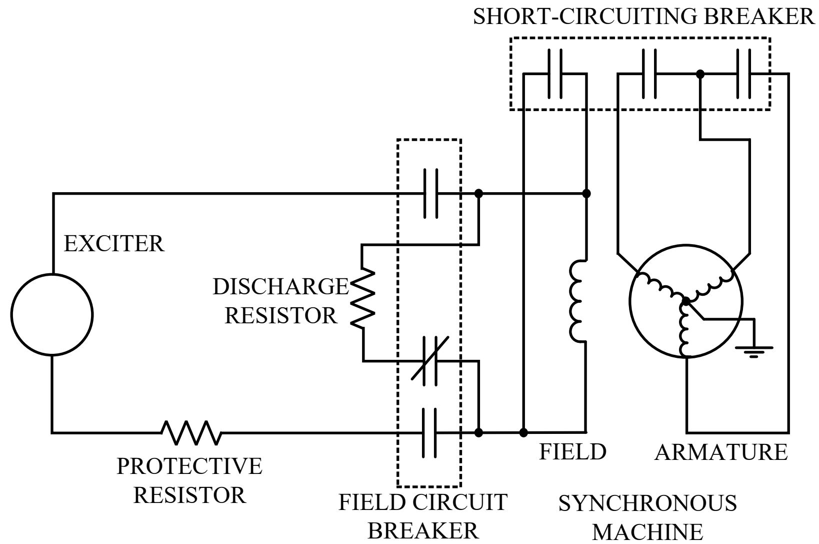


Figure 28—Field winding circuit for open-circuit and short-circuit loading (Method 4)

7.3 Duration of test

7.3.1 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. Continue the test if the coolant temperature for three half-hourly readings varies by more than 2 °C.

7.3.2 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.

7.3.3 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.

7.4 Methods to measure temperature

7.4.1 General

Temperatures may be measured using the following methods:

- Method 1. Resistance thermometer or thermocouples (see 7.4.2)
- Method 2. Embedded detector (see 7.4.3)

— Method 3. Winding resistance (see 7.4.4)
— Method 4. Local temperature detector (see 7.4.5)
— Method 5. Infrared thermography (see 7.4.6)
— Method 6. Fiber optic sensor (see 7.4.7)

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

7.4.2 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.

7.4.3 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.

7.4.4 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 (59).

$$t_t = t_b + \left(\frac{R_t - R_b}{R_b}\right)(t_b + k) \tag{59}$$

where

t_t is the total temperature of winding when R_t was measured, in °C
R_t is the resistance measured during the test, in ohms (see 4.3)
R_b is the reference value of resistance previously measured at known temperature, t_b, in ohms (see 4.3)
t_b is the temperature of winding when reference value of resistance R_b was measured, in °C
k is 234.5 for pure copper, in °C
k is 225 for aluminum based on a volume conductivity of 62% of pure copper, in °C

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

$$k = \frac{R_0}{\dfrac{R_{0a}}{k_a} + \dfrac{R_{0c}}{k_c}} \tag{60}$$

where

R_0 is the calculated total resistance of the winding at 0 °C, in ohms
R_{0a} is the calculated resistance of the aluminum portion of the winding at 0 °C, in ohms
R_{0c} is the calculated resistance of the copper portion of the winding at 0 °C, in ohms

k_c is 234.5 for pure copper, in °C

k_a is 225 for aluminum based on a volume conductivity of 62% of pure copper, in °C

Since a small error in measuring the reference value resistance will make a comparatively large error in determining temperature, measure the winding resistance 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.

7.4.5 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.

7.4.6 Method 5. Infrared thermography

Surface temperatures can be measured using an infrared thermo-camera. This sensing method expands the completeness of temperature testing not previously permitted by single point detectors. It spans a large surface area and thus can be used to verify the exact locations of the hot spots. This information can facilitate the reallocation of any single point detectors or facilitate further refinement of hot spot temperature accuracy with the thermo-camera, itself, by specifically calibrating to the exact emissivity at the hot spots. This subclause elaborates on this infrared thermography method.

The camera must guarantee adequate accuracy, precision, sensitivity, resolution, and field of vision necessary to achieve the purposes of the measurements. The measurements must be made with recently calibrated thermo-camera equipment with the focus precisely adjusted and taken orthogonally to the desired surface with a maximum incidence of 30°. The range of the temperature measurement must be adjusted to avoid saturation of the image.

The surface emissivity must be identified using a contact thermometer, and the emissivity adjustment of the camera must be changed until it indicates the same temperature shown by the contact thermometer. After this procedure, the emissivity of the surface is defined and can be used for related surface area.

Each picture element (pixel) of the image brings the temperature measurement of the small pixel covering area. The temperature information of the whole image can be exported from the camera to a computer as a spreadsheet file. In the spreadsheet, each cell's contents represents the temperature of each related pixel, which now can be handled individually, as isotherms, or averaged; and other calculations, such as temperature differences, can be calculated. For additional details, refer to Muniz et al. [B38] and Bortoni et al. [B9].

7.4.7 Method 6. Fiber optic sensor

Temperature fiber optical sensors are those in which the optic fiber is an integral part of the sensor. Such sensors are suitable for energized machines as they are intrinsically insulant and not prone to electromagnetic interference. Several technologies are available; some allow distributed temperature measurement of various parts of a machine using a single fiber. The fiber optic performs a temperature sensing function equivalent to that of an RTD or thermocouple when used as a local temperature detector (see 7.4.5). However, great care must be taken when positioning and installing fiber optic sensors to avoid measurement errors and sensor failure, and specialist knowledge is usually required.

7.5 Preparation for test

7.5.1 Location of measuring devices

Check local temperature devices for proper functioning and appropriate calibration before installation. Install non-insulated devices such as thermocouples on grounded parts of the machine or used only in de-energized runs with appropriate protection for personnel and instruments. Install insulated measuring devices or devices without physical connections to avoid influencing the temperature being measured.

7.5.2 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.

7.5.3 Open-ventilated machines

When preparing for a temperature test, shield an open-ventilated machine 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, use a suitable screen to protect the machine under test when necessary. Use great care to see that the screen does not interfere with the normal ventilation of the machine under test. Verify 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.

7.5.4 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 help ensure that these elements and their indicating instruments are functioning properly. Verify that there are no loose connections in the wiring between the detecting elements and the indicating instrument. Shut down the machine 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. Compare these readings 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. Check for loose connections, stray fields, and the possibility that the machine has not reached a uniform temperature if appreciable temperature differences exist.

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 help minimize the effects of stray fields.

7.6 Determination of coolant temperature

7.6.1 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 may not change appreciably during the test (see 7.3.1). The method of determining the coolant temperature is dependent on the method of cooling the machine.

7.6.2 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. Ensure 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 7.6.7) 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.

7.6.3 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, take the coolant temperature as the weighted average of the air temperature measured at the inlet of the blower.

7.6.4 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 as described in 7.6.3. Adjust the distribution of the external cooling medium so that the temperatures of the internal coolant leaving each heat exchanger are approximately equal.

When measuring the internal coolant temperature, locate the thermometers 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, hold the internal coolant temperature 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.

7.6.5 Machines cooled by other means

Machines cooled by means other than discussed in 7.6.2 through 7.6.4 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.

7.6.6 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.

7.6.7 Thermometer oil cups

Immerse the thermometers 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.

7.7 Temperature readings

7.7.1 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.

7.7.2 Thermometer method

Temperatures taken by the thermometer method (see 7.4.2) should be measured on the following parts or flow paths during the temperature tests and, if specified, after shutdown:

a) Armature coils, which are measured in at least four places
b) Armature core, which is measured in at least four places

c) Field, which is measured after shutdown (see 7.8.2)
d) Coolant (see 7.6)
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)

Locate the temperature-sensing elements 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.

7.7.3 Embedded-detector method

Temperatures of the armature winding of machines equipped with embedded detectors should be determined by the embedded-detector method (see 7.4.3) during the temperature test. In many large 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 7.4.5) on prototype machines indicate preferred methods of test and of correlating the results with conductor temperature.

7.7.4 Resistance method for fields

Temperatures of the field winding should be determined by the resistance method (see 4.3 and 7.4.4) 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.

7.7.5 Resistance method for armature

Temperatures of the armature winding may be determined by the resistance method (see 4.3 and 7.4.4) after shutdown. Measure the resistance across any two line terminals for which a reference value of resistance has been measured at a known temperature. Measure the resistance 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.

7.7.6 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 7.4.4). General principles outlined in 7.8 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 4.3 and 7.4.4).

7.8 Shutdown temperatures

7.8.1 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, stop the machines 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, correct the temperatures in accordance with 7.8.2 and extrapolated to the time given in Table 1.

7.8.2 Location of measuring devices

Place thermometers 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, make them as quickly as possible. Do not attempt to take resistance measurements until the rotor has stopped completely. Disconnect any apparatus that is connected to the armature terminals. 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 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, take the highest value. 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.

7.9 Temperature rise

7.9.1 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 7.6.6) from the average of the last three half-hourly readings of the device indicating the highest temperature.

7.9.2 Shutdown

The temperature rises corresponding to the various readings taken on shutdown are obtained by subtracting the test reference coolant temperature (see 7.6.6) from the temperatures at shutdown as defined in 7.8.

8. Torque tests

8.1 General

For the definitions of the quantities in Table 2, refer to the *IEEE Standards Dictionary Online*.

Table 2—Classification of various torque tests

Asynchronous quantities	Synchronous quantities
Locked-up 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 8.2.2) and pull-out torque (see 8.4). Values of all asynchronous quantities may be obtained from the speed-torque curve tests (see 8.3); 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 8.3.6). 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.

8.2 Locked-rotor current and torque

8.2.1 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 is normally 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 is normally made at the maximum current that will not cause injurious heating during the test. Subsequent tests are 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.

8.2.2 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 need to 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 (see 8.2.3)
- Method 2. Torque by electric input (see 8.2.4)

The armature current to be plotted is the average of all phases. The data from the tests are plotted as shown in Figure 29.

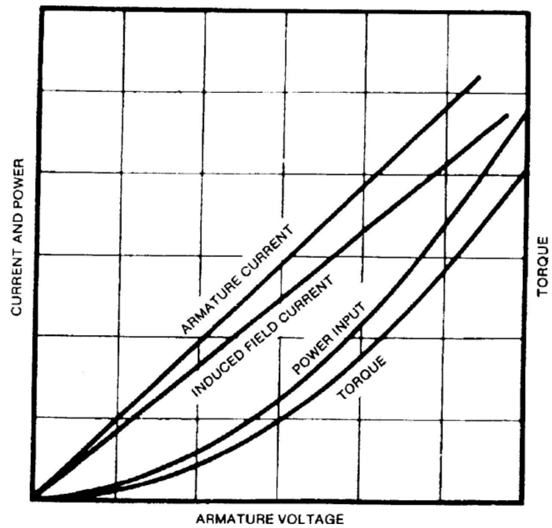


Figure 29—Torque characteristics with locked rotor

8.2.3 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 is 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 needs to 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 (61) and Equation (62).

$$T_g = \frac{T_t}{T_n} \tag{61}$$

where

- T_g is the air-gap torque at test conditions, in per unit on output base
- T_t is $F \times l$, the mechanical output torque of motor at test conditions, in N·m
- F is the net force, in N
- l is the length of the lever arm, in meters
- T_n is the base mechanical output torque of motor, in N·m

The base mechanical output torque, T_n, is defined as shown in Equation (62).

$$T_n = \frac{1000 P_{MN}}{\frac{2\pi}{60} n_s} \tag{62}$$

where

- n_s is the synchronous speed, in rpm
- P_{MN} is the rated output of motor being tested, in kW

The air-gap torque is adjusted to torque at specified conditions in accordance with 8.2.5.

8.2.4 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 per unit 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 5.3.4.4, 5.1.3, and 5.3.2.6) 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 8.2.3.

The air-gap torque is adjusted to specified conditions in accordance with 8.2.5.

8.2.5 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 (63).

$$T_{LR} = T_g \left(\frac{I_s}{I_t} \right)^2 \tag{63}$$

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 8.2.2)
I_t is the locked-rotor current from same test used to obtain T_g

Equation (63) assumes that the currents I_s and I_t are expressed in the same units. This method of adjustment is more accurate than adjusting in proportion to the square of the voltage when saturation effects are present.

8.2.6 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).

8.3 Speed-torque tests

8.3.1 General

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

- Method 1. Measured output (see 8.3.2)
- Method 2. Acceleration (see 8.3.3)
- Method 3. Input (see 8.3.4)
- Method 4. Direct measurement (see 8.3.5)

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 are to be recorded to help 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 per unit torque, per unit armature current, and induced field current, in amperes, are 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.

8.3.2 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 is 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 is normally set 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 needs to 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 is 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 needs to be accurately adjusted or calibrated at synchronous speed. All points are 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 (64).

$$T_g = \frac{P_{GO} + P_{GL}}{nP_{MN}} + T_{FW} \tag{64}$$

where

P_{GO} is the output of the dc generator, in kW
P_{GL} is the losses of the dc generator (including friction and windage), in kW
P_{MN} is the rated output of motor being tested, in kW
n is the test speed of motor, in rpm (if directly coupled, $n = n_s$)

and

$$T_{FW} = \frac{n_s P_{FW}}{nP_{MN}} \tag{65}$$

where

T_{FW} is the motor friction windage torque, in per unit on output base
P_{FW} is the motor friction windage loss at speed for test point (see 5.1.2 and 5.3.4.2), in kW
n_s is the synchronous speed of motor, in rpm

At the speed for the test point, the torque of the motor, T, adjusted to specified voltage E, is obtained from Equation (69) and Equation (71) (see 8.3.6).

8.3.3 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 is 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 8.3.1. The accelerating time needs to 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 should also be long enough to permit recording the necessary number of mechanical and electrical measurements with sufficient accuracy to plot the required curves (see 8.3.1).

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 (66).

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 is 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 may be increased until the acceleration is at about this rate. If the accelerating time is too short at minimum starting voltage, a lower voltage can 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 are taken at approximately 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 8.3.4) 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 need to 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 5.3.4.7.3.

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

Air-gap torque, T_g, at each speed is calculated from the acceleration using Equation (66).

$$T_g = \frac{\left(\frac{\pi}{30}\right)^2 n_s J \frac{dn}{dt}}{1000 P_{MN}} + T_{FW} \tag{66}$$

where

n_s is the synchronous speed, in rpm
T_{FW} is the torque due to friction and windage at each speed [see Equation (65)], in per unit on output base
dn/dt is the acceleration at each speed, in rpm/s
J is the moment of inertia of rotating parts, in kg.m^2
P_{MN} is the rated output of motor being tested, in kW

At the speed for the test point, the torque of the motor, T, adjusted to specified voltage E, is obtained from Equation (69) or Equation (71) (see 8.3.6).

8.3.4 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 are normally 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 8.3.3, except that it does not have to be unloaded. The input readings called for in 8.3.3 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 8.2), 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 (67).

$$T_g = \frac{P_{Si} - P_{SC} - P_C}{P_{MN}} \tag{67}$$

where

P_{Si} is the input power to stator, in kW
P_{SC} is the short-circuit loss at test current (see 5.3.2.6), in kW
P_C is the open-circuit core loss at test voltage, in kW
P_{MN} is the rated output of motor being tested, in kW

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 (69) or Equation (71) (see 8.3.6).

8.3.5 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 8.3.2 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 (68).

$$T_g = \frac{T_t}{T_n} + T_{FW} \tag{68}$$

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 (62)]

T_{FW} is the torque due to friction and windage at each speed [see Equation (65)], 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 (69) and Equation (71) (see 8.3.6).

8.3.6 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 (69) and Equation (70) as appropriate.

$$T = T_g \left(\frac{E}{E_t} \right)^{K_1} - T_{FW} \tag{69}$$

$$I = I_t \left(\frac{E}{E_t} \right)^{K_2} \tag{70}$$

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 (64)], 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 the torque exponent of voltage ratio ($K_1 = 2$, neglecting saturation effects)

K_2 is the current exponent of voltage ratio ($K_2 = 1$, neglecting saturation effects)

The torque and current exponents can be calculated as shown in Equation (71) and Equation (72).

$$K_1 = \frac{\log_{10}\left(\frac{T_1}{T_2} \right)}{\log_{10}\left(\frac{E_1}{E_2} \right)} \tag{71}$$

$$K_2 = \frac{\log_{10}\left(\frac{I_1}{I_2} \right)}{\log_{10}\left(\frac{E_1}{E_2} \right)} \tag{72}$$

where

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 30, 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.

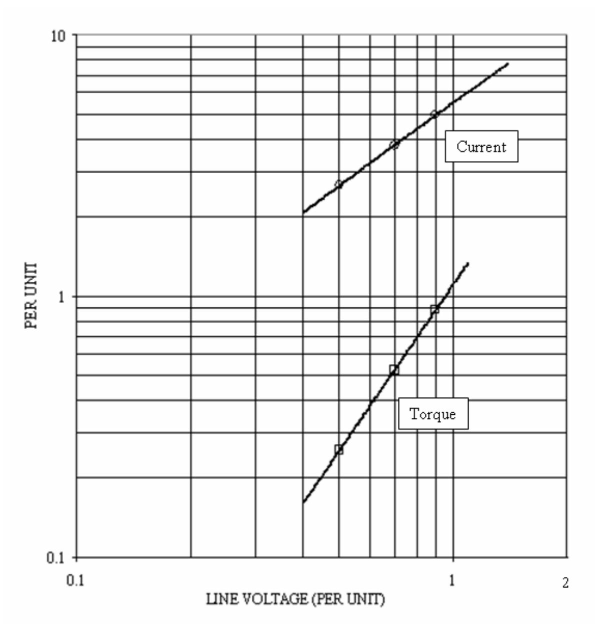


Figure 30—Correction for voltage effects

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 (64), Equation (65), and Equation (67), contain the term T_{FW}. Equation (66) 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 is 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 (69) and Equation (70) can be used in place of Equation (63) to plot the curves described in 8.2.

8.4 Pull-out torque

8.4.1 General

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

- Method 1. Direct measurement (see 8.4.2)
- Method 2. Calculation from machine constants (see 8.4.3)

8.4.2 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 per unit pull-out torque. This method is usually not practicable for large machines.

8.4.3 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 (73).

$$T_{PO} = \frac{K I_{FL} E_S}{\eta I_{FSI} \cos\theta} \tag{73}$$

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 the same units as I_{FL}
$\cos\theta$	is the rated power factor
η	is the efficiency at rated load

The factor K in Equation (73) 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 (74) as a function of δ.

$$K = \sin\delta + \frac{I_{FSI} E_S (X_{ds} - X_{qs})}{2 I_{FL} X_{ds} X_{qs}} \sin 2\delta \tag{74}$$

where

X_{ds} is the saturated direct-axis synchronous reactance, in per unit
X_{qs} is the saturated quadrature-axis 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.

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 standstill frequency response (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 unsaturated direct-axis synchronous reactance, X_{du}, and the unsaturated 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 6. 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 should 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 Per unit (p.u.) quantities

9.2.1 Comments

This guide provides 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 per unit quantities, care should be used in defining clearly the per unit base used for each quantity and making sure all base quantities are consistently chosen. The preferred procedure is to select only three base quantities and to derive the others base values from the selected three base values. The three normally chosen base vales are base three-phase power, $S_{3\phi}$, base line-to-line voltage, E_{LL}, 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 the per unit value by the corresponding base value. Any per unit quantity expressed on one base can be converted to another base by multiplying by the old base quantity and dividing by the new base quantity. The use of per unit quantities is described in most textbooks related to power system analysis, such as Anderson [B3] and Stevenson [B42].

Per unit 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 ($S_{base3\phi}$) is taken as the rated apparent power *output* of the machine, usually expressed in kilovoltamperes or megavoltamperes in the equipment nameplate.

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.

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, $S_{base1\phi}$, is derived from the base three-phase power, $S_{3\phi}$, by Equation (75).

$$S_{base1\phi} = \frac{S_{base3\phi}}{3} \tag{75}$$

where

$S_{base3\phi}$ is the three-phase base apparent power, in VA, kVA or MVA
$S_{base1\phi}$ is the single-phase base apparent power, in the same units used for $S_{base3\phi}$

9.2.3 Base armature voltage and current

Base line-to-line voltage, V_{LLbase}, is normally selected equal to the rated line-to-line voltage, $V_{LLrated}$, as provided on the equipment nameplate. The base line-to-line voltage (rms) might be expressed in volts or kilovolts.

0 presents the schematic representation of the winding connections and the convention for the direction of the terminal currents for generator and motor.

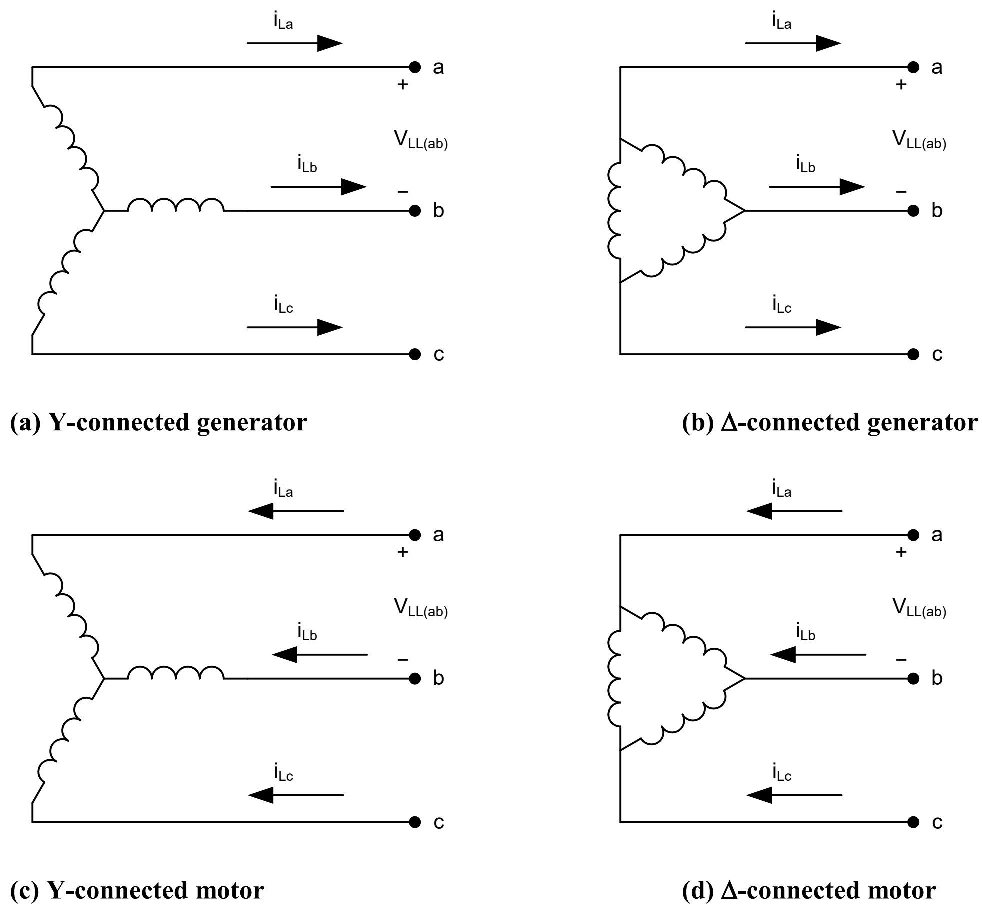


Figure 31—Schematic winding connections

Single-phase voltages, as may be specified in this guide, are expressed in per unit by dividing by the base single-phase voltage, $V_{base1\phi}$, which is related to the selected base line-to-line voltage, V_{LLbase}, and the type of winding connection of the machine.

Referring to 0, the base single-phase voltage for Δ-connected machines, $V_{base\Delta 1\phi}$, is the same as the base line-to-line voltage, $V_{base\Delta 1\phi} = V_{LLbase}$. For wye-connected machines, the base single-phase voltage is calculated from the base line-to-line voltage, V_{LLbase}, by Equation (76).

$$V_{baseY1\phi} = \frac{V_{LLbase}}{\sqrt{3}} \tag{76}$$

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

Base line current, I_{Lbase}, is obtained from the three-phase power ($S_{base3\phi}$) and base line-to-line voltage, V_{LLbase}, and is equal to the line current when the circuit is carrying base power at base voltage, as expressed in Equation (77).

$$I_{Lbase} = \frac{S_{base3\phi}}{\sqrt{3}\, V_{LLbase}} \tag{77}$$

where

$S_{base3\phi}$ is the base three-phase apparent power, in VA, kVA, or MVA
V_{LLbase} is the base line-to-line voltage, in volts or kilovolts
I_{Lbase} is the base line voltage, in amperes or kiloamperes depending on the units used for $S_{base3\phi}$ and V_{LLbase}

Referring to 0, the base single-phase current for wye-connected machines is the same as the base line current, $I_{baseY1\phi} = I_{Lbase}$. For Δ-connected machines, the base single-phase current, $I_{base\Delta 1\phi}$, is calculated from the base line current, I_{Lbase}, by Equation (78), or directly from the base three-phase apparent power and base line-to-line voltage, considering the expression in Equation (78).

$$I_{base\Delta 1\phi} = \frac{I_{Lbase}}{\sqrt{3}} = \frac{S_{base3\phi}}{3V_{LLbase}} \tag{78}$$

It can be shown that the base single-phase apparent power, $S_{base1\phi}$, defined in Equation (75), can be calculated based on the selected base values for single-phase voltage and current, as shown in Equation (79), and the same expression $(V_{base1\phi} \times I_{base1\phi})$ would apply independently of the winding connections of the machine.

$$\begin{aligned} S_{base1\phi} &= V_{baseY1\phi} I_{baseY1\phi} = \frac{V_{LLbase}}{\sqrt{3}} I_{Lbase} = \frac{V_{LLbase}}{\sqrt{3}} \frac{S_{base3\phi}}{\sqrt{3} V_{LLbase}} = \\ &= V_{base\Delta 1\phi} I_{base\Delta 1\phi} = V_{LLbase} \frac{S_{base3\phi}}{3\, V_{LLbase}} = \frac{S_{base3\phi}}{3} \end{aligned} \tag{79}$$

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 per unit values.

9.2.4 Base armature impedance

The base armature impedance, Z_{base}, 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 (80).

$$\begin{aligned} Z_{base} &= \frac{V_{baseY1\phi}}{I_{Lbase}} = V_{baseY1\phi} \frac{V_{baseY1\phi}}{S_{baseY1\phi}} = \frac{(V_{baseY1\phi})^2}{S_{base1\phi}} = \\ &= \frac{\left(V_{LLbase} / \sqrt{3} \right)^2}{S_{base3\phi} / 3} = \frac{(V_{LLbase})^2}{S_{base3\phi}} \end{aligned} \tag{80}$$

where

Z_{base} is the base armature impedance, in ohms or kiloohms, depending on the units used for the values of V_{LLbase} and $S_{base3\phi}$

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

The base impedance Z_{base} is expressed 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.

9.2.5 Base field winding quantities

Base values for field voltage and field current are required for system modelling studies and for discussion and specification of equipment where grid code or other regulatory compliance is required. However, the following different conventions have historically been used to specify base field winding quantities:

- The reciprocal system
- The nonreciprocal system
- Systems using a base field voltage in per unit of rated field voltage

To understand all of these systems, it is necessary to consider the synchronous machine open-circuit saturation curve as shown in Figure 32.

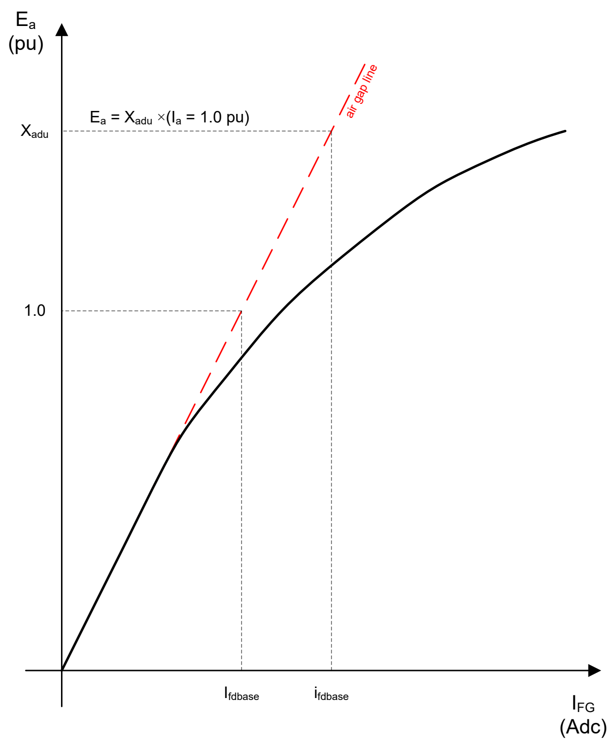


Figure 32—Open-circuit saturation curve and base values for field current

9.2.5.1 The reciprocal per unit system

The reciprocal per unit system is used where an equivalent circuit for the synchronous machine is needed as discussed by Rankin [B40] in great detail. The convention is to per-unitize field circuit equivalent resistances and inductances and to refer these physical values to per unit values as viewed from the armature terminals. (Note that the field winding is usually mounted on the rotor and the armature winding on the stator.) The need to obtain equivalent circuits was driven by the requirement to use analog computers to represent the synchronous machine. These equivalent circuits are still used on occasions (see IEEE Std 1110), but they are no longer a major requirement when using digital computers for the dynamic simulation of power systems. On the other hand, the use of models properly reflected to the armature terminals provides a major simplification and is the approach used in practically all dynamic simulation tools for large interconnected systems. These equivalent circuits are the foundation for other models that are derived from these circuits. The operational parameters for the synchronous machine (e.g., synchronous, transient and subtransient reactances) are expressed in per unit of the armature base impedance defined in Equation (80), as the operation parameters are defined as variables reflected to the armature terminals. Therefore, models that directly use the operational parameters for the synchronous machine do not require the explicit definition of the base values for the field winding quantities.

The base value for the field current in the reciprocal per unit system (i_{fdbase}) is defined as the field current, in amperes, required to induce a terminal voltage $E_a = I_a \times X_{adu}$ on the open-circuit air-gap line of the machine open-circuit saturation curve. The terminal voltage, E_a, is expressed in per unit of the appropriate base value, V_{LLbase} or $V_{base1\phi}$, while I_a is the rated armature current, expressed in per unit of the machine stator current base (I_{Lbase}). From Equation (77), it can be seen that the rated stator current will be equal to 1.0 p.u. (i.e., $I_a = I_{Lbase}$). The unsaturated direct-axis magnetizing reactance X_{adu} is also expressed in per unit and is defined in 9.2.5.2. In Figure 32, the base value for the field current in the reciprocal per unit system is i_{fdbase}.

This choice of per unit base values is necessary to enforce that the stator-to-field and field-to-stator mutual inductances, when expressed in per unit, are equal or reciprocal in value so that an equivalent circuit can be defined. It should be noted that the determination of the base value for the field current, in the reciprocal per unit system (i_{fdbase}), requires prior knowledge of the magnetizing reactance, X_{adu}. Furthermore, the per unit value for the magnetizing reactance can reach values significantly higher than 1.0 p.u., particularly for large utility-scale machines. Thus, the terminal voltage $E_a = X_{adu}$ might not be reachable during a field test, as it would exceed equipment capability (flashover).

9.2.5.2 The nonreciprocal system

Many models used for power system stability studies are derived from the basic equations or the equivalent circuits but are then re-defined in terms of the operational parameters (reactances and time constants) that are usually provided by the manufacturers or obtained from the tests described in this guide. These models often adopt the so-called nonreciprocal per unit system, although this is a misnomer. In reality, these models redefine variables used in the equivalent circuits and based on the reciprocal per unit system. In particular, these models calculate a derived quantity, $I_{fd} = X_{adu} \times i_{fd}$, related to the field current, i_{fd}, in per unit. Thus, if the field current, expressed in per unit of the reciprocal base, is $i_{fd} = 1.0$ p.u., these models would calculate a field current $I_{fd} = X_{adu}$. On the other hand, assuming that the models calculated a value of the field current $I_{fd} = 1.0$ p.u., it can be seen that $i_{fd} = 1/X_{adu}$. Referring to Figure 32, and considering the fact that the air-gap line represents a linear relationship between field current and terminal voltage in open-circuit conditions, it can be seen that a field current, $i_{fd} = 1/X_{adu}$, would result in a terminal voltage (at the air-gap line) $E_a = 1.0$ p.u. In other words, a field current $I_{fd} = 1.0$ p.u. corresponds to an induced voltage $E_a = 1.0$ p.u. at the air-gap line.

Therefore, the base value for the derived quantity $I_{fd} = X_{adu} \times i_{fd}$, to match the selected base value of the reciprocal per unit system defined above, is the field current I_{fdbase} in Figure 32, corresponding to the field current necessary to induce rated terminal voltage ($E_a = 1.0$ p.u.) on the open-circuit air-gap line.

For more details on the nonreciprocal system, see Annex B of IEEE Std 421.5™-2016 [B26], Canay [B11], and IEEE Std 1110.

The relationship between the two field current bases is shown in Equation (81).

$$i_{fdbase} = X_{adu} I_{fdbase} \tag{81}$$

where

X_{adu} is the unsaturated value of the direct-axis magnetizing reactance, in per unit

9.2.5.3 Systems using a base field voltage in per unit of rated field voltage

It is important to note that grid codes often define ceiling field voltage in per unit of rated field voltage or rated field current, instead of the base values described above. The rated field voltage and rated field current are the values needed for the machine to operate (online) at rated conditions. As the field voltage and field current required to produce rated terminal voltage on the air gap line are inherently much less than the corresponding values at rated conditions, it is necessary to convert the per unit values to the correct bases in order to compare results. Models using the nonreciprocal per unit system described above would calculate rated field voltage and rated field current as a value typically between $E_{fd} = 2.0$ p.u. and $E_{fd} = 3.0$ p.u. Thus, a particular value of per unit ceiling voltage, expressed in per unit of the rated values (e.g., 2.0 p.u. of rated field voltage), would correspond to calculated values between $E_{fd} = 4.0$ p.u. and $E_{fd} = 6.0$ p.u. in the simulation models based on the nonreciprocal per unit system.

9.2.5.4 Base value for field voltage in the nonreciprocal per unit system

The base field voltage is defined by the base field current multiplied by the field winding resistance, as shown in Equation (82).

$$E_{fdbase} = R_{fd} I_{fdbase} \tag{82}$$

where

E_{fdbase} is the base field voltage, in volts, for the nonreciprocal per unit system
I_{fdbase} is the base field current, in amperes, for the nonreciprocal per unit system
R_{fd} is the field resistance, in ohms, for a given reference field winding temperature

The field resistance is not constant, but depends on the temperature of the field winding. Thus, it might be necessary to adjust the base value for the field voltage to match the operating temperature of the machine when analyzing test results. Conversely, simulation models have to assume, implicitly or explicitly, a reference temperature for the field winding resistance in order to define the base value for the per unit system in the model. Typically, a reference temperature of 100 °C has been used for round rotor machines and a reference temperature of 75 °C for salient-pole units.

It should be noted that with the use of the nonreciprocal per unit system and the definition of the base field voltage given in Equation (82), the values of the field voltage and field current of the machine, in steady state, will be numerically equal when expressed in per unit of the nonreciprocal per unit system.

9.2.5.5 Base value for field winding impedance in the reciprocal per unit system

In some of the issues being discussed in Clause 12, the base value for the field circuit impedance, referred to the stator, is given in Equation (83).

$$Z_{fdbase} = \frac{S_{base3\phi}}{\left(i_{fdbase}\right)^2} \tag{83}$$

where

$S_{base3\phi}$ is the base three-phase apparent power of the machine (see 9.2.2)
i_{fdbase} is the base field current in the reciprocal per unit system (see 9.2.5.1)
Z_{fdbase} is the base field impedance in the reciprocal per unit system, in ohms when $S_{base3\phi}$ is in voltamperes and i_{fdbase} is in amperes

9.2.5.6 Base value for field winding voltage in the reciprocal per unit system

Considering Equation (83), the base value for the field winding voltage in the reciprocal per unit system can be defined as given in Equation (84).

$$e_{fdbase} = Z_{fdbase} i_{fdbase} = \frac{S_{base3\phi}}{i_{fdbase}} \tag{84}$$

where

$S_{base3\phi}$ is the base three-phase apparent power of the machine (see 9.2.2)
i_{fdbase} is the base field current in the reciprocal per unit system (see 9.2.5.1)
Z_{fdbase} is the base field impedance in the reciprocal per unit system, in ohms
e_{fdbase} is the base field voltage in the reciprocal per unit system, in volts

9.2.6 Base frequency

The base frequency is regularly selected as equal to the rated frequency. From this value, the base electrical angular velocity, ω_N is obtained by Equation (85).

$$\omega_N = 2\pi f_N \tag{85}$$

where

ω_N is the base electrical angular velocity, in rd/s
f_N is the base (rated) electrical frequency (synchronous frequency), in Hz

If needed, the base value for time, t_N, can be calculated by Equation (86).

$$t_N = \frac{1}{f_N} \tag{86}$$

where

t_N is the base time, in seconds

A time constant, in seconds, may be converted to per unit by dividing its value by the base value for time, t_N. However, in accordance with usual practice, this guide is arranged so that the time constants are expressed in seconds, not in per unit.

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 power 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 magnitude with 120° electrical displacement between phase currents, and each of the three-phase voltages have equal magnitudes, with 120° electrical displacement between voltages.

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 this guide. However, since some of these sequence quantities are used in stability studies or in dynamic analyses, they are included parameter determination clauses. In any case, tests for such parameters sometimes need to be performed to help 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 expressed in per unit, see Clause 9) 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.

X_{du} unsaturated direct-axis synchronous reactance, as defined by test
X_{ds} some particular saturated value of X_{du}
X_{adu} unsaturated direct-axis synchronous mutual reactance
X_{ads} saturated portion of X_{ds}
X_{qu} unsaturated quadrature-axis synchronous reactance
X_{qs} some particular saturated value of X_{qu}, 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 Clause 3. 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 5.1.1) and the short-circuit saturation test (see 5.1.3). 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 5.1.1).

In terms of the quantities identified in Figure 16 (see 6.2.2.1), synchronous reactance can be calculated using Equation (87). It should be noted that Figure 16 provides the scales already expressed in per unit of the nonreciprocal per unit system (see 9.2). Figure 16 could also be provided with the scales in actual physical quantities (amperes or volts).

$$X_{du} = \frac{I_{FSI}}{I_{FG}} \tag{87}$$

where

X_{du} is the unsaturated synchronous reactance, in per unit
I_{FSI} is the field current corresponding to the base armature current (see 9.2.3) on the short-circuit saturation curve

I_{FG} is the field current corresponding to base armature voltage (see 9.2.3) on the air-gap line. It should be noted that $I_{FG} = I_{fdbase}$, the base value for the field current in the nonreciprocal per unit system (see 9.2.5.2)

As long as I_{FSI} and I_{FG} are both expressed in the same units (amperes or per unit using a common base value), the value for X_{du} will be correctly expressed in per unit.

Saturated values of synchronous reactance, X_{ds}, depend upon synchronous machine operating conditions. As noted in Clause 6, 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, Equation (88) applies.

$$X_{ds} = X_{ads} + X_\ell \tag{88}$$

where

X_{ds} is the saturated direct-axis synchronous reactance, in per unit, for the given operating conditions
X_{ads} is the saturated portion of X_d, in per unit
X_ℓ is the stator leakage reactance, in per unit, assumed independent of machine saturation

When the machine is unsaturated, as a corollary of Equation (88), Equation (89) applies.

$$X_{du} = X_{adu} + X_\ell \tag{89}$$

where

X_{du} is the unsaturated direct-axis synchronous reactance, in per unit
X_{adu} is the unsaturated portion of X_d, in per unit
X_ℓ is the stator leakage reactance, in per unit

10.4 Quadrature-axis synchronous reactance, X_q

10.4.1 General

For the definition of *quadrature-axis synchronous reactance*, see Clause 3. 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 values of X_q, but the usual assumption is similar to what is used for the direct axis, as shown in Equation (90).

$$X_{qs} = X_{aqs} + X_\ell \tag{90}$$

where

X_{qs} is the saturated quadrature-axis synchronous reactance, in per unit, for the given operating conditions
X_{aqs} is the saturated portion of X_{qs}, in per unit

X_ℓ is the stator leakage reactance, in per unit, assumed independent of machine saturation (and the same value as for the direct axis)

Similarly to the direct-axis definitions, when the machine is unsaturated, Equation (91) applies.

$$X_{qu} = X_{aqu} + X_\ell \tag{91}$$

where

X_{qu} is the unsaturated quadrature-axis synchronous reactance, in per unit
X_{aqu} is the unsaturated portion of X_{qu}, in per unit
X_ℓ is the stator leakage reactance, in per unit

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

— Method 1. Slip test (see 10.4.2)
— Method 2. Maximum lagging current (see 10.4.3)
— Method 3. Empirical function (see 10.4.4)
— Method 4. Load angle (see 10.4.5)

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 33 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.

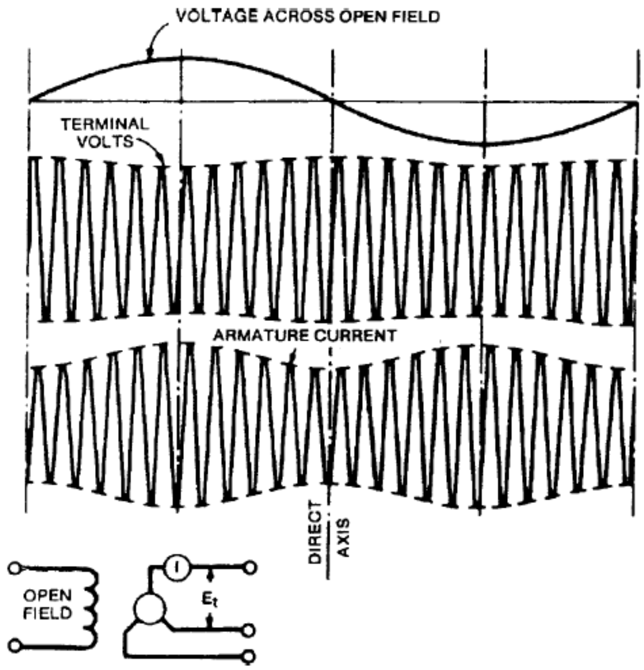


Figure 33—Slip method of obtaining quadrature-axis synchronous reactance

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 help 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 reactances, X_{qs} and X_{ds}, can be obtained by Equation (92) and Equation (93). If X_{du} value is known by test (see 10.3), an approximate value for unsaturated quadrature-axis synchronous reactance, X_{qu}, can be derived using Equation (94). The analyst must bear in mind that this equation is merely an approximation. Its use can lead to appreciable error for salient-pole machines.

$$X_{qs} = \frac{E_{\min}}{I_{\max}} \tag{92}$$

where

X_{qs} is the saturated quadrature-axis synchronous reactance, in per unit, for the saturation level for the test conditions

$$X_{ds} = \frac{E_{\max}}{I_{\min}} \tag{93}$$

where

X_{ds} is the saturated direct-axis synchronous reactance, in per unit, for the saturation level for the test conditions

$$X_{qu} = X_{du}\left(\frac{X_{qs}}{X_{ds}}\right) = X_{du}\frac{E_{\min}}{E_{\max}}\frac{I_{\min}}{I_{\max}} \tag{94}$$

where

X_{qs} is the saturated quadrature-axis synchronous reactance, in per unit, for the saturation level for the test conditions
$E_{\min}$ minimum effective value of the armature voltage during the slip test
$E_{\max}$ maximum effective value of the armature voltage during the slip test
$I_{\min}$ corresponding minimum effective value of the armature current during the slip test
$I_{\max}$ corresponding maximum effective value of the armature current during the slip test

The minimum ratio [see Equation (92)] occurs when the field voltage is a maximum while the maximum ratio [see Equation (93)] occurs when the field voltage passes through zero, as indicated in Figure 33.

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 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 (95).

$$X_{qs} = \frac{E}{I_t} \tag{95}$$

where

E is the armature voltage during the test, in per unit
I_t is the armature current at stability limit, in per unit

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 unsaturated quadrature-axis synchronous reactance is then determined by multiplying the unsaturated direct-axis 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, methods 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 (117) 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 Clause 3.

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 [B17].

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 sudden-three-phase 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 (96), Equation (97), and Equation (98).

$$Z_2 = \frac{E}{I} \tag{96}$$

$$R_2 = \frac{P}{I^2} \tag{97}$$

$$X_2 = \sqrt{(Z_2)^2 - (R_2)^2} \tag{98}$$

where

E is the average of rms values of fundamental component of the three line-to-line voltage, in per unit (see 9.2.3)
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 (see 9.2.3)
Z_2 is the negative sequence impedance, in per unit (see 9.2.2)
R_2 is the negative-sequence resistance, in per unit
X_2 is the negative-sequence reactance, in per unit

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 (98), 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 (96) and Equation (97). 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 (96), 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 (99).

$$X_2 = \frac{(X''_d)^2}{2X''_d - X_{2t}} \tag{99}$$

where

X_{2t} is the negative-sequence reactance calculated using Equation (98), but based on the measured values of E, I, and P following Method 2 (see 10.5.1.4)
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 11.5.3.1.4).

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 34. 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.

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.

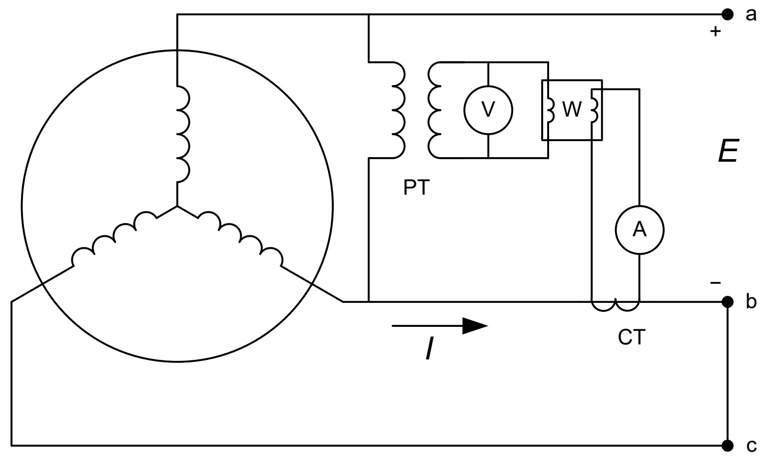


Figure 34 —Diagram for determining negative-sequence impedance using Method 3

10.5.1.5.2 Parameter determination using Method 3

The negative-sequence impedance for this line-to-line sustained short-circuit test is obtained using Equation (100).

$$Z_{2(LL)} = \frac{E}{I} \tag{100}$$

where

E is the fundamental component of voltage, in per unit of base line-to-line voltage (see 9.2.3)
I is the fundamental component of short-circuit current, in per unit of base line current (see 9.2.3)
$Z_{2(LL)}$ is the negative sequence impedance determined by Method 3, in per unit

The negative-sequence reactance for a line-to-line short-circuit test is obtained using Equation (101).

$$X_{2(LL)} = \frac{P_{v-a}}{\sqrt{3}EI} Z_{2(LL)} \tag{101}$$

where

P_{v-a} is the measured power, in per unit of *base single-phase power* (see 9.2.2)
$X_{2(LL)}$ is the negative sequence reactance determined by Method 3, in per unit

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 using Equation (102). To make this correction, the direct-axis subtransient reactance, X''_d, in per unit, should be known for approximately the same conditions. To correct the per unit 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 11.5.3.1.4). The results give the per unit rated-current and rated-voltage values of the negative-sequence reactance, respectively.

$$X_2 = \frac{\left(X_{2(LL)}\right)^2 + \left(X''_d\right)^2}{2X''_d} \tag{102}$$

where

X''_d is the direct-axis subtransient reactance, in per unit

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 per unit value of the wattmeter reading should be corrected in accordance with Equation (103).

$$P'_{v-a} = P_{v-a} - \sqrt{3}E_3 I_3 \tag{103}$$

where

P'_{v-a} is the adjusted value of the measured power, compensated for third-harmonics contents
P_{v-a} is the measured power, in per unit of *base single-phase power*
E_3 is the rms third-harmonic voltage, in per unit of base line-to-line voltage (see 9.2.3)
I_3 is the rms third-harmonic current, in per unit of base line current (see 9.2.3)

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

See 11.5.3.5.3 for Method 6 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 11.5.3.5.3 (for X''_d) and 11.5.3.5.3 (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 11.5.3.5.3, negative-sequence reactance can be calculated using Equation (104).

$$X_2 = \frac{K}{2} \tag{104}$$

where

X_2 is the negative-sequence reactance calculated by Method 5, in per unit
K is defined in Equation (144)

The negative-sequence current in each test is the per unit 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 components. 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 Clause 3.

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 (see 10.5.2.1)
— Method 2. Single-phase line-to-line sustained short circuit (see 10.5.2.2)

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 (97). 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 (105).

$$R_2 = \sqrt{(Z_2)^2 - (X_2)^2} \tag{105}$$

where

R_2 is the negative-sequence resistance determined by Method 2, in per unit
Z_2 is the negative-sequence impedance from Equation (100), in per unit
X_2 is the negative-sequence reactance from Equation (101), in per unit

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 those associated with Method 3 for determining negative-sequence reactance (see 10.5.1.5).

10.6 Zero-sequence quantities

10.6.1 Determining zero-sequence reactance, X_0

For the definition of *zero-sequence reactance*, see Clause 3. 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 (see 10.6.1.2)
— Method 2. Series circuit (see 10.6.1.3)
— Method 3. Sustained short circuit (see 10.6.1.4)

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 35).

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.

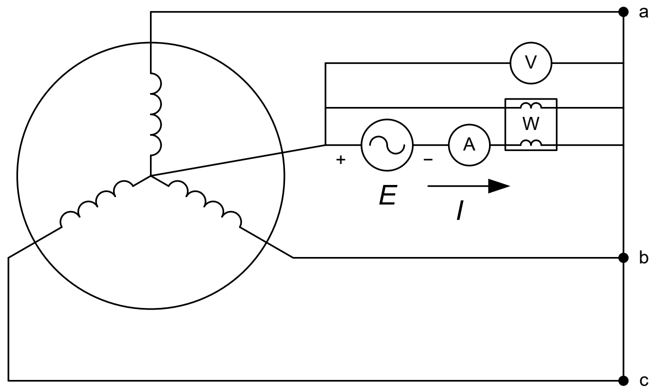


Figure 35—Test setup for Z_0 measurement using Method 1

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. Experience had shown that it is possible to measure a good value of X_0, at least for large salient-pole machines, at standstill with current as small as 0.002 p.u. rated current (Karmaker et al. [B30]).

It is highly recommended to use the short-circuit bar, generally supplied by the alternator manufacturer, instead of cables to connect together the three line terminals. Therefore, the best time to conduct this test is right after the short-circuit saturation curve test (see 5.1.3).

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 7.7.5) 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 (106).

$$Z_0 = \frac{3E}{I} \tag{106}$$

where

Z_0 is the zero-sequence impedance determined by Method 1, in per unit
E is the test voltage, in per unit of base *line-to-neutral* voltage (see 9.2.3)
I is the total test current, in per unit of base line current (see 9.2.3)

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 (107) can be used.

$$X_0 = Z_0\sqrt{1-\left(\frac{P}{EI}\right)^2} \tag{107}$$

where

X_0 is the zero-sequence reactance determined by Method 1, in per unit
P is the test power (wattmeter reading), in per unit of base *single-phase* power (see 9.2.2)

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 36. 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 10.6.1.2.1). 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 7.7.5) 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.

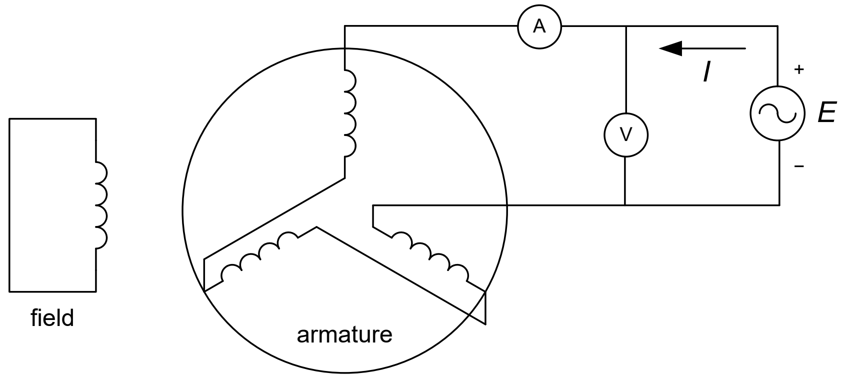


Figure 36—Connection diagram for determining zero-sequence reactance using Method 2

10.6.1.3.1 Parameter determination using Method 2

The zero-sequence impedance for the series circuit connection is obtained by Equation (108).

$$Z_0 = \frac{E}{3I} \tag{108}$$

where

Z_0 is the zero-sequence impedance determined by Method 2, in per unit
E is the test voltage, in per unit of base *line-to-neutral* voltage (see 9.2.3)
I is the total test current, in per unit of base line current (see 9.2.3)

The correction for resistance, if needed, is made using Equation (107). 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 37. 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.

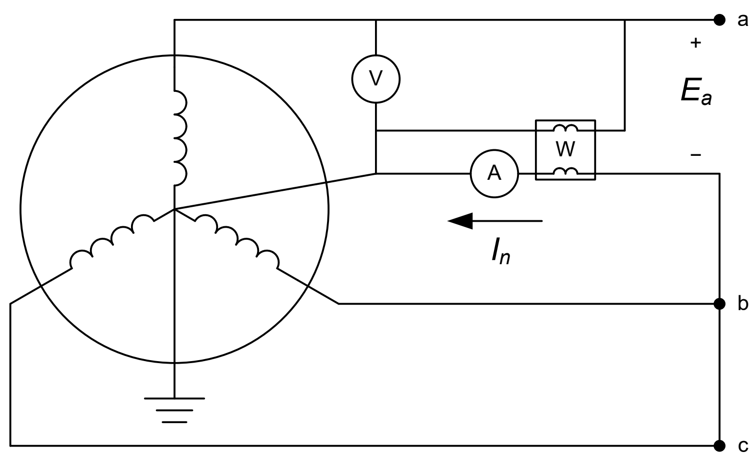


Figure 37—Diagram for determining zero-sequence parameters using Method 3

10.6.1.4.1 Parameter determination using Method 3

The zero-sequence impedance is obtained by Equation (109).

$$Z_0 = \frac{E_a}{I_n} \tag{109}$$

where

Z_0 is the zero-sequence impedance determined by Method 3, in per unit
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 (110).

$$X_0 = Z_0\sqrt{1-\left(\frac{P_{an}}{E_a I_n}\right)^2} \tag{110}$$

where

X_0 is the zero-sequence reactance determined by Method 3, in per unit
P_{an} is the test power (wattmeter reading), in per unit of base *single-phase* power (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 36 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 help minimize the impedance.

c) For large machines, having a small value of X_0, Equation (109) and Equation (110) may lead to unacceptable error on X_0. In this case, the metering scheme of Figure 38 should be considered, and Equation (111) should be applied to mitigate the effect of cable impedances.

$$X_0 = \frac{Q_{an} + (2+k)Q_{pn}}{I_n^2}\frac{60}{f} \tag{111}$$

where

Q_{an} is the reactive power measured with voltage E_a and current I_n, in per unit of base single-phase power.
Q_{pn} is the reactive power measured with voltage V_{pn} and current I_n, in per unit of base single-phase power. The voltage V_{pn} would be close to zero if the cable impedances are negligible; Q_{pn} would approach zero in that case.
k is the ratio between the cable lengths l_{bp} (between points *b* and *p* in Figure 38) and l_{pn}
f is the electrical frequency associated with the machine speed when the measurements were taken, in hertz.

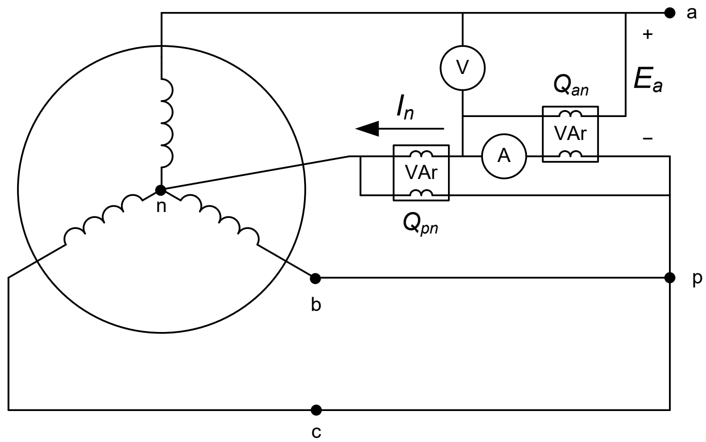


Figure 38—Additional measurements to mitigate effects from cable impedances

d) The instrumentation should be set to fundamental measurements or harmonic analysis conducted to get rid of the third harmonic present in measured voltages and currents.

10.6.2 Determining zero-sequence resistance, R_0

For the definition of *zero-sequence resistance*, see Clause 3. 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 (see 10.6.2.1)
— Method 2. Series circuit (see 10.6.2.2)
— Method 3. Sustained short circuit (see 10.6.2.3)

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 (112).

$$R_0 = \frac{3P}{I^2} \tag{112}$$

where

R_0 is the zero-sequence resistance determined by Method 1, in per unit
P is the measured power (from the wattmeter), in per unit of base *single-phase* power

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 (113).

$$R_0 = \frac{P}{3I^2} \tag{113}$$

where

R_0 is the zero-sequence resistance determined by Method 1, in per unit
P is the measured power (from the wattmeter), in per unit of base *single-phase* power
I is the total test current, in per unit of base line current

For this test, the zero-sequence current is equal to the total 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 (114).

$$R_0 = \frac{P_{an}}{I_n^2} \tag{114}$$

where

R_0 is the zero-sequence resistance determined by Method 3, in per unit
P_{an} is the measured power (from the wattmeter), in per unit of base *single-phase* power
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 Clause 3.

10.7.2 Determination from test

First, the dc armature resistance, R_a, is determined by test and corrected to a specified temperature (see 4.3).

The stray-load loss, W_{LO}, is determined according to 5.3.2.5. No correction for temperature is included. The positive-sequence resistance is determined by Equation (115)

$$R_1 = R_a + \frac{W_{LO} \times 10^3}{3I_N^2} \tag{115}$$

where

- R_1 is the positive-sequence resistance, in ohms. The positive-sequence resistance, in per unit, is obtained by dividing the value, in ohms, by the base armature impedance (see 9.2.4).
- 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 kW
- I_N is the base line current, in amperes (see 9.2.3)

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 5.3.2.4 and 5.3.2.5.

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 Online*.

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 (116) (See Figure 16 in 6.2.2.1.)

$$SCR = \frac{I_{FNL}}{I_{FSI}} \tag{116}$$

where

I_{FNL} is the field current for rated voltage, rated frequency, at no load (full speed, no load conditions)

I_{FSI} is the field current for rated armature current on a sustained three-phase short-circuit condition 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.

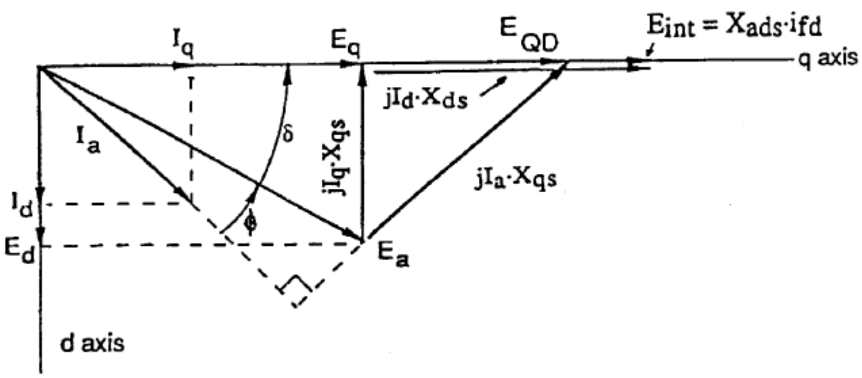


Figure 39—Phasor diagram for a synchronous generator

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 $X_{ds} - X_{\ell} = X_{ads}$. The stator leakage reactance is X_{ℓ}. The phasor $E_I = X_{ads} \times i_{fd}$ (product) corresponds to the internal field excitation in the Rankin reciprocal per unit system and is the field current, expressed in per unit of the nonreciprocal per unit system. 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, in one possible manner to represent saturation effects in a synchronous machine model. (See IEEE Std 1110 for more detail.)

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

— Method 1. Equation (117) (see 10.8.2.2)
— Method 2. Optical measurement (see 10.8.2.3)
— Method 3. Electronic measurement (see 10.8.2.4)

10.8.2.2 Method 1. Equation (117)

A method of calculating δ may be approximated in accordance with Equation (117).

$$\delta = \tan^{-1} \frac{X_{qs} I_a \cos\phi}{E_a + X_{qs} I_a \sin\phi} \tag{117}$$

where

δ is the internal load angle, angle between the terminal voltage phasor E_a and the phasor E_I, in Figure 39
X_{qs} is the saturated quadrature-axis synchronous reactance, in per unit
E_a is the magnitude of the terminal voltage, in per unit
I_a is the magnitude of the terminal current, in per unit
ϕ is the power factor angle (phase angle between the terminal voltage and current)

Referring to Figure 39, the load angle δ in Equation (117) is calculated from the generator terminal conditions: terminal voltage, E_a, and terminal current, I_a, and the power factor angle, ϕ, between them. Alternatively, I_a and power factor angle, ϕ, can be calculated from terminal active and reactive power outputs. The phasor E_I is then calculated considering the voltage drop across the reactance X_{qs}, and the phase angle of the phasor E_I with respect to the terminal voltage E_a is the load angle δ. This general process is applicable to the calculation of the load angle δ for most synchronous machine models, and the differences between the models are essentially related to the determination of the saturated value of X_{qs} to be used in the calculations (see IEEE Std 1110 for more details).

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 (118).

$$\delta = 2\pi f \times \Delta t \tag{118}$$

where

f is the frequency, in Hz
Δt is the change in signal time difference, in seconds

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. No markings are needed when the tested machine is equipped with gap sensors. These were used successively on many occasions at least for large salient-pole machines.

10.8.2.5 Precaution with Method 2 and Method 3

For large machines, terminal voltage may be drifting when changing from no-load to an operating load point. Unacceptable uncertainty is then introduced in the determination of load angle if, for all load levels, the zeroing uses the same initial no-load phase difference between terminal voltage and rotor position. An alternate method consists of using the terminal voltage of an adjacent alternator having its proper power transformer instead of the terminal voltage of the machine under test. During the measurements, the load of the adjacent alternator must be kept constant to keep its voltage phase as constant as possible (Karmaker et al. [B30]).

11. Tests for evaluating transient or subtransient characteristic values

11.1 Introduction

Traditionally, synchronous-machine transient and subtransient parameters have been determined from transient tests such as applying sudden short circuits to the machine terminals and/or the field winding. Subclause 10.4 describes test procedures for some of the tests that have commonly been used for this purpose. Based upon the data obtained from these tests, 10.5 presents procedures for determining the parameters for a specific model, a direct-quadrature model with two windings on each of the rotor direct and quadrature axes. See IEEE Std 1110-2002, Table 1, model 1.1, for more details on these models.

The characteristic values of transient and subtransient reactances and time constants of synchronous machines determined in this fashion have been used for about 85 years for many purposes. Such reactances and time constants were used originally 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, and they are used to calculate the mechanical stresses on armature windings resulting from excessive currents that occur during electrical disturbances at or near the machine terminals. In addition, these characteristics are used to devise protective schemes so that relays may be correctly applied to trip armature or field circuit breakers and thus remove a faulted machine from the power system. Over the years, this model and its corresponding characteristics have been used for a wide variety of power system stability studies.

11.2 Instrumentation

For the purposes of model parameter determination, it is necessary to measure and record the machine terminal voltages and currents. In addition, in some cases it may be necessary to include field winding voltages and currents. Suitable non-inductive shunts or low-frequency 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. In any case, care should be taken to help ensure that the current and voltage sensors have sufficient range that linearity of measurement is achieved for the full range of the signals being measured. Leads from shunts or current-transformer secondaries should be kept close together, twisted, or in conduit to help reduce induced voltages in the instrument circuits. Alternatively, the use of optical fiber technology is strongly suggested. This is especially true in the case of currents whose transient values can greatly exceed the steady-state values associated with the machine under test.

For further analysis, the time-transient voltages and currents must be recorded, preferably in a digital format. This can be done using a digital data acquisition system, a recording oscilloscope or equivalent, in each case with sufficient channels to record the data required for each test. The data acquisition system should have sufficient bandwidth to accurately capture the test results. A bandwidth in the range of 10 to 20 times the rated frequency of the machine under test should be sufficient. For example, for a 60 Hz machine, a bandwidth of 2 kHz should be adequate although a choice of 5 kHz to 10 kHz is easily achievable and is found to be more helpful in some cases.

11.3 Caution

Transient tests such as those discussed in this clause can result in significant mechanical and electrical stress on both the machine under test and external components (cables, bus work, etc.). These stresses have the potential for damage to the machine as well as to injury to personnel and they should be carefully considered and reviewed prior to conducting any such tests.

11.3.1 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, 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 can be 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.

11.3.2 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 applied on the conductors. To prevent damaging movement, the 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 helps reduce the risk of hazardous voltages at the test instrumentation 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.

11.4 Test procedures

11.4.1 Sudden-three-phase short-circuit test

A sudden-three-phase short-circuit test is conducted with the machine operating initially open-circuited in the steady state; at constant speed and constant terminal voltage. The test is initiated by applying a simultaneous short circuit to the three-phase windings. This short circuit is typically maintained until the transient currents have achieved clearly identifiable steady-state conditions. Note that in the case of a delta-connected machine the three phase terminals are simply shorted together while in the case of a wye-connected machine, they can be either shorted together (phase-phase) or shorted to neutral. Three-phase short-circuit current waveforms with a neutral connection may be more difficult to interpret due to the presence of third harmonics in the current waveforms.

11.4.1.1 Switchgear

The switchgear chosen for this test should be sized based upon the expected peak value of the transient currents and the machine terminal voltage prior to the test. Breaker-pole synchronization may affect the accuracy of subtransient time constants determined from the tests results. Should such parameters be of interest, it is recommended that the breaker pole closings be adjusted to within a span of no more than 5 electrical degrees.

11.4.1.2 Excitation system

A sudden-three-phase short-circuit test, can be conducted using the machine's standard excitation system. However, if the excitation system is supplied from the machine terminals, an alternate external source must be employed to feed the excitation system, Machines with brushless excitation systems can be fitted with temporary slip rings to provide external access to the main rotor connections. It is important to recognize that the parameter-determination techniques discussed in 11.5 assume that the sudden-three-phase short-circuit test results are obtained from a test in which the excitation voltage applied to the field winding is constant. If this is not the case, the resultant parameter values will not be valid. This may be achievable by setting the excitation-system to its manual mode. However, it should be noted that manual mode in excitation systems results in constant field current control rather than constant field voltage. In such cases, this may require the use of an independent excitation system capable of maintaining constant field voltage. In either case, it is recommended that, if possible, the field voltage be monitored and recorded to verify the constant-field-voltage condition.

11.4.1.3 Initial speed

Although, since they are inductance dominated, short-circuit current magnitudes are relatively independent of speed. However it is recommended that sudden-three-phase short-circuit tests be conducted from the rated speed whenever possible.

11.4.1.4 Initial conditions

The initial level of the field excitation/open-circuit voltage should be adjusted depending on the purpose of the test. For example, traditionally unsaturated values of the transient parameters are obtained from short-circuit tests in which the maximum values of the rms transient currents are on the order of the rated currents of the machine. Similarly, the saturated values of the transient parameters are traditionally obtained from short-circuit tests conducted with the machine operating initially at rated open-circuit voltage.

11.4.1.5 Measurements

For the purposes of parameter determination, the steady-state terminal voltage (phase-phase or phase-neutral) should be recorded prior to conducting the test. Although ideally only a single phase current is sufficient for parameter determination, it is recommended that all three phase currents be recorded. In general, the short circuit should be maintained and the currents recorded until the currents have reached a steady-state condition. As mentioned in 10.4.1.2, if possible it is recommended that the field-winding excitation voltage be recorded to help ensure that the test conditions are consistent with the assumptions required for parameter determination. Note that for the purposes of parameter determination, it may be helpful to determine the initial field- and stator-winding temperatures. The rotor temperature can be determined from the steady-state values of the field voltage and current prior to the application of the short circuit and the stator-winding temperature can be measured using RTDs or equivalent means.

11.4.1.6 Cautions

Recommendations for safety precautions are provided in 11.2. 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 currents. A review of protective devices that should be made inoperative during the tests is also recommended. A sudden-three-phase short circuit can result in extreme mechanic stresses in the windings and other components of the machine under test. It is recommended that the manufacturer be consulted for guidance prior to conducting such a test. In addition, it should be noted that all temporary connections (cables or bus bars) as well as any moving parts of the breaker represent a serious threat to personnel safety. It is recommended that these components be properly barricaded to prevent access during the tests. The floor of the test area should withstand the weight of the breaker and its accessories. To reduce movement, the breaker should be securely fastened to floor. In addition, a fire-extinguisher should be easily accessible to the test area.

11.4.2 Sudden-two-phase short-circuit test

A sudden-two phase short-circuit test is conducted with the machine operating initially open-circuited in the steady state; at constant speed and constant terminal voltage. The test is initiated by applying a simultaneous short circuit to two of the phase windings while the third phase remains open. This short circuit is typically maintained until the transient currents have reached clearly identifiable steady-state conditions. Note that in the case of a delta-connected machine, the two phase terminals are simply shorted together while in the case of a wye-connected machine, they can be either shorted together (phase-phase) or shorted to neutral.

11.4.2.1 Switchgear

The switchgear chosen for this test should be sized based upon the expected peak value of the transient currents determined through analysis or past experience and the machine terminal voltage prior to the test.

11.4.2.2 Excitation system

A sudden-two-phase short-circuit test can be conducted using the machine's standard excitation system. However, if the excitation system is supplied from the machine terminals, an alternate external source must be employed to feed the excitation system. Machines with brushless excitation systems can be fitted with temporary slip rings to provide external access to the main rotor connections. It is important to recognize that the parameter-determination techniques discussed in 11.5 assume that the sudden-three-phase short-circuit test results are obtained from a test in which the excitation voltage applied to the field winding is constant. If this is not the case, the resultant parameter values will not be valid. This may be achievable by setting the excitation-system to its manual mode. However, it should be noted that "manual" mode in some excitation systems results in constant field-current control rather than constant field voltage. In such cases, this may require the use of an independent excitation system capable of maintaining constant field voltage. In either case, it is recommended that, if possible, the field voltage be monitored and recorded to verify the constant-field-voltage condition.

11.4.2.3 Initial speed

Although, since they are inductance dominated, short-circuit current magnitudes are relatively independent of speed, it is recommended that sudden-two-phase short-circuit tests be conducted from the rated speed whenever possible.

11.4.2.4 Initial conditions

The initial level of the field excitation/open-circuit voltage should be adjusted depending on the purpose of the test. For example, traditionally unsaturated values of the transient parameters are obtained from tests in which the maximum values of the rms transient currents are on the order of the rated currents of the machine. Similarly, the saturated values of the transient parameters are traditionally obtained from tests conducted with the machine at rated open-circuit voltage.

11.4.2.5 Measurements

For the purposes of parameter determination, the steady-state terminal voltage (phase-phase or phase-neutral) should be recorded prior to conducting the test. In general, the short circuit should be maintained and the current recorded until the current has reached a steady-state condition. As mentioned in 11.4.2.2, if possible it is recommended that the field-winding excitation voltage be recorded to help ensure that the test conditions are consistent with the assumptions required for parameter determination. Note that for the purposes of parameter determination, it may be helpful to determine the initial field- and stator-winding temperatures. The rotor temperature can be determined from the steady-state values of the field voltage and current prior to the test and the stator-winding temperature can be measured using RTDs or equivalent means.

11.4.2.6 Cautions

Recommendations for safety precautions are provided in 11.3. 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. A sudden-two-phase short circuit can result in extreme mechanical stresses in the windings and other components of the machine under test. It is recommended that the manufacturer be consulted for guidance prior to conducting such a test. In addition, it should be noted that all temporary connections (cables or bus bars) as well as any moving parts of the breaker represent a serious threat to personnel safety. It is recommended that these components be properly barricaded to prevent access during the tests. The floor of the test area should withstand the weight of the breaker and its accessories. To reduce breaker movements, this latter should be securely fastened to floor. In addition, a fire-extinguisher should be easily accessible to the test area.

11.4.3 Armature-and-field sudden short-circuit test

An armature-and-field sudden short-circuit test is conducted with the machine operating initially open-circuited in the steady state; at constant speed and constant terminal voltage. The test is initiated by disconnecting the field excitation and applying a short circuit to the field winding, followed a few cycles later (2 to 5 cycles) by a three-phase short circuit applied to the stator terminals. Note that in the case of a Δ-connected machine the three phase terminals are simply shorted together while in the case of a wye-connected machine, they can be either shorted together (phase-phase) or shorted to neutral.

11.4.3.1 Switchgear

The switchgear chosen for this test should be sized based upon the expected peak value of the transient currents determined by analysis or past experience and the machine terminal voltage prior to the test. Breaker-pole synchronization may affect the accuracy of subtransient time constants determined from the tests results. Should such parameters be are of interest, it is recommended that the breaker pole closings should be adjusted to within a span of no more than 5 electrical degrees. The switchgear should have an accurate predictable closing time response to appropriately coordinate its closing with that of the field breaker. A coordination circuit (a temporized relay) should be installed to initiate the main three-phase short-circuit breaker closing 2 to 5 cycles after the opening of the field breaker and the application of the short circuit to the field winding. Tests to verify the coordination between the two breakers should be conducted prior to conducting the armature-and-field sudden short-circuit test.

11.4.3.2 Excitation system

This test can be conducted using the machine's standard excitation system. However, if the excitation system is supplied from the machine terminals, an alternate external source must be employed to feed the excitation system. In modern excitation systems, when the field breaker is opened, a discharge resistor is automatically inserted in the circuit, either through a second breaker pole or using a thyristor. In the former case, a diode, of appropriate rating and polarity should be connected across the discharge resistor. In the latter case, the thyristor can be shorted directly with a cable. In either case, an excitation specialist should be consulted to verify the safety of the installation. Also, the excitation-system inverter mode should be inhibited to avoid rotor demagnetization prior to the field breaker opening.

Because of the time constant associated with the magnetic circuits in a brushless excitation system, the field excitation for the brushless exciter must be removed well ahead (several seconds for large equipment) of the stator short circuit. The decay of the armature voltage is accommodated by considering the pre-fault voltage as that measured 1 to 2 cycles prior to application of the short circuit. The delay needs to be sufficient that the field voltage has decayed to a constant (near zero) value. Ideally, this is confirmed by measurement of the field voltage, usually via a special instrumentation slip ring.

11.4.3.3 Initial speed

Although, since they are inductance dominated, short-circuit current magnitudes are relatively independent of speed, it is recommended that armature-and-field sudden short-circuit tests be conducted from the machine's rated speed whenever possible.

11.4.3.4 Initial conditions

The initial level of the field excitation/open-circuit voltage should be adjusted depending on the purpose of the test. For example, traditionally unsaturated values of the transient parameters are obtained from tests in which the maximum values of the rms transient currents are on the order of the rated currents of the machine. Similarly, the saturated values of the transient parameters are traditionally obtained from tests conducted with the machine at rated open-circuit voltage.

11.4.3.5 Measurements

For the purposes of parameter determination, the steady-state terminal voltage (phase-phase or phase-neutral) should be recorded prior to conducting the test. If possible it is recommended that the field-winding terminal voltage be recorded to help ensure that the test conditions are consistent with the assumptions that the field voltage is zero for the purposes of this test. In general, the armature short circuit should be maintained and the current recorded until the current has reached a steady-state condition. Note that for the purposes of parameter determination, it is a good practice to record the initial field- and stator-winding temperatures. The rotor temperature can be determined from the steady-state values of the field voltage and current prior to the test and the stator-winding temperature can be measured using RTDs or other means.

11.4.3.6 Cautions

Recommendations for safety precautions are provided in 11.3. 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. An armature-and-field sudden short circuit can result in extreme mechanical stresses in the windings and other components of the machine under test. It is recommended that the manufacturer be consulted for guidance prior to conducting such a test. In addition, it should be noted that all temporary connections (cables or bus bars) as well as any moving parts of the breaker represent a serious threat to personnel safety. It is recommended that these components be properly barricaded to prevent access during the tests. The floor of the test area should withstand the weight of the breaker and its accessories. To reduce breaker movements, this latter should be securely attached to floor. In addition, a fire-extinguisher should be easily accessible to the test area.

11.4.4 Load rejection test

A load rejection test is conducted by opening the main breaker to disconnect a machine from the power system.

11.4.4.1 Initial conditions

Load rejection tests can be conducted from any desired initial machine loading. For the purposes of parameter determination, a common choice is a loading with reactive power only for which the net magnetic flux in the machine is aligned with the rotor direct axis. With the use of rotor-angle instrumentation, the loading can be adjusted, subject to acceptable operating limits, such that the initial net flux is aligned with any chosen rotor orientation, including the quadrature axis.

11.4.4.2 Excitation system

A load rejection test can be conducted using the machine's standard excitation system. It is important to recognize that the parameter-determination techniques discussed in 11.5 assume that the load-rejection test results are obtained from a test in which the excitation voltage applied to the field winding is constant. If this is not the case, the resultant parameter values will not be valid. This may be achievable by setting the excitation-system to its manual mode. However, it should be noted that "manual" mode in some excitation systems results in constant field-current control not constant field voltage. In such cases, this may require the use of an independent excitation system capable of maintaining constant field voltage. In either case, it is recommended that, if possible, the field voltage be monitored and recorded to verify the constant-field-voltage condition.

11.4.4.3 Initiating the test

A load rejection test is initiated by opening the main breaker to disconnect the machine under test for the power system. In the case of turbine-driven generators, it is typically not desirable to have the turbine or the excitation system automatically transfer-trip once the main breaker has been opened as this event will skew the results of the test. For example, when performing a reactive-power load-rejection test, it is undesirable to transfer-trip the turbine and exciter because ideally the 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 and a turbine trip will cause undesirable changes in the initial operating point of the 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.

11.4.4.4 Measurements

The initial machine terminal voltage, current and loading (real and reactive power) should be recorded prior to the start of the test. Once the test is initiated, the machine terminal voltage (phase-phase or phase-neutral) should be recorded, typically until the voltage has reached a steady-state value. As mentioned in 11.4.4.2, if possible it is recommended that the field-winding excitation voltage be recorded to help ensure that the test conditions are consistent with the assumptions required for parameter determination. Note that for the purposes of accurate parameter determination, it is a good practice to record the initial field- and stator-winding temperatures. The rotor temperature can be determined from the steady-state values of the field voltage and current prior to the test and the stator-winding temperature can be measured using RTDs or equivalent means. Monitoring the stator currents waveforms at the start of the test can be helpful in verifying the degree of breaker-pole synchronization.

11.4.4.5 Speed

Although the machine under test is initially operating at synchronous speed, the machine speed may vary significantly following the initiation of the test. Thus it is recommended to record machine speed, either directly or through observation of the frequency of the recorded terminal voltage.

11.4.4.6 Cautions

Initial conditions for a load-rejection test must be chosen to reduce the potential for adverse effects on the equipment. For example, load rejection from large active-power loadings will likely result in overspeed conditions or other large changes in prime mover conditions. In addition, in some cases the generator terminal voltage will decay considerably and may result in interruption of auxiliary loads if they are 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.

11.4.5 Voltage-recovery test

With its stator terminals initially short-circuited and with the machine operating at a selected level of excitation, the test is performed by suddenly opening the shorting breaker.

11.4.5.1 Switchgear

The switchgear chosen for this test must be capable of safely interrupting the initial steady-state current.

11.4.5.2 Excitation system

A voltage-recovery test can be conducted using the machine's standard excitation system. However, if the excitation system is supplied from the machine terminals, an alternate, externally fed excitation system must be employed. It is important to recognize that the parameter-determination techniques discussed in 11.5 assume that the voltage-recovery test results are obtained from a test in which the excitation voltage applied to the field winding is constant. If this is not the case, the resultant parameter values will not be valid. This may be achievable by setting the excitation-system to its manual mode. However, it should be noted that "manual" mode in some excitation systems results in constant field-current control not constant field voltage. In such cases, this may require the use of an independent excitation system capable of maintaining constant field voltage. In either case, it is recommended that, if possible, the field voltage be monitored and recorded to verify the constant-field-voltage condition.

11.4.5.3 Speed

The rate of decay of the rotor flux from this test is independent of the initial speed of the machine. However, the magnitude of the armature voltage is a function of speed and an initial speed sufficient to produce an easily measurable voltage magnitude is recommended. Although a voltage-recovery test can be performed from any initial speed, it is common to conduct the test at the machine's rated speed.

11.4.5.4 Measurements

The initial steady-state stator current prior to initiating the test should be recorded. Current monitoring can also be useful in verifying the degree of synchronization of the breaker poles. Following the initiation of the test, the stator terminal voltage should be recorded, preferably until a steady-state value is reached. As stated in 11.4.5.2, it is also helpful to record the excitation voltage supplied to the field winding. Note that for the purposes of accurate parameter determination, it may be helpful to determine the initial field-winding temperature. The rotor temperature can be determined from the steady-state values of the field voltage and current prior to the test.

11.4.6 Field short circuit with armature open-circuited test

For this test, the machine is operated with the armature open-circuited and the field excited. The test is initiated by opening the field circuit breaker to short-circuit the field winding, and the decay of the armature voltage and field current are recorded.

11.4.6.1 Test configuration

In modern excitation systems, when the field breaker is opened, a discharge resistor is automatically inserted in the circuit, either through a second breaker pole or using a thyristor. In the former case, a diode, of appropriate rating and polarity should be connected across the discharge resistor. In the latter case, the thyristor can be shorted directly with a cable. In either case, an excitation specialist should be consulted to verify the safety of the installation.

11.4.6.2 Excitation system

Depending on the choice of initial terminal voltage for the test, it may be necessary to connect the exciter transformer to a separate source.

11.4.6.3 Initial speed

The rate of decay of the rotor flux in this test is independent of speed. However, the magnitude of the armature voltage is a function of speed and an initial speed sufficient to produce an easily measurable voltage magnitude is recommended.

11.4.6.4 Measurements

The initial terminal voltage should be recorded along with, if possible, the initial field voltage and current. Following the initiation of the test, the terminal voltage should be recorded, preferably until it reaches a negligibly small value. If possible, the rotor field current should also be recorded. Note that for the purposes of accurate parameter determination, it may be helpful to determine the initial field-winding temperature. The rotor temperature can be determined from the steady-state values of the field voltage and current prior to the test.

11.4.6.5 Cautions

Prior to conducting this test, an excitation specialist should be consulted to verify that the test can be conducted safely without risk of damage to the excitation system.

11.4.7 Stationary test

For this test, the rotor is stationary, and the field winding is short-circuited. Single-phase voltage of rated frequency is briefly applied to any two stator terminals, and the third is isolated. The test is conducted by applying this procedure to the three stator-terminal combinations in rapid succession.

11.4.7.1 Test configuration

It is important that the rotor position remains same throughout this test. Blocking of the rotor to prevent turning should be used if necessary. Note that for large machines the only single-phase source typically available may be a large alternator. This will place an unbalanced load on the alternator so care should be taken to avoid negative-sequence heating and other adverse effects.

11.4.7.2 Measurements

For each of the three connections, the applied terminal voltage and resultant current should be recorded along with the induced field current.

11.4.7.3 Cautions

The manufacturer should be consulted prior to conducting this test. To avoid possible injurious rotor heating during the test, reduced voltage is normally used and the measurements should be taken quickly. It is recommended that the stator winding temperatures be monitored during the course of the test.

11.5 Models and methods to extract parameters from tests

11.5.1 Theoretical background for determining short-circuit reactances and time-constants

11.5.1.1 AC and dc components of short-circuit currents

The procedure to perform a sudden-three-phase short-circuit test is described in 11.4.1. The synchronous reactance (X_d), transient reactance (X'_d), subtransient reactance (X''_d), transient short-circuit time constant (T'_d), and subtransient short-circuit time constant (T''_d) are used to describe the machine's behavior following a sudden short circuit. This calculation can be done in accordance with Equation (119) for the ac component of current following a three-phase short circuit from no load when neglecting armature-circuit resistances and assuming constant exciter voltage. The dc component of the short-circuit current is defined by Equation (120). Details on the calculation method can be found in Harrington and Whittlesey [B20] and Kilgore [B31] (also see Annex F for mathematical details).

$$I(t)=\sqrt{2}E\left[\frac{1}{X_d}+\left(\frac{1}{X'_d}-\frac{1}{X_d}\right)e^{\frac{-t}{T'_d}}+\left(\frac{1}{X''_d}-\frac{1}{X'_d}\right)e^{\frac{-t}{T''_d}}\right]=$$
$$=\sqrt{2}\left[I_{ss}+I'_{d0}e^{\frac{-t}{T'_d}}+I''_{d0}e^{\frac{-t}{T''_d}}\right]=\sqrt{2}\left[I_{ss}+I'_d(t)+I''_d(t)\right] \tag{119}$$

$$I_{dc}(t)=\sqrt{2}E\left(\frac{1}{X''_d}+\frac{1}{X''_q}\right)e^{\frac{-t}{T_a}}=\sqrt{2}I_{dc0}e^{\frac{-t}{T_a}} \tag{120}$$

where

- $I(t)$ is the time-variant maximum values (envelope curve) of the ac component of short-circuit current, in amperes
- E is the ac rms voltage before the short circuit, in volts
- t is the time measured from the instant the short circuit is applied, in seconds
- I_{ss} is the steady-state rms component of the current $I(t)$, in amperes
- $I'_d(t)$ is the transient component of the current $I(t)$, in amperes
- $I''_d(t)$ is the subtransient component of the current $I(t)$, in amperes
- I'_{d0} is the initial value of the transient component of the current $I(t)$, in amperes
- I''_{d0} is the initial value of the subtransient component of the current $I(t)$, in amperes
- I_{dc0} is the initial dc component of the short circuit $I_{dc}(t)$, in amperes
- X_d is the direct-axis synchronous reactance, in ohms
- X'_d is the direct-axis transient reactance, in ohms
- X''_d is the direct-axis subtransient reactance, in ohms
- X''_q is the quadrature-axis subtransient reactance, in ohms
- T'_d is the direct-axis transient short-circuit time constant, in seconds
- T''_d is the direct-axis subtransient short-circuit time constant, in seconds
- T_a is the three-phase short-circuit armature time constant, in seconds

The saturated synchronous reactance $(X_d = X_{ds})$ is used for short circuits tested at normal open-circuit (rated) voltage since there will be a small degree of direct-axis machine saturation. The unsaturated reactance ($X_d = X_{du}$) may be used in place of X_{du} if the short-circuit test is performed with a sufficiently low initial terminal voltage so the magnetic saturation effects would be negligible in the recorded response. This is usually accomplished with an initial terminal voltage at around 0.4 p.u. of normal voltage or below 0.4 p.u.

The parameters X'_d, T'_d, X''_d, T''_d, and X''_q are defined in the *IEEE Standards Dictionary Online*.

In Equation (119), 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 axis 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.

11.5.1.2 Numerical implementation

11.5.1.2.1 General

This automated procedure is based primarily on published references such as Harrington and Whittlesey [B20], Marxsen and Morsztyn [B33], and Kamwa et al. [B27]. 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.

Short-circuit test armature currents $i_a(t)$, $i_b(t)$, and $i_c(t)$ should be sampled simultaneously at a rate of at least 2 kHz to properly capture the waveforms of these currents, with the instruments zeroed and not saturated (see 11.4.1.2). The data are stored digitally in physical values (amperes or kiloamperes), along with the nominal nameplate specifications of the machine V_{nom} (rated phase-to-phase rms in volts or kilovolts) and I_{nom} (rated rms line current in amperes or kiloamperes). Quite often, the rated line current is calculated from the rated apparent power of the machine, S_{nom}. These values are the usually the choices for the base values for the per unit system (see 9.2). 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 $N_f = 120$ (total test duration after short circuit of 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 (119) is chosen, but also including the effect of T_a, the short-circuit armature time constant. However, this new equation excludes any subtransient saliency (assumes $X''_d = X''_q$) and ignores any possible second-harmonic terms in the current waveforms.

11.5.1.2.2 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 $[T_{upp}, I_{upp}]$ and $[T_{low}, I_{low}]$ are determined for the total window length of N_f cycles. Time and current are given in physical units, seconds and kiloamperes (or amperes), respectively.

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.

11.5.1.2.2.1 Polynomial fitting

The approach 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} developed in Annex F.

Similarly to Equation (119) and Equation (120), the dc (P_{dc}) and symmetrical ac (P_{sym_ac}) components at a given time, t , are expressed as shown in Equation (121) and Equation (122), respectively.

$$P_{dc}(t) = \frac{P_{upp}(t) + P_{low}(t)}{2} \tag{121}$$

$$P_{sym\_ac}(t) = \frac{P_{upp}(t) - P_{low}(t)}{2} \tag{122}$$

11.5.1.2.2.2 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 [B6]). 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}): $I_{lows} = \text{spline}\,(T_{low}, I_{low}, T_{upp})$ (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 40.

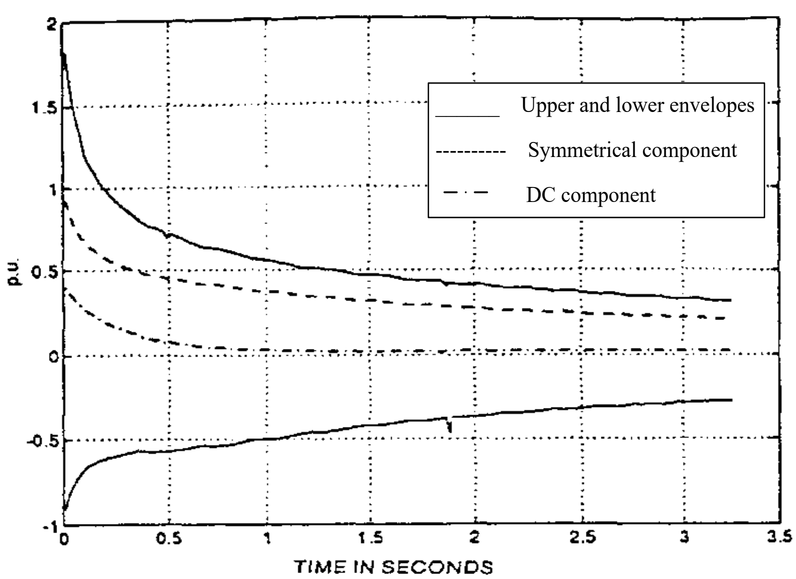


Figure 40 —Example of Component data for automatic analysis

11.5.2 Theoretical background for determining open-circuit reactances and time constants

The technical guideline to perform the load rejection test is described in 11.4.4. Open-circuit values of transient (T'_{do}) and subtransient (T''_{do}) time constants can be calculated from armature opened tests such as load rejection, voltage recoverage and field short circuit with armatures in open circuit, also known as running time-domain rotor decrement tests (RTD-RDT). Details on analysis of the load rejection tests and their application for the determination of synchronous machine parameters using advanced estimation techniques can be found in Wamkeue et al. [B44].

11.5.2.1 Terminal voltage prediction following load rejection of purely capacitive and inductive loads in terms of open-circuit reactance and time constants

11.5.2.1.1 Load rejection of a purely capacitive load

For the direct-axis load rejection test, the generator terminal flux is on the direct axis, the rotor angle $\delta_0 = 0$ and the active power $P = 0$ W. The rotor speed is constant and equal to the synchronous speed $\omega(t) = \omega_0$ (rad/s) during the direct-axis load rejection test. If the load is capacitive, the load angle $\phi = -\frac{\pi}{2}$ (rad) the generator terminal current is entirely in the direct axis, $I_d = -I_0$ and the terminal voltage is aligned with the quadrature axis, thus $E_q = E_0$. The voltage following the load-rejection of the purely capacitive load (direct-axis load rejection test) is defined by Equation (123) (mathematical details are given in Annex G).

$$\begin{aligned} E(t) &= \omega_0 \left\{ E_0 - \left[X_d - (X_d - X'_d) e^{\frac{-t}{T'_{d0}}} - (X'_d - X''_d) e^{\frac{-t}{T''_{d0}}} \right] I_0 \right\} = \\ &= E_{q\infty} + E'_q(t) + E''_q(t) = E_{q\infty} + E'_{q0} e^{\frac{-t}{T'_{d0}}} + E''_{q0} e^{\frac{-t}{T''_{d0}}} \end{aligned} \tag{123}$$

where

- $E(t)$ is the time-variant rms magnitude of the terminal voltage, in volts
- E_0 is the ac rms voltage before the load rejection (breaker opening), in volts
- I_0 is the initial rms current before the load rejection (breaker opening), in amperes
- t is the time measured from the instant of the load rejection, in seconds
- $E_{q\infty}$ is the steady-state rms component of the terminal voltage $E(t)$, in volts
- $E'_q(t)$ is the transient component of the voltage $E(t)$, in volts
- $E''_q(t)$ is the subtransient component of the voltage $E(t)$, in volts
- E'_{q0} is the initial value of the transient component of the voltage $E(t)$, in volts
- E''_{q0} is the initial value of the subtransient component of the voltage $E(t)$, in volts
- X_d is the direct-axis synchronous reactance, in ohms
- X'_d is the direct-axis transient reactance, in ohms
- X''_d is the direct-axis subtransient reactance, in ohms
- T'_{d0} is the direct-axis transient open-circuit time constant, in seconds
- T''_{d0} is the direct-axis subtransient open-circuit time constant, in seconds

11.5.2.1.2 Load rejection of a purely inductive load

If the load to be rejected is purely inductive, the load angle $\phi = \frac{\pi}{2}$, the generator terminal current is entirely in the direct axis, $I_d = -I_0$, the terminal is the given by Equation (124).

$$E(t) = \omega_0 \left\{ E_0 + \left[X_d - (X_d - X'_d) e^{\frac{-t}{T'_{d0}}} - (X'_d - X''_d) e^{\frac{-t}{T''_{d0}}} \right] I_0 \right\} \tag{124}$$

As previously mentioned for short-circuit test (see 11.5.1), the saturated synchronous reactance $(X_d = X_{ds})$ is used for load rejection test at normal operation (rated) voltage since there will be a direct-axis machine saturation. The appropriated use of Equation (123) is when unsaturated reactance ($X_d = X_{du}$) is required. Accordingly, the load rejection test must be performed at around 0.4 p.u. of normal voltage or below 0.4 p.u. Figure 41 illustrates synchronous generator variable waveforms after the load rejection test of a purely capacitive load. Note that the initial conditions of example in Figure 41 are appropriated to the model defined in Equation (123) since the initial power $P = 0$ and the field voltage is maintained constant during the test.

11.5.2.2 Terminal voltage prediction following voltage recovery tests

The procedure to perform the voltage recovery test is described in 11.4.5. As previously stated in 11.5.2.1, the voltage recovery is similar to the load rejection of a purely inductive load; thus, the rotor angle $\delta_0 = 0$ (the electrical power of the machine is $P = 0$ MW, as the test initial condition is a three-phase short circuit at the machine terminals), the power factor angle $\phi = 90\,°$, and the terminal current is aligned with the direct axis. Given that all three phases of the generator are short-circuited, the initial terminal voltage $E_0 = 0$, in Equation (123). The terminal voltage is computed from Equation (125).

$$\begin{aligned} E_\Delta(t) &= \omega_0 \left[X_d - (X_d - X'_d) e^{\frac{-t}{T'_{d0}}} - (X'_d - X''_d) e^{\frac{-t}{T''_{d0}}} \right] I_0 = \\ &= E_{\Delta\infty} + E'_\Delta(t) + E''_\Delta(t) = E_{\Delta\infty} + E'_{\Delta 0} e^{\frac{-t}{T'_{d0}}} + E''_{\Delta 0} e^{\frac{-t}{T''_{d0}}} \end{aligned} \tag{125}$$

where

- $E_\Delta(t)$ is the time-variant rms magnitude of the envelope curve of the peak values of the terminal voltage, in volts
- I_0 is the initial rms current before the breaker opening, in amperes
- t is the time measured from the instant of the load rejection, in seconds
- $E_{\Delta\infty}$ is the steady-state rms component of the terminal voltage $E_\Delta(t)$, in volts
- $E'_\Delta(t)$ is the transient component of the voltage $E_\Delta(t)$, in volts
- $E''_\Delta(t)$ is the subtransient component of the voltage $E_\Delta(t)$, in volts
- $E'_{\Delta 0}$ is the initial value of the transient component of the voltage $E_\Delta(t)$, in volts
- $E''_{\Delta 0}$ is the initial value of the subtransient component of the voltage $E_\Delta(t)$, in volts
- X_d is the direct-axis synchronous reactance, in ohms
- X'_d is the direct-axis transient reactance, in ohms
- X''_d is the direct-axis subtransient reactance, in ohms
- T'_{d0} is the direct-axis transient open-circuit time constant, in seconds
- T''_{d0} is the direct-axis subtransient open-circuit time constant, in seconds

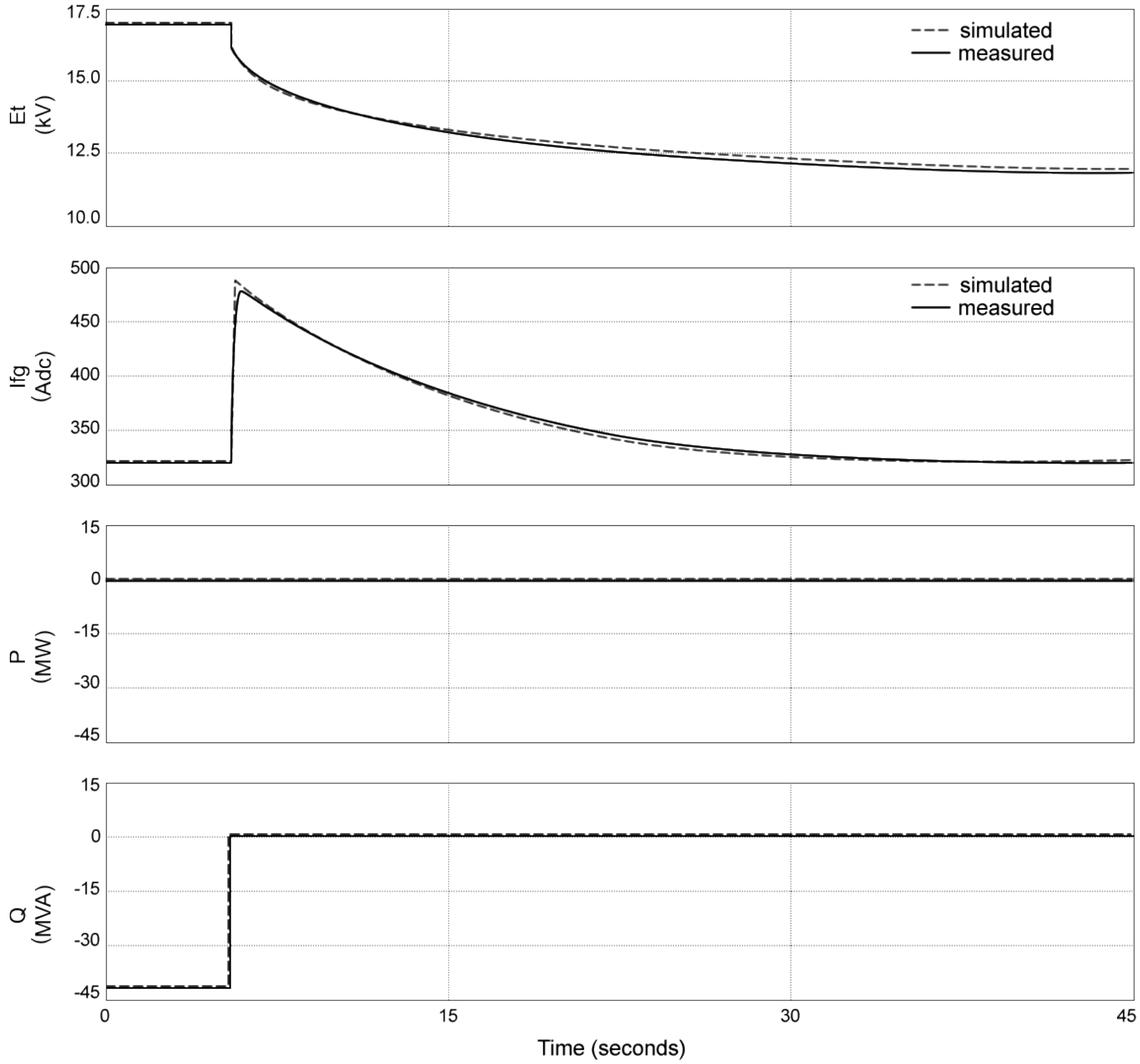


Figure 41 —Example of model parameter identification based on simulations: Terminal voltage, field current, active power and reactive power after the load rejection test of purely reactive load

11.5.3 Determination of generator reactances from three-phases sudden short circuit, load rejection, voltage recovery, and stationary and unbalanced tests

Methods for determining direct-axis synchronous reactance (X_d), transient reactance (X'_d), and subtransient reactance (X''_d), along with quadrature-axis subtransient reactance (X''_q) and negative sequence reactance (X_2), are developed in this subclause. Derived reactances are associated to each method.

- Method 1. AC component from sudden short-circuit tests to determine X_d, X'_d, and X''_d (see 11.5.3.1)
- Method 2. DC component from sudden short-circuit tests to determine X'_d and X''_d (see 11.5.3.2)
- Method 3. Load rejection tests to determine X_d, X'_d, and X''_d (see 11.5.3.3)

— Method 4. Voltage recovery tests to determine X_d , X'_d , and X''_d (see 11.5.3.4)
— Method 5. Stationary tests to determine X''_d and X''_q (see 11.5.3.5)
— Method 6. Unbalanced test to determine X_2 (see 11.5.3.6)

11.5.3.1 Method 1. AC component from sudden short-circuit tests to determine X_d , X'_d , and X''_d

11.5.3.1.1 Description

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 (see 11.4.1). 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 (see Equation (119) and 11.5.1) to the instant of application of the short circuit when neglecting the rapid variation of current during the first few cycles. Figure 42 and Figure 43 illustrate the graphical approach associated with this method of determining the direct-axis transient reactance.

The rated-voltage value of direct-axis subtransient reactance may also be obtained using Method 1 or Method 2 (see 11.5.3.2). The direct-axis subtransient reactance is determined from the same sudden-three-phase 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 43.

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 of 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 values of the alternating components of the currents at each value of time may be obtained from the envelopes by the method discussed in 11.5.1.2. It is not necessary to obtain a value for zero time by extrapolating the envelopes. Examples of simulated variables for a sudden-three-phase short-circuit test are illustrated in Figure 44 and Figure 45.

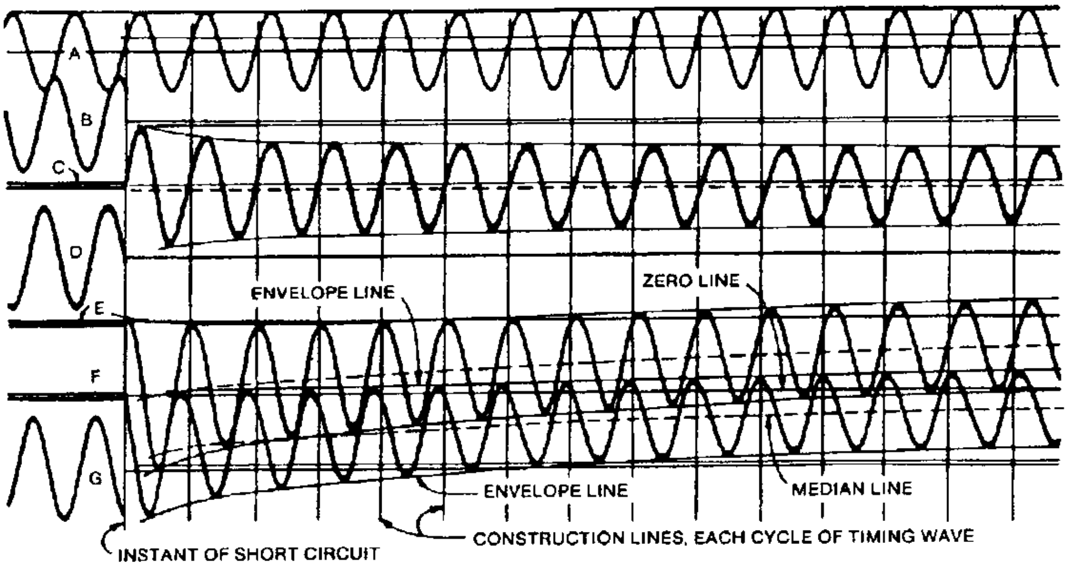


Figure 42—Oscillogram of sudden-three-phase short circuit

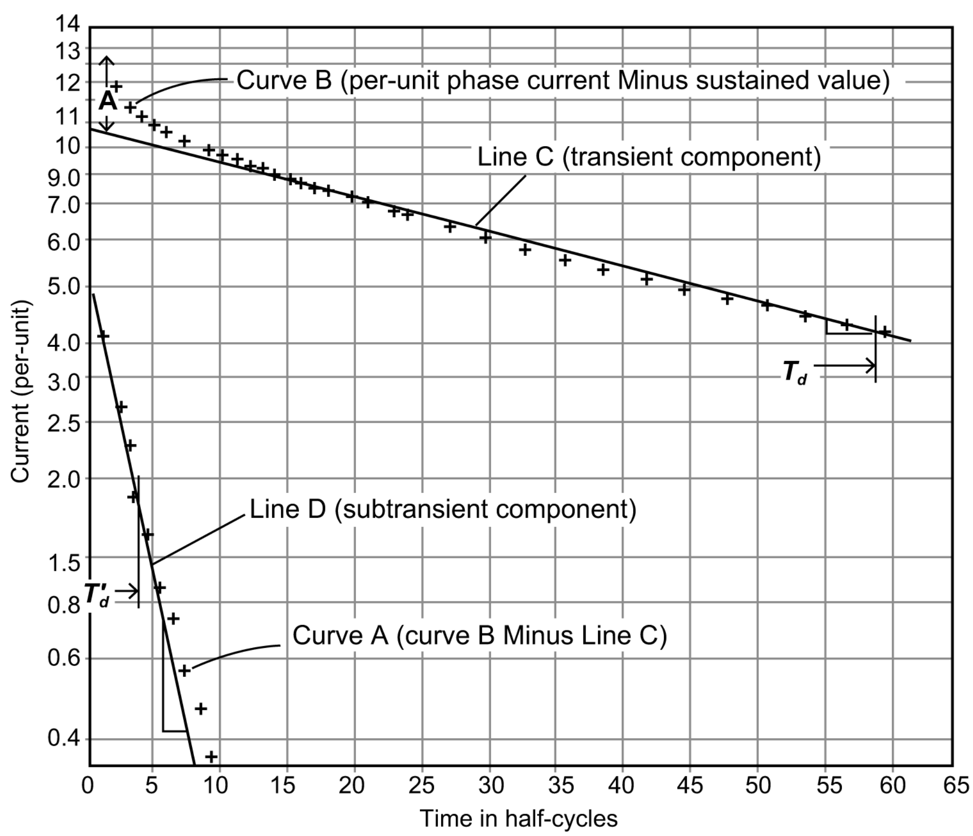


Figure 43—Analysis of ac component of short-circuit current

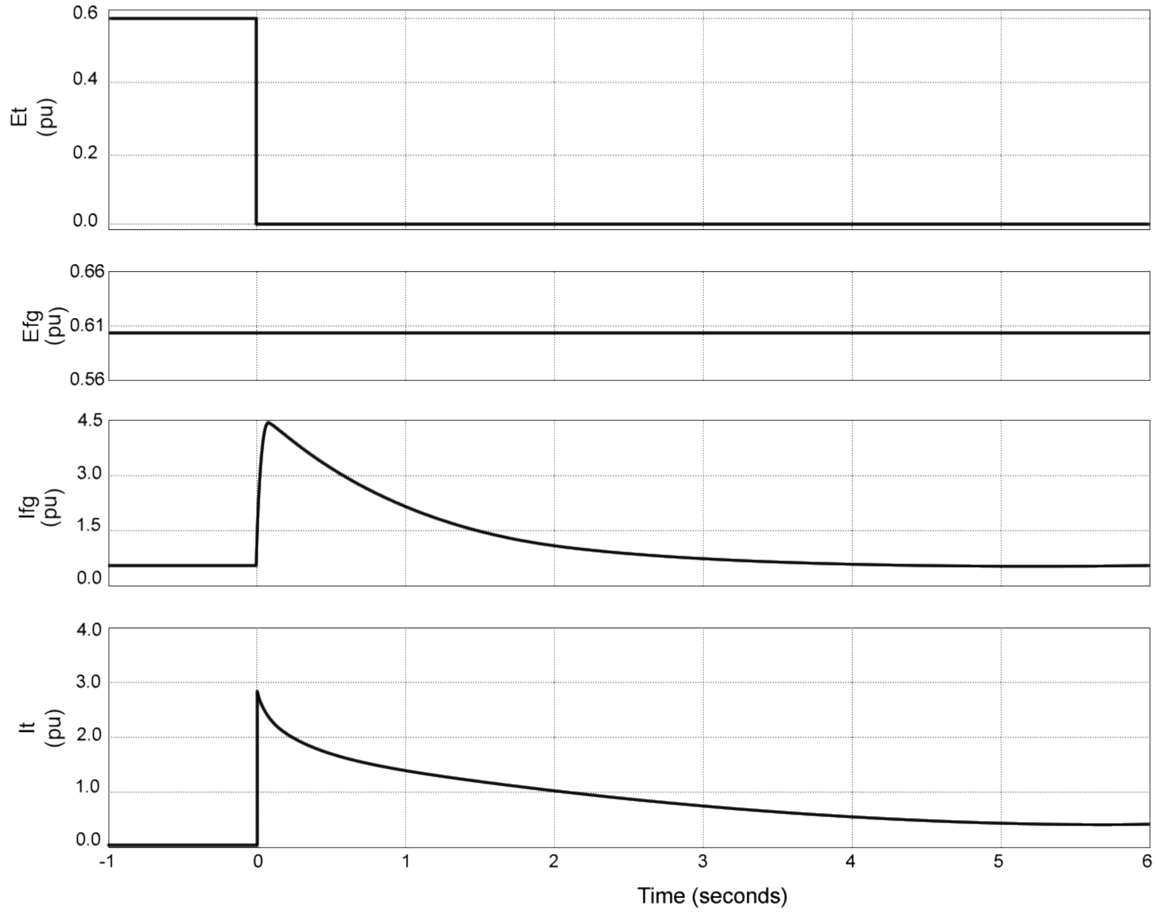


Figure 44—Example of simulated variables for sudden three-phase short circuit: Terminal voltage, field voltage, field current and terminal current envelope

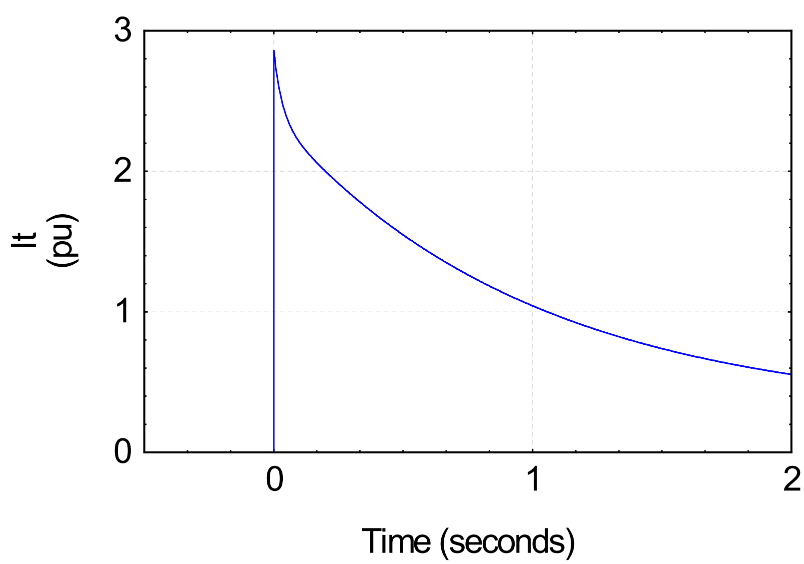


Figure 45—Simulated terminal current envelope following sudden three-phase short circuit

11.5.3.1.2 Determination of synchronous reactance, X_d, from Method 1

In the steady state after the transient period $(t \to \infty)$, the short-circuit rms current is equal to the steady-state current, I_{ss}. The synchronous reactance is obtained from Equation (126).

$$X_d = \frac{E}{I_{ss}} \tag{126}$$

11.5.3.1.3 Determination of transient reactance, X'_d, from Method 1

The transient reactance for the value of current I' is then obtained from Equation (127), based on Equation (119) (also refer to 11.5.3.1.5).

$$I'_{d0} = E\left(\frac{1}{X'_d} - \frac{1}{X_d}\right) \quad \Rightarrow \quad X'_d = \frac{E}{I'_{d0} + I_{ss}} = \frac{E}{I'} \tag{127}$$

where

I' is the initial value of the transient component I'_{d0} of the current $I(t)$ of Equation (119), plus the steady-state component I_{ss}

11.5.3.1.4 Determination of subtransient reactance, X''_d, from Method 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 (128) derived from Equation (119) and Equation (127) (also see Figure 43 and Table 3).

$$X''_d = \frac{E}{I_{ss} + I'_{d0} + I''_{d0}} = \frac{E}{I''} \tag{128}$$

Note that parameters and variables given in Equation (128) are defined in 11.5.1.1.

11.5.3.1.5 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.

Table 3—Example of determining transient and subtransient reactance

	Phase 1	Phase 2	Phase 3	Average
Initial voltage E in Equation (119)	—	—	—	0.994
Steady-state current I_{ss} in Equation (119)	1.4	1.4	1.4	—
Initial transient component I'_{d0} in Equation (119)	9.4	10.2	9.3	—
$I' = I_{ss} + I'_{d0}$	10.8	11.6	10.7	11.0
Transient reactance X'_d from Equation (127)	—	—	—	0.0904
Initial subtransient component I''_{d0} in Equation (119)	3.6	5.8	3.8	—
$I'' = I_{ss} + I'_{d0} + I''_{d0}$	14.4	17.4	14.5	15.4
Subtransient reactance X''_d from Equation (128)	—	—	—	0.0645
Initial direct current component I_{dc0} in Equation (119) and Figure 50(c)	11.0	25.0	13.6	—
Identified as phase (see 11.5.3.2.2) Method 2	**c**	**a**	**b**	—
Weighted average of initial direct current component I_{dc0} for each phase in Equation (130), Equation (131), and Equation (132)	$I''_{(1)}$	$I''_{(2)}$	$I''_{(3)}$	—
	17.7	17.7	17.4	—
Average of initial direct current component I_{dc0} in Equation (133)	—	—	—	17.6
Subtransient reactance X''_d from Equation (134)	—	—	—	0.0565
NOTE—All values expressed in per unit (see 9.2).				

11.5.3.1.6 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 X'_{di}, tests from initial voltages in the vicinity of the calculated value of X'_d should be made (voltage and reactance, expressed in per unit). 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 value of rated current (1.0 p.u., see 9.2.3). 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 X'_{dv}, 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.

11.5.3.2 Method 2. DC component from sudden short-circuit tests to determine X_d' and X_d''

A method of evaluating the direct-axis subtransient reactance from the oscillograms of the three-phase short-circuit test of 11.4.3 may be used as a check of Method 1 (see 11.5.3.1) when it is known that the short circuit of all three phases is established at nearly the same instant, preferably within five electrical degrees or less. Note that Method 1 is preferred as it is a more direct approach. The values of the dc component for each phase may now be plotted in a similar way to that used for the ac components (see Figure 46). The initial values of the dc component for the three phases are obtained by extrapolating the plotted curves back to zero time.

In Method 2, 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 (see 11.4.3).

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 11.5.3.2.1).

11.5.3.2.1 Determination of transient reactance, X_d', from Method 2

Equation (119) would be considered to apply to the current in this test if two of the terms of the formula (E/X_d) 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 40, it is not necessary to subtract the steady-state armature current since it is zero.

The value of I' from this Method 2, to be used in Equation (129), is the true initial value of the transient component of short-circuit current.

$$X_d' = \frac{E}{I'} = \frac{E}{I_{d0}'} \tag{129}$$

11.5.3.2.2 Determination of subtransient reactance, X_d'', from Method 2

Referring to 11.5.3.2, 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. 11.5.3.1.5 gives an example, and Figure 46 should be examined.

A weighted average of the initial dc component of the three short-circuit currents can be found by calculating $I_{(1)}''$, $I_{(2)}''$, and $I_{(3)}''$, and taking a weighted value. The weighting is somewhat arbitrary. The three values of the dc component of current, I'', are obtained from Equation (130), Equation (131), and Equation (132).

$$I_{(1)}'' = \frac{2}{3}\sqrt{\left(a^2 + b^2 - ab\right)} \tag{130}$$

$$I_{(2)}'' = \frac{2}{3}\sqrt{\left(a^2 + c^2 - ac\right)} \tag{131}$$

$$I''_{(3)} = \frac{2}{3}\sqrt{\left(b^2 + c^2 + bc\right)} \tag{132}$$

where

- a is the largest absolute value of the initial dc component of the three-phase currents at the selected time, in per unit
- b is the second largest value of the initial dc component, in per unit
- c is the smallest value of the initial dc component, in per unit
- $I''_{(1)}$ is the weighted average of the initial dc component for the largest absolute value, a
- $I''_{(2)}$ is the weighted average of the initial dc component for the second largest absolute value, b
- $I''_{(3)}$ is the weighted average of the initial dc component for the smaller absolute value, c

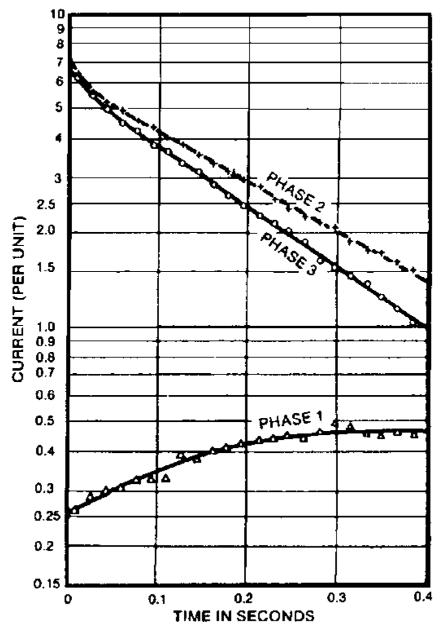


Figure 46—DC components of phase currents

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 (133).

$$I'' = \frac{3I''_{(1)} + 2I''_{(2)} + I''_{(3)}}{6} \tag{133}$$

The weighted average of I'' in Equation (133) is used in Equation (134) to calculate the subtransient reactance X''_d.

$$X''_d = \frac{E}{I''} \tag{134}$$

11.5.3.3 Method 3. Load rejection tests to determine X_d, X'_d, and X''_d

11.5.3.3.1 Determination of synchronous reactance, X_d, from Method 3

A graphical approach similar to the method defined in 11.5.3.1 can be also used to compute the direct-axis parameters in Equation (135). A low terminal voltage magnitude is required prior to the load rejection test to avoid the impact of saturation phenomenon on obtained parameters.

$$\begin{aligned} E_{q\infty} &= \omega_0(E_0 - X_d I_0) \\ E'_{q0} &= \omega_0(X_d - X'_d)I_0 \\ E''_{q0} &= \omega_0(X'_d - X''_d)I_0 \end{aligned} \tag{135}$$

where

- E_0 is the ac rms voltage before the load rejection (breaker opening), in volts
- I_0 is the initial rms current before the load rejection (breaker opening), in amperes
- $E_{q\infty}$ is the steady-state rms component of the terminal voltage $E(t)$, in volts
- E'_{q0} is the initial value of the transient component of the voltage $E(t)$, in volts
- E''_{q0} is the initial value of the subtransient component of the voltage $E(t)$, in volts
- X_d is the direct-axis synchronous reactance, in ohms
- X'_d is the direct-axis transient reactance, in ohms
- X''_d is the direct-axis subtransient reactance, in ohms

The direct-axis synchronous reactance can be computed from Equation (136) obtained from the first line of Equation (135), considering the rotor speed constant and equal to rated speed ($\omega_0 = 1$ p.u.).

$$X_d = \frac{E_0 - E_{q\infty}}{I_0} \tag{136}$$

Figure 47 presents an application example, with the terminal voltage following the load rejection test of a purely capacitive load performed on a small laboratory synchronous turbine generator (208 V, 1.5 kVA, four-pole, 60 Hz). The steady-state terminal voltage and current prior to the load rejection are $E_0 = 0.5232$ p.u. and $I_0 = 0.16$ p.u. corresponding to a total reactive power output of $Q = -0.083712$ p.u. The steady-state voltage, in Figure 47, corresponds to $E_{q\infty} = 0.4136$ p.u.; thus, the direct-axis reactance calculated using Equation (136) results in $X_d = 0.685$ p.u.

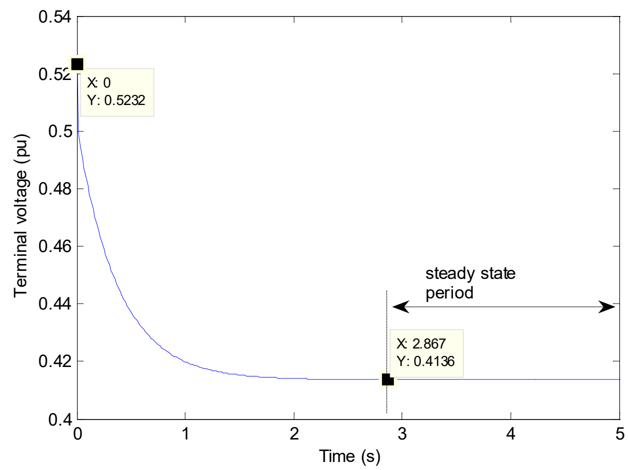


Figure 47—Terminal voltage following load rejection of purely capacitive load

11.5.3.3.2 Determination of transient reactance, X'_d, from Method 3

The direct-axis transient reactance is computed from the second line of Equation (135) and using Equation (137).

$$X'_d = X_d - \frac{E'_{q0}}{I_0} = \frac{E_0 - E_{q\infty} - E'_{q0}}{I_0} \tag{137}$$

where

- E_0 is the ac rms voltage before the load rejection (breaker opening), in per unit
- I_0 is the initial rms current before the load rejection (breaker opening), in per unit
- $E_{q\infty}$ is the steady-state rms component of the terminal voltage $E(t)$, in per unit
- E'_{q0} is the initial value of the transient component of the voltage $E(t)$, in per unit
- X_d is the direct-axis synchronous reactance, in per unit
- X'_d is the direct-axis transient reactance, in per unit

From Figure 48, it is estimated that $E'_q(0) = E'_{q0} = 0.087$ p.u., and the transient reactance is then computed using Equation (137): $X'_d = 0.141$ p.u., considering the previously calculated value for the synchronous reactance $X_d = 0.685$ p.u.

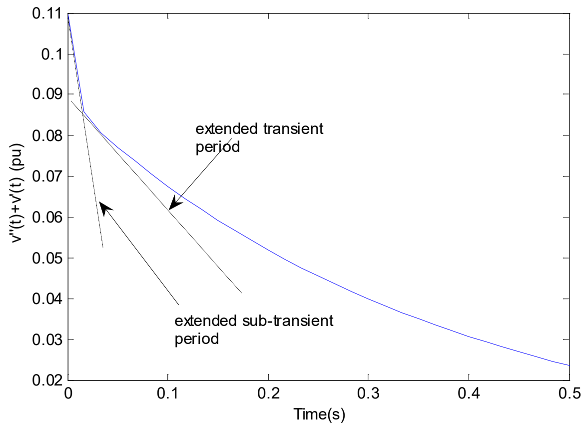


Figure 48—Transient and subtransient terminal voltage

11.5.3.3.3 Determination of subtransient reactance, X''_d, from Method 3

The direct-axis subtransient reactance following the load rejection test is computed using Equation (138) derived from the second line of Equation (135) and using Equation (137).

$$X''_d = X'_d - \frac{E''_{q0}}{I_0} = \frac{E_0 - E_{q\infty} - E'_{q0} - E''_{q0}}{I_0} \tag{138}$$

where

- E_0 is the ac rms voltage before the load rejection (breaker opening), in volts
- I_0 is the initial rms current before the load rejection (breaker opening), in amperes
- $E_{q\infty}$ is the steady-state rms component of the terminal voltage $E(t)$, in volts
- E'_{q0} is the initial value of the transient component of the voltage $E(t)$, in volts
- E''_{q0} is the initial value of the subtransient component of the voltage $E(t)$, in volts
- X_d is the direct-axis synchronous reactance, in ohms
- X'_d is the direct-axis transient reactance, in ohms
- X''_d is the direct-axis subtransient reactance, in ohms

For the numerical example presented in 11.5.3.3.1 and 11.5.3.3.2, and considering $E''_{q0} = 0.0176$ p.u. (see Figure 48), Equation (138) yields $X''_d = 0.031$ p.u.

11.5.3.4 Method 4. Voltage recovery tests to determine X_d, X'_d, and X''_d

11.5.3.4.1 Determination of synchronous reactance, X_d, from Method 4

The direct-axis reactance following the voltage recovery test is computed using Equation (139) derived from Equation (125).

$$X_d = \frac{E_{\Delta\infty}}{I_0} \tag{139}$$

where

I_0 is the initial rms current before the breaker opening, in per unit

$E_{\Delta\infty}$ is the steady-state rms component of the terminal voltage $E_{\Delta}(t)$, in per unit

X_d is the direct-axis synchronous reactance, in per unit

11.5.3.4.2 Determination of transient reactance, X'_d, from Method 4

The direct-axis transient reactance, X'_d, 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 49). 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 in Figure 49). The time-zero value of this transient differential voltage is denoted by $E'_{\Delta 0}$, as shown in Figure 49.

The direct-axis transient reactance following the voltage recovery test is computed using Equation (140) derived from Equation (125).

$$X'_d = X_d - \frac{E'_{\Delta 0}}{I_0} = \frac{E_{\Delta\infty} - E'_{\Delta 0}}{I_0} \tag{140}$$

where

I_0 is the initial rms current before the breaker opening, in amperes

$E_{\Delta\infty}$ is the steady-state rms component of the terminal voltage $E_{\Delta}(t)$, in volts

$E'_{\Delta 0}$ is the initial value of the transient component of the voltage $E_{\Delta}(t)$, in volts

X_d is the direct-axis synchronous reactance, in ohms

X'_d is the direct-axis transient reactance, in ohms

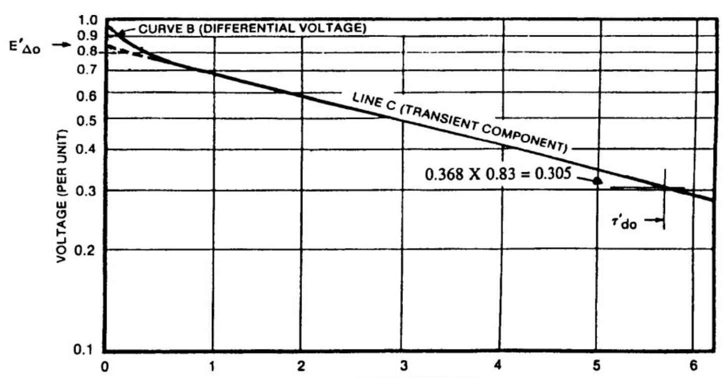


Figure 49—Transient component of voltage recovery test

11.5.3.4.3 Determination of subtransient reactance, X''_d, from Method 4

The direct-axis subtransient reactance, X''_d, is computed from the voltage recovery using Equation (141) obtained from Equation (125).

$$X''_d = X'_d - \frac{E''_{\Delta 0}}{I_0} = \frac{E_{\Delta\infty} - E'_{\Delta 0} - E''_{\Delta 0}}{I_0} \tag{141}$$

where

- I_0 is the initial rms current before the breaker opening, in amperes
- $E_{\Delta\infty}$ is the steady-state rms component of the terminal voltage $E_\Delta(t)$, in volts
- $E'_{\Delta 0}$ is the initial value of the transient component of the voltage $E_\Delta(t)$, in volts
- $E''_{\Delta 0}$ is the initial value of the subtransient component of the voltage $E_\Delta(t)$, in volts
- X'_d is the direct-axis transient reactance, in ohms
- X''_d is the direct-axis subtransient reactance, in ohms

11.5.3.4.4 Error correction for speed changes

Equation (125) shows that the voltage $E_\Delta(t)$ associated with the envelope curve for the peak values of the voltages from the oscillogram is proportional to the rotor speed ω (considered constant in Equation (125), $\omega = \omega_0$). If the rotor speed has been recorded during the test, the values for $E_\Delta(t)$ obtained directly from the recorded oscillogram for the voltages can be corrected for the observed speed deviation during the test, as shown in Equation (142).

$$E_{\Delta c}(T) = \frac{\omega(T)}{\omega_0} E_\Delta(T) \tag{142}$$

where

- T is the time instant associated with each one of the points of the envelope curve $E_\Delta(t)$ as determined from the oscillogram with the recorded test results, in seconds
- ω_0 is the rated speed of the rotor
- $\omega(T)$ is the recorded speed of the rotor at the time instant T, in the same units as ω_0
- $E_\Delta(T)$ is the voltage for the point on the envelope curve $E_\Delta(t)$, at the time instant T, from the oscillogram with recorded test results, in volts
- $E_{\Delta c}(T)$ is the voltage for the point on the envelope curve $E_\Delta(T)$, corrected for a speed deviation $\omega(T) - \omega_0$

The steps in this correction process are as follows:

a) The speed-corrected voltage recovery curve $E_{\Delta c}(T)$ should be replotted.
b) A new differential voltage curve similar to Figure 49 is then drawn and projected back to zero time to obtain speed-corrected values of $E_{\Delta\infty}$, $E'_{\Delta 0}$, and $E''_{\Delta 0}$.
c) Equation (139), Equation (140), and Equation (141) are used with the speed-corrected values calculated above.

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.

11.5.3.5 Method 5. Stationary tests to determine X''_d and X''_q

11.5.3.5.1 Determination of direct-axis subtransient reactance, X''_d, from Method 5

It is assumed that the single-phase stationary rotor reactance, determined for any one pair of terminals, 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 (143).

$$K = \frac{X + Y + Z}{3} \tag{143}$$

where

X is the stationary rotor reactance for the first selected pair of terminals
Y is the stationary rotor reactance for the second selected pair of terminals
Z is the stationary rotor reactance for the third selected pair of terminals
K is the average of X, Y, and Z

The amplitude of the sinusoidal component of voltage reactance variation is given by Equation (144).

$$M = \sqrt{(Y-K)^2 + \frac{(Z-X)^2}{3}} \tag{144}$$

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 in Equation (144), 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 (145). Usually, the direct-axis reactance corresponds to the smallest possible stationary rotor reactance. For this case, the use of the negative sign in Equation (145) is suggested.

$$X''_d = \frac{K \pm M}{2} \tag{145}$$

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, and the plus sign should be used in Equation (145).

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 11.5.3.5.3). 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.

11.5.3.5.2 Indirect method for determining X''_d from Method 5

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.

11.5.3.5.3 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 11.5.3.2.1) has rated value. The corresponding total ac component (see I'' in 11.5.3.1.1) including the subtransient component would, therefore, be somewhat greater. In Method 1 and Method 2 the direct-axis subtransient reactance is determined from the same tests that are used for determining transient reactance (see 11.5.3.1.1). 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. 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.

11.5.3.5.4 Determination of quadrature-axis subtransient reactance, X_q'', from Method 5

For the definition of *quadrature-axis subtransient reactance*, see Clause 3.

The rated-current value of quadrature-axis subtransient reactance may be obtained using Method 5, and an approximation to the rated-voltage value from sudden short-circuit test Method 6.

The quadrature-axis subtransient reactance is determined from the data obtained in the determination of the direct-axis subtransient reactance by Method 5. In terms of the quantities defined in 11.5.3.5.2, the quadrature-axis subtransient reactance is obtained by Equation (146). Usually, the quadrature-axis reactance corresponds to the largest stationary rotor reactance. For this case, the use of the positive sign in Equation (146) is suggested.

$$X_q'' = \frac{K \pm M}{2} \tag{146}$$

where

K is the average X, Y, and Z in Equation (143)(144)
M is the amplitude of the sinusoidal component of voltage reactance variation in Equation (144)

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 11.4.6, and the minus sign should be used in Equation (146).

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 11.5.3.5.3. 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.

11.5.3.6 Method 6. Unbalanced test to determine quadrature-axis negative sequence reactance, X_2

The open-circuit voltage, E of rated voltage, is measured before the short circuit, and the rms value of the initial ac component of armature current, I'' of rated current, is determined as for a three-phase short circuit (see 11.4.1). Then the quadrature-axis negative sequence reactance is obtained as shown in Equation (147).

$$X'_{2LL} = \frac{\sqrt{3}E}{I''} - X_d'' \tag{147}$$

where

E is the open-circuit rated voltage measured before the short circuit
I'' is the rms value of the initial ac component of armature current
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 $-I''/\sqrt{3}$), 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.

11.5.3.7 Determining X''_q from combined Method 1 and Method 6

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 and one sudden single-phase line-to-line short circuit (see 11.5.3.6). The direct-axis subtransient reactance obtained from the three-phase test is designated as X''_{d3}. For the single-phase test (see 11.5.3.6), the open-circuit voltage, E, and the initial ac component of armature current (I'' obtained by Method 1 in 11.5.3.1.4) are obtained and used in Equation (148).

$$X_{LL} = \frac{\sqrt{3}E}{I''} \tag{148}$$

where

E is the open-circuit rated voltage measured before the short circuit
I'' is the rms value of the initial ac component of armature current
X_{LL} is the line-to-line reactance from Equation (148)

The quadrature-axis subtransient reactance is obtained using Equation (149).

$$X''_q = \frac{X_{LL} - X''_{d3}}{X''_{d3}} \tag{149}$$

where

X''_{d3} is the direct-axis subtransient reactance obtained from the three-phase test

11.5.3.8 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 sudden-three-phase 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.

11.5.4 Determination of direct-axis short-circuit time constants

11.5.4.1 Computation of transient short-circuit time constant, T_d', from straight-line representation

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 11.5.3.1). It is the time, in seconds, required for the transient alternating component of the short-circuit current (see line C in Figure 43) 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 43.

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 11.5.3.1), 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.

In addition to the hypotheses used in the second paragraph of 11.5.1.2.1 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 (150).

$$\ln \Delta i'(t) = \ln i(t) = A' t + B' \tag{150}$$

where

$\Delta i'(t)$	is equal to $I_d'(t)$, the transient component of the current $I(t)$, in amperes in Equation (119)
$i(t)$	is the ac component of the straight-line equivalent model of short-circuit current $I(t)$ minus (I_{ss}), the steady-state rms component of the current $I(t)$, ($i(t) \simeq I(t) - I_{ss} = I_d'(t)$) in per unit
A' and B'	are straight line equivalent model parameters of $\ln \Delta i'(t)$
t	is the time, in seconds, in the range beyond 20 cycles

Decoupled time scales analysis is shown graphically in Figure 50.

a) Transient data:
$\Delta i'(t)$

b) Subtransient data:
$\Delta i''(t)$

c) Direct current data:
$abs[i_{dc}(t)]$. ___ Model. o Test

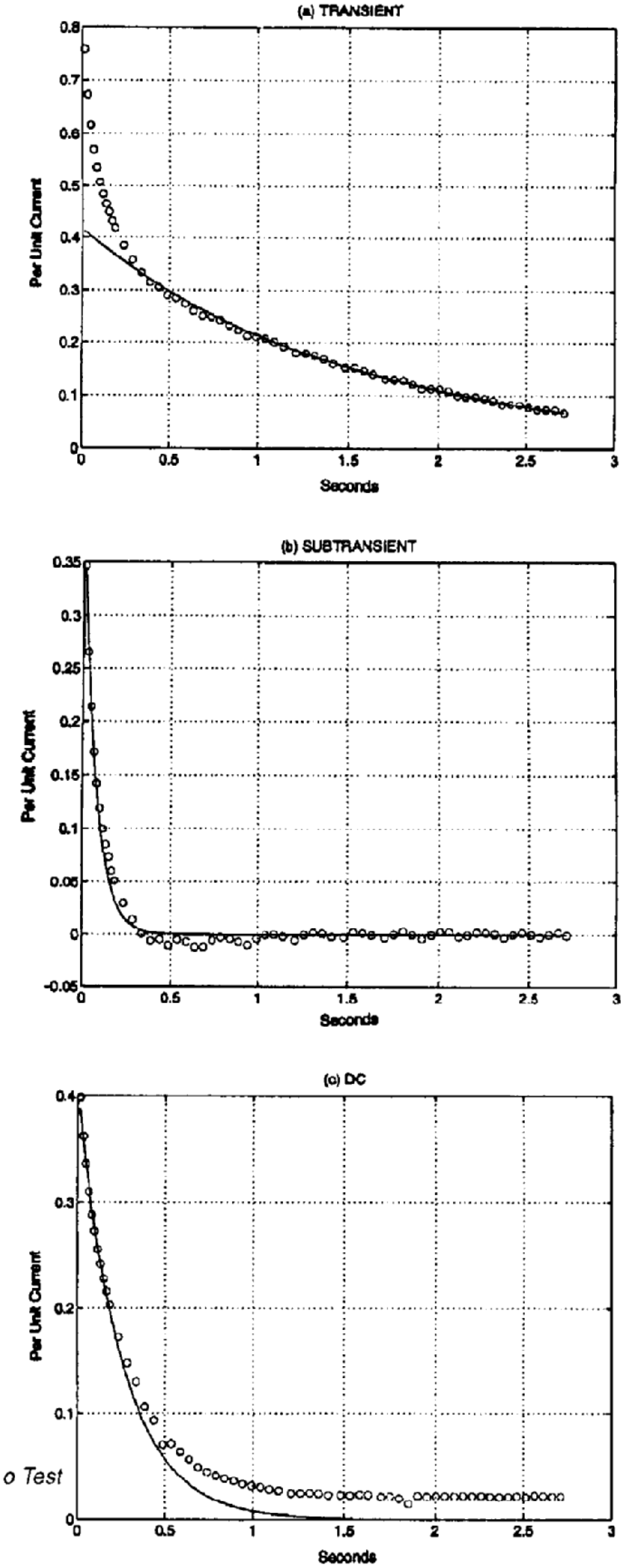


Figure 50 —Decoupled time scales analysis

Applying this model to the data in Figure 50, 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 (151) and Equation (152) (see Kamwa et al. [B27]).

$$T_d' = \frac{1}{A'} \tag{151}$$

$$\Delta i'(0) = e^{B'}\,; \qquad x_d' = \frac{E/E_b}{\Delta i'(0) + I_{ss}/I_b} \text{ in per units} \tag{152}$$

where

- T_d' is the direct-axis transient short-circuit time constant, in seconds
- $\Delta i'(0)$ is the initial straight line equivalent model of the transient component $I_d'(t)$ of the short-circuit current $I(t)$ in Equation (119), in per unit
- E_b is voltage base
- I_b is current base
- x_d' is the direct-axis transient reactance, in per unit; also see Equation (127)

11.5.4.2 Computation of subtransient short-circuit time constant, T_d'', from straight-line representation

The direct-axis subtransient short-circuit time constant, T_d'', is obtained from the short-circuit test data used to determine the direct-axis subtransient reactance (see 11.5.1.1). It is the time, in seconds, required for the subtransient alternating component of the short-circuit current (see Figure 43, line D) to decrease to $1/e$, or 0.368, times its initial value. The determination of this time constant is shown in Figure 43.

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 11.5.3.2.1), 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. 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 (153).

$$\Delta i''(t) = i(t) - \Delta i'(t) = i(t) - e^{A't+B'} \tag{153}$$

where

- $\Delta i''(t)$ is the initial straight line equivalent model of the subtransient component $I_d''(t)$ of the short-circuit current $I(t)$ in Equation (119), in per unit
- $\Delta i'(t)$ is the initial straight line equivalent model of the transient component $I_d'(t)$ of the short-circuit current $I(t)$ in Equation (119), in per unit

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 (154).

$$\ln \Delta i''(t) = A''t + B'' \tag{154}$$

For example, in the envelope data in Figure 45, 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 (155) and Equation (156).

$$T_d'' = \frac{1}{A''} \tag{155}$$

$$\Delta i''(0) = e^{B''} ; \qquad x_d'' = \frac{E/E_b}{\Delta i''(0) + \Delta i'(0) + I_{ss}/I_b} \text{ in per unit} \tag{156}$$

where

- T_d'' is the direct-axis subtransient short-circuit time constant, in seconds
- $\Delta i''(0)$ is the initial straight line equivalent model of the subtransient component $I_d''(t)$ of the short-circuit current $I(t)$ in Equation (117), in per unit
- x_d'' is the direct-axis subtransient reactance, in per unit; also see Equation (128)

11.5.4.3 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 (see 7.4.4) based on the field resistance, R_f . The direct-axis transient short-circuit time-constant can be corrected to specified temperature by using Equation (157).

$$T_d' = T_{dt}' \frac{k + t_t}{k + t_s} \tag{157}$$

where

- T_d' is the direct-axis transient short-circuit time constant at specified temperature t_s , in seconds
- T_{dt}' is the direct-axis transient short-circuit time constant at test temperature t_t , in seconds
- t_t is the average temperature of the field winding during the test, in °C
- t_s is the specified temperature, in °C
- k is the factor described in 7.4.4, which depends on the conducting material in the winding

11.5.5 Determination of armature short-circuit time constant, T_a

11.5.5.1 Computation of armature short-circuit time constant, T_a, from 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 (158).

$$\ln\left|I_{dc}(t)\right| = A_{dc}t + B_{dc} \tag{158}$$

where

$I_{dc}(t)$ is the dc component of the short-circuit current in Equation (118)
A_{dc} and B_{dc} are straight line equivalent model parameters of $\ln \Delta I_{dc}(t)$
t is the time, in seconds, in the range from 4 cycles to about 20 cycles

For the I_{dc} data in Figure 40, 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 (159) and Equation (160).

$$T_a = \frac{1}{A_{dc}} \tag{159}$$

$$i_{dc}(0) = e^{B_{dc}} \tag{160}$$

where

T_a is the armature short-circuit time constant, in seconds
$i_{dc}(0)$ is the initial dc component of the short-circuit current

11.5.5.2 Determining short-circuit armature time constant, T_a

11.5.5.2.1 General

For the definition of *short-circuit time constant of the armature winding*, see Clause 3.

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 11.5.3.2). The following methods may be used to obtain the time constant from the test data:

— Method 1. Resolved dc component (see 11.5.5.2.2)
— Method 2. DC components of phase currents (see 11.5.5.2.3)
— Method 3. Field current response (see 11.5.5.2.4)

11.5.5.2.2 Method 1. Resolved dc component

Values of the dc components for the three-phase currents are obtained from the plots described in 11.5.3.2.1 for several values of time. A resolved value of the dc components, I_{dc} is calculated for each value of time using Equation (161) (see Harrington and Whittlesey [B20] and Kamwa et al. [B27]).

$$I_{dc} = \sqrt{\frac{4}{27}(a^2 + b^2 - ab)} + \sqrt{\frac{4}{27}(a^2 + c^2 - ac)} + \sqrt{\frac{4}{27}(b^2 + c^2 - bc)} \tag{161}$$

where

- I_{dc} is the resolved value of the dc components, in per unit
- a is the largest value of dc component of the three phase currents at the selected time, in per unit
- b is the second largest value of dc component of the three phase currents at the selected time, in per unit
- c is the smallest value of dc component of the three phase currents at the selected time, in per unit

The values of resolved current from Equation (161) 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.

11.5.5.2.3 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 11.5.3.2. 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 43). Method 1 is preferred because it makes better use of the data.

11.5.5.2.4 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 11.5.3.1.1). 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.

11.5.5.2.5 Rated-current and rated-voltage values of T_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 11.5.3.1.1), 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.

11.5.5.2.6 Correction of T_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, T_a, is corrected to the specified temperature using Equation (162).

$$T_a = T_{at} \frac{k + t_t}{k + t_s} \tag{162}$$

where

T_a	is the short-circuit armature time constant at specified temperature, t_s, in seconds
T_{at}	is the short-circuit armature time constant at test temperature, t_t, in seconds
t_t	is the temperature of the armature winding by detector before the test, in °C
t_s	is the specified temperature, in °C
k	is the factor described in 7.4.4, which depends on the conducting material in the winding

11.5.6 Determination of direct-axis transient and subtransient open-circuit time constants

11.5.6.1 Determining direct-axis transient open-circuit time constant, T'_{d0}

For the definition of *direct-axis transient open-circuit time constant*, see Clause 3. Direct-axis transient open-circuit time constant can be determined by the following methods:

— Method 1. Field short circuit (see 11.5.6.1.1)
— Method 2. Discharge resistor connection (see 11.5.6.1.2)
— Method 3. Field current (see 11.5.6.1.3)
— Method 4. Load rejection (see 11.5.6.1.4)
— Method 5. Voltage recovery (see 11.5.6.1.5)

11.5.6.1.1 Method 1. Field short circuit

The rms residual armature voltage is determined with the field winding open and with the machine operated at rated speed. This residual voltage is subtracted from the rms of armature voltage obtained from the oscillogram at selected points of time. The resulting varying component of voltage is plotted against time on semilogarithmic plot with the armature voltage on the logarithmic scale, as shown in Figure 51. 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, T'_{d0}.

The time constant, T'_{d0}, can be corrected to a specified temperature, t_s, using Equation (163).

$$T'_{d0} = T'_{d0t}\frac{k+t_t}{k+t_s} \tag{163}$$

where

T'_{d0}	is the direct-axis transient open-circuit time constant at specified temperature, t_s, in seconds
T'_{d0t}	is the direct-axis transient open-circuit time constant at test temperature, t_t, in seconds
t_t	is the average temperature of the field winding during the test, in °C
t_s	is the specified temperature, in °C
k	is the factor described in 7.4.4, which depends on the conducting material in the winding

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 11.5.6.1.3).

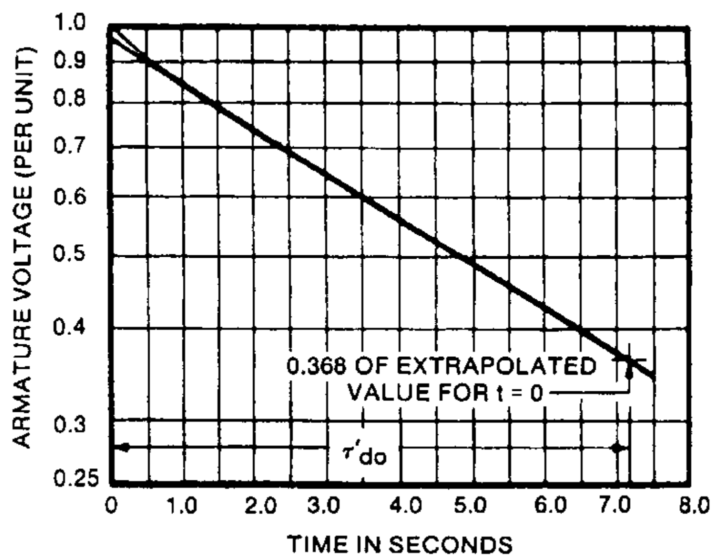


Figure 51 —Determination of direct-axis transient open-circuit time constant

11.5.6.1.2 Method 2. Discharge resistor connection

A semilogarithmic plot of the time-varying component of armature voltage is obtained as described in Method 1. The time required for the transient component of voltage to decay $1/e$, 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, T'_{d0R}, 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 4.3.5) 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 4.3.2 using a previously determined reference value of field resistance at a known temperature (see 4.3.3).

The apparent direct-axis transient open-circuit time constant, corrected to the specified temperature, is calculated using Equation (164).

$$T'_{d0A} = T'_{d0R} \frac{R_{fd} + R_D}{R_{fds}} \tag{164}$$

where

T'_{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
T'_{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 the discharge resistor during the period of analysis, in ohms

11.5.6.1.2.1 Corrections to allow for discharge resistor using Method 2

The discharge resistor may have an effect that cannot be completely accounted for by the method of 11.5.6.1.2. 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 (164) 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.

11.5.6.1.3 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 plot 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.

11.5.6.1.4 Method 4. Load rejection

In general, the direct-axis subtransient open-circuit time constant T''_{d0} is smaller than the transient time constant T'_{d0}. Thus, for $t > 3\,T''_{d0}$, the subtransient can then be neglected; from Equation (123), the transient period is given by Equation (165).

$$E'_q(t) = E(t) - E_{q\infty} - E''_q(t) \quad \Rightarrow \quad E(t) - E_{q\infty} \cong E'_{q0} e^{\frac{-t}{T'_{d0}}} \tag{165}$$

where

$E(t)$ is the time-variant rms magnitude of the terminal voltage, in volts
$E_{q\infty}$ is the steady-state rms component of the terminal voltage $E(t)$, in volts
$E'_q(t)$ is the transient component of the voltage $E(t)$, in volts
$E''_q(t)$ is the subtransient component of the voltage $E(t)$, in volts
E'_{q0} is the initial value of the transient component of the voltage $E(t)$, in volts
T'_{d0} is the direct-axis transient open-circuit time constant, in seconds
t is the time measured from the instant of the load rejection, in seconds

The direct-axis transient open-circuit time constant T'_{d0} is graphically evaluated from semilogarithmic plots of the transient formulation given in Equation (166). From Figure 52, $T'_{d0} = 0.3667 \approx 0.37$ s.

$$\ln E'_q(t) = \ln E'_{q0} e^{\frac{-t}{T'_{d0}}} = \ln E'_{q0} - \frac{t}{T'_{d0}} \tag{166}$$

where

$E'_q(t)$ is the transient component of the voltage $E(t)$, in volts
E'_{q0} is the initial value of the transient component of the voltage $E(t)$, in volts
T'_{d0} is the direct-axis transient open-circuit time constant, in seconds
t is the time measured from the instant of the load rejection, in seconds

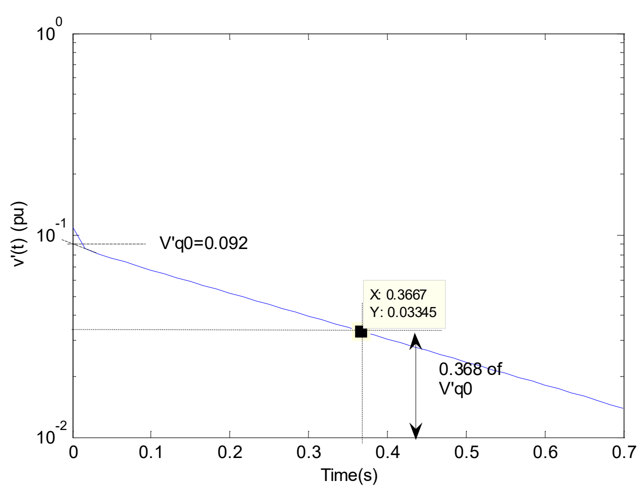


Figure 52—Semilogarithmic plot of transient terminal voltage, $E'_q(t)$

11.5.6.1.5 Method 5. 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 (see Figure 51). Correction for temperature can be made as in Method 1 (see 11.5.6.1.1).

11.5.6.2 Determining direct-axis subtransient open-circuit time constant, T''_{d0}

For the definition of *direct-axis subtransient open-circuit time constant*, see Clause 3.

- — Method 1. Load rejection (see 11.5.6.2.1)
- — Method. 2. Voltage recovery (see 11.5.6.2.2)

11.5.6.2.1 Method 1. Load rejection

As previously for the determination of the direct-axis transient open-circuit time constant (see 11.5.6.1), a semilogarithmic plot of Equation (167) yields the direct-axis subtransient open-circuit time constant $T''_{d0} = 0.065$ s for the previous example.

$$\ln E''_q(t) = \ln E''_{q0} e^{\frac{-t}{T''_{d0}}} = \ln E''_{q0} - \frac{t}{T''_{d0}} \tag{167}$$

where

$E''_q(t)$ is the subtransient component of the voltage $E(t)$, in volts
E''_{q0} is the initial value of the subtransient component of the voltage $E(t)$, in volts
T''_{d0} is the direct-axis subtransient open-circuit time constant, in seconds
t is the time measured from the instant of the load rejection, in seconds

Finally, the terminal voltage (see Equation (123)) can be written as shown in Equation (168).

$$E(t) = 0.4136 + 0.087 e^{\frac{-t}{0.37}} + 0.0176 e^{\frac{-t}{0.065}} \tag{168}$$

Figure 53 compares model and actual data.

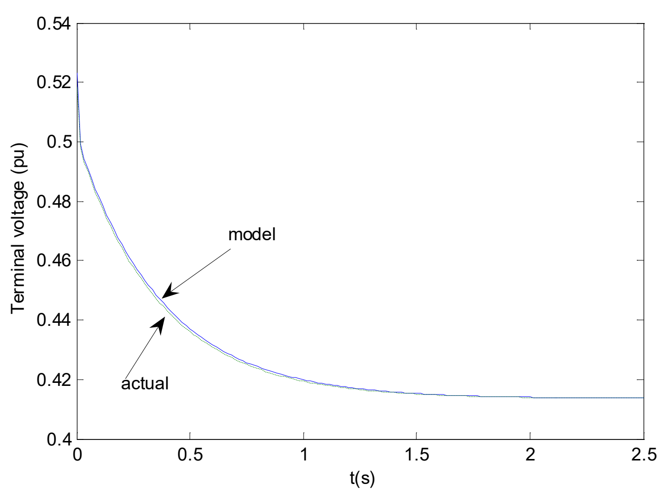


Figure 53—Comparison between model and actual data

11.5.6.2.2 Method 2. Voltage recovery

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 5 in 11.5.6.1.5). The subtransient voltage (curve A of Figure 54) 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 49 to obtain a better time scale. A semilogarithmic plot of the subtransient voltage versus time is made, with the voltage on the logarithmic axis.

A straight line (line D of Figure 54) 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.

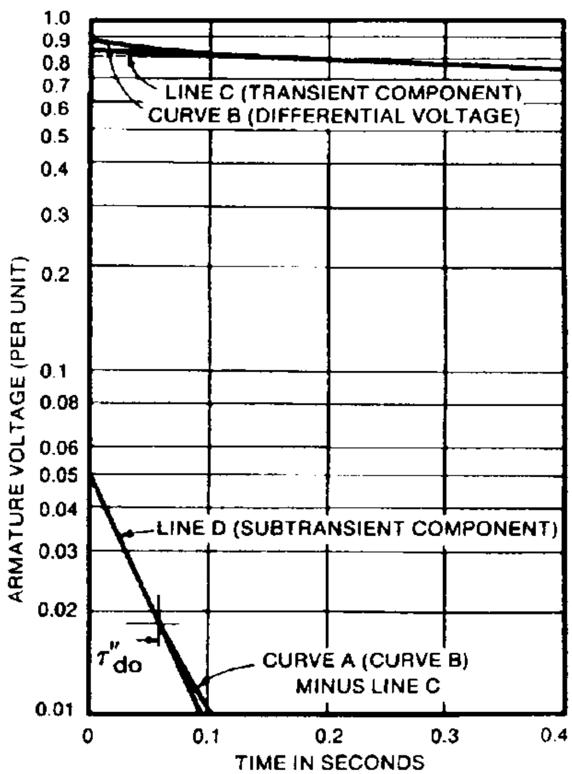


Figure 54—Subtransient component of voltage recovery test

12. Standstill frequency response (SSFR) testing

12.1 General considerations and basic theory

12.1.1 Purpose of this form of testing

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 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 Clause 11. 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 [B24] 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 [B25], Bortoni and Jardini [B7], 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 [B12] 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 [B16]), 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. [B15]).

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. [B29]) where it is applied for commissioning and retrofitting all facilities of 10 MW and greater. In the foreseeable future, SSFR and sudden short-circuit experimental tests results could be used to validate finite element models in order to carry out, other, less sensitive simulations and analysis. Note that it is advised to rely on unit-specific data (from tests). Parameters obtained by design or simulation may be validated by measurements.

12.1.3 Theoretical background

The IEEE Committee Report [B24] 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, see Equation (169).

$$\begin{aligned}\Delta\psi_d(s) &= G(s)\Delta e_{fd}(s) - L_d(s)\Delta i_d(s)\\ \Delta\psi_q(s) &= \qquad\qquad\quad - L_q(s)\Delta i_q(s)\end{aligned} \tag{169}$$

where

- ψ_d is the direct-axis stator flux linkage, in per unit
- ψ_q is the quadrature-axis stator flux linkage, in per unit
- i_d is the direct-axis stator current, in per unit
- i_q is the quadrature-axis stator current, in per unit
- e_{fd} is the machine field voltage around a particular operating point, in per unit
- Δ is a small perturbation around some operating point

Equation (169) leads to the concept of a two-port network for the direct-axis and one-port network for the quadrature axis. Figure 55 is a block diagram representation of Equation (169). Note that a second port has been drawn for the quadrature axis for symmetry, but it is, in fact, inaccessible.

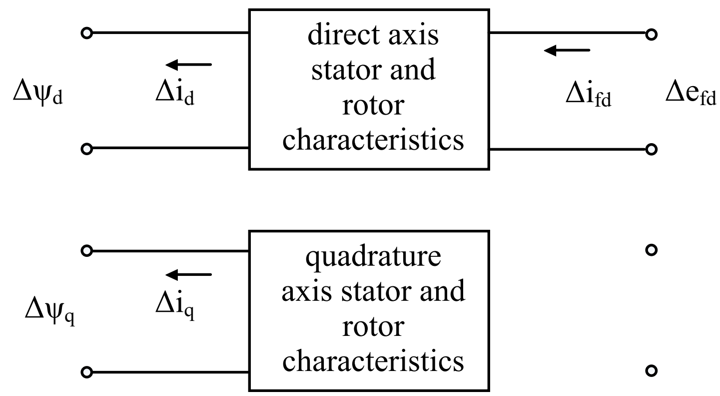


Figure 55—Two-port direct-axis and quadrature-axis representation of a synchronous machine

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 [B24]). Note that functions of the Laplace variable s are complex quantities, where $s = j\omega = j2\pi f$ rad/s when frequency-domain techniques such as Bode or Nyquist plots are applied.

- $L_d(s)$ is the 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 $(\Delta e_{fd}(s) = 0)$
- $L_q(s)$ is the 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 the direct-axis armature flux to field voltage 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 $(\Delta i_d(s) = 0)$

An alternative way of describing the armature to field transfer function is as follows (see IEEE Committee Report [B24]):

- $sG(s)$ is *armature current to field transfer function*, which is the ratio of the Laplace transform of the field current to the direct-axis stator current, with the field winding short-circuited (see 12.2.6.3)

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 (see 12.2.6.4)

12.1.4 Model representation possible from this form of testing

Canay [B11] 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 56. Although the values of L_{ad} and L_{aq} in Figure 56 can be derived from measurements described in Clause 10, they are often taken from generator design data. L_ℓ is also generally taken from design data.

Note that in Figure 56, on the direct axis, an additional inductance, L_{f1d}, is shown. This inductance has been identified as a differential leakage inductance. It was shown in Rusche et al. [B41] that L_{f1d} equals the difference between the relatively large mutual inductances. L_{mf1d} 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 $L_{f1d} = L_{mf1d} - L_{ad}$. In turbine generators, L_{mf1d} is slightly greater than L_{ad}; thus L_{f1d} usually has a positive value. In hydro-generators, the opposite is true, and L_{f1d} often has a negative value.

Canay [B11] and Moeini et al. [B37] show that ignoring L_{f1d}, by assuming L_{mf1d} equals L_{ad}, results in inaccurate calculation of field current responses under generator transient conditions. This omission of L_{f1d} is permissible if only stator responses to generator transient conditions are of importance.

Alternate forms of model representation are available in transfer function form or in inductance matrix form. These forms are discussed in IEEE Std 1110.

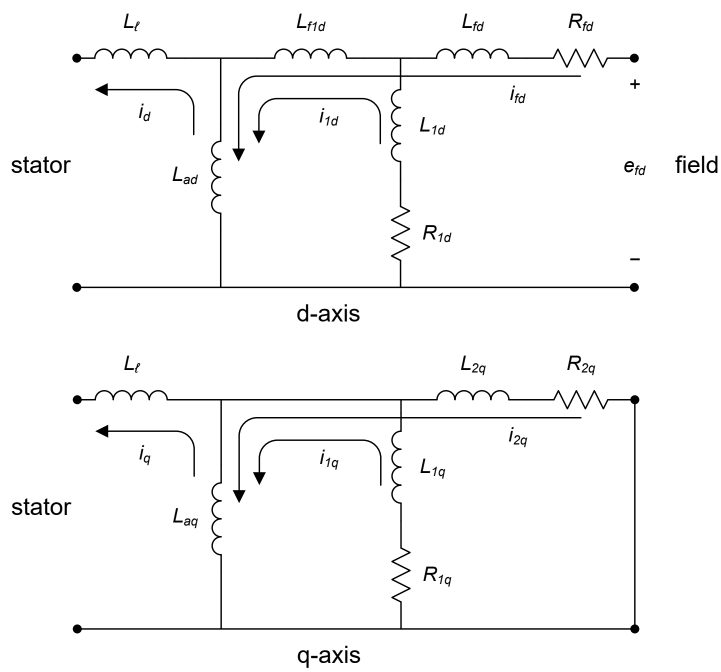


Figure 56—Complete (direct-axis and quadrature-axis) second-order equivalent circuit for synchronous generator

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 (see Canay [B12]).

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) with a better than 0.02 dB and 0.02° of accuracy 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, or line switching tests, is 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. [B41], EPRI EL-1424 [B18], Dandeno et al. [B15], and Hurley and Schwenk [B22] 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 [B25], these techniques have been applied with a similar success to machines of salient-pole construction. That report insists that particular attention should be given to rotor positioning. When possible, the position of the rotor poles, relative to the stator core slots, may be computed beforehand by finite element simulation and serve as an on-site validation, of precise positioning.

12.2 Testing conditions for SSFR procedures and instrumentation requirements

12.2.1 Machine conditions for SSFR tests for turbine generators

The machine should be shut down and electrically isolated. The unit transformer should be disconnected from the armature terminals, and any armature-winding grounds removed. Also all connections to the field terminals should 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 desirable to maintain the armature-winding temperature at a constant value during the measurements ($\Delta t < 0.1$ °C, in the frequency range from dc to 1 Hz) since the low-frequency test points are sensitive to the armature resistance. To this end, the machine can be cooled as close to ambient temperature as possible, and any stator heat exchangers are turned off. A continuous temperature monitoring scheme is implemented to confirm its stability during the tests and thus ensuring the validity of the results, especially at low frequency.

Circulation of the water through the stator winding can be maintained to help 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 can be performed with the turning gear being operated very slowly (start/stop), the operator should be looking at the induced voltage on the field winding. To give an achievable figure, a 10 m diameter rotor, with 42 pole pairs has to be moved of 2 mm on its circumference to move it by 1 electrical degree. Also, the turning gear could be hand-cranked. The oil injection on the bearings needs to be activated to decrease friction as much as possible. 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.

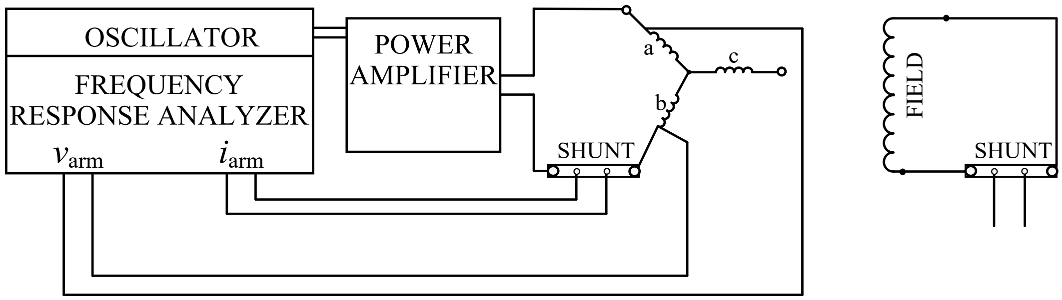
The rotor positioning can also be realized by mean of an electric winch. The fine tuning is then simply accomplished by pulling manually the tensioned cable. For rotors having natural resting positions, it is recommended to use two pull-outs mounted in opposition to counter the natural impulse of the rotor. When the minimum rotor voltage is obtained, the brakes are applied and the oil injection, into the thrust bearing, is stopped.

12.2.2 Instrumentation and connections

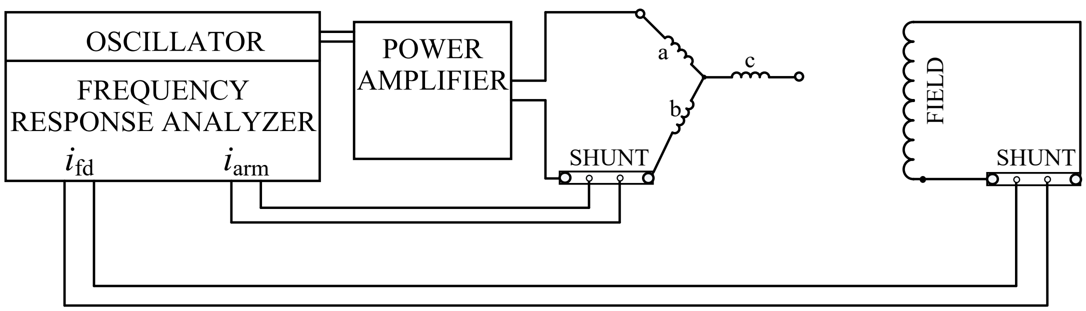
The frequency response measurements are performed, most conveniently, with a low-frequency, dual-channel spectrum analyzer. This type of instrument will measure the magnitudes and relative phase-angle of two signals and extract only the fundamental components from any distorted waveforms. The basic specifications of the analyzer include frequency measurement in the frequency range 0.001 Hz to 1 kHz, phase resolution down to at least 0.02 degrees, and differential inputs. The phase resolution should be at least equal to the phase accuracy in order to accommodate small phase variations at very low frequency. 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

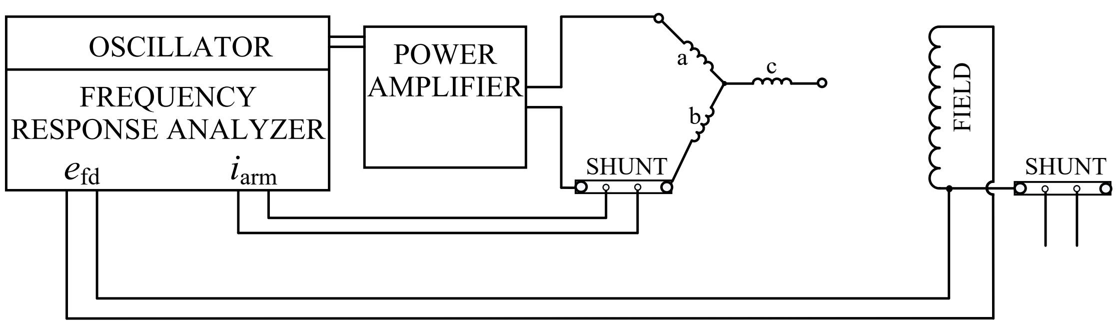
The relationship between the *measured* quantities and the *desired* variables is given in 12.2.6. An oscillator, sometimes an integral part of the above-mentioned analyzer, provides the test signal. This signal goes to a power amplifier, the output of which is connected to two terminals of the generator armature winding. The metering error of any measured transfer function is recommended to 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 57.



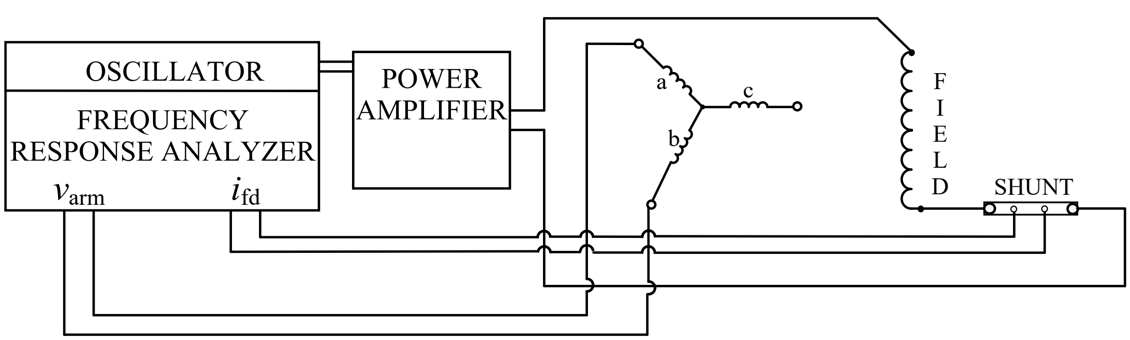
(a) Measurement of $\Delta v_{arm}(s) / \Delta i_{arm}(s)$



(b) Measurement of $\Delta i_{fd}(s) / \Delta i_{arm}(s)$



(c) Measurement of $\Delta e_{fd}(s) / \Delta i_{arm}(s)$



(d) Measurement of $\Delta v_{arm}(s) / \Delta i_{fd}(s)$

Figure 57 —Test setup for direct-axis measurements

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, especially in the frequency range from dc to 20 Hz. The power amplifier also feeds the stator with the same constant current for all measured transfer functions at least in the frequency range from dc to 20 Hz. Voltages at the armature or field winding terminals should 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 need to 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 is bolted directly to the conductor in the isolated phase bus and as close to the generator terminals as possible; conducting grease may be used to enhance the contact. As noted in 12.2.2, an instrument having differential inputs is preferred for making the measurements. Figure 58 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 connections in Figure 59 are appropriate.

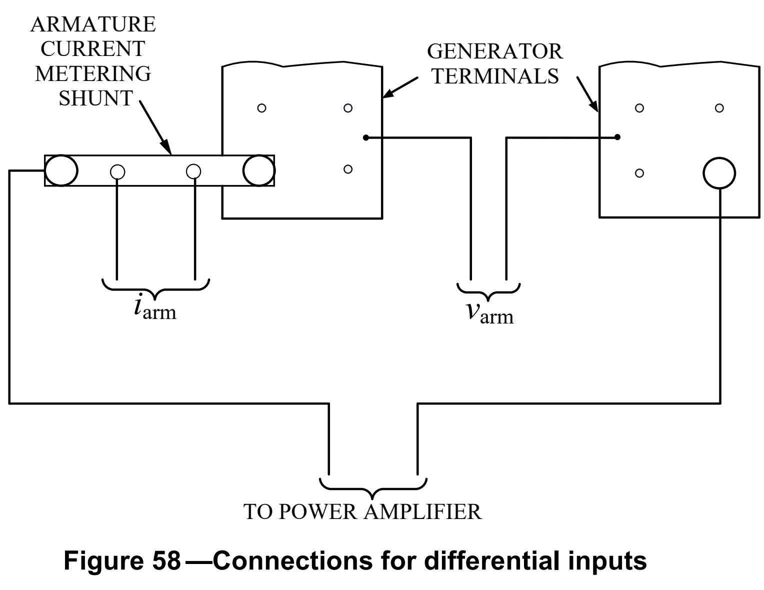


Figure 58 —Connections for differential inputs

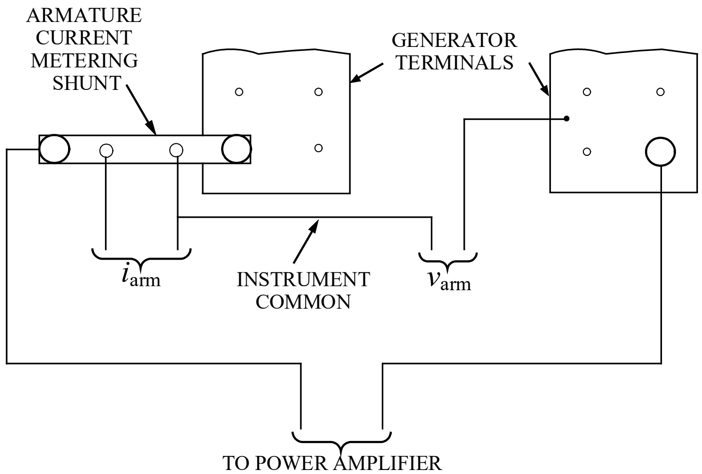


Figure 59—Connections for single-ended inputs

Current metering shunts are used to measure the test current supplied to the armature winding and the induced field current. Shunt rating is 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 the value shown in Equation (170).

$$i_{fd} < \sqrt{3}\,\frac{I_{fdbase}}{I_{Lbase}}\,i_s \tag{170}$$

where

i_{fd} is the maximum induced field current during the test, in amperes
i_s is the peak value of the largest armature current used during the test, in amperes
I_{Lbase} is the base line (armature) current, in amperes (see 9.2.3)
I_{fdbase} is the base field current in the nonreciprocal per unit system, in amperes (see 9.2.5)

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. The parameter’s determination process helps ensure the removal of the shunt resistance before providing the desired machine parameters.

12.2.5 Precautions and ancillary matters relating to machine safety

It should 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 help reduce 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 may 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 [B13] among others.

The principal parameters described in the following subclauses relate to the definitions listed in 12.1.3.1.

12.2.6.1 Synchronous machine direct-axis operational impedance, $Z_d(s)$

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. See Equation (171).

$$Z_d(s) = -\left.\frac{\Delta e_d(s)}{\Delta i_d(s)}\right|_{\Delta e_{fd}=0} \tag{171}$$

$Z_d(s)$ 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 (172) through Equation (176).

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 (171).

12.2.6.2 Synchronous machine quadrature-axis operational impedance, $Z_q(s)$

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 (172).

$$Z_q(s) = -\frac{\Delta e_q(s)}{\Delta i_q(s)} \tag{172}$$

12.2.6.3 Direct-axis armature flux to field voltage transfer function, $G(s)$

A third machine quantity is given by the relation shown in Equation (173).

$$G(s) = \left.\frac{\Delta e_d(s)}{s\Delta e_{fd}(s)}\right|_{\Delta i_d=0} \tag{173}$$

An alternative method of measuring this parameter is suggested as shown in Equation (174).

$$sG(s) = \left.\frac{\Delta i_{fd}(s)}{\Delta i_d(s)}\right|_{\Delta e_{fd}=0} \tag{174}$$

The advantage of the form of measurement in Equation (174) is that it can be measured at the same time as $Z_d(s)$.

12.2.6.4 Transfer function from armature current to field voltage, $Z_{afo}(s)$

A fourth measurable synchronous machine parameter at standstill is the armature-to-field transfer impedance as shown in Equation (175).

$$Z_{afo}(s) = \left.\frac{\Delta e_{fd}(s)}{\Delta i_d(s)}\right|_{\Delta i_{fd}=0} \tag{175}$$

$\Delta i_{fd} = 0$ in Equation (175) means that the field is open during this test measurement.

12.2.6.5 Transfer function from field current to armature voltage, $Z_{fao}(s)$

A fifth measurable synchronous machine parameter at standstill may be obtained by exciting the field with the armature open-circuited, as shown in Equation (176). It has been called the *field-to-armature transfer impedance*. The limited application of this last function is discussed in de Mello et al. [B35].

$$Z_{fao}(s) = \left.\frac{\Delta e_d(s)}{\Delta i_{fd}(s)}\right|_{\Delta i_d=0} \tag{176}$$

Frequency response tests are conducted by using a calibrated (magnitude and frequency) sinusoidal signal as the input and comparing it to the magnitude and phase of a measured output quantity. In steady-state sinusoidal conditions, the output quantity will be a sinusoidal signal with the same frequency as the forcing function, the input signal. For each frequency used in the frequency response, the magnitude of the transfer function is calculated as the ratio between the magnitude of the output signal to the magnitude of the input signal. The phase of the transfer function for the given test frequency is calculated by the phase difference between the input and output sinusoidal signals.

12.3 Test procedures

12.3.1 Required measurements

The magnitude and phase angle of the frequency response of the transfer functions $Z_d(s)$, $sG(s)$, and $Z_q(s)$ is measured over a range of frequencies. The minimum frequency ($f_{\min}$) is at least one order of magnitude less than the frequency corresponding to the transient open-circuit time constant at ambient temperature of the generator as shown in Equation (177).

$$f_{\min} = \frac{1}{10}\frac{1}{2\pi}\frac{1}{T'_{d0}} \tag{177}$$

where

T'_{d0} is the direct-axis open-circuit transient time constant (see 11.5.6.1) at the ambient temperature for the test conditions, in seconds

The maximum frequency for the test can 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 are deemed sufficient when a heavy averaging is performed to help reduce the noise at each step (see 11.5.3.1.5). The measurements in the two intervals of Table 4 can be performed successively without any delay to avoid temperature variation resulting in two significantly different values obtained at 1 Hz. Users of this guide should also bear in mind the importance of temperature recording especially when scanning the 1 mHz to 20 Hz range to help validate the test results.

Table 4—Typical SSFR configuration for transfer function measurement

Frequency range	Number of points	Integration or averaging time (in cycles of test frequency)	Test duration
0.001 Hz to 1 Hz	45 (15 points/decade)	5 cycles	10 hours
1 Hz to 1000 Hz	60 (20 points/decade)	10 cycles	2 minutes

The information provided in Table 4 is purely indicative. The actual figures are determined by the user to enable an optimal use of the test equipment capability and accuracy. In addition, the duration of the test can be extended by up to one to two hours, depending on the accuracy of the frequency response analyser being used.

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}, is obtained as shown in Equation (178) (see Ontario [B39]).

$$L_{afd} = \frac{3}{2}\frac{1}{s}\lim_{s \to 0} Z_{afo}(s) \tag{178}$$

where

L_{afd} is the mutual inductance between the field and armature windings, in henries

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 SSFR tests with the field winding open-circuited (see 12.2.6.4). Alternatively, it can be calculated by multiplying the low-frequency asymptote of the magnitude of $\Delta i_{fd}(s)/\Delta i_d(s)$ (see 12.2.6.3) by r_{fd}, where 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 winding resistance (at the field winding temperature during the tests) plus metering shunt resistance plus connecting lead and contact resistances.

The frequency response of $Z_{afo}(s)$ is measured by injecting a sinusoidal direct-axis armature current $\Delta i_d(s)$ (input signal) and measuring the field voltage $\Delta e_{fd}(s)$ (output signal), with the field winding open-circuited. For each frequency ω in the frequency response test, the value of $Z_{afo}(s)$ can be determined from the magnitude and phase of the input and output sinusoidal signals.

12.3.2 Positioning the rotor for direct-axis tests

Positioning the rotor is accomplished by temporarily connecting the power amplifier as shown in Figure 60. Drive the amplifier with an approximately 100 Hz sinusoidal signal, and measure the induced field voltage with an oscilloscope. Inject oil in the thrust bearing, and 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. Then stop oil injection and apply the brakes. To verify that latter minor break movements have not affected rotor position, a second rotor voltage measurement is recommended.

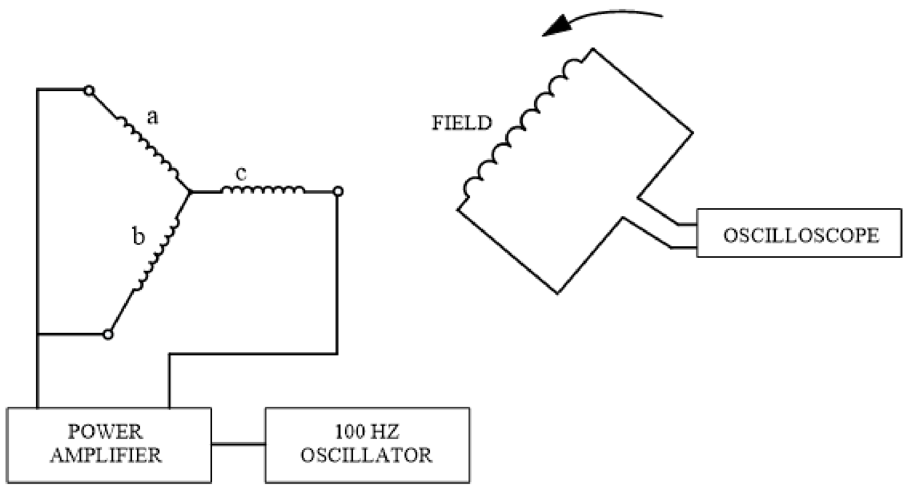


Figure 60 —Positioning of rotor for direct-axis tests

12.3.3 Direct-axis tests

12.3.3.1 Measurement of $Z_d(s)$ and stator resistance, R_a

Referring to Figure 57(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 57. The following notations are used to distinguish between the mathematical quotients in Equation (171) through Equation (176) 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 57(a) permit the stator direct-axis operational impedance and stator resistance to be obtained as shown in Equation (179) and Equation (180).

$$Z_d(s) = \frac{1}{2} Z_{armd}(s)\ \Omega \tag{179}$$

$$R_a = \frac{1}{2}\left\{\lim_{s\to 0}\left[Z_{armd}(s)\right]\right\}\ \Omega \tag{180}$$

$Z_d(s)$ quantities are plotted in Figure 61 and Figure 62.

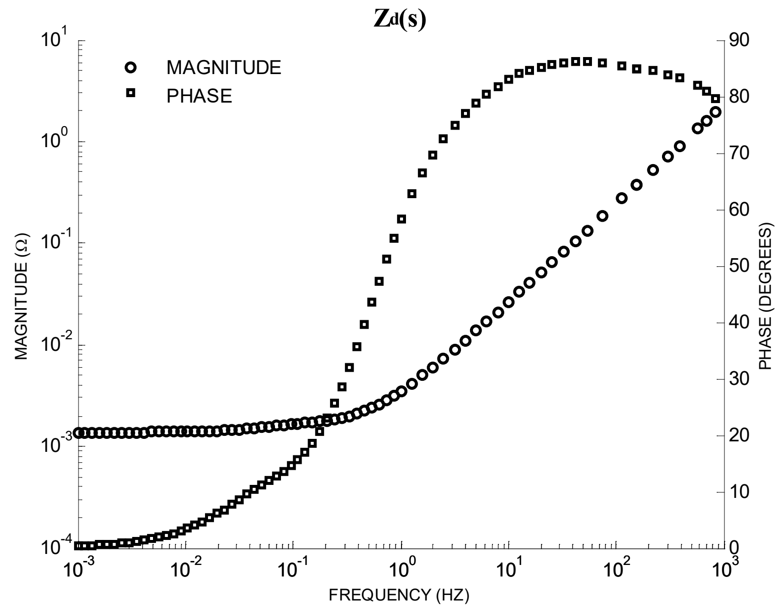


Figure 61 —Direct-axis impedance $Z_d(s)$ (short-circuited field winding)

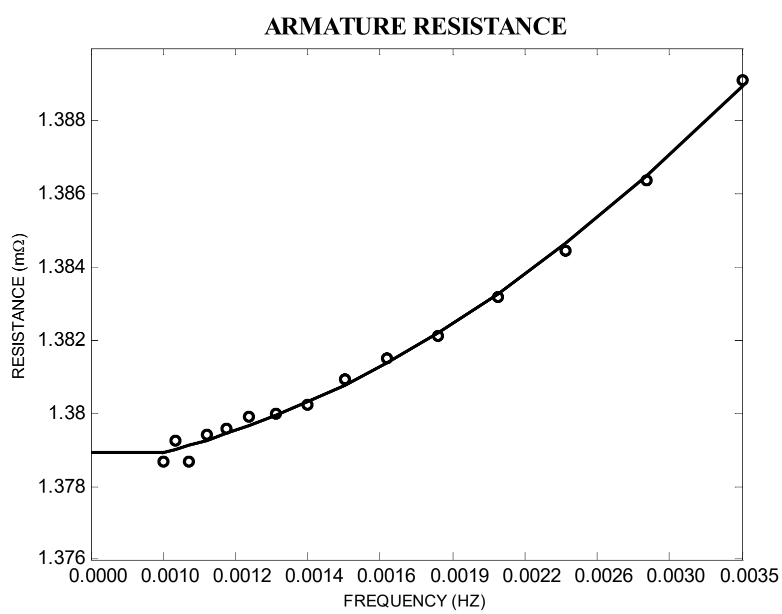


Figure 62 —Resistive component of $Z_d(s)$

To obtain R_a, plot the real, or resistive, component of the measured 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, $2R_a$. It is recommended 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 is supposed to be close to the value for the armature resistance quoted by the manufacturer.

The calculated values of $Z_d(s)$ and R_a from Equation (179) and Equation (180) will be used to calculate $L_d(s)$ as shown in Equation (181).

$$L_d(s) = \frac{Z_d(s) - R_a}{s} \tag{181}$$

Figure 63 presents the calculated values for $L_d(s)$, which are obtained from the results shown in Figure 61 and Figure 62. Interpretation and utilization of the $L_d(s)$ data are discussed in 12.5.

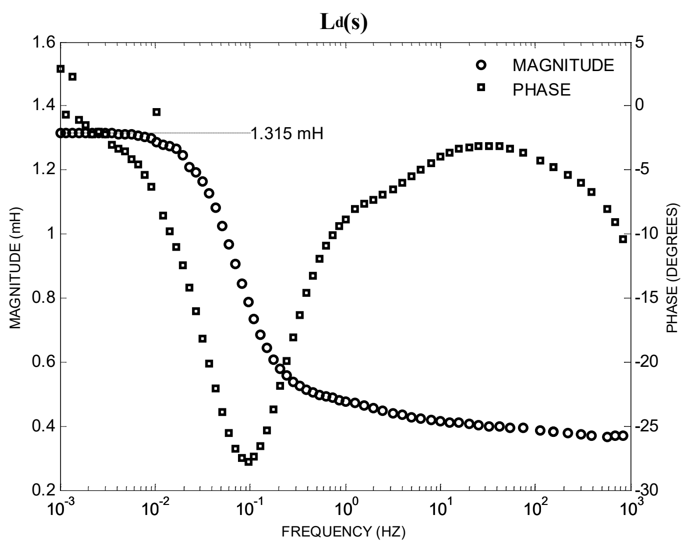


Figure 63—Calculated direct-axis operational inductance $L_d(s)$

12.3.3.2 Measurement of $sG(s)$

Now, connect the instrument to the i_{fd} and v_{arm} signal leads as shown in Figure 57(b), and measure the frequency response $\Delta i_{fd}(s)/\Delta i_{arm}(s)$ over the frequency range as described in 12.3.1. Then, solving Equation (182) will lead to a plot similar to Figure 64. The cosine 30° factor in Equation (182), Equation (183), and Equation (184) recognizes the physical or electrical phase displacement between the field (as aligned in 12.3.2) and either phase *b* or *c*.

$$\frac{\Delta i_{fd}(s)}{\Delta i_d(s)} = \frac{\Delta i_{fd}(s)}{\Delta i_{arm}(s)/\cos(30°)} = \sqrt{\frac{3}{4}}\,\frac{\Delta i_{fd}(s)}{\Delta i_{arm}(s)} \tag{182}$$

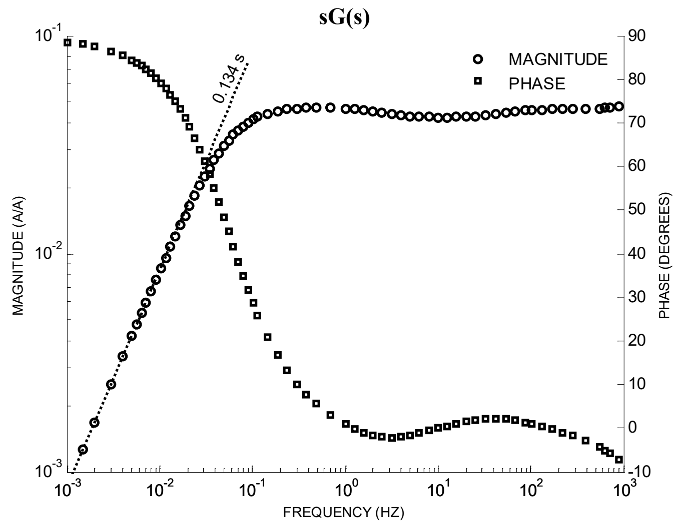


Figure 64—Direct-axis $sG(s)$ (direct-axis SSFR test with short-circuited field winding)

12.3.3.3 Measurement of $Z_{afo}(s)$

Finally, open the field winding by removing the field current metering shunt, and connect the e_{fd} and i_{arm} signal leads to the measuring instrument, as shown in Figure 57(c). Measure $\Delta e_{fd}(s)/\Delta i_{arm}(s)$ for the necessary number of frequencies and calculate as shown in Equation (183).

$$Z_{afo}(s) = \frac{\Delta e_{fd}(s)}{\Delta i_d(s)} = \frac{\Delta e_{fd}(s)}{\Delta i_{arm}(s)/\cos(30°)} = \sqrt{\frac{3}{4}}\frac{\Delta e_{fd}(s)}{\Delta i_{arm}(s)}\ \Omega \tag{183}$$

When plotted, these points will be similar to Figure 65. This completes the direct-axis tests that are usually performed.

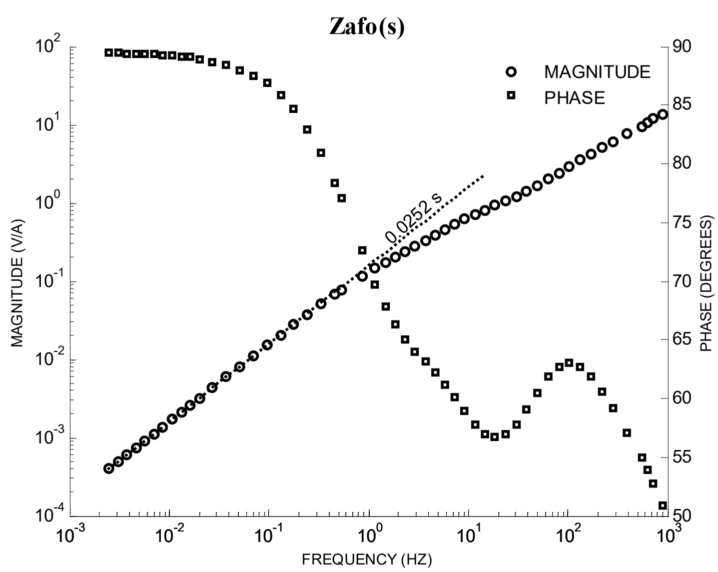


Figure 65—Direct-axis $Z_{afo}(s)$ (direct-axis SSFR test with open-circuited field winding)

12.3.3.4 Measurement of $Z_{fao}(s)$

This measurement of field-to-stator transfer impedance is occasionally required (see 12.1.5). For this value, the test setup of Figure 57(c) can be modified to that of Figure 57(d). The i_{arm} leads would then be connected to the field shunt. The e_{fd} leads of Figure 57(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 57(d). Then $Z_{fao}(s)$ is determined as shown in Equation (184).

$$Z_{fao}(s) = \frac{\Delta e_d(s)}{\Delta i_{fd}(s)} = \frac{1}{2}\left\{\frac{\Delta v_{arm}(s)/\cos(30°)}{\Delta i_{fd}(s)}\right\} = \sqrt{\frac{1}{3}}\frac{\Delta v_{arm}(s)}{\Delta i_{fd}(s)}\ \Omega \tag{184}$$

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 57 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. Compared to the direct-axis position, the rotor will have moved by 90 electrical degrees. That is 2.14 mechanical degrees (360/(84/2)/4) in an 84-pole machine.

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 57(a).

Instrument readings over the complete frequency range obtained from the new test setup of Figure 57(a) permit the stator quadrature-axis operational impedance and stator resistance to be obtained as shown in Equation (185) and Equation (186).

$$Z_q(s) = \frac{1}{2} Z_{armq}(s)\ \Omega \tag{185}$$

$$R_a = \frac{1}{2}\left\{\lim_{s\to 0}\left[Z_{armq}(s)\right]\right\}\ \Omega \tag{186}$$

Note that the dc resistance of one phase of the armature winding, R_a, is nominally the same as obtained during the direct-axis tests. However, because of the sensitivity of the results to this value, it may 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.

The values of $Z_q(s)$ and R_a from Equation (185) and Equation (186) are used to calculate $L_q(s)$ as shown in Equation (187).

$$L_q(s) = \frac{Z_q(s) - R_a}{s} \tag{187}$$

Figure 66 presents an example of the results obtained with quadrature-axis SSFR test.

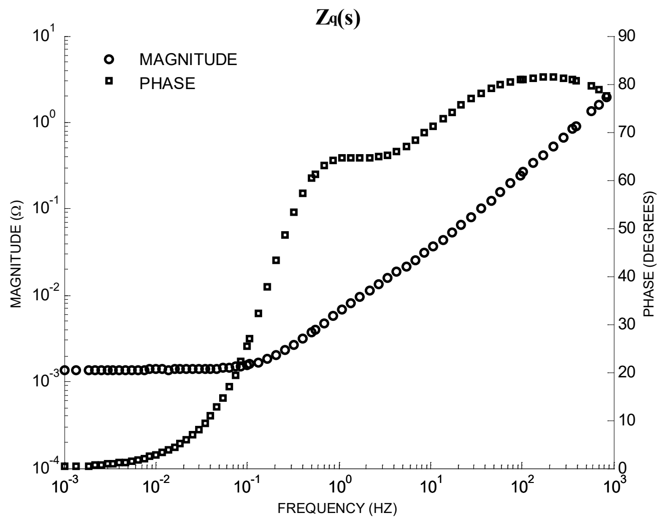


Figure 66—Quadrature-axis $Z_q(s)$ (quadrature-axis SSFR test)

Interpretation and utilization of $L_q(s)$ data, which are plotted in Figure 67, are considered in detail in 12.5.

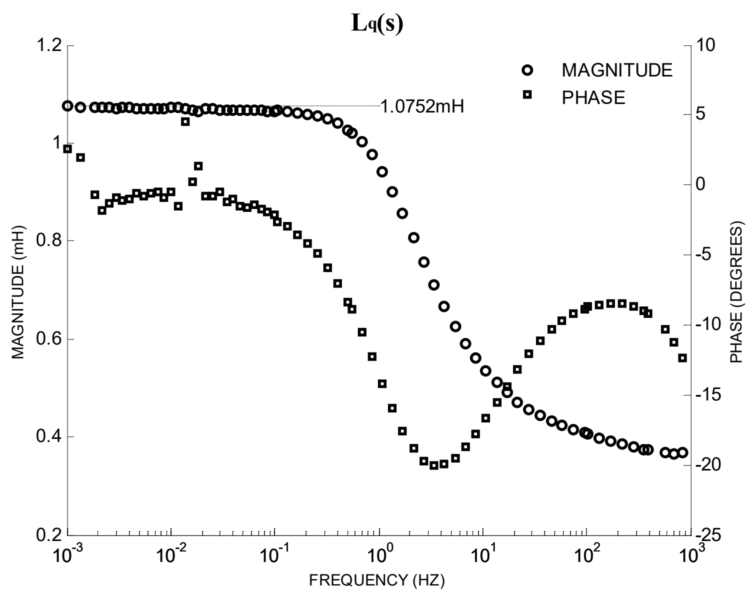


Figure 67—Quadrature-axis operational inductance

12.4 Interpretation of test data

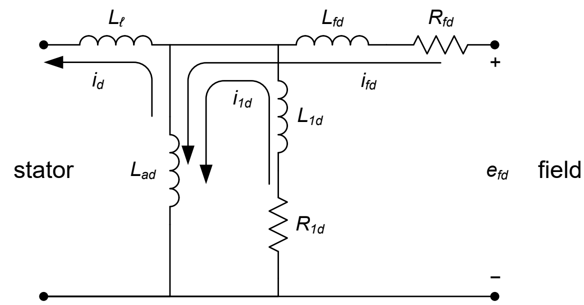
Interpretation of test data is one of the practical problems in fitting operational test data to a particular chosen model network. It has been maintained that the presence of "noise," particularly in the frequency range below 0.01 Hz, has a "corrupting" effect on the matching process below that frequency. 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 as follows:

a) *Structure:* For the direct-axis network, it is possible to choose between the structures proposed by IEEE Std 1110. The models in Figure 68 for the direct axis and in Figure 69 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 68, 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 69. For consistency, if a third-order model is chosen for the direct axis, a third-order model is also recommended for the quadrature axis.

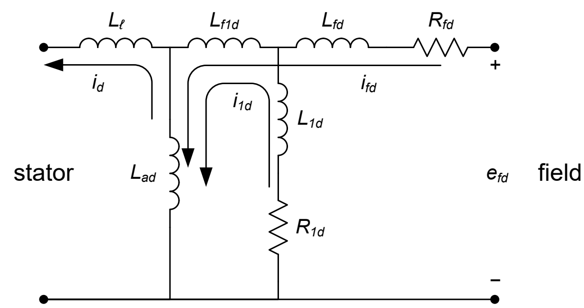
b) *Per unit system:* It is well known that different choices of the per unit system and/or the armature leakage reactance can lead to networks with markedly different parameter values. In particular, a network with or without L_{f1d}, L_{f12d}, or L_{f2d} can be constructed for the same machine (see IEEE Std 1110). It should be noted that the equivalent circuits shown in can only be defined as such by using the reciprocal per unit system (see 9.2.5).

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.

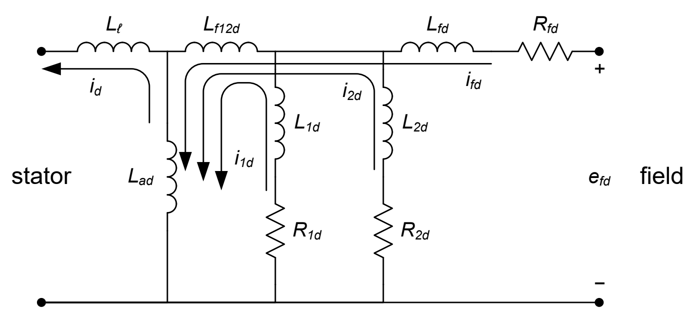
d) *Non-solid damper windings:* It should be noted that for some rotor designs, e.g., for salient-pole machines, damper circuits in a specific axis (direct, quadrature, or both) are constituted with different parts. The electrical resistance of these damper circuits can be greatly affected by centrifugal forces (which render measurements at standstill not conclusive), metal surface contamination degree, and aging and runaway history of the machine. In such situations, analyst judgment and expertise are required.



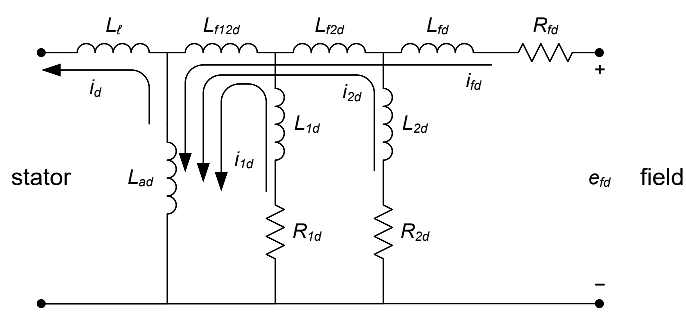
(a) Subtransient model (second order) with equal mutual inductances



(b) Subtransient model (second order) with unequal mutual inductances

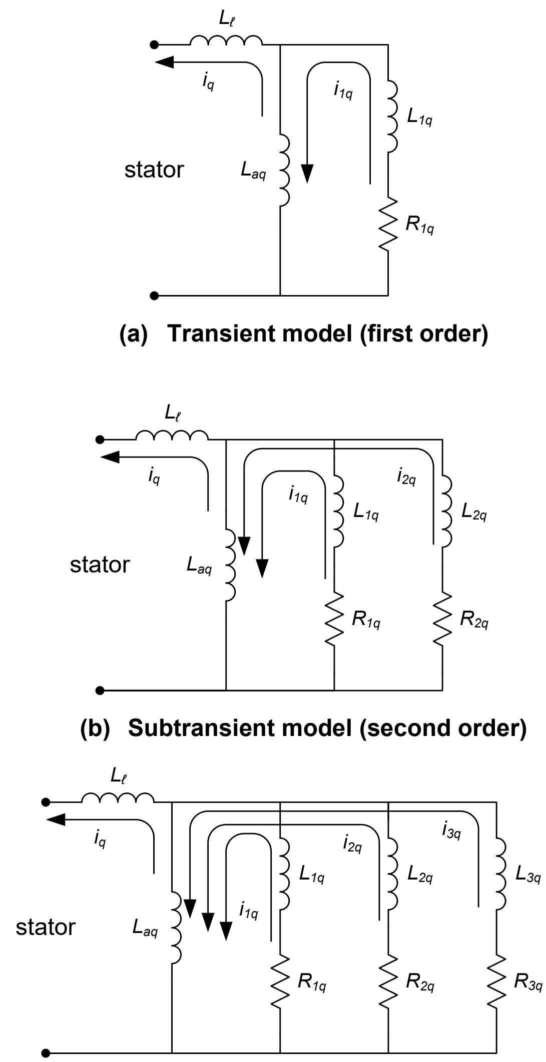


(c) Sub-subtransient model (third order)



(d) Sub-subtransient model (third order) with unequal mutual inductances

Figure 68 —Direct-axis equivalent circuits



(a) Transient model (first order)

(b) Subtransient model (second order)

(c) Sub-subtransient model (third order)

Figure 69—Quadrature-axis equivalent circuits

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, in general, without an analytical solution. It is difficult to solve in the general case of two transfer functions [$L_d(s)$, $sG(s)$], especially of third order or higher.

It should be noted that the third-order models might be required to fit frequency response test results, particularly at higher frequencies. However, these models are not usually used in transient stability simulations because, in part, sub-subtransient parameters (see IEEE Std 1110) are usually not available from manufacturers. In addition, such parameters would result in very small sub-subtransient time constants, which are often incompatible with the usual assumptions for the modeling of the synchronous machines (e.g., neglecting the transformer effects of the armature voltages) and the network (e.g., using algebraic network equivalents).

12.4.1 Parameter determination based on SSFR test results

12.4.1.1 General comments

In the IEEE Committee Report [B24] 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. [B43] that other approaches to using the test data were available. An alternate approach to fitting SSFR data was later described in 1993 (see Canay [B12]). 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'_{d0}, 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 [B24] 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 68 and Figure 69 of this guide can 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, although it is recognized that time constants and reactances are the most common form obtained from manufacturers and used in power system stability studies. Thus, it might still be necessary to calculate the reactances and time constants once the parameters for the selected model, such as those in Figure 68, have been determined. The remarks above can 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, particularly equivalent circuit models such as those in Figure 68. Thus, the SSFR data obtained from the tests described in 11.4 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 per unit values by dividing the base impedance or inductance of the machine (see Clause 9), 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. Then determine the value of $L_{ad}(0)$ using Equation (188)

$$L_{ad}(0) = L_d(0) - L_\ell \tag{188}$$

NOTE—This value of $L_{ad}(0)$ corresponds to the flux levels that existed during the test and, thus, to the magnetic saturation level 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.

b) When the information in step a) has been determined, use the $Z_{afo}(s)$ frequency response defined in Equation (183) to find a field-to-armature-turns ratio as shown in Equation (189).

$$N_{af}(0) = \left\{ \frac{1}{sL_{ad}(0)} \lim_{s \to 0} \left[\frac{\Delta e_{fd}(s)}{\Delta i_d(s)} \right] \right\} \tag{189}$$

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 [B40] 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 (190).

$$K \frac{PN_{fd}}{N_a} = \frac{3}{2} \frac{i_{abase}}{i_{fdbase}} = N_{afbase} \tag{190}$$

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 armature turns (in parallel) per phase
K	is the combination of design and physical factors noted above

N_{afbase} is the direct-axis magnetizing reactance at low frequencies, in henries
i_{abase} is the peak armature rated current per phase, in amperes
i_{fdbase} is the base field current in the reciprocal per unit system (see 9.2.5), in amperes

It has been observed that generally, $N_{af}(0)$ has a lower value than N_{afbase}. However, in the following direct-axis model development, $N_{af}(0)$ will be used to help ensure consistency with measured dc values asymptotes. The use of both $N_{af}(0)$ and N_{afbase} is discussed in Annex H.

c) The field resistance, referred to the armature winding, is given by Equation (191).

$$R_{fd} = \frac{sL_{ad}(0)}{\frac{2}{3}N_{af}(0)\lim_{s\to 0}\frac{\Delta i_{fd}(s)}{\Delta i_d(s)}} \tag{191}$$

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.

d) Choose an equivalent circuit structure for the direct-axis model, such as one of those shown in Figure 68.

e) Adjust the unknown values for the circuit elements in the selected direct-axis model that produce the best fit to the two measured direct-axis frequency responses $L_d(s)$ and $sG(s)$. Iterative numeric techniques (see 12.5.3) are usually applied in this step.

NOTE—The values for L_ℓ, $L_{ad}(0)$, $N_{af}(0)$, and r_{fd} have already been determined in the previous steps.

f) Adjust L_{ad} calculated in step a), Equation (188), to its unsaturated value L_{adu} (see Annex H).

g) 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, considering a copper winding converted to 100 °C, see Equation (192).

$$R_{fd} = \frac{234.5+100}{234.5+T_f} r_{meas} \frac{3}{2}\left[\frac{1}{N_{af}(0)}\right]^2 \tag{192}$$

where

r_{meas} is the measured value for the field winding resistance, at the measurement temperature T_f, in ohms
T_f is the average field winding temperature, in °C, during the measurement

Substitute this value for R_{fd} in the equivalent circuit. For field winding materials other than copper, appropriate values of temperature coefficients (234.5 for copper) should be used.

h) Normalize the equivalent circuit elements to their per unit values. The reciprocal per unit system is used whenever equivalent circuits such as those shown in Figure 68 are used (see 9.2.5).

i) To determine as an initial value, the quantity i_{fdbase} in the reciprocal system (see Rankin [B40] and 9.2.5), refer to Equation (193).

$$i_{fdbase} = \frac{3}{2}\frac{i_{abase}}{N_{af}(0)} \tag{193}$$

NOTE—The use of $N_{af}(0)$ in place of N_{afbase} is necessary to help ensure consistency of the measured low-frequency asymptotes for all three transfer functions.

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, L_ℓ, that was used in the direct axis. Then calculate $L_{aq}(0)$ based on $L_q(0)$, the low-frequency asymptote for $L_q(s)$, as shown in Equation (195).

$$L_{aq}(0) = L_q(0) - L_\ell \tag{194}$$

NOTE—This value of $L_{aq}(0)$ corresponds to the flux levels that existed during the test and, thus, to the magnetic saturation level during the test; in general, it might be lower than the unsaturated value associated with the air-gap line. However, it has been observed that for large salient-pole machines, the values of $L_{aq}(0)$ and L_{aqu} are generally close.

b) Choose an equivalent circuit structure for the quadrature-axis model, such as one of those shown in Figure 69.

c) Adjust the unknown values for the circuit elements in the selected quadrature-axis model that produce the best fit to the two measured quadrature-axis frequency response $L_q(s)$. Iterative numeric techniques (see 12.5.3) are usually applied in this step.

d) Adjust $L_{aq}(0)$ calculated in step a), Equation (194), to its unsaturated value L_{aqu} (see Annex H).

e) Normalize the equivalent circuit elements to their per unit values. The reciprocal per unit system is used whenever equivalent circuits such as those shown in Figure 69 are used (see 9.2.5).

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 considering a third-order model, as shown in Equation (195) for the quadrature axis,

$$L_q(s) = L_q(0)\frac{1+sT_1}{1+sT_4}\frac{1+sT_2}{1+sT_5}\frac{1+sT_3}{1+sT_6} \tag{195}$$

or the actual equivalent circuit (see Figure 69, for instance).

Some analysts tend to assign, for example, quadrature-axis time constants to the quantities in Equation (195) (see Aliprantis et al. [B2]). Thus T_1 would be considered to be representative of T_q', T_4 to be representative of T_{q0}', and so on. Such time constants derived from Equation (195) may be reasonably close in value to the quadrature-axis time constants described in Clause 11, 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_{d0}'.

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. Refer also to Annex H.

Many well-established methods might be used for the optimization process associated with the identification of the model parameters that provide the best approximation to the measured SSFR test results.

One approach is to use a pattern-search technique (see Hooke and Jeeves [B21]). 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 (196).

$$\begin{aligned}\Gamma_0 &= \left[L_\ell \quad L_{aq}(0) \quad L_{1q} \quad R_{1q} \quad L_{ad}(0) \quad L_{f1d} \quad L_{1d} \quad R_{1d} \quad L_{fd} \quad R_{fd} \quad \frac{1}{N_{af}(0)} \right] = \\ &= \left[\gamma_1 \quad \gamma_2 \quad \cdots \quad \gamma_{n-1} \quad \gamma_n \right]\end{aligned} \tag{196}$$

where

- n is the number of parameters that can be adjusted, in the selected model
- γ_i is the i^{th} parameter in the parameter list Γ_0. Equation (196) shows 11 parameters, corresponding to the choice of the second-order model in Figure 68(b) for the direct axis and the first-order model in Figure 69(a) for the quadrature axis

Each frequency point used in the SSFR tests (see 12.3) corresponds to a frequency $\omega_j = 2\pi f_j$ and will have a user-selected 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 of the SSFR test results, $(F_{data})_i$, [e.g., $L_d(s)$, $sG(s)$, or $L_q(s)$] also has an associated user-selected weighting factor, Ω_i. It is necessary to assign weighting factors to each measured frequency response because functions such as $sG(s)$ contain less information about the stator circuit due to the stator-to-field transformation. As a result $sG(s)$ can 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 (197).

$$e_0 = \sum_i \sum_j e_{ij} = \sum_i \sum_j \Omega_i \Omega_j \left(\left(FR_{data}\right)_i \Big|_{\omega_j = 2\pi f_j} - \left[FR_{calc}(\Gamma_0)\right]_i \Big|_{\omega_j = 2\pi f_j} \right)^2 \tag{197}$$

where

- e_0 is the summation of the weighted errors squared, for all frequencies f_j in each SSFR frequency response test data FR_i
- f_j is the frequency associated with the j^{th} point in the SSFR test $(F_{data})_i$, in Hz
- Γ_0 is the vector of parameters for the selected model structure, as exemplified in Equation (196)
- $(FR_{data})_i$ is the i^{th} SSFR test result (see 12.3), usually one of the following: $L_d(s)$, $sG(s)$, or $L_q(s)$
- $(FR_{calc})_i$ is the i^{th} calculated frequency response of the model defined by the parameters Γ_0, calculated at the same frequency as the measured value in the corresponding SSFR test result $(F_{data})_i$
- Ω_i is the user-selected weighting factor for each SSFR test sets $(FR_{data})_i$
- Ω_j is the user-selected weighting factor for each frequency f_j in the SSFR test results

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.

The process might have to be repeated with different user-selected weighting factors until the calculated frequency responses from the selected model structure (with the parameters determined by the optimization method described above) provide a satisfactory match to the measured SSFR test results. Of particular concern are the responses over the frequency range of interest (usually between 0.01 Hz and 5 Hz) for stability studies.

12.5.4 Numerical example for a large salient-pole machine

This example is based on a synchronous machine rated 285 MVA, 13.8 kV, 60 Hz, 72 poles, 648 slots, with non-continuous damper windings.

The base armature line current and armature impedance (see 9.2.4) are calculated from Equation (77) and Equation (80), respectively, as shown in Equation (198) and Equation (199).

$$I_{Lbase} = \frac{285}{13.8\sqrt{3}} = 11.9235 \text{ kA} \tag{198}$$

$$Z_{base} = \frac{(13.8)^2}{285} = 0.6682 \ \Omega \tag{199}$$

The base value for the armature inductance can be derived from the base value for armature impedance as shown in Equation (200).

$$L_{base} = \frac{Z_{base}}{\omega_{base}} = \frac{Z_{base}}{2\pi f_{base}} = \frac{0.6682}{2\pi(60)} = 1.773 \text{ mH} \tag{200}$$

where

I_{Lbase} is the base line armature current (see 9.2.4)
L_{base} is the base armature inductance
Z_{base} is the base armature impedance
ω_{base} is the base electrical angular speed, in rd/s
f_{base} is the base electrical frequency, in Hz

The value for the unsaturated direct-axis synchronous reactance $X_{du} = 0.908$ p.u. was determined from the short-circuit and saturation curves. The leakage reactance $X_{\ell} = 0.10$ p.u. is given by the manufacturer. The base peak armature current and the base field current will be established in order to find the value of the theoretical N_{afbase}. The base peak armature current is related to the base (rms) line armature current as shown in Equation (201).

$$i_{abase} = \sqrt{2} I_{Lbase} = \sqrt{2} \times 11.9235 = 16862.4 \text{ A} \tag{201}$$

where

i_{abase} is the base peak armature current

The base value for the field current, when using an equivalent circuit model for the synchronous machine such as those shown in Figure 68, must be the base value for the reciprocal per unit system i_{fdbase} (see 9.2.5). It is also shown in 9.2.5 that $i_{fdbase} = L_{adu} \times I_{fdbase}$, where I_{fdbase} is the base value for the field current in the nonreciprocal per unit system. The nonreciprocal per unit system field current base value I_{fdbase} corresponds to the field current required to obtain nominal terminal voltage in the air-gap line of the open-circuit saturation curve, shown in Figure 32, which can be easily obtained from the manufacturer or a tested open-circuit saturation curve (see 5.1.1).

In this example, $I_{fdbase} = 1321$ A and therefore $i_{fdbase} = 0.808 \times 1321 = 1067$ A. The base turn ratio N_{afbase} can be calculated using Equation (202):

$$N_{afbase} = \frac{3}{2} \frac{i_{abase}}{i_{fdbase}} = \frac{3}{2} \frac{16862.4}{1067} = 23.7 \tag{202}$$

The four measured SSFR functions are $Z_d(s)$, $sG(s)$, $Z_{afo}(s)$, and $Z_q(s)$ (see 12.3), and these results are presented in Figure 61, Figure 64, Figure 65, and Figure 67, respectively. Figure 62 is the plot of the resistive component of $Z_d(s)$ zooming into the low-frequency end of the measurements. At zero frequency (dc steady state), the asymptote of the measurements equals $2R_a$ (see 12.3.3.1); thus, $R_a = 1.379$ mΩ for this example. The values shown in Figure 62 are already calculated values for R_a, one half of the measured resistive component of $Z_d(s)$ measured with two armature windings in series.

The operational inductance can be calculated for each frequency, and the calculated values for $L_d(s)$ are shown in Figure 63. All the calculations based on these frequency response results are based on complex numbers calculated for each individual frequency associated with that measured value.

For example, at 0.13 Hz, $Z_d(j2\pi \times 0.13) = 1.704 \ \underline{|-17.1°}$ mΩ. The corresponding operational inductance, at this particular frequency, is calculated as shown in Equation (203).

$$L_d\Big|_{f=0.13\text{ Hz}} = \frac{1.704\angle 17.1° - 1.379}{j2\pi 0.13} = 0.6853\angle -26.5° \text{ mH} \tag{203}$$

The unit H [Ω s / rd] is used with a complex inductance similar to what is commonly done with complex voltages and currents.

Similar calculations as shown in Equation (203) are repeated for each frequency at which $Z_d(s)$ was measured, and the result is the direct-axis operational inductance $L_d(s)$ shown in Figure 63. The quadrature-axis operational inductance $L_q(s)$, presented in Figure 67, is calculated in the same way from the measured values for $Z_q(s)$.

12.5.4.1 Direct axis

Beginning with the direct axis and following the steps in 12.5.2.1:

a) Considering the base inductance value from Equation (200) and the manufacturer value for the leakage reactance $X_\ell = 0.10$ p.u., it can be calculated that $L_\ell = 0.1773$ mH.

   It should be noted that reactances and inductances have the same numerical value, when expressed in per unit, as the nominal frequency is used as the base value for frequency.

b) From Figure 63, $L_d(0) = 1.315$ mH $= 0.742$ p.u. Based on the given value for L_ℓ, $L_{ad}(0)$ can be calculated as $L_{ad}(0) = L_d(0) - L_\ell = 1.138$ mH $= 0.642$ p.u.

c) From Equation (189) and referring to Figure 65, see Equation (204).

$$\begin{aligned} N_{af}(0) &= \left\{ \frac{1}{sL_{ad}(0)} \lim_{s\to 0} \left[\frac{\Delta e_{fd}(s)}{\Delta i_d(s)} \right] \right\} = \frac{1}{s(0.001138)}(0.0252s) \\ N_{af}(0) &= \frac{0.0252}{0.001138} = 22.14 \end{aligned} \tag{204}$$

   The low frequency $(s \to 0)$ limit of 25.2 mH used above can be obtained by observing that the low-frequency asymptote of Figure 65 approaches a straight line (positive inclination). Thus, it is possible to fit a simple first-order transfer function (with a transfer function zero at the origin) $F(s) = Ks/(1+sT)$ to the low-frequency test points in Figure 65. It can be seen that the frequency response of the transfer function $F(s)$ approaches $F(s) \approx Ks(s = j\omega)$ for low frequencies $(\omega \to 0)$, which corresponds to the straight dotted line in Figure 65: $F(s) \approx 25.2$.

d) From Equation (191) and considering the results in Figure 64, see Equation (205).

$$R_{fd} = \frac{sL_{ad}(0)}{\lim\limits_{s\to 0}\left\{\frac{\Delta i_{fd}(s)}{\Delta i_d(s)}\right\}\frac{2}{3}\left[N_{af}(0)\right]} = \frac{s(0.001138)}{(0.134s)\left(\frac{2}{3}\right)(22.14)}$$
$$R_{fd} = 0.575 \text{ m}\Omega \tag{205}$$

Thus, a value of R_{fd} can also be obtained directly from the standstill test data (at 17 °C). This process is an alternative method of obtaining the field resistance, compared to step d).

e) The equivalent circuit structure in Figure 68(d) (third-order model) will be used for determining the direct-axis parameter values. The values for L_ℓ, $L_{ad}(0)$, and R_{fd} were established in the previous steps and are thus fixed during the model parameter fitting process.

f) An iterative curve fit procedure, described in 12.5.3, yields the values in Equation (206) for the unknown parameters for the equivalent circuit in Figure 68(d):

$$\begin{aligned} L_{f12d} &= -0.446\text{c mH} \\ L_{f2d} &= -6.632 \text{ mH} \\ L_{1d} &= 4.763 \text{ mH} \\ R_{1d} &= 0.0848\ \Omega \\ L_{2d} &= 377.81 \text{ mH} \\ R_{2d} &= 420.49\ \Omega \\ L_{fd} &= 7.522 \text{ mH} \end{aligned} \tag{206}$$

g) At rated armature voltage on the air-gap line of the open-circuit saturation curve, $I_{fd}(\text{base}) = 1321$ Adc and $N_{af}(\text{base}) = 23.7$. Then, see Equation (207).

$$L_{adu} = \left[\frac{3}{2}\right]\left[\frac{1}{N_{af}(\text{base})}\right]\left[\frac{13800\sqrt{2}}{\sqrt{3}(120\pi)(1321)}\right] = \left[\frac{3}{2}\right]\left[\frac{0.0226}{23.7}\right]$$
$$L_{adu} = 1.4320 \text{ mH} \tag{207}$$

From short-circuit and saturation curves, a similar value was determined: $L_{adu} = 0.808$ p.u. $= 1.433$ mH. This value is substituted to 1.138 mH in the equivalent circuit.

h) The measured field winding resistance (using a Kelvin bridge), r_{fd}, was 87.24 mΩ at 17 °C. At 100 °C, Equation (208) applies.

$$r_{fd} = \left[\frac{234.5+100}{234.5+17}\right].\left[87.24\right] = 116.03 \text{ m}\Omega \tag{208}$$

Then, referred to the armature at 100 °C, see Equation (209).

$$R_{fd} = 116.03\left(\frac{3}{2}\right)\left(\frac{1}{N_{af}\,(\text{base})}\right)^2 = 116.03\left(\frac{3}{2}\right)\left(\frac{1}{23.7}\right)^2 = 0.3098\ \text{m}\Omega \tag{209}$$

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 that

Z_{base} (armature) = 0.6682 Ω

L_{base} (armature) = 1.773 mH

The per unit values of all the desired elements are shown in Equation (210) and Equation (211).

$$\begin{aligned}
L_{\ell} &= \frac{0.177}{1.773} = 0.10 \text{ p.u.}\\
L_{adu} &= \frac{1.433}{1.773} = 0.808 \text{ p.u.}\\
L_{f12d} &= \frac{-0.446}{1.773} = -0.252 \text{ p.u.}\\
L_{1d} &= \frac{4.763}{1.773} = 2.686 \text{ p.u.}
\end{aligned} \tag{210}$$

$$\begin{aligned}
R_{1d} &= \frac{0.0848}{0.6682} = 0.127 \text{ p.u.}\\
L_{f2d} &= \frac{-6.632}{1.773} = -3.741 \text{ p.u.}\\
L_{2d} &= \frac{377.81}{1.773} = 213.09 \text{ p.u.}\\
R_{2d} &= \frac{420.49}{0.6682} = 629.29 \text{ p.u.}\\
L_{fd} &= \frac{7.522}{1.773} = 4.243 \text{ p.u.}\\
R_{fd} &= \frac{0.3098\times 10^{-3}}{0.6682} = 0.00046 \text{ p.u.}
\end{aligned} \tag{211}$$

j) Z_{base} for the field, referred to the stator, is shown in Equation (212).

$$\frac{\text{Rated machine voltamperes}}{\left[i_{fd}\,(\text{base})\right]^2} = \frac{285\times 10^6}{(1067)^2} = 250.33\ \Omega \tag{212}$$

Again, see Equation (213).

$$R_{fd} = \frac{r_{fd}\,(\text{corrected to 100 °C})}{250.33} = \frac{116.03\times 10^{-3}}{250.33} = 0.00046\ \text{p.u.} \tag{213}$$

which agrees with the calculation in step i).

12.5.4.2 Quadrature axis

The quadrature axis is considered next.

a) $L_\ell = 0.177$ mH.

b) From Figure 66, see Equation (214).

$$\begin{aligned} &L_q(0) = 1.0752 \text{ mH} \\ &L_{aq}(0) = (1.0752 - 0.177) \text{ mH} = 0.8982 \text{ mH} \end{aligned} \tag{214}$$

c) The quadrature-axis equivalent circuit structure is shown in Figure 69(c); L_ℓ and $L_{aq}(0)$ are known at this point. An iterative procedure, identical to that described above, fitted to the quadrature-axis operational inductance gave the model element values shown in Equation (215).

$$\begin{aligned} &L_{aq}(0) = 0.8982 \text{ mH} \\ &L_{1q} = 2.000 \text{ mH} \\ &R_{1q} = 0.0271\ \Omega \\ &L_{2q} = 0.5883 \text{ mH} \\ &R_{2q} = 0.0386\ \Omega \\ &L_{3q} = 0.5098 \text{ mH} \\ &R_{3q} = 0.3134\ \Omega \end{aligned} \tag{215}$$

d) Converting to per unit values, see Equation (216).

$$\begin{aligned} &L_\ell = \frac{0.177}{1.773} = 0.10 \text{ p.u.} \\ &L_{aqu} = \frac{0.8982}{1.773} = 0.507 \text{ p.u.} \\ &L_{1q} = \frac{2.000}{1.773} = 1.128 \text{ p.u.} \\ &R_{1q} = \frac{0.0271}{0.6682} = 0.041 \text{ p.u.} \\ &L_{2q} = \frac{0.5883}{1.773} = 0.332 \text{ p.u.} \\ &R_{2q} = \frac{0.0386}{0.6682} = 0.0578 \text{ p.u.} \\ &L_{3q} = \frac{0.5098}{1.773} = 0.288 \text{ p.u.} \\ &R_{3q} = \frac{0.3134}{0.6682} = 0.469 \text{ p.u.} \end{aligned} \tag{216}$$

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 68(d) and Figure 69(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.

As a matter of fact, the second-order representation is sufficient for fitting the direct-axis frequency response data of this large salient-pole generator up to the subtransitory frequency range. Therefore, a second-order model will be adequate when stability analysis according to IEEE Std 1110 is the main area of concern. However, with a third-order model, high values of R_{2d} and L_{2d} allow for extending the fitting beyond the subtransitory region and even up to 120 Hz and beyond. Such extension improves the model adequacy for electromagnetic and harmonic studies.

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 [B14].

This reference also relates the measurements derived from the preceding equations [see Equation (177) through Equation (187) to a particular complexity level of the model. As indicated in 12.5, as well as in Coultes and Watson [B14], 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

Bibliographical references are resources that provide additional or helpful material but do not need to be understood or used to implement this guide. Reference to these resources is made for informational use only.

[B1] Adkins, B., and R. G. Harley, *The General Theory of Alternating Current Machines: Application to Practical Problems*, London: Chapman & Hill, 1975.

[B2] Aliprantis, D. C., S. D. Sudhoff, and B. T. Kuhn, "Experimental Characterization Procedure for a Synchronous Machine Model with Saturation and Arbitrary Rotor Network Representation," *IEEE Transactions on Energy Conversion*, vol. 20, no. 3, pp. 595–603, Sept. 2005.

[B3] Anderson, P. M, *Analysis of Faulted Power Systems*, New York: Wiley-IEEE Press, 1995, http://ieeexplore.ieee.org/servlet/opac?bknumber=5263441.

[B4] Auckland, D. W., S. M. L. Kabir, and R. Shuttleworth, "Generator Model for Power System Studies," *IEE Proceedings C*, vol. 137, pp. 333–390, Nov. 1990.

[B5] Beckwith, S., "Approximating Potier Reactance," *AIEE Transactions*, vol. 56, pp. 813–818, July 1937.

[B6] de Boor, C., *A Practical Guide to Splines*, New York: Springer-Verlag, 1978.

[B7] Bortoni, E. C., and J. A. Jardini, "Experience with standstill frequency response (SSFR) testing and analysis of salient pole synchronous machines," *IEEE Transactions on Energy Conversion*, vol. 19, no. 4, pp. 687–691, Dec. 2004.

[B8] Bortoni, E. C., and J. A. Jardini, "Identification of synchronous machine parameters using load rejection test data," *IEEE Transactions on Energy Conversion*, vol. 17, no. 2, pp. 242–247, June 2002.

[B9] Bortoni, E. C., R. T. Siniscalchi, and J. A. Jardini, "Determination of Hydro Generator Efficiency Using Infrared Thermal Imaging Techniques," *IEEE Transaction on Energy Conversion*, vol. 26, issue 4, pp. 1134–1139, 2011.

[B10] Canay, I. M., "A New Method of Determining q-axis Quantities of a Synchronous Machine," *ETZ A*, vol. 86, pp. 561–568, 1965.

[B11] 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.

[B12] 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.

[B13] Concordia, C., *Synchronous Machines – Theory and Performance*, New York: John Wiley, 1951.

[B14] Coultes, M. E., and W. Watson, "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.

[B15] Dandeno, P. L., P. Kundur, A. T. Poray, and M. E. Coultes, "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.

[B16] Diggle, R., and J. L. Dineley, "Generator Works Testing: Sudden-Short-Circuit or Standstill Variable-Frequency-Response Method," *IEE Proceedings C*, vol. 128(4), pp.177–182, July 1981.

[B17] 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.

[B18] 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].

[B19] EPRI Report EL-5036, Electric Generator, vol. 1, 1982.

[B20] Harrington, D. and J. I. Whittlesey, "The Analysis of Sudden Short-Circuit Oscillograms of Steam Turbine Generators," *AIEE Transactions*, vol. 78, no. 3, pp. 551–562, 1959.

[B21] Hooke, R., and T. Jeeves, "Direct Search Solution of Numerical and Statistical Problems," *J. Assoc. Comput,* vol. 8, no. 2, Apr. 1961.

[B22] Hurley, J. D., and H. R. Schwenk, "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.

[B23] IEC 60034-4:1985, Rotating electrical machines—Part 4: Methods for determining synchronous machine quantities from tests.

[B24] 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. 99, no. 4, pp. 1625–1633, July 1980.

[B25] IEEE PES WG 12 Report (P. L. Dandeno, Chair), "Experience with standstill frequency response (SSFR) testing and analysis of salient pole synchronous machines," *IEEE Transactions on Energy Conversion*, vol. 14, no. 4, pp. 1209–1217, Dec. 1999.

[B26] IEEE Std 421.5™-2016, IEEE Recommended Practice for Excitation System Models for Power System Stability Studies.[11,12]

[B27] Kamwa, I., M. Pilote, H. Carle, P. Viarouge, B. Mpanda-Mabwe, and R. Crappe, "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.

[B28] Kamwa, I., P. Viarouge, and J. Dickinson, "Identification of Generalized Models of Synchronous Machines from Time-Domain Tests," *IEE Proceedings C*, vol. 138(6), pp. 485–498, Nov. 1991.

[B29] Kamwa, I., P. Viarouge, and R. Mahfoudi, "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.

[B30] Karmaker, H., E. Bortoni, A. Belqorchi, S. Umans, R. Wamkeue, and I. Kamwa, "Upgrading IEEE Std 115 to reflect new testing approachesand emerging sensing technologies," IEEE PES General Meeting panel presentations, 2018.

[B31] Kilgore, L. A., "Calculation of Synchronous Machine Constants—Reactances and Time Constants Affecting Transient Characteristics," *AIEE Transactions*, vol. 50, no. 4, pp. 1201–1213, Dec. 1931.

[B32] March, L. A., and S. B. Crary, "Armature Leakage Reactance of Synchronous Machines," *AIEE Transactions*, vol. 54, pp. 378–381, Apr. 1935.

[B33] Marxsen, A. L. and K. Morsztyn, "Analysis of Synchronous Machine Transient Tests Using a Microcomputer," *IEE Proceedings*, vol. 124(4), pp. 377–380, 1977.

[11] IEEE publications are available from The Institute of Electrical and Electronics Engineers (http://standards.ieee.org/).
[12] The IEEE standards or products referred to in this annex are trademarks of The Institute of Electrical and Electronics Engineers, Inc.

[B34] de Mello, F. P., and L. N. Hannett, "Validation of Synchronous Machine Models and Derivation of Model Parameters from Tests," *IEEE Transactions on Power Apparatus and Systems*, vol. 100, no. 2, pp. 662–672, Feb. 1981.

[B35] de Mello, F. P., L. N. Hannett, and J. R. Willis, "Determination of Synchronous Machine Stator and Field Leakage Inductances from SSFR Tests," *IEEE Transactions on Power Systems*, vol. 3, no. 4, pp. 1625–1632, Nov. 1988.

[B36] 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.

[B37] Moeini, A., I. Kamwa, P. Brunelle, and G. Sybille, "Synchronous Machine Stability Model, an Update to IEEE Std 1110-2002 Data Translation Technique," IEEE PES General Meeting 2018.

[B38] Muniz, P. R., S. P. N. Cani, and R. S. Magalhães, "Influence of Field of View of Thermal Imagers and Angle of View on Temperature Measurements by Infrared Thermovision," *IEEE Sensors Journal*, vol. 14, issue 3, pp. 729–733, 2014.

[B39] Ontario Hydro Research Division, "Electrical Parameters of Large Turbo-Generators," Canadian Electrical Association Report No. 004 G213, Dec. 1986.

[B40] Rankin, A. W., "Per Unit Impedance of Synchronous Machines," *AIEE Transactions*, vol. 64, pp. 569–572 and pp. 839–841, Aug. 1945.

[B41] Rusche, P. A. E., G. J. Brock, L. N. Hannett, and J. R. Willis, "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.

[B42] Stevenson, W. D., *Elements of Power System Analysis*, 4th ed., McGraw-Hill, 1982.

[B43] Umans, S. D., J. A. Mallick, and G. L. Wilson, "Modeling of Solid Rotor Turbogenerators—Parts I and II," *IEEE Transactions on Power Apparatus and Systems*, vol. 97, no. 1, pp. 269–291, Jan./Feb. 1978.

[B44] Wamkeue, R., F. Baetscher, and I. Kamwa, "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

B.1 Overview

This nomenclature pertains to Clause 4 through Clause 12. If any parameters throughout this guide are not otherwise defined, they have the following meanings:

V	voltage
A	ampere
R	resistance
I	current
W	watt
k , K	local variables defined in associated clauses or subclauses

B.2 Parameters used in Clause 4

a_n	cosine term of the n^{th} harmonic
b_n	sine term of the n^{th} harmonic
E_0	dc value of the waveform
E_i	i^{th} sample data of the waveform
E_j	instantaneous value of the voltage wave at the j^{th} point
E_n	rms magnitude of the n^{th} harmonic
E_{OM}	zero-to-peak amplitude of the equivalent sine wave
E_{RMS}	rms value of the input waveform
F_{DEV}	deviation factor
F_{Di}	distortion factor
N	number of sample data in one period
n	order of the harmonic component
R_s	specified temperature, in °C
R_t	test value of winding resistance, in ohms
T_t	temperature of winding when resistance was measured, in °C
ϕ_n	relative phase angle of the n^{th} harmonic

B.3 Parameters used in Clause 5

a	radius of the bearing journal, in meters
A	speed increment above and below n_s, in rpm, that define the time instants t_1 and t_2
b	distance from rotor axis to centroid of unbalance, in meters
c_p	specific heat of the oil (relative to water)
dE_D/dt	decrease of differential voltage, in volts per second
dn/dt	deceleration, in rpm/s

dn/dt	rate of deceleration as determined from the slope of speed-time curve at n, in rpm/s
E_B	voltage of battery
E_D	differential voltage
E_{DC}	differential voltage at speed n_C
g	acceleration constant due to gravity (9.807 m/s^2)
J	moment of inertia of rotating parts, in kg.m^2
M	mass of the rotor, in kg
n	rotational speed, in revolutions per minute (rpm)
n_C	speed, in rpm, at which losses are to be determined (usually rated speed)
n_r	number of revolutions of the rotor in each of the time intervals
n_s	synchronous speed in rpm
P	power, in kW
P_{input}	measured motor electrical power input
P_{loss}	power loss, in kW
P_{mech}	mechanical power (input of a generator, output of a motor), in kW
P_{output}	measured generator electrical power output
Q	rate of water flow, in liters per second
R_1	radius of bearings, in meters
R_2	radius of journals, in meters
R_g	radius of gyration, in meters
t	time of one cycle of oscillation, in seconds
T	torque, in N·m
t_a	ambient temperature, in °C
t_c	temperature of water entering cooler, in °C
t_h	temperature of water leaving cooler, in °C
t_i	time instant (i is an integer)
t_r	average temperature of the entire radiating surface, in °C
U	mass of the added unbalance, in kg
ϕ	power-factor angle
$\pi/30$	conversion factor from rpm to rd/s

B.4 Parameters used in Clause 6

E_a	machine terminal voltage (or kilovolts), in per unit
E_{GU}	generated voltage back of X_{du}, in per unit
E_I	field excitation in per unit
E_P	voltage back of Potier reactance
E_{QD}	location of a phasor relative to E_a, defining the quadrature magnetic axis of the machine and hence the phase displacement δ relative to E_a
I_a	machine armature current, in per unit
I_{FG}	1.0 p.u. field amperes corresponding to $E_a = 1.0$ p.u. on the air-gap line
I_{FS}	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
I_{FSI}	field current corresponding to specified armature current on the short-circuit saturation curve

I_{FU}	field current (usually in amperes or sometimes in per unit) required to induce a voltage E_{GU} on the air-gap line
K_d	saturation factor
R_1	positive sequence resistance, generally assumed to be equal to R_a
R_a	armature resistance
T_e	electrical torques
X_{du}	unsaturated direct-axis synchronous reactance
X_ℓ	stator leakage reactance, in per unit
X_P	Potier reactance
X_{qu}	unsaturated quadrature-axis synchronous reactance

B.5 Parameters used in Clause 7

$I_{f,s}$	field current, in amperes, corresponding to a specified load
$I_{f,t}$	field current, in amperes, under test conditions
k_a	225 for aluminum based on a volume conductivity of 62% of pure copper, in °C
k_c	234.5 for pure copper, in °C
P_A	total armature losses at the specified load, in kW
P_F	total field losses at the specified load, in kW
P_{Fo}	field losses during over excitation, in kW
P_{Fu}	field losses during under excitation, in kW
P_I	current-dependent armature loss, in kW
P_s	field current losses at a specified load
P_t	field current losses at the test load
P_V	voltage-dependent armature loss, in kW
R_0	calculated total resistance of the winding at 0 °C, in ohms
R_{0a}	calculated resistance of the aluminum portion of the winding at 0 °C, in ohms
R_{0c}	calculated resistance of the copper portion of the winding at 0 °C, in ohms
R_b	reference value of resistance previously measured at known temperature, t_b, in ohms
R_t	resistance measured during the test, in ohms
t_1	time at start of test, in seconds
t_2	time at finish of test, in seconds
t_b	temperature of winding when reference value of resistance R_b was measured, in °C
$t_{c,s}$	specified coolant temperature, in °C, for specified field current, $I_{f,s}$
$t_{c,t}$	reference coolant temperature, in °C, obtained during measurement of temperature rise
t_t	total temperature of winding when R_t was measured, in °C
Δt_{fan}	temperature rise, in °C, through fan (or blower)
Δt_o	test time interval for over excitation, in seconds
Δt_R	time interval of the test ($t_2 - t_1$), in seconds
Δt_t	temperature rise, in °C, for test field current, $I_{f,t}$
Δt_u	test time interval for under excitation, in seconds
β	slope of the temperature rise

B.6 Parameters used in Clause 8

$\cos\theta$	rated power factor
dn/dt	acceleration at each speed, in rpm/s
E_1	convenient line voltage at which T_1 and I_1 were measured, in per unit
E_2	convenient line voltage at which T_2 and I_2 were measured, in per unit
E_S	specified terminal voltage, in per unit
E_t	line-to-line voltage of the motor at the test point, in per unit
F	net force, in N
I_1	armature current measured at line voltage E_1, in per unit
I_2	armature current measured at line voltage E_2, in per unit
I_{FL}	specified field current, in amperes or per unit
I_{FSI}	field current corresponding to base armature current on the short-circuit saturation curve, in the same units as I_{FL}
I_s	locked-rotor current at specified voltage (usually rated)
I_t	armature current at test point corresponding to voltage E_t, in per unit
I_t	locked-rotor current from same test used to obtain T_g
J	moment of inertia of rotating parts, in kg.m^2
K_1	torque exponent of voltage ratio ($K_1 = 2$, neglecting saturation effects)
K_2	current exponent of voltage ratio ($K_2 = 1$, neglecting saturation effects)
l	length of the lever arm, in meters
n	test speed of motor, in rpm (if directly coupled, $n = n_s$)
n_s	synchronous speed, in rpm
P_C	open-circuit core loss at test voltage, in kW
P_{FW}	motor friction windage loss at speed for test point (see 5.1.2 and 5.3.4.2), in kW
P_{GL}	losses of the dc generator (including friction and windage), in kW
P_{GO}	output of the dc generator, in kW
P_{MN}	rated output of motor being tested, in kW
P_{SC}	short-circuit loss at test current (see 5.1.3, 5.3.3.9, and 5.3.4.4), in kW
P_{Si}	input power to stator, in kW
T_1	air-gap torque measured at line voltage E_1, in per unit on output base
T_2	air-gap torque measured at line voltage E_2, in per unit on output base
T_{FW}	motor friction windage torque, in per unit on output base
T_{FW}	torque due to friction and windage at each speed, see Equation (65), in per unit on output base
T_{FW}	torque due to motor friction and windage at speed for the test point, see Equation (64), in per unit on output base
T_g	air-gap torque at test conditions, in per unit on output base
T_g	air-gap torque at test point corresponding to voltage E_t, in per unit on output base
T_{LR}	locked-rotor torque corresponding to specified voltage, in per unit on output base
T_n	base mechanical output torque of motor, in N·m
T_n	base mechanical output torque of motor, see Equation (62)
T_{PO}	pull-out torque, in per unit of base mechanical output torque
T_t	mechanical output torque of motor at test condition
T_t	mechanical output torque of motor at test conditions, in N·m

X_{ds} saturated direct-axis synchronous reactance, in per unit

X_{qs} saturated quadrature-axis synchronous reactance, in per unit

δ load angle between terminal voltage and the voltage that would be generated by field current acting alone

η efficiency at rated load

B.7 Parameters used in Clause 9

e_{fdbase} base field voltage in the reciprocal per unit system

E_{fdbase} base value for field voltage, in volts, for the nonreciprocal per unit system

F_N base (rated) electrical frequency (synchronous frequency), in Hz

$I_{base\Delta 1\phi}$ base single-phase current for Δ-connected machines

I_{fd} $X_{adu} \times i_{fd}$

i_{fd} field current

I_{fdbase} base value for field current, in amperes, for the nonreciprocal per unit system

I_{Lbase} base line voltage, in amperes or kiloamperes depending on the units used for $S_{base3\phi}$ and V_{LLbase}

R_{fd} value of the field resistance, in ohms, for a given reference field winding temperature

$S_{base1\phi}$ single-phase base apparent power, in the same units used for $S_{base3\phi}$

$S_{base3\phi}$ three-phase base apparent power, in VA, kVA, or MVA

t_n base value for time, in seconds

$V_{base1\phi}$ base single-phase voltage

$V_{base\Delta 1\phi}$ base single-phase voltage for Δ-connected machines (equals the base line-to-line voltage)

V_{LLbase} base line-to-line voltage, in volts or kilovolts

Z_{base} base armature impedance

Z_{fdbase} base field impedance in the reciprocal per unit system

ω_N base electrical angular velocity, in rd/s

B.8 Parameters used in Clause 10

E armature voltage during the test, in per unit

E average of rms values of fundamental component of the three line-to-line voltage, in per unit (see 9.2.3)

E_3 rms third-harmonic voltage, in per unit of base line-to-line voltage (see 9.2.3)

E_a line-to-neutral voltage of the open phase, in per unit of base *line-to-neutral* voltage

$E_{\max}$ maximum effective value of the armature voltage during the slip test

$E_{\min}$ minimum effective value of the armature voltage during the slip test

f electrical frequency associated with machine speed when measurements were taken, in Hz

f frequency, in Hz

I average of rms values of fundamental component of the three line currents, in per unit

I_3 rms third-harmonic current, in per unit of base line current (see 9.2.3)

I_{FNL} field current for rated voltage, rated frequency, at no load (full speed, no load conditions)

I_{FSI} field current for rated armature current on a sustained three-phase short-circuit condition at rated frequency

$I_{\max}$ corresponding maximum effective value of the armature current during the slip test

$I_{\min}$	corresponding minimum effective value of the armature current during the slip test
I_N	base line current, in amperes
I_n	neutral current, in per unit of base line current
I_t	armature current at stability limit, in per unit
P	electric power input, in per unit
P'_{v-a}	adjusted value of the measured power, compensated for third-harmonics contents
P_{v-a}	measured power, in per unit of *base single-phase power* (see 9.2.2)
Q_{an}	reactive power measured with voltage E_a and current I_n, in per unit of base single-phase power
Q_{pn}	reactive power measured with voltage V_{pn} and current I_n, in per unit of base single-phase power
R_0	zero-sequence resistance, as defined by tests
R_1	positive-sequence resistance, in ohms
R_2	negative-sequence resistance, as defined by tests
R_a	armature resistance per phase corrected to specified temperature, in ohms
SCR	short-circuit ratio, as defined by test
W_{LO}	stray-load loss at base line current, in kW
X''_d	direct-axis subtransient reactance, in per unit
X_0	zero-sequence reactance, as defined by tests
X_2	negative-sequence reactance, as defined by tests
$X_{2(LL)}$	negative sequence reactance determined by Method 3, in per unit
X_{2t}	negative-sequence reactance calculated using Equation (98), but based on the measured values of E, I, and P following Method 2 (see 10.5.1.4)
X_{ads}	saturated portion of X_d, in per unit
X_{ads}	saturated portion of X_{ds}
X_{adu}	unsaturated direct-axis synchronous mutual reactance
X_{adu}	unsaturated portion of X_d, in per unit
X_{aqs}	saturated portion of X_{qs}, in per unit
X_{aqu}	unsaturated portion of X_{qu}, in per unit
X_{ds}	saturated direct-axis synchronous reactance, in per unit, for the given operating conditions
X_{du}	unsaturated direct-axis synchronous reactance, as defined by test
X_ℓ	stator leakage reactance, in per unit, assumed independent of machine saturation
X_ℓ	stator leakage reactance, in per unit, assumed independent of machine saturation (and the same value as for the direct axis)
X_{qs}	saturated quadrature-axis synchronous reactance, in per unit, for the given operating conditions
X_{qs}	saturated quadrature-axis synchronous reactance, in per unit, for the saturation level for the test conditions
X_{qs}	a particular saturated value of X_{qu}, as defined by tests
X_{qu}	unsaturated quadrature-axis synchronous reactance, in per unit
Z_0	zero-sequence impedance determined by Method 1, in per unit
Z_2	negative sequence impedance, in per unit
$Z_{2(LL)}$	negative sequence impedance determined by Method 3, in per unit
δ	internal electrical angle

B.9 Parameters used in Clause 11

a	largest absolute value of initial dc component of three-phase currents at selected time, in per unit
A_{dc} and B_{dc}	straight line equivalent model parameters of $\ln \Delta I_{dc}(t)$
b	second largest value of the initial dc component, in per unit
c	smallest value of the initial dc component, in per unit
E	rms voltage before the short circuit, in volts
$E(t)$	time-variant rms magnitude of the terminal voltage, in volts
$E''_q(t)$	subtransient component of the voltage $E(t)$, in volts
$E'_q(t)$	transient component of the voltage $E(t)$, in volts
E''_{q0}	initial value of the subtransient component of the voltage $E(t)$, in volts
E'_{q0}	initial value of the transient component of the voltage $E(t)$, in volts
$E''_\Delta(t)$	subtransient component of the voltage $E_\Delta(t)$, in volts
$E'_\Delta(t)$	transient component of the voltage $E_\Delta(t)$, in volts
$E''_{\Delta 0}$	initial value of the subtransient component of the voltage $E_\Delta(t)$, in volts
$E'_{\Delta 0}$	initial value of the transient component of the voltage $E_\Delta(t)$, in volts
E_0	ac rms voltage before the load rejection (breaker opening), in volts
E_0	ac rms voltage before the load rejection (breaker opening), in per unit
$E_{q\infty}$	steady-state rms component of the terminal voltage $E(t)$, in volts
$E_\Delta(t)$	time-variant rms magnitude of the envelope curve of the peak values of the terminal voltage, in volts
$E_\Delta(T)$	voltage for the point on the envelope curve $E_\Delta(t)$, at the time instant T, from the oscillogram with recorded test results, in volts.
$E_{\Delta\infty}$	steady-state rms component of the terminal voltage $E_\Delta(t)$, in volts
$E_{\Delta\infty}$	steady-state rms component of the terminal voltage $E_\Delta(t)$, in per unit
$E_{\Delta c}(T)$	voltage for the point on the envelope curve $E_\Delta(T)$, corrected for a speed deviation $\omega(T) - \omega_0$
$I(t)$	time-variant maximum values (envelope curve) of ac component of short-circuit current, in amperes
I'	$I' = I_{ss} + I'_{d0}$
$I''_{(1)}$	weighted average of the initial dc component for the largest absolute value, a
$I''_{(2)}$	weighted average of the initial dc component for the second largest absolute value, b
$I''_{(3)}$	weighted average of the initial dc component for the smaller absolute value, c
I''	$I'' = I_{ss} + I'_{d0} + I''_{d0}$
I''_{d0}	initial subtransient component
I''_{dc0}	initial direct current component
$I''_d(t)$	subtransient component of the current $I(t)$, in amperes
$I'_d(t)$	transient component of the current $I(t)$, in amperes
I'_{d0}	initial transient component
I'_{d0}	initial value of the transient component of the current $I(t)$, in amperes
I''_{d0}	initial value of the subtransient component of the current $I(t)$, in amperes
I_0	initial rms current before the breaker opening, in amperes
I_0	initial rms current before the load rejection (breaker opening), in amperes

I_0	initial rms current before the breaker opening, in per unit
I_{dc}	resolved value of the dc components, in per unit
$i_{dc}(0)$	initial value of the dc component of the short-circuit current
$I_{dc}(t)$	dc component of the short-circuit current in Equation (120)
I_{dc0}	initial value of the dc component of the short circuit $I_{dc}(t)$, in amperes
I_{ss}	steady-state current
I_{ss}	steady-state rms component of the current $I(t)$, in amperes
M	amplitude of the sinusoidal component of voltage reactance variation in Equation (144)
t	time measured from the instant of the load rejection, in seconds
t	time measured from the instant the short circuit is applied, in seconds
T''_d	direct-axis subtransient short-circuit time constant, in seconds
T'_d	direct-axis transient short-circuit time constant, in seconds
T''_{d0}	direct-axis subtransient open-circuit time constant, in seconds
T'_{d0}	direct-axis transient open-circuit time constant, in seconds
T_a	armature short-circuit time constant, in seconds
T_a	three-phase short-circuit armature time constant, in seconds
t_s	specified temperature, in °C
t_t	average temperature of the field winding during the test, in °C
X	stationary rotor reactance for the first selected pair of terminals
X''_d	direct-axis subtransient reactance, in ohms
X'_d	direct-axis transient reactance, in ohms
X''_{d3}	direct-axis subtransient reactance obtained from the three-phase test
X''_q	quadrature-axis subtransient reactance, in ohms
X_d	direct-axis synchronous reactance, in ohms
X_{LL}	line-to-line reactance from Equation (148)
Y	stationary rotor reactance for the second selected pair of terminals
Y	stationary rotor reactance for the third selected pair of terminals
$\Delta i'(0)$	initial value of straight line equivalent model of the transient component $I'_d(t)$ of the short-circuit current $I(t)$ in Equation (119), in per unit
$\Delta i''(t)$	initial value of straight line equivalent model of the subtransient component $I''_d(t)$ of the short-circuit current $I(t)$ in Equation (119), in per unit
$\Delta i'(t)$	initial value of straight line equivalent model of the transient component $I'_d(t)$ of the short-circuit current $I(t)$ in Equation (117), in per unit
T'_{d0}	direct-axis transient open-circuit time constant at specified temperature t_s, in seconds
T'_{d0A}	apparent direct-axis transient open-circuit time constant (which has been corrected to eliminate the resistive effect of the discharge resistor), in seconds
T'_{d0R}	modified time constant obtained from semilogarithmic plot (which includes resistive effect of the discharge resistor), in seconds
T'_{d0t}	direct-axis transient open-circuit time constant at test temperature, t_t, in seconds
T'_{dt}	direct-axis transient short-circuit time constant at test temperature, t_t, in seconds
T_a	short-circuit armature time constant at specified temperature, t_s, in seconds
T_{at}	short-circuit armature time constant at test temperature, t_t, in seconds
ω_0	rated speed of the rotor
$\omega(T)$	recorded speed of the rotor at the time instant T, in the same units as ω_0

B.10 Parameters used in Clause 12

d	subscript for direct axis
e_d	direct-axis armature voltage
e_{fd}	field voltage
e_q	quadrature-axis armature voltage
$f_{\min}$	minimum frequency for the frequency response tests, in Hz
$G(s)$	armature to field transfer function
i_{arm}	instantaneous value of armature current during test
i_d	direct-axis armature current
i_{fd}	field current
I_{fdbase}	base field current in the nonreciprocal per unit system, in amperes
I_{Lbase}	base line (armature) current, in amperes
i_q	quadrature-axis armature current
i_s	peak value of the largest armature current used during the test, in amperes
L_{adu}	direct-axis armature to rotor mutual inductance (unsaturated)
L_{aqu}	quadrature-axis armature to rotor mutual inductance (unsaturated)
$L_d(s)$	direct-axis operational inductance
L_{f1d}	Canay inductance
L_{fd}	field winding leakage inductance
L_{fkd}	differential leakage inductances proportional to fluxes that link one or more damper windings and the field
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_ℓ	armature leakage inductance
$L_q(s)$	quadrature-axis operational inductance
N_a	number of turns on one phase of the armature winding
$N_{af}(0)$	effective turns ratio determined from $Z_{afo}(s)$
N_{afbase}	base turns ratio determined by stator and field current bases (reciprocal system)
N_{fd}	number of turns in the field winding/per pole
q	subscript for quadrature axis
R_a	armature dc resistance determined from the frequency response tests, in ohms
R_{fd}	field resistance referred to the armature
r_{fd}	field resistance measured directly in physical ohms
R_{kd}	direct-axis damper winding resistance; $k = 1, 2, \ldots, n$
s	Laplace operator
$sG(s)$	armature current to field transfer function
v_{arm}	voltage between two energized armature terminals during SSFR tests
$Z_{afo}(s)$	standstill armature to field transfer impedance
$Z_{armd}(s)$	impedance measured between two armature terminals during direct-axis tests
$Z_{armq}(s)$	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 indicator of incremental or small change
$\psi_d(s)$ direct-axis stator flux linkage
$\psi_q(s)$ quadrature-axis stator flux linkage
ω electrical frequency, in rd/s

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)

Telephone-influence factor (TIF)

C.1 General

TIF is defined as the ratio between a weighted function of the weighted rms value of the fundamental and harmonics of a voltage wave and the rms of the wave. This concept was introduced to help reduce the interference of harmonics in the synchronous machine voltage and telephone lines using the technology then available (analog land lines). The weighting factors associated with TIF were defined precisely for that purpose. Considering that this telephone technology is no longer being deployed, the significance of TIF is reduced accordingly. As such, it is suggested to phase out the use of TIF and use, instead, other forms of quantifying and describing the harmonic content of the synchronous machine voltage, such as those described in NEMA MG1. This annex will describe TIF as it has been applied over the years, for compatibility with previous versions of this guide.

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 Equation (C.1) and Equation (C.2).

$$TIF = \frac{E_{TIF}}{E_{RMS}} \tag{C.1}$$

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

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.

C.1.1 Weighting factors

For the weighting factors to be used in calculating TIF, see NEMA MG1.

C.1.2 Voltage transformer considerations

If a voltage transformer is connected between the machine and the instrument, it is recommended 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) can be placed across the terminals of the machine with the voltage transformer disconnected, and the harmonic content of the machine voltage is obtained. The voltage transformer is then 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.

C.2 Balanced TIF

C.2.1 General

For the definition of *balanced telephone-influence factor* (*TIF*), see Clause 3. Balanced TIF can be measured using the following test methods:

— Method 1. Line-to-line voltage (see C.2.2)
— Method 2. Phase voltage (see C.2.3)

C.2.2 Method 1. Line-to-line voltage

For a three-phase wye-connected machine, Equation (C.1) 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 (C.2). Readings are taken with the machine operating at rated voltage and speed, without load.

C.2.3 Method 2. Phase voltage

The balanced TIF of a three-phase wye-connected machine can be obtained using Equation (C.1) and Equation (C.2) 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.

C.3 Residual-component TIF

C.3.1 General

For the definition of *residual-component telephone-influence factor (TIF)*, (see Clause 3). The residual-component TIF can be determined by the following test methods:

— Method 1. Machines that can be connected in delta (see C.3.2)
— Method 2. Machines that cannot be connected in delta (see C.3.3)
— Method 3. Line-to-neutral test (see C.3.4)

C.3.2 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 (C.3) is used to evaluate residual TIF from this method.

$$\text{Residual } TIF = \frac{E_{TIF}}{3E_{RMS}} \tag{C.3}$$

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 (C.2).

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 (C.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 help reduce 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 is kept to a minimum.

C.3.3 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 is 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, with low values of TIF, the accuracy may be affected by the exaggerated effect of slight variations among the transformers.

C.3.4 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 (C.1) and Equation (C.2) 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.

C.4 Line-to-neutral TIF

C.4.1 General

The line-to-neutral TIF of a three-phase machine is calculated from Equation (C.1) 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 C.4.3).

C.4.2 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 (C.2). The TIF is obtained from Equation (C.1).

C.4.3 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 relationship shown in Equation (C.4).

$$\text{line-to-neutral } TIF = \sqrt{(\text{balanced } TIF)^2 + (\text{residual } TIF)^2} \tag{C.4}$$

Annex D

(informative)

Discussion on leakage and Potier reactances

Subclause 6.2.2.1 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 6.3.2.2 or 6.3.2.3. 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 6.2.2.1) 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 [B32] 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 [B32] 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 [B31] extends and confirms the armature leakage flux calculations of March and Crary.

In summary, March and Crary [B32] 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-axis (*d*) and quadrature-axis (*q*) 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. One possible approach is to define a factor K_d, obtained by dividing the per unit excitation on the open-circuit saturation curve at voltage E_ℓ by the excitation at E_ℓ per unit voltage on the air-gap line. The factor K_d (always equal to or greater than unity) is divided into X_{adu} to obtain a saturated value for the magnetizing reactance, X_{ads}. It can be noted that other approaches to consider the effect of magnetic saturation are also used and the results obtained with these different models might differ. Magnetic saturation effects might also apply to the *q* axis.

Park's two-axis equations for flux linkage representation of both the stator and field have several variations involving the machine inductances and currents, but the derivation of the Park models always starts by disregarding the effects of magnetic saturation. Then, once the decoupled two-axis models obtained by Park's approach are defined, the magnetic saturation effects are represented in different ways and applied to the Park model (decoupled direct-axis and quadrature-axis models obtained by disregarding the effects of saturation). These approaches are described generally in IEEE Std 1110.

Annex E

(informative)

Example of calculation of field current I_{fd} in per unit

Generator MVA $= 0.900 + j.435 = S$ Generator steady-state constants: $R_a = 0.0107$; $X_{du} = 0.906$

Output: $E_a = 1.05$ p.u. $X_p = 0.136$; $X_{qu} = 0.546$

$I_a = 0.952\underline{/-25.84}$ (in per unit); $\phi = -25.84$ °

NOTE—From 6.3.2.1, E_a is the machine terminal voltage (or kilovolts), in per unit.

a) Calculation of internal angle, δ; see Equation (36)

$$E_{QD} = E_a + I_a R_a + jI_a \times X_{qu} = 1.3246 + j0.4423 = 1.367\underline{/19.83°}$$

$\delta = 19.83$ ° [Alternatively, can calculate δ using Equation (36)]

b) $I_d = 0.952 \sin(19.83° - (-25.8°))\underline{/19.83° - 90°}$ [see Equation (37)]

$= 0.681\underline{/-70.18°}$

$I_q = 0.952 \cos(19.83° - (-25.8°))\underline{/19.83°}$ [see Equation (38)]

$= 0.666\underline{/19.83°}$

c) $E_{GU} = E_a + I_a R_a + jI_d \times X_{du} + jI_q \times X_{qu}$

$= 1.517 + j0.547 = 1.612\underline{/19.83°}$

d) $I_{FU} = 1.612$ and $E_{GU} = 1.612$ on air gap line (see Figure E.1)

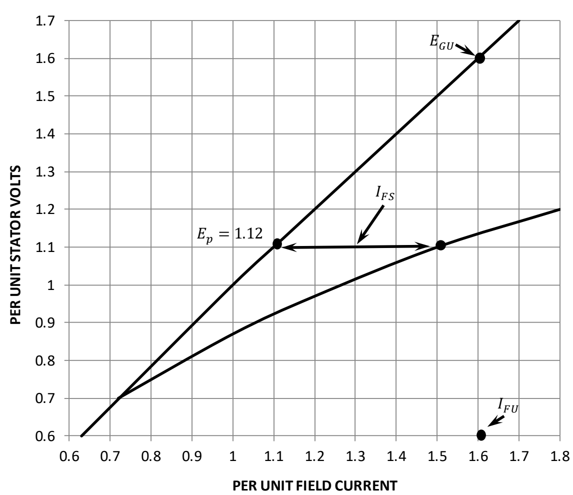


Figure E.1—Air gap line and open-circuit saturation curve of machine

e) $E_p = E_a + I_a \times R_a + jI_a \times X_p = 1.116 + \mathrm{j}0.112 = 1.121\underline{/5.74°}$

f) For $E_p = 1.121$ on air gap line, and on open-circuit saturation curve

$$I_{FS} = 1.5 - 1.121 = 0.379 \text{ p.u.}$$

$$I_F = I_{FU} + I_{FS} = 1.625 + 0.379 = 2.004 \text{ p.u.}$$

NOTE 1—Neglecting resistance $E_{QD}\underline{/\delta} = 1.360\underline{/20.13°}$

$$E_P = 1.113\underline{/6.01°}$$

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 F

(informative)

Details on the mathematical background for Clause 11

F.1 General

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 using 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 damper winding in each axis [second-order model for the direct axis, first-order model for the quadrature axis (see 12.4)] yields the corresponding direct-axis and quadrature-axis operational reactances as shown in Equation (F.2).

$$\begin{aligned}X_d(s) &= X_d\frac{1+sT'_d}{1+sT'_{d0}}\frac{1+sT''_d}{1+sT''_{d0}} = X_d-(X_d-X'_d)\frac{sT'_{d0}}{1+sT'_{d0}}-(X'_d-X''_d)\frac{sT''_{d0}}{1+sT''_{d0}}\\ X_q(s) &= X_q\frac{1+sT'_q}{1+sT'_{q0}} = X_q-(X_q-X'_q)\frac{sT'_{q0}}{1+sT'_{q0}}\end{aligned} \tag{F.2}$$

where

- $X_d(s)$ is the direct-axis operational reactance, in ohms
- X_d is the direct-axis synchronous reactance, in ohms
- X'_d is the direct-axis transient reactance, in ohms
- X''_d is the direct-axis subtransient reactance, in ohms
- X''_q is the quadrature-axis subtransient reactance, in ohms
- T'_d is the direct-axis transient short-circuit time constant, in seconds
- T''_d is the direct-axis subtransient short-circuit time constant, in seconds
- T'_{d0} is the direct-axis transient open-circuit time constant, in seconds
- T''_{d0} is the direct-axis subtransient open-circuit time constant, in seconds
- $X_q(s)$ is the quadrature-axis operational reactance, in ohms
- X_q is the quadrature-axis synchronous reactance, in ohms
- X'_q is the quadrature-axis transient reactance, in ohms
- T'_q is the quadrature-axis transient short-circuit time constant, in seconds
- T''_q is the quadrature-axis subtransient short-circuit time constant, in seconds
- T'_{q0} is the quadrature-axis transient open-circuit time constant, in seconds
- T''_{q0} is the quadrature-axis subtransient open-circuit time constant, in seconds

F.2 Theoretical background for ac and dc components of short-circuit current

In Equation (F.1) the direct-axis and quadrature-axis currents before the short-circuit test (see 11.4.1) are zero, and the voltages are $V_d = 0$ and $V_q = E$ with a constant field voltage V_f. At the short circuit, the direct-axis and the field voltages did not change ($\Delta v_d = \Delta e_f = 0$), and the quadrature-axis voltage in Laplace domain becomes $V_q = \frac{E}{s}$. The direct-axis and quadrature-axis current transients in Equation (F.1) are given in time domain by Equation (F.3) and Equation (F.4).

$$i_d(t) = E\sqrt{2}\left[\frac{1}{X_d} + \left(\frac{1}{X'_d} - \frac{1}{X_d}\right)e^{\left(\frac{-t}{T'_d}\right)} + \left(\frac{1}{X''_d} - \frac{1}{X'_d}\right)e^{\left(\frac{-t}{T''_d}\right)}\right] - \frac{E\sqrt{2}}{X''_d}e^{(-at)}\cos(\omega t) \tag{F.3}$$

$$i_q(t) = \frac{E\sqrt{2}}{X''_d}e^{(-at)}\sin(\omega t) \tag{F.4}$$

These two equations result in the armature current in Equation (F.5).

$$\begin{aligned} i_a(t) = {} & E\sqrt{2}\left[\frac{1}{X_d} + \left(\frac{1}{X'_d} - \frac{1}{X_d}\right)e^{\left(\frac{-t}{T'_d}\right)} + \left(\frac{1}{X''_d} - \frac{1}{X'_d}\right)e^{\left(\frac{-t}{T''_d}\right)}\right]\sin(\omega t + \lambda) \\ & - E\sqrt{2}\left[\left(\frac{1}{X''_d} + \frac{1}{X''_q}\right)e^{\left(\frac{-t}{T_a}\right)}\right]\sin(\lambda) \\ & - E\sqrt{2}\left[\left(\frac{1}{X''_d} - \frac{1}{X''_q}\right)e^{\left(\frac{-t}{T_a}\right)}\right]\sin(2\omega t + \lambda) \end{aligned} \tag{F.5}$$

As explained in de Mello et al. [B34] , the influence of the term with 2ω due to the generator saliency in the phase A short-circuit current formulation is very small. This term can be omitted. Accordingly, the phase A current following a three-phase short circuit from the no load when neglecting armature-circuit resistances and assuming constant exciter voltage can be reformulated as expressed in Equation (F.6).

$$i_a(t) = I(t)\sin(\omega t + \lambda) - I_{dc}(t)\sin(\lambda) \tag{F.6}$$

where

$I(t)$	is the ac component of the short-circuit current, in amperes
$I_{dc}(t)$	is the dc component of the short-circuit current, in amperes
E	is the ac rms voltage before the short circuit, in volts

$\lambda = \alpha - \phi$ in Equation (F.6) is the angle between the magnetic axis of phase A current and the magnetic axis of the rotor (direct-axis), a is the angle of the phase A voltage defined by $e_a(t) = E\sqrt{2}\sin(\omega t + a)$. During the armature short circuit of the no-load generator, the load equivalent is inductive, the load angle $\phi = \frac{\pi}{2}$. Performing the short circuit at instant $t_0 = 0$, where phase A voltage is crossing the time origin, $a = 0$ and $\lambda = -\frac{\pi}{2}$. Equation (F.7) yields the following:

$$i_a(t) = I(t)\cos(\omega t + \pi) + I_{dc}(t) \tag{F.7}$$

The short-circuit current in Equation (F.7) can be bounded as shown in Equation (F.8).

$$\underbrace{-I(t)+I_{dc}(t)}_{I_{low}} \leq I(t)\cos(\omega t+\pi)+I_{dc}(t) \leq \underbrace{I(t)+I_{dc}(t)}_{I_{upp}} \tag{F.8}$$

The upper and lower short-circuit current envelops are defined by Equation (F.9).

$$\begin{aligned} I_{upp} &= I(t)+I_{dc}(t) \\ I_{low} &= -I(t)+I_{dc}(t) \end{aligned} \tag{F.9}$$

The ac and dc components of short-circuit current are computed from upper and lower envelops, respectively, as shown in Equation (F.10) and Equation (F.11).

$$I(t)=\frac{I_{upp}-I_{low}}{2}=\sqrt{2}E\left[\frac{1}{X_d}+\left(\frac{1}{X'_d}-\frac{1}{X_d}\right)e^{\left(-\frac{t}{T'_d}\right)}+\left(\frac{1}{X''_d}-\frac{1}{X'_d}\right)e^{\left(-\frac{t}{T''_d}\right)}\right] \tag{F.10}$$

$$I_{dc}(t)=\frac{I_{upp}+I_{low}}{2}=\sqrt{2}E\left(\frac{1}{X''_d}+\frac{1}{X''_q}\right)e^{\left(-\frac{t}{T_a}\right)} \tag{F.11}$$

F.3 Polynomial fitting of upper and lower short-circuit current envelopes

If the same order is used for upper envelop (P_{upp}) and lower envelop (P_{low}) of the short-circuit current (for instance, if the chosen order is 10), the two polynomials may be expressed as shown in Equation (F.12) and Equation (F.13).

$$P_{upp}(t)=A_{upp0}+A_{upp1}t+\cdots+A_{upp10}t^{10} \tag{F.12}$$

$$P_{low}(t)=A_{low0}+A_{low1}t+\cdots+A_{low10}t^{10} \tag{F.13}$$

F.4 Theoretical background for load rejection test

F.4.1 Terminal voltage in terms of transient reactance and time constants after load rejection test

In Equation (F.1), $\Delta I_d(s)=\frac{I_d}{s}$ 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 in Equation (F.1) are given in time domain by Equation (F.14).

$$\begin{aligned} \Delta\psi_d(t) &= X_d I_d + I_d(X'_d-X_d)e^{\left(-\frac{t}{T'_{d0}}\right)}+I_d(X''_d-X'_d)e^{\left(-\frac{t}{T''_{d0}}\right)} \\ \Delta\psi_q(t) &= X_q I_q + I_q(X'_q-X_q)e^{\left(-\frac{t}{T'_{q0}}\right)} \end{aligned} \tag{F.14}$$

I_d and I_q are steady-state currents before the load rejection obtained from Equation (F.15).

$$I_d = I\sin(\delta_0 + \phi) \qquad I_q = I\cos(\delta_0 + \phi) \tag{F.15}$$

$$E_d = E\sin\delta_0 \qquad E_q = E\cos\delta_0 \tag{F.16}$$

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 in Equation (F.17), contains only direct-axis parameters of the generator as shown previously. Similarly, the quadrature-axis armature flux, ψ_q in Equation (F.17), 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.18) and Equation (F.19), respectively. θ is the rotor angle (equivalent Park angle).

$$\psi_d(t) = \Psi_d + \Delta\psi_d(t) = E_q + \Delta\psi_q(t)\,; \;\; \psi_q(t) = \Psi_q + \Delta\psi_q(t) = -E_d + \Delta\psi_q(t) \tag{F.17}$$

$$E_d(t) = -\omega(t)\psi_q(t) = \frac{2}{3}\left[E_a(t)\cos\theta + E_b(t)\cos\left(\theta - \frac{2\pi}{3}\right) + E_c(t)\cos\left(\theta + \frac{2\pi}{3}\right)\right] \tag{F.18}$$

$$E_q(t) = \omega(t)\psi_d(t) = -\frac{2}{3}\left[E_a(t)\sin\theta + E_b(t)\sin\left(\theta - \frac{2\pi}{3}\right) + E_c(t)\sin\left(\theta + \frac{2\pi}{3}\right)\right] \tag{F.19}$$

F.4.2 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 $\omega(t) = \omega_0$ (rad/s) during the direct-axis load rejection test. Since $\phi = -\frac{\pi}{2}$, the direct-axis current defined by Equation (F.15) becomes $I_d = -I$ and $E_q = E$ in Equation (F.16). Accordingly, Equation (F.18) and Equation (F.19) lead to Equation (F.21) and Equation (F.22).

$$E_d(t) = -\omega_0(t)\psi_q(t) = 0 \tag{F.20}$$

$$\begin{aligned} E(t) = E_q(t) = v(t) = \omega_0\psi_d(t) &= -\frac{2}{3}\omega_0\left[E_a(t)\sin(\omega_b t) + E_b(t)\sin\left(\omega_b t - \frac{2\pi}{3}\right) + E_c(t)\sin\left(\omega_b t + \frac{2\pi}{3}\right)\right] \\ &= \omega_0\left(E - X_d I - I(X'_d - X_d)e^{\left(-\frac{t}{T'_{d0}}\right)} - I(X''_d - X'_d)e^{\left(-\frac{t}{T''_{d0}}\right)}\right) \end{aligned} \tag{F.21}$$

$$E_a(t) = E_q(t)\sin(\omega_b t) \tag{F.22}$$

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 the magnetic permeability
B	is the magnetic flux density, in teslas
H	is the 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) and, at the limit, would approach the magnetic permeability of the air. 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. It should be noted that the incremental inductance at very high flux densities is the lowest (minimum) value, lower than the incremental inductance at low flux densities.

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 [B36].

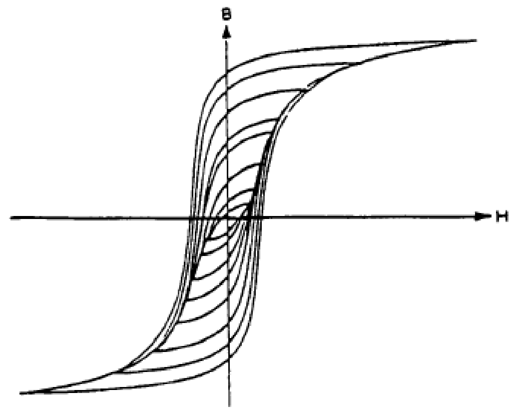


Figure G.1—Magnetic nonlinearity of iron (B-H loops)

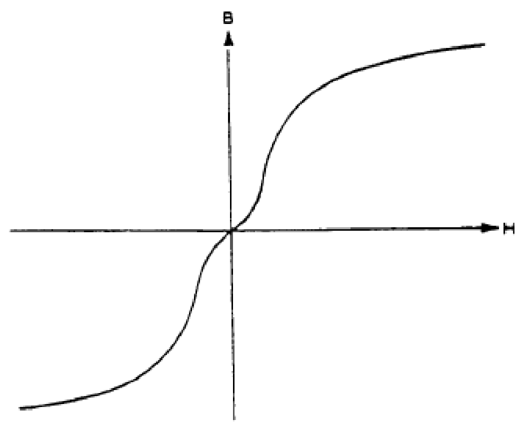


Figure G.2—Magnetic nonlinearity of iron (locus of tip of B-H loops)

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, 5.1.1, and Figure 32] as shown in Equation (G.3).

$$L_{adu} = \frac{3}{2}\frac{1}{N_{af}(0)}\frac{V_t}{\omega_n I_{fg}} \tag{G.3}$$

where

L_{adu}	is unsaturated direct axis magnetizing inductance
$N_{af}(0)$	is field to armature turns ratio
V_t	is the peak value of the rms terminal voltage, E_a, in the open-circuit saturation curve, in volts
I_{fg}	is the field current, in amperes
ω_n	is the rated rotor speed, in rd/s

The value of $N_{af}(0)$ can be determined as shown in step c) of the example in 12.5.4.1. The terminal voltage, V_t, and field current, I_{fg}, define a point on the air-gap line. Note that V_t in Equation (G.3) should be the peak voltage, line-to-neutral, while the open-circuit saturation curve is usually represented as shown in Figure 32, with terminal voltage expressed either in per unit (of the rated line-to-line voltage) or as the rms value of the line-to-line voltage in volts. L_{adu} is substituted for $L_{ad}(0)$ determined in step b) of 12.5.2.1 in the direct-axis equivalent circuit. Similarly, in the quadrature-axis equivalent circuit, $L_{aq}(0)$, as determined in 12.5.2.2, must be adjusted to its unsaturated value. One possible approach is to multiply it by $L_{adu}/L_{ad}(0)$, the same factor that is used in the direct axis.

Annex H

(informative)

Example of SSFR test data analysis for a large turbogenerator

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 turbogenerator models in the direct axis for determining model parameters from a given set of SSFR test data. In this annex, a case of a high-speed salient-pole machine is presented.

H.2 Machine technical details

The machine constants required to initiate an analysis of the SSFR data are in Table H.1 (see 9.2 for the definition of base values for the per unit system).

Table H.1—Machine constants required to initiate SSFR analysis

Nameplate	**Nominal voltage 16.5 (kV)** **Nominal power 250 (MVA)**	**Required current to induce 16.5 kV** **On the air-gap line curve I_{fd} (base) = 918 (A)**
Base peak values Voltage/Current	**Stator** 13.472 kV 12.371 kA	**Rotor** 200.243 kV 1.248 kA
Z_{base} (Stator) = 1.0890 Ω	**From manufacturer**	$L_{\ell} = 0.11$ p.u., $L_{du} = 1.47$ p.u.

A pre-processing stage was performed on the SSFR test data to determine values of $L_d(s)$ magnitude, in henries (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/ampere, and the armature-to-field-transfer impedance, $Z_{afo}(s)$, [of the transfer inductance, $L_{afo}(s)$] is given as volts/ampere.

An extract of the data available for analysis is shown in Table H.2. The full frequency range and measured data are from 1 mHz up to 1 kHz.

Table H.2—Samples of SSFR data for a 234 MVA gas turbine-generator

Frequency (Hz)	**$L_d(s)$**		**$sG(s)$**		**$Z_{afo}(s)$**	
	Magnitude	**Phase (degrees)**	**Magnitude (A/A)**	**Phase (degrees)**	**Magnitude (V/A = Ω)**	**Phase (degrees)**
0,00118	26,6382	0,00	0,00217	88,11	0,00033	89,69
0,00140	31,6461	–0,03	0,00251	87,91	0,00039	89,65
0,00166	37,4671	–0,44	0,00306	87,61	0,00046	89,58
0,00197	44,4320	–1,02	0,00363	86,91	0,00054	89,25

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 [B40], as described in 12.5.2. The approach is centered on determining the base value for the field current in the Rankin (or reciprocal) system, as described in 9.2.5.1. The base value for the field current in the reciprocal per unit system is related to the base value in the nonreciprocal system by Equation (81). Thus, see Equation (H.1).

$$i_{fd}\,(\text{base}) = I_{fd}\,(\text{base}) \times L_{adu} = 918(1.36) = 1248.48\ \text{Adc} \tag{H.1}$$

The base value for the field to armature turns ratio is calculated based on Equation (H.2).

$$N_{af}\,(\text{base}) = \frac{1.5(i_a\,(\text{base})\ \text{peak amperes})}{i_{fd}\,(\text{base})} = \frac{1.5(12.371\ \text{kA})}{1248.48\ \text{A}} = 14.863 \tag{H.2}$$

H.4 Approach to model development

In the present example, only the direct-axis network is considered in order to illustrate schemes for using field-to-armature-turns ratio and rotor resistance in building the equivalent network. As opposed to the experience chosen in the example of 12.5.4.1, the machine temperature during $Z_d(s)$ measurement is significantly different from that of $sG(s)$. A thoughtful value of N_{afd} and R_{fd} can alleviate the temperature effect on rotor resistance.

H.5 Method I: Single-step full data fitting

In this method, $L_d(s)$ and $sG(s)$ are fitted for the frequency between 1 mHz and 20 Hz using known values of $N_{fd}(0)$ and R_{fd}, determined from Equation (189) and Equation (191). See Equation (H.3).

$$\Gamma = \left[L_{fd}, L_{1d}, R_{1d}, L_{2d}, R_{2d}, L_{f1d}, L_{f2d}\right] \tag{H.3}$$

To initialize the first identification round, an initial value is given to all the parameters. 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 0.11 p.u.) It will be in later stages kept constant. Other network values are somewhat arbitrarily chosen, using typical data (from the existing literature, for instance) or from prior in-house knowledge.

If the amplitudes are scaled in decibels, they will show, over the 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 $sG(s)$. The weighting factor for each transfer function mostly depends on the studied machine and its configuration. The results of the first method are given in Table H.3.

Table H.3—Final network parameters (method I)

$L_{ad}(0)$ (p.u.)	L_{fd} (p.u.)	R_{fd} (p.u.)	L_{1d} (p.u.)	R_{1d} (p.u.)	L_{f1d} (p.u.)	L_{2d} (p.u.)	R_{2d} (p.u.)	L_{f2d} (p.u.)	$N_{af}(0)$
1.134	1.532e0	1.147e-3	0.804	1.213e-2	–1.300e-1	31.318e0	3.238e0	–1.121e0	13.41

H.6 Method II: Fitting with unknown values of R_{fd} and N_{afd}

To alleviate the temperature variation when measuring $L_d(s)$ and $sG(s)$, a better fitting is possible when considering R_{fd} and N_{afd} unknown. The optimum parameters obtained at convergence of the fitting process are given in Table H.4.

Table H.4—Final network parameters (method II)

$L_{ad}(0)$ (p.u.)	L_{fd} (p.u.)	R_{fd} (p.u.)	L_{1d} (p.u.)	R_{1d} (p.u.)	L_{f1d} (p.u.)	L_{2d} (p.u.)	R_{2d} (p.u.)	L_{f2d} (p.u.)	$N_{af}(0)$
1.134	1.395e0	1.045e-3	1.487	2.363e-2	–2.414e-1	41.380e0	6.693e0	–9.012e-1	14.86

H.7 Method III: Fixed N_{af}

From the past observation that the determined $N_{afd}(0)$ is similar to the theoretical value, the turns ratio is considered a fix parameter in the fitting process. This method is an alternative procedure for the cases in which the third transfer function is not available. The unknown parameters then become as shown in Equation (H.4).

$$\Gamma = \left[R_{fd}, L_{fd}, L_{1d}, R_{1d}, L_{2d}, R_{2d}, L_{f1d}, L_{f2d} \right] \tag{H.4}$$

From Equation (H.4), 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 $N_{af}(0)$ consistent with open-circuit measurements is hard to reach owing to random and/or systematic measurement errors. Such errors usually bound the iterative fitting process to spurious convergence. The results are given in Table H.5.

Table H.5—Final network parameters (method III)

$L_{ad}(0)$ (p.u.)	L_{fd} (p.u.)	R_{fd} (p.u.)	L_{1d} (p.u.)	R_{1d} (p.u.)	L_{f1d} (p.u.)	L_{2d} (p.u.)	R_{2d} (p.u.)	L_{f2d} (p.u.)	$N_{af}(0)$
1.134	1.316e0	1.045e-3	1.507	2.389e-2	–2.437e-1	36.741e0	5.922e0	–8.204e-1	14.86

This observation is illustrated graphically in Figure H.1 to Figure H.4 where the three models are compared against test data. Note that the plots of some of the models are close to each other in value or tend to overlap in these figures.

H.8 Presentation of data for stability studies

The last step of the analysis consists of computing characteristic stability constants (e.g., X'_d, T'_d, T''_d) based on the preferred model and using the data translation method described in IEEE Std 1110. Prior to this task, the field resistance needs to be corrected for the operating rotor temperature. Also, $L_{ad}(0)$ 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) at rated voltage from the air-gap line (singular), plus a knowledge of $N_{af}(0)$. The latter turns ratio is used to refer L_{afdu}, in henries, to L_{adu}, in henries [see step h) in 12.5.4.1].

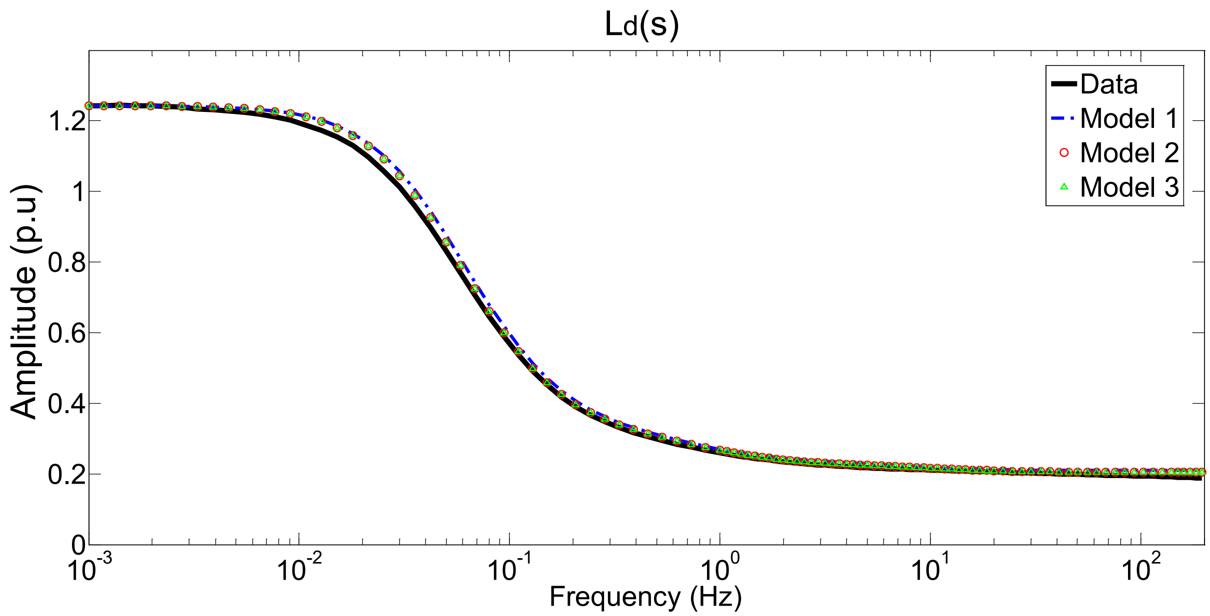


Figure H.1—Plot of magnitude of direct-axis operational inductance

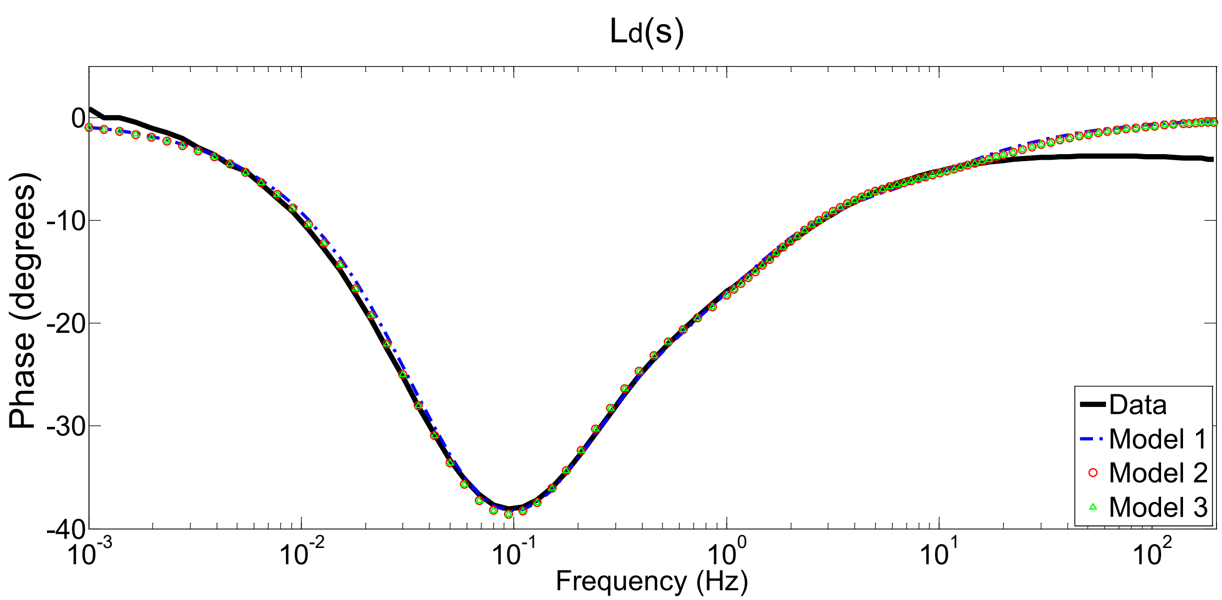


Figure H.2—Plot of phase angle of direct-axis operational inductance

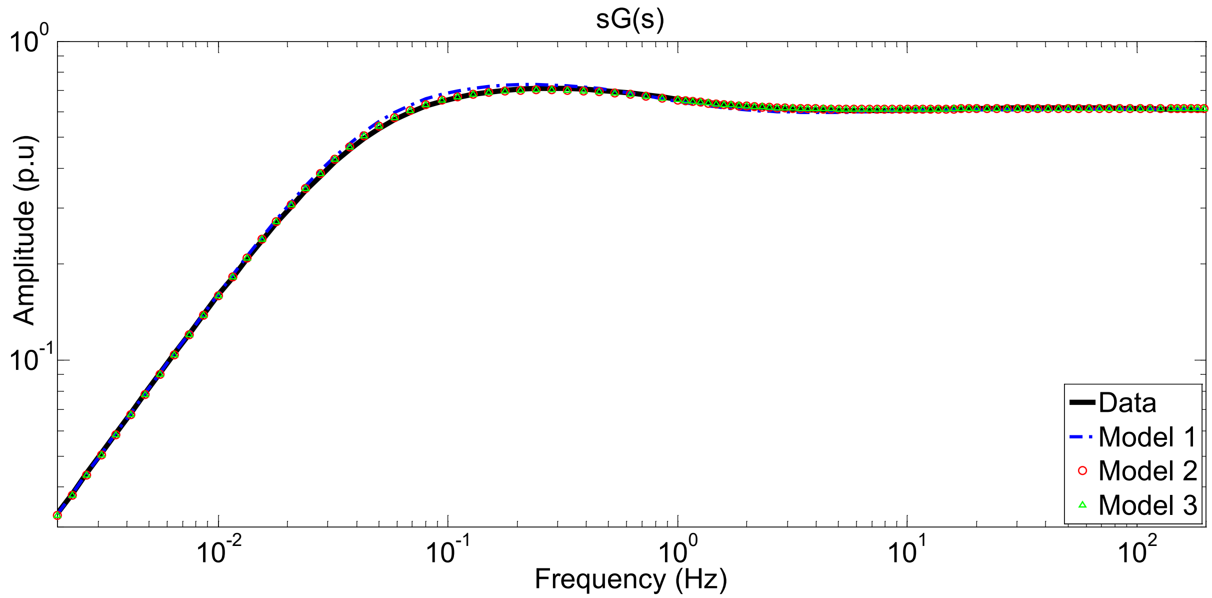


Figure H.3—Plots of magnitude of *sG(s)* transfer function

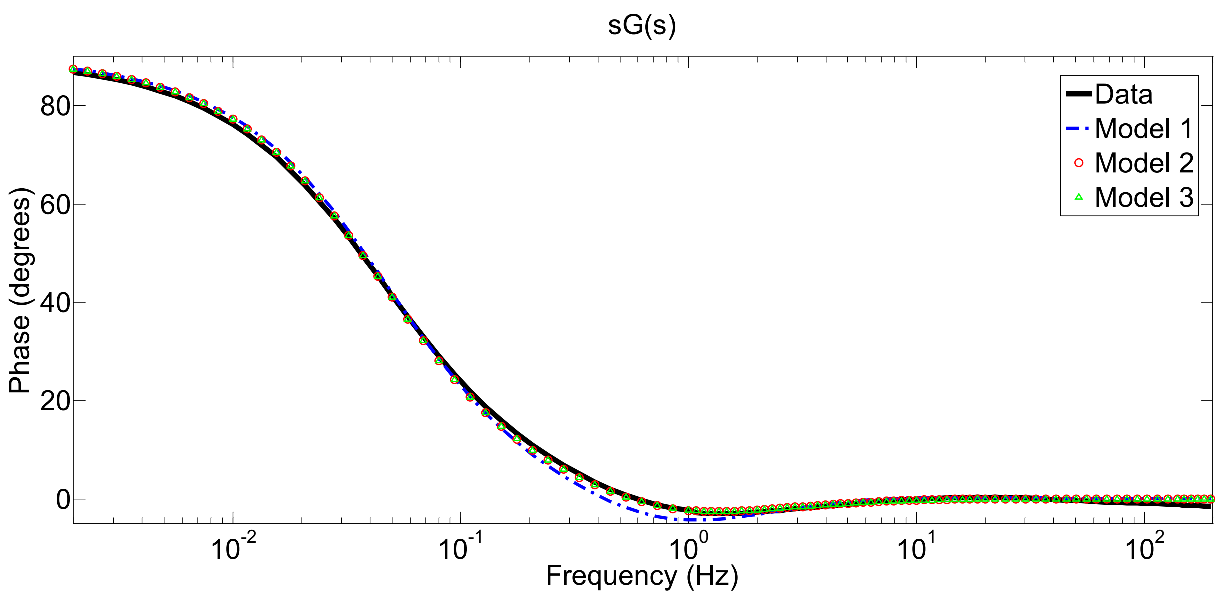


Figure H.4—Plots of phase angle of *sG(s)* transfer function

IEEE SA
STANDARDS
ASSOCIATION

RAISING THE WORLD'S STANDARDS

Connect with us on:

Twitter: twitter.com/ieeesa

Facebook: facebook.com/ieeesa

LinkedIn: linkedin.com/groups/1791118

Beyond Standards blog: beyondstandards.ieee.org

YouTube: youtube.com/ieeesa

standards.ieee.org
Phone: +1 732 981 0060

IEEE