



IEEE Guide for Synchronous Generator Modeling Practices and Parameter Verification with Applications in Power System Stability Analyses

IEEE Power and Energy Society

Developed by the
Electric Machinery Committee

IEEE Std 1110™-2019
(Revision of IEEE Std 1110-2002)



STANDARDS

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Approved 7 November 2019

IEEE SA Standards Board

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Abstract: Categorized in this guide are three direct-axis and four quadrature-axis models, along with the basic transient reactance model. Also discussed are some of the assumptions made in using various models. The fundamental equations and concepts involved in generator/system interfacing are presented. Covered, generally, are the various attributes of power system stability, recognizing two basic approaches. The first is categorized under large disturbance nonlinear analysis; the second approach considers small disturbances, where the corresponding dynamic equations are linearized. Applications of a range of generator models are discussed and treated. The manner in which generator saturation is treated in stability studies, both in the initialization process as well as during large or small disturbance stability analysis procedures is addressed. Saturation functions that are derived, whether from test data or by the methods, of finite elements are developed. Different saturation algorithms for calculating values of excitation and internal power angle depending upon generator terminal conditions are compared. The question of parameter determination or verification is covered. Two approaches in accounting for generator field and excitation system base quantities are identified. Conversion factors are given for transferring field parameters from one base to another for correct generator/excitation system interface modeling. Suggestions for modeling of negative field currents and other field circuit discontinuities are included.

Keywords: IEEE 1110™, modeling practices, saturation practices, stability data determination and application, synchronous generator stability models

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Chandan Kumar
Ruediger Kutzner
Leonardo Lima
Ali Moeini
Nils E. Nilsson

Eli Pajuelo
Uwe Seeger
Jayapalan Senthil
Jose Taborda
Stephen Umans
Rene Wamkeue
Allen Windhorn

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

Matthias Baechle
Thomas Bishop
William Bloethe
Edson Bortoni da Costa
Gustavo Brunello
Demetrio Bucaneg Jr.
Luis Coronado
Gary Donner
Rostyslaw Fostiak
Alexander Glaninger-Katschnig
J. Travis Griffith
Randall Groves
Paul Hamer
Scott Hietpas
Werner Hoelzl
John Houdek

Geza Joos
Innocent Kamwa
Haran Karmaker
Isidoro Kerszenbaum
Ruediger Kutzner
Mikhail Lagoda
Chung-Yiu Lam
Justin Lane
Leonardo Lima
Lawrenc Long
O. Malik
Kevin Mayor
Omar Mazzoni
James Michalec
Ali Moeini
Arthur Neubauer

Michael Newman
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Lorraine Padden
Eli Pajuelo
Shawn Patterson
Iulian Profir
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Introduction

This introduction is not part of IEEE Std 1110-2019, IEEE Guide for Synchronous Generator Modeling Practices and Parameter Verification with Applications in Power System Stability Analyses.

The Joint Working Group on Determination and Application of Synchronous Machine Models for Stability Studies was formed in 1973. The scope of the Working Group was updated in 1986 and its purpose was stated:

“Define synchronous machine models, particularly for solid iron rotor machines, for use in stability studies, and recommend standard methods for determining the values of parameters for use in these models by calculation and/or test. Assess the effect of magnetic saturation on these parameters. Devise and recommend analytical methods for incorporating such machine models, including representation of saturation, into stability programs.”

The Joint Working Group was responsible for two particular IEEE Committee Reports on the subject of machine modeling. The first was published in PA&S in 1980. In 1983, the Working Group (W/G) organized a one-day symposium on the subject of machine modeling and generator stability data acquisition at the IEEE PES Winter Power Meeting. Following publication of our second IEEE committee report in March 1986 (vol. EC-1), the group and the two committees to whom we then reported (PSE and Electric Machinery) suggested that application be made to the New Standards Committee (NesCom) of the Standards Board for permission to publish a guide outlining the work which we had sponsored over the past ten to fifteen years. A Project Authorization Request was made through the Power System Engineering Committee, which was approved by the IEEE Standards Board on 12 December 1985. This occurred at the 12 December 1985 meeting of NesCom, and the request was issued as Project Authorization Request (PAR) number P1110.

The membership of the Joint Working Group remained essentially unchanged between 1986 and 1991, when the complete document was approved as a guide by the IEEE Standards Board in 1991 (IEEE Std 1110).

With the publication of IEEE Std 1110 in 1991, the Joint Working Group had discharged its original mandate and so was disbanded. Its principal thrust was then subsequently organized under the PES Electric Machinery Committee (EMC). One of the newer working groups in the EMC also involved a merging of IEEE Std 115™ and IEEE Std 115A™, which related to test procedures for synchronous machines. This second WG project was completed in 1995 and this new standard consists of two portions. The first portion was subtitled “Acceptance and Performance Testing.” The second portion included a lengthy example consisting of the many steps followed in parameter determination for machine stability analysis. Both sudden short-circuit test data and test data from frequency response measurements were used in Part II.

The Synchronous Machinery Subcommittee recommended, with the publishing, especially of Part II of IEEE Std 115, in 1995, that a review of the related IEEE Std 1110 was very much in order.

In 1996 a new PAR was approved. Its form and outline are about the same as the 1991 document, but many clauses have been completely rewritten. The older (1991) document had the title “IEEE Guide for Synchronous Generator Modeling Practices in Stability Analysis.” The 2002 guide has the title “IEEE Guide for Synchronous Generator Modeling Practices and Applications in Power System Stability Analyses.”

It should be noted that one of the Joint Working Group members, Charles Concordia, had made an interesting prediction in the discussion of his 1960 paper on solid cylindrical rotor synchronous machines. This prediction stated that “by a more detailed consideration of actual rotor configurations, equations amenable to attack by frequency response techniques may be obtained.” This prediction has been verified in the two standards produced, namely IEEE Std 1110-2019 and IEEE Std 115-2019.

Charles Concordia was a key member of the Working Group, which produced the 1991 IEEE Std 1110 document. He also was involved prior to 1991 in suggested improvements in the “first” guide after it was published. Therefore, the current Working Group wishes to highlight his many contributions by dedicating this latest guide in his honor.

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IEEE Guide for Synchronous Generator Modeling Practices and Parameter Verification with Applications in Power System Stability Analyses

1. Overview ~~and objectives~~

1.1 Introduction

The basic techniques for studying the stability of interconnections of synchronous generators stem from the late nineteenth century and the early years of last century. The key concept of transforming stator variables into quantities rotating in synchronism with the rotor was developed by Blondel [[B2](#) [B1](#)],¹ Park (([B65](#)], [[B66](#) [B62](#)], [[B63](#)]), and others [[B9](#)] and remains the basis for synchronous machine analysis to this day.

To some extent, the techniques developed in those early years remained relatively untouched until the last three or four decades of the twentieth century. Although it was in theory possible to develop relatively complex generator models prior to this time, limited computational capability meant that such models were impractical for use in large-scale stability studies. However, with the advent of the digital computer, the picture changed significantly and computational capability continues to grow at a rapid rate. In addition, the growing complexity of electric power systems combined with the advent of more sophisticated generator and system controls, such as high-speed, solid-state excitation systems, greatly increased the demands on stability programs.

¹ The numbers in brackets correspond to those of the bibliography in Annex A.

In response, the latter part of the twentieth century saw an increased interest in synchronous generator modeling. This interest took many forms. For example, initial investigations attempted to correlate the performance of synchronous machine models with the measured performance of specific machines following transient disturbances on a power system (Chorlton and Shackshaft [B7 B6], Dandeno et al. [B13 B12]). Other investigators developed alternate techniques for determining machine parameters (Manchur et al. [B58 B57]). The objective of this and related work, which continues to this day, is to improve the existing capability to analyze and predict the dynamic behavior of electric power systems. This work becomes increasingly important with the ever-increasing demands being placed on power systems as they continue to grow in size and complexity and as deregulation significantly modifies the way these systems are operated and controlled.

The objective of this guide is to summarize available practices in synchronous machine models used in power system stability studies. As will be discussed, computational capability has increased to the point that it is possible to model generators (along with their excitation systems and other controls) with a significant level of detail, subject to the availability of the appropriate data from which to form the model.

1.2 Scope

This guide contains instructions for modeling synchronous machines in direct-and quadrature-axis equivalent circuits, along with the basic transient and subtransient reactance/time-constants model in view of stability studies. It discusses assumptions made in using various models and presents the fundamental equations and concepts involved in generator/system interfacing. The manner in which generator saturation is treated in network studies, both in the initialization process as well as during large or small disturbance stability analysis procedures is addressed. Approaches for improving the accuracy of field and excitation system quantities are identified and conversion factors are given for transferring field parameters from one base to another for correct generator/excitation system interface modeling. Parameter determination and translation from equivalent-circuits to operational impedances or vice-versa is covered. Data analysis methods for obtaining these parameters using measurements from field tests or finite-element computations are explained and illustrated with a wide range of generator and test data. However, this guide refers to applicable standards (such as IEEE Std 115) or contract specification for scheduling such tests. Also, this guide does not attempt to recommend specific procedures for machine representation in non-standard or atypical cases such as generator tripping and overspeed operation or models for harmonics or unbalanced operation.

1.3 Purpose

The modeling of synchronous machines for stability studies and analyses is subject to continuing review and possible improvements. The guide addresses both parameter identification for static and dynamic stability analyses while accounting for generator saturation. Emphasis is placed on discussing various aspects of synchronous generator/power system interactions in steady and dynamic operation modes.

1.4 Specialized problems in stability not discussed in this guide

This guide does not attempt to recommend specific procedures for machine representation in non-standard or atypical cases such as generator tripping and overspeed operation or models for harmonics or unbalanced operation. Similarly, modeling suggestions for subsynchronous resonance (SSR) studies are documented in Dandeno and Iravani [B10 B9] and IEEE [B35]. Recent investigations have shown that models developed from small-signal analyses, based on standstill-frequency-response data, are also adequate for SSR investigations. This applies to situations where third-order models have been found to be necessary to cover the frequency spectrum from 15 Hz to 50 Hz (IEEE [B35]).

1.5 Overview of the guide

Clause 3 discusses the various categories of stability studies [that](#) ~~which~~ are commonly performed during power system studies and the corresponding synchronous generator modeling requirements. Clause 4 then reviews some of the basic principles of synchronous generator modeling and discusses the range of models which can be used in the study of synchronous generator dynamic behavior as is summarized in Table 1 of Clause 4. This clause emphasizes the point that a model is uniquely determined only when both its structure (e.g., the number of assumed conducting paths in the rotor) and its parameters (as obtained from test data or analytical techniques) are specified. Clause 5 next presents guidelines as to how the various models discussed in Clause 4 can be applied to the various types of stability studies [that](#) ~~which~~ are discussed in Clause 3.

Clause 6 then discusses the effects of saturation on the performance of synchronous machines and various techniques which have been developed for incorporating these effects in synchronous generator models. Included in Annex D is the development of direct-and quadrature-axis saturation functions. Because saturation is an inherently nonlinear phenomenon while the commonly-used generator models are linear, the techniques used for incorporating saturation effects into generator models are somewhat ad hoc. This is an area in which further investigation is clearly required.

Finally, Clause 7 discusses the techniques [that](#) ~~which~~ have been developed for obtaining parameters for synchronous generator models. Such parameters are found either by test, as described in IEEE Std 115™-1995, or from calculations by manufacturers.² The issue of the translation of parameters from the inductances and resistances of d-and q-axis models to transient and [subtransient](#) ~~estrangement~~ reactances and time constants or to transfer functions form is also discussed.

1.6 Word usage

[The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted \(shall equals is required to\).](#)^{3,4}

[The word *should* indicates that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required \(should equals is recommended that\).](#)

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2. Normative references

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

² Information on references can be found in Clause 2.

³ [The use of the word *must* is deprecated and shall not be used when stating mandatory requirements, *must* is used only to describe unavoidable situations.](#)

⁴ [The use of *will* is deprecated and shall not be used when stating mandatory requirements, *will* is only used in statements of fact.](#)

~~This guide shall be used in conjunction with the following publication. If the following publication is superseded by an approved revision, the revision shall apply.~~

IEEE Std 115TM, ~~1995~~, IEEE Guide: Test Procedures for Synchronous Machines, Part I—Acceptance and Performance Testing, and Part II—Test Procedures and Parameter Determination for Dynamic Analysis. ^{5,6} ~~3,4~~

IEEE Std C50.12TM, IEEE Standard for Salient Pole 50 Hz and 60 Hz Synchronous Generators and Generators/Motors for Hydraulic Turbine Applications Rated 5 MVA and Above.

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

3. Classification of power system stability and synchronous machine modeling requirements

3.1 General background

Traditionally, power system stability studies focused on the system's ability to maintain synchronous operation following a severe disturbance. However, with continuing growth in interconnections, more use of new technologies, and the increased need to operate power systems in highly stressed conditions, other forms of stability have emerged as greater sources of concern than in the past.

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Clearly, instability in a power system may be manifested in many different ways depending on the system configuration, operating mode, and form of disturbance. Analysis of stability problems, including identifying essential factors that contribute to instability and devising methods of improving stable operation, is greatly facilitated by classification into appropriate categories.

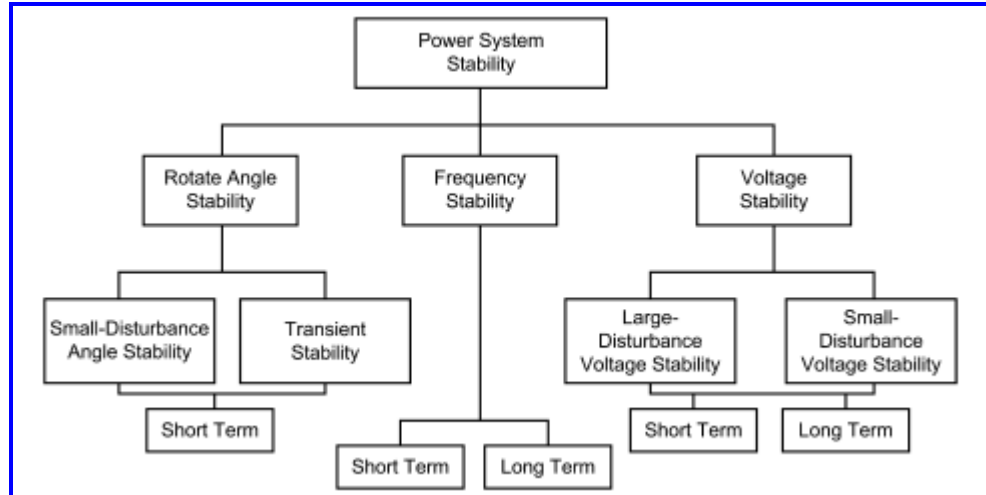
[The problem of defining and classifying power system stability is an old one, and there have been several previous reports on the subject by CIGRÉ and IEEE Task Forces. One effort from a Joint CIGRÉ/IEEE Task Force \[B34\] documents many of these past efforts and offers a thorough review of definitions and the classification of power system stability problems.](#)

[The classification of stability problems is usually](#) ~~These are~~ based on the following considerations:

- The physical nature of the resulting instability, i.e., the main system parameters in which instability can be observed;
- The size of disturbance considered, impacting on the applicable method of analysis;
- [The devices, processes, and the time span that must be taken into consideration in order to assess stability.](#)

Based on the physical nature of the phenomena, power system stability may be classified into three main categories: (a) rotor-angle stability, (b) voltage stability, and (c) frequency stability ([Joint CIGRÉ/IEEE TF ~~Kundur and Morrison~~ \[B34 B51\]](#), Kundur [B54]).

[The classification shown in Figure 1, to a great extent, is related to the tools, methods, and models that are necessary to properly investigate these phenomena.](#)



(New)

Figure 1—Classification of power system stability [B34]

3.2 Rotor-angle stability

Rotor-angle stability (or **angle stability**) is concerned with the ability of interconnected synchronous machines of a power system to remain in synchronism under normal operating conditions and after being subjected to a disturbance. A fundamental factor in this aspect of stability is the manner in which the torque or power outputs of the synchronous machines vary as their rotors oscillate. The mechanism by which synchronous machines maintain synchronism with one another is through the development of restoring torques whenever there are forces tending to accelerate or decelerate the machines with respect to each other.

The change in electromagnetic torque of a synchronous machine following a perturbation can be resolved into two components: (i) a synchronizing torque component, in phase with the rotor-angle deviation, and (ii) a damping torque component, in phase with the speed deviation. Lack of sufficient synchronizing torque results in aperiodic instability, whereas lack of damping torque results in oscillatory instability. Loss of synchronism can occur between one machine and the rest of the system, or between groups of machines, possibly with synchronism maintained within each group after separating from each other.

For convenience in analysis and for gaining insight into the nature of stability problems, it is useful to characterize angle stability into the following subcategories based on the size of disturbance considered:

- a) **Large-disturbance angle stability**, commonly referred to as **transient stability**, is concerned with the ability of the power system to maintain synchronism when subjected to a severe disturbance, such as a [short circuit](#) ~~transient fault~~ on a transmission circuit, ~~or loss of a large generator~~. The resulting system response involves large excursions of generator rotor angles and is influenced by the nonlinear power-angle relationship ~~of synchronous machines~~. Usually, the disturbance alters the system such that the post-disturbance conditions will be different from those prior to the disturbance. Instability is [usually](#) in the form of an aperiodic drift of the rotor angle due to insufficient synchronizing torque, [but could also be the result of lack of damping torque in the post-fault system configuration](#). In large power systems, transient instability may not always occur as first swing instability associated with a single mode; it could be the result of increased peak deviation caused by superposition of [several modes of oscillation](#) causing large excursions of rotor angle beyond the first swing. The period of interest in transient stability is usually limited to about [3s](#) ~~3~~ to 5 [s](#) ~~seconds~~ following the disturbance, [but may extend to 10s to 20 s for very large systems with dominant low-frequency inter-area oscillation modes](#).
- b) **Small-disturbance [\(or small-signal\)](#) angle stability** is concerned with the ability of the power system to maintain synchronism under small disturbances such as those that continually occur in the normal operation of the power system. The disturbances are considered to be sufficiently small that linearization of system equations [around an equilibrium point](#) is permissible for purposes of analysis. Small-signal analysis using linear techniques provides valuable information about the inherent dynamic characteristics of the power system. Instability that may result can be of two forms: (i) increase in rotor angle through a non-oscillatory or aperiodic mode due to lack of synchronizing torque, or (ii) rotor oscillations of increasing amplitude due to lack of sufficient damping torque.

In present-day power systems, the small-disturbance angle stability problem is usually one of insufficient damping of oscillations. [The aperiodic instability problem, that is sometimes called steady-state stability, has been largely eliminated by use of continuously acting generator voltage regulators \(AVR\) controlling the excitation systems of synchronous machines. The aperiodic instability problem might still be a concern for operation of large synchronous generators on manual excitation control.](#) The stability of the following types of oscillations is of concern:

- Local-plant-mode oscillations, associated with units in a power plant swinging against the rest of the power system.
- Inter-area-mode oscillations, associated with the swinging of a group of generators in one area against a group of generators in another area.
- Torsional-mode oscillations, associated with the turbine-generator shaft system rotational components of individual generators.

[The case of multigenerator plant \(such as a large hydropower plant with 3 units or 20 units\) is special because while all generators oscillate coherently in the plant mode and in any inter-area modes, there are intra-plant electromechanical modes in which the generators in the same plant oscillate against each other. The frequencies of the intra-plant modes are generally higher than that of the coherent mode, and the intra-plant modes may be destabilized by a power system stabilizer designed to stabilize the plant mode \[B29\].](#)

3.3 Voltage stability

Voltage stability is concerned with the ability of a power system to maintain steady acceptable voltages at all buses in the system under normal operating conditions and [restoring and maintaining normal voltages](#) after being subjected to a disturbance. Instability that may result occurs in the form of a progressive fall or rise of voltage of some buses with only moderate excursions of generator angles; [or from an inability to restore normal voltages after a fault, usually associated with induction motor loads.](#) The main factor causing voltage instability is the inability of the power system to maintain a proper balance of reactive power throughout the system. This is significantly influenced by the characteristics of system loads and voltage control devices, including generators and their excitation system.

As in the case of angle stability, it is useful to classify voltage stability into the following two subcategories based on the size of disturbance considered:

- a) **Large-disturbance voltage stability** is concerned with a system's ability to [recover and](#) maintain steady voltages following severe disturbances. The evaluation of stability usually requires the examination of the dynamic performance of the power system over a period of time sufficient to capture the interactions of such devices as [induction motors](#), under-load transformer tap changers and generator field-current limiters. The study period may extend from a few seconds to several minutes.
- b) **Small-disturbance voltage stability** is concerned with a system's ability to maintain steady voltages following small perturbations, such as incremental changes in load. Small disturbance analysis using linear techniques gives valuable voltage-stability related information from a system-wide perspective and clearly identifies areas that have potential problems.

3.4 Frequency stability

Frequency stability is concerned with the ability of a power system to maintain the frequency within a nominal range following a severe system upset, which may or may not result in the system being divided into subsystems (electrical islands). It depends on the ability to restore balance between system generation and load with minimum loss of load.

Analysis of frequency stability is carried out using time-domain simulations that include all appropriate fast and slow dynamics sufficient for modeling the control and protective systems that respond to large frequency excursions as well as the accompanying large shifts in voltages and other system variables. In the case of large interconnected power systems, simulations required may include severe disturbances beyond the normal design criteria, which result in cascading and splitting of the power system into a number of separate islands with generators in each island remaining in synchronism. Stability in this case is a question of whether or not each island will reach an acceptable state of equilibrium with minimum loss of load.

Over the course of a disturbance that results in frequency instability, the characteristic times of the processes and devices that are activated by the large shifts in frequency and other system variables will range from a few seconds, corresponding to the responses of devices such as generator controls, to several minutes, corresponding to the responses of devices such as prime mover energy supply systems, [automatic generation control \(AGC\)](#), and load voltage regulators.

3.5 Modeling requirements for synchronous machines

Synchronous machines may be modeled in as much detail as possible in the study of most categories of power system stability. This includes appropriate representation (subject to the availability of data) of the dynamics of the field circuit, excitation system, and rotor damper circuits (Kundur [B54]). With today's computing tools, there is no pressing need to simplify models for specific types of studies. In addition, experience has shown that critical problems may be masked by the use of simplified models [that](#) ~~which~~ are sometimes perceived to be acceptable for a particular type of study.

For the analysis of many voltage-stability and frequency-stability problems using time-domain simulations, the study periods are in the range of tens of seconds to several minutes. To improve computational efficiency of such long-term dynamic simulations, instead of simplifying the models by neglecting fast dynamics, it [might be](#) ~~is~~ better to use singular perturbation techniques to separate fast and slow dynamics and appropriately approximate the fast dynamics (Xu et al. [[B91](#) ~~B82~~]).

Notwithstanding the above, it is important to recognize the following special requirements in representing synchronous machines for different categories of stability studies:

- a) For large-disturbance rotor-angle stability analysis, particularly for generators with high-initial-response excitation systems [\(\[B38\]\)](#), magnetic saturation effects should be accurately represented at flux levels corresponding to normal operation all the way up to the highest values experienced with the excitation at its ceiling. With discontinuous excitation controls, such as those described in Lee and Kundur [\[B54 B56\]](#) and Taylor et al. [\[B81 B74\]](#), the excitation remains at its ceiling for about two seconds leading to very high flux levels. ~~If saturation effects are understated, the results of analysis would be overly optimistic.~~ It is particularly important to represent the dynamics of the field circuit, as it has a significant influence on the effectiveness of excitation system in enhancing large-disturbance rotor-angle stability. If saturation effects are understated, the results of analysis would be overly optimistic.
- b) For small-disturbance rotor-angle stability analysis, accurate representation of the field circuit as well as the rotor damper circuits is important.
- c) For voltage stability studies, the voltage control and reactive power supply capabilities of generators are of prime importance. During conditions of low system voltages, the reactive power demand on generators may exceed their field-current limits. In such situations, usually the generator field currents are automatically limited by overexcitation limiters, further aggravating the situation and possibly leading to voltage instability (Kundur [B54]). Therefore, the generator models should be capable of accurately determining the transient field currents and accounting for the actions of field-current limiters.

- d) Frequency stability problems are generally associated with inadequacies in equipment response and poor coordination of control and protection equipment. Stability is determined by the overall response of the system as evidenced by its mean frequency, rather than relative motions of machines. The generator models used should be capable of accurately representing, under conditions of large variations in voltage and frequency, the responses of control and protective devices, such as the voltage regulator, power system stabilizer, V/Hz limiter and protection, and over-excitation and under-excitation limiters. But the proper representation of the turbine/speed governor control is arguably the most important aspect of the dynamic modeling of generator, for the analysis of frequency stability problems. Then, the correct representation of the acceleration equations (using torque instead of simplifying it by using power) and the correct representation of the speed effect on induced voltages in the generator model are very important.

4. Types of models available

4.1 Introduction

Synchronous generators are most commonly constructed with a three-phase armature winding on the stator (although other polyphase arrangements are also found) and an excitation winding (known as the field winding) on the rotor [B57]. In addition, synchronous generator rotors include other conducting paths in which currents can be induced during a transient. In some cases, these conducting paths are intentionally included by the designer; e.g., pole-face damper windings. In other cases, they are inherent to the machine design, such as in the case of the currents which can be induced in the rotor body of a solid-rotor turbogenerator.

Early on in the process of developing techniques for the analysis of synchronous machines, it was recognized that analyses can be greatly simplified if they are performed in a reference frame rotating with the rotor. For such analyses, the armature currents and voltages are transformed into two sets of orthogonal variables, one set aligned with the magnetic axis of the field winding, known as the rotor **direct axis (d-axis)**, and a second set aligned along the rotor at a position 90 electrical degrees from the field-winding magnetic axis. This second axis is known as the rotor **quadrature axis (q-axis)**.

Much of the simplification associated with such an approach stems from ~~three~~ two key features of this analysis:

- 1) Under steady-state operating conditions, all of the currents and fluxes, including both those of rotor windings and the transformed armature windings, have constant (dc) values.
- 2) By choosing the two axes 90 electrical degrees apart, fluxes produced by currents in the windings on one axis do not produce flux linkages in the windings on the other axis. Thus, these sets of windings are orthogonal. This greatly simplifies the flux-current relationship of the model and gives rise to a model structure consisting of two independent networks, one for the direct axis and one for the quadrature axis.

3) Saturation must be neglected to achieve a decomposition of the fluxes into the d-and q-axes as described in item 2).

To illustrate the use of this transformation (often referred to as the d-q-0 or Park transformation), consider a machine consisting only of a three-phase armature winding and a cylindrical rotor with only a field winding. Using generator notation, in which the reference direction for terminal current is chosen to be out of the machine terminals, the flux-current relations for this machine can be written in the form:

$$\begin{bmatrix} \psi_a \\ \psi_b \\ \psi_c \\ \psi_{fd} \end{bmatrix} = \begin{bmatrix} L_a & L_{ab} & L_{ab} & L_m \cos \theta \\ L_{ab} & L_a & L_{ab} & L_m \cos \left(\theta - \frac{2\pi}{3} \right) \\ L_{ab} & L_{ab} & L_a & L_m \cos \left(\theta + \frac{2\pi}{3} \right) \\ L_m \cos \theta & L_m \cos \left(\theta - \frac{2\pi}{3} \right) & L_m \cos \left(\theta + \frac{2\pi}{3} \right) & L_f \end{bmatrix} \begin{bmatrix} -i_a \\ -i_b \\ -i_c \\ i_{fd} \end{bmatrix} \quad (1)$$

and the voltage equations can be written in the form:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \\ e_{fd} \end{bmatrix} = \begin{bmatrix} R_a & 0 & 0 & 0 \\ 0 & R_a & 0 & 0 \\ 0 & 0 & R_a & 0 \\ 0 & 0 & 0 & R_{fd} \end{bmatrix} \begin{bmatrix} -i_a \\ -i_b \\ -i_c \\ i_{fd} \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \psi_a \\ \psi_b \\ \psi_c \\ \psi_{fd} \end{bmatrix} \quad (2)$$

In these equations:

ψ is the winding flux linkage

i is the winding current

v is the armature-winding voltage

e_{fd} is the field voltage

L_a is the armature-phase self inductance

L_{ab} is the armature phase-phase mutual inductance

L_m is the peak armature-phase to field-winding mutual inductance

L_f is the field-winding self inductance

R_a is the armature phase resistance

R_{fd} is the field-winding resistance

θ is the electrical angle between the magnetic axis of phase a and the magnetic axis of the field winding $\left[\left(N_p/2 \right) \right]$ times the mechanical angle between these axes $\frac{1}{2}$ where N_p is the number of magnetic poles.

Subscripts a, b, c , and fd refer to the three armature phases and the field winding respectively.

The time dependence of the inductance matrix of Equation (1) can be clearly seen when one substitutes the fact that under steady-state operating conditions the rotor angle θ has the time dependence,

$$\theta = \left(\frac{N_p}{2} \right) \omega_m t = \omega t \quad (3)$$

where

ω_m is the rotor mechanical angular velocity

ω is the rotor electrical angular velocity

With S representing a variable to be transformed, the d-q-0 transformation can be written as⁵

$$\begin{bmatrix} S_d \\ S_q \\ S_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos \theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ -\sin \theta & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix} \quad (4)$$

(New)

~~$$\begin{bmatrix} S_d \\ S_q \\ S_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos \theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ -\sin \theta & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix} \quad (4)$$~~

(Deleted)

$$\begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix} = \begin{bmatrix} \cos \theta & -\sin \theta & 1 \\ \cos\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta - \frac{2\pi}{3}\right) & 1 \\ \cos\left(\theta + \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) & 1 \end{bmatrix} \begin{bmatrix} S_d \\ S_q \\ S_0 \end{bmatrix} \quad (5)$$

(New)

⁵The transformation as presented here is one of a number of alternative forms of the dq transformation. The form presented here has the advantage of being unitary (i.e., the transformation matrix and its inverse matrix are the transpose of each other) and it is also power invariant in that the total power is simply the sum of the ui products, $p = v_d i_d + v_q i_q$. This transformation also results in a symmetrical inductance matrix of Equation (7).

~~$$\begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta & -\sin\theta & \frac{1}{\sqrt{2}} \\ \cos\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta - \frac{2\pi}{3}\right) & \frac{1}{\sqrt{2}} \\ \cos\left(\theta + \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} S_d \\ S_q \\ S_0 \end{bmatrix} \quad (5)$$~~

(Deleted)

Applying this transformation to the flux-current relationship of Equation (1) gives

$$\begin{bmatrix} \Psi_d \\ \Psi_q \\ \Psi_{fd} \\ \Psi_0 \end{bmatrix} = \begin{bmatrix} L_a - L_{ab} & 0 & L_m & 0 \\ 0 & L_a - L_{ab} & 0 & 0 \\ \frac{3}{2}L_m & 0 & L_f & 0 \\ 0 & 0 & 0 & L_a + 2L_{ab} \end{bmatrix} \begin{bmatrix} -i_d \\ -i_q \\ i_{fd} \\ -i_0 \end{bmatrix} \quad (6)$$

(New)

~~$$\begin{bmatrix} \Psi_d \\ \Psi_q \\ \Psi_{fd} \\ \Psi_0 \end{bmatrix} = \begin{bmatrix} L_a - L_{ab} & 0 & \sqrt{\frac{3}{2}}L_m & 0 \\ 0 & L_a - L_{ab} & 0 & 0 \\ \sqrt{\frac{3}{2}}L_m & 0 & L_f & 0 \\ 0 & 0 & 0 & L_{al} \end{bmatrix} \begin{bmatrix} -i_d \\ -i_q \\ i_{fd} \\ -i_0 \end{bmatrix} \quad (6)$$~~

(Deleted)

which can be rewritten in the form

$$\begin{bmatrix} \Psi_d \\ \Psi_q \\ \Psi_{fd} \\ \Psi_0 \end{bmatrix} = \begin{bmatrix} L_d & 0 & L_{af} & 0 \\ 0 & L_q & 0 & 0 \\ \frac{3}{2}L_{af} & 0 & L_f & 0 \\ 0 & 0 & 0 & L_l \end{bmatrix} \begin{bmatrix} -i_d \\ -i_q \\ i_{fd} \\ -i_0 \end{bmatrix} \quad (7)$$

(New)

~~$$\begin{bmatrix} \Psi_d \\ \Psi_q \\ \Psi_{fd} \\ \Psi_0 \end{bmatrix} = \begin{bmatrix} L_d & 0 & L_{af} & 0 \\ 0 & L_q & 0 & 0 \\ L_{af} & 0 & L_f & 0 \\ 0 & 0 & 0 & L_{al} \end{bmatrix} \begin{bmatrix} -i_d \\ -i_q \\ i_{fd} \\ -i_0 \end{bmatrix} \quad (7)$$~~

(Deleted)

Where $L_l = L_a + 2L_{ab}$ is the armature-winding leakage inductance.

Similarly, the transformed voltage equations⁶ are

$$v_d = -i_d R_s - \left(\frac{N_f}{2} \right) \omega_m \psi_q + \frac{d\psi_d}{dt} \quad (8)$$

$$v_q = -i_q R_s + \left(\frac{N_f}{2} \right) \omega_m \psi_d + \frac{d\psi_q}{dt} \quad (9)$$

$$e_{fd} = -i_{fd} R_f + \frac{d\psi_{fd}}{dt} \quad (10)$$

$$v_0 = -i_0 R_s + \frac{d\psi_0}{dt} \quad (11)$$

⁶When written for per-unit quantities rather than actual quantities, these equations must be modified with the terms $\left(\frac{N_f}{2} \right) \omega_m$ replaced by $\left(\frac{\omega_m}{\omega_{m0}} \right)$ where ω_{m0} is the synchronous mechanical angular velocity of the rotor and $\frac{d}{dt}$ replaced by $\frac{1}{\omega_0} \frac{d}{dt}$ where ω_0 is the synchronous electrical frequency.

In these equations, subscripts d and q refer to the direct-and quadrature-axis equivalent armature windings respectively. Note the presence of an additional term, known as the **zero-sequence component** and indicated by the subscript 0 . This term is analogous to the zero-sequence term in symmetrical-component analyses. The zero-sequence component plays a relatively minor role in stability studies (in fact, no role at all in studies [that which](#) assume balanced operating conditions) and hence is neglected in most introductory discussions of stability analyses.

Note that, as is discussed above, there is no time dependence in the transformed inductance matrix. In addition, it can be clearly seen that the two axes are decoupled; currents in the direct axis produce only direct-axis fluxes and quadrature-axis currents produce only quadrature-axis fluxes.

In addition to the electrical equations given above, modeling of a synchronous machine requires an expression for the electromechanical torque to be used in the calculation of the machine mechanical dynamics. In terms of dq variables, the electromechanical torque can be calculated as:

$$T = \frac{3}{2} \left(\frac{N_f}{2} \right) (\psi_d i_q - \psi_q i_d) \quad (12)$$

[\(New\)](#)

$$T = \left(\frac{N}{2}\right)(\psi_d i_q - \psi_q i_d) \quad (12)$$

~~(Deleted)~~

This modeling concept forms the basis for all but the simplest of synchronous machine models. Hence, most of the models discussed in this clause, and indeed in this guide, are based upon direct- and quadrature-axis representations of the synchronous machine. These representations may take a number of forms: equivalent circuits, transfer functions, flux-current and voltage relationships, etc. Each of these forms is equivalent and will give the same results; the choice of the representation is typically based upon user preference.

Note that the direct- and quadrature-axis models presented here represent the direct and quadrature axes as being magnetically uncoupled [as can ~~be been~~ seen from the inductance matrices of Equation (6) and Equation (7)]. This representation is based upon the assumption that currents in one axis do not produce flux in the other axis (or produce any changes in the flux in the other axis). In reality, magnetic nonlinearities (magnetic saturation) will produce some degree of coupling between the axes. Although models that neglect this coupling have been found to be adequate for many studies, work is currently underway to develop techniques for incorporating the effects of magnetic nonlinearities in both steady-state and transient analyses.

Finally, as will be discussed later in this clause, in addition to the field winding, it is common to represent other current paths in the rotor, such as damper windings, both on the direct and quadrature axes. It will be shown that the equations presented here can readily be extended to include these additional windings.

4.2 Terminology

For the purposes of this document, it is helpful to specify the following terminology:

- **Model structure:** The basic form or configuration of a model constitutes its structure. This structure can be combined with model parameters whose values are initially unspecified. A model structure is characterized both by its form (e.g., lumped-parameter equivalent circuit, transfer function, differential-equation representation, etc.) as well as by its order (i.e., the number of equivalent rotor windings).
- **Model parameter values:** Synchronous-machine-model parameter values are derived from the characteristics of actual machine behavior. Although these characteristics may take many forms, the following two basic categories are common:
 - 1) Test data obtained from measurements, or
 - 2) Analytic “data” obtained from sophisticated analyses that simulate the detailed internal electromagnetic phenomena ~~that~~ ~~which~~ occur in the machine. A common technique for performing such analyses is that of the finite-element method. Using this technique, it is possible to solve for the details of the magnetic flux distributions within synchronous machines, including the nonlinear effects of magnetic saturation as well as the effects of eddy currents and rotor motion.
- **Model:** A complete synchronous-machine model consists of the combination of a model structure and a set of parameter values. Thus, for example, the same model structure in combination with parameter values obtained by different test methods and under different machine operating conditions could yield models which differ sufficiently that the machine behavior predicted by these models could be noticeably different. This is due to the fact that synchronous machines are inherently complex (nonlinear, high-order, etc.) and the conventional models are relatively simple (lumped-parameter, low-order, and linear, with adjustments made to approximate the effects of nonlinearities).

A given model can appear in various equivalent representations, e.g., in the form of an equivalent circuit or in the form of a transfer function, among others. These representations are identical, provided that the following conditions are met:

- The model parameters for each form of the model have been determined from the same set of tests or analytically derived data.
- The order of each representation is the same.
- Modifications to the element/parameter values to account for nonlinearities such as saturation effects are typically made after the nominal values for each of the model parameters have been determined. These saturation modifications must be made in such a fashion as to ensure ~~insure~~ that the behavior of the various forms of the model representation remain consistent.

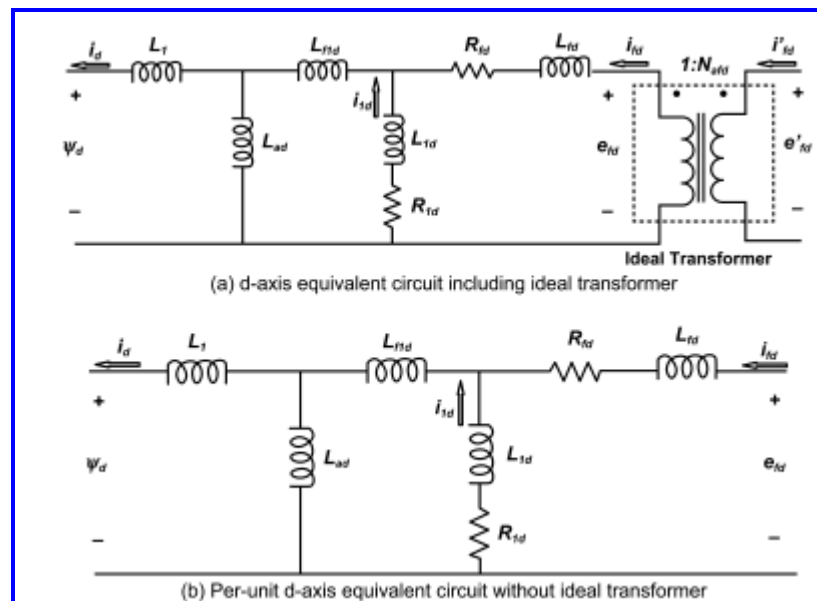
This clause discusses the various model structures that are commonly used to represent synchronous machines in stability analyses. Later clauses discuss the various methods that can be used to derive parameter values for these model structures.

4.3 Direct-axis model structures

The direct axis of a synchronous machine includes two terminal pairs (ports). These correspond to the direct-axis equivalent armature winding and the field winding. An accurate representation of the direct axis must fully account for the characteristics of both of these terminals.

The simplest direct-axis representation assumes that there are no other current paths in the direct axis other than the direct-axis armature winding and the field winding. However, it is well known that damper-winding currents (in the case of salient-pole machines) or rotor-body currents (in the case of solid-rotor machines) play a significant role in determining the characteristics of the direct axis. Hence, the most common direct-axis model includes an additional winding, known as the direct-axis damper winding.

Part (a) of Figure 2.1 shows the equivalent-circuit representation for the direct-axis model with a single damper winding. This equivalent circuit includes an ideal transformer, representing the fact that there are differing numbers of turns on the armature and field winding, just as is the case for the primary and secondary windings of a transformer. The variables e'_{fd} and i'_{fd} correspond to the actual values of field voltage and current that would be measured at the field-winding terminals. The variables e_{fd} and i_{fd} correspond to the values of field voltage and current reflected to the armature winding through the field to direct-axis armature winding turns ratio, N_{afd} .



(New)

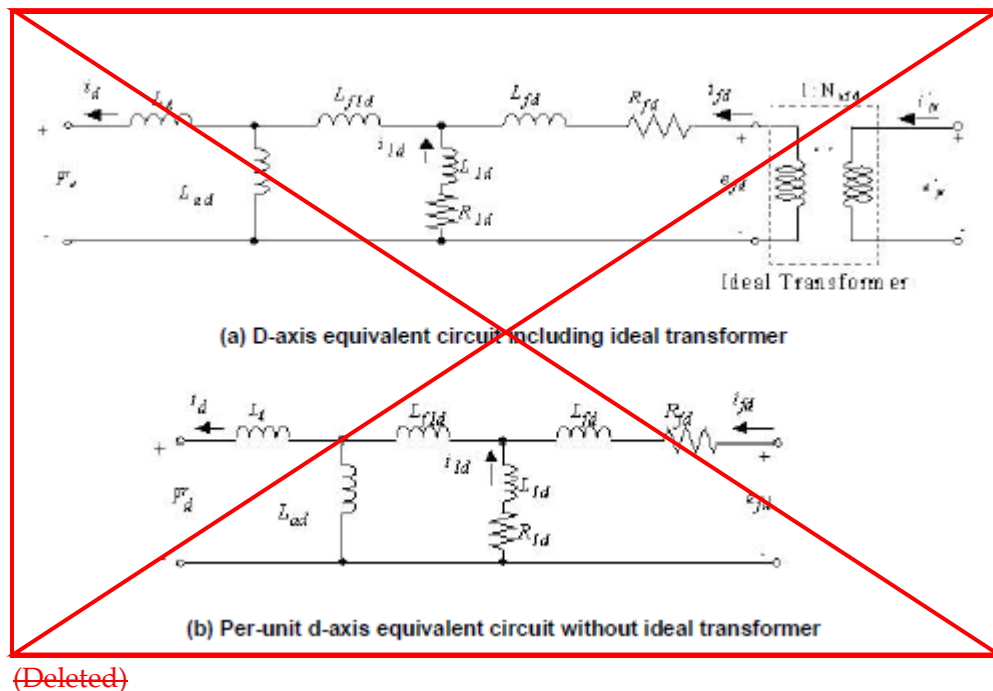


Figure 2—D-axis equivalent circuits including a single d-axis damper winding

It is common to represent synchronous machines using a per-unit representation, rather than actual units, in which case an ideal transformer may or not be required, depending upon the choice of the base for the per-unit system. Whether in actual units or in per unit, the ideal transformer is typically left out of the equivalent circuit, resulting in the equivalent circuit of part (b) of Figure 2.1 in which the field voltage and current are as reflected to the armature winding. Care must be taken to relate these reflected values to the actual values. The choice of the field-winding base values is equivalent to selecting a turns ratio in the equivalent circuit of part (a) of Figure 2.1.

The direct-axis equivalent circuit of part (b) of Figure 2.1 can be expressed in the alternate forms of a flux-current relationship or a transfer function. The flux-current relationship is

$$\begin{bmatrix} \psi_d \\ \psi_{fd} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} L_d & M_{ad} & M_{fd} \\ M_{ad} & L_{ad} & M_{fd} \\ M_{fd} & M_{fd} & L_{fd} \end{bmatrix} \begin{bmatrix} -i_d \\ i_d \\ i_{fd} \end{bmatrix} \quad (13)$$

(New)

$$\begin{bmatrix} \psi_d \\ \psi_{1d} \\ \psi_{fd} \end{bmatrix} = \begin{bmatrix} L_d & M_{d1d} & M_{fd} \\ M_{d1d} & L_{11d} & M_{f1d} \\ M_{fd} & M_{f1d} & L_{ffd} \end{bmatrix} \begin{bmatrix} -i_d \\ i_{1d} \\ i_{fd} \end{bmatrix} \quad (13)$$

~~(Deleted)~~

where

$$L_d = L_l + L_{ad} \quad (14)$$

$$L_{11d} = L_{1d} + L_{f1d} + L_{ad} \quad (15)$$

$$L_{fd} = L_{fd} + L_{f1d} + L_{ad} \quad (16)$$

$$M_{d1d} = L_{ad} \quad (17)$$

$$M_{fd} = L_{ad} \quad (18)$$

$$M_{f1d} = L_{f1d} + L_{ad} \quad (19)$$

~~(L_{mf1d} may also be used alternatively to M_{f1d})~~

~~(Deleted)~~

Note that the “differential-leakage” inductance L_{f1d} accounts for the fact that the mutual inductance between the field winding and the armature winding is not necessarily equal to that between the field winding and the damper winding: $L_{f1d} = M_{f1d} = L_{ad}$. For turbogenerators L_{f1d} is often found to be positive while for salient-pole machines, L_{f1d} is usually negative. This reflects the different physical couplings between the field circuit and the equivalent rotor body circuits in turbogenerators as compared to hydrogenerators.

The corresponding voltage equations will be those of Equation (8), Equation (9), and Equation (10), with the addition of an equation for the d-axis damper winding.

$$v_{1d} = 0 = i_{1d} R_{1d} + \frac{d\psi_{1d}}{dt} \quad (20)$$

Where R_{1d} represents the resistance of the d-axis damper winding. Note that the d-axis damper-winding voltage is equal to zero because the damper winding is an internally shorted winding with no external terminals.

Note also that the torque of Equation (12) remains unchanged independent of the number of damper windings included in the representation.

The transfer function representation for this model structure consists of a set of three Laplace transforms relating the terminal quantities of the d-axis two-port network. The choice of the three transforms ~~that~~ ~~which~~ define the properties of the network is not unique and many choices are possible. However, common practice has settled on the following three transfer functions:

Direct-axis operational inductance:

$$L_d(s) \equiv \frac{\psi_d}{i_d} \bigg|_{e'_{fd}=0} = L_d \left[\frac{(1+T_{1d}s)(1+T_{2d}s)}{(1+T_{3d}s)(1+T_{4d}s)} \right] \quad (21)$$

Field-to-armature-winding current transfer relation:

$$sG(s) \equiv \frac{i'_{fd}}{i_d} \bigg|_{e'_{fd}=0} = sG_0 \left[\frac{(1+T_{3d}s)}{(1+T_{3d}s)(1+T_{4d}s)} \right] \quad (22)$$

Field-winding input impedance:

$$Z_{fd}(s) \equiv -\frac{e'_{fd}}{i'_{fd}} \bigg|_{\psi_d=0} = N_{af}^2 R_{fd} \left[\frac{(1+T_{1d}s)(1+T_{2d}s)}{(1+T_{3d}s)} \right] \quad (23)$$

Note that the second and third of these transfer functions have been defined in terms of actual field quantities rather than referred quantities, although this choice is not required.

If field-terminal effects are not of interest (e.g. ~~for example~~, if the field winding is excited from a constant-voltage source) or if it is not possible to make measurements at the field-winding terminals, the direct axis can be considered to be a single-port network and it is not necessary to determine transfer functions ~~that which~~ relate the field winding to the armature. In such a case, the direct axis is simply described by the direct-axis operational inductance $L_d(s)$. This in fact was the basis for the traditional approach in which generator models were developed based upon armature-terminal open-and short-circuit tests. It must be understood that although direct-axis models developed under such conditions include a representation for the field-winding, there is no reason to expect that the model will properly represent the effects of changes in the field voltage or current on the machine behavior.

In the equivalent-circuit representation of part (a) of Figure 2-1 there are eight unknown parameters. On the other hand, in the transfer function representation of Equation (21), Equation (22), and Equation (23), there are nine measurable parameters; six time constants, and three coefficients. Thus, it would appear that by external measurements, one could determine all of the parameters of the equivalent circuit, including values for the turns ratio and the armature leakage inductance. However, this is not the case, and in fact only seven of the nine parameters can be determined independently.

This is similar to the issues ~~that which~~ arise when determining the parameters for the equivalent circuit of a transformer. It can be readily shown that, although the turns ratio is typically set equal to the nominal voltage ratio of the transformer (or perhaps the voltage ratio as measured under open circuit conditions), this choice is arbitrary and in fact, any ratio can be selected [B50]. The terminal characteristics of the transformer equivalent circuit, based upon any particular choice of turns ratio in combination with a self-consistent set of the remaining equivalent-circuit parameters, will be indistinguishable for those of any other choice of turns ratio. Similarly, it is not possible to make a terminal measurement ~~that which~~ will uniquely determine the proportion of leakage inductance to be allocated to the primary versus the secondary windings (Kirley [B50], Kamwa and Viarouge [B37]).

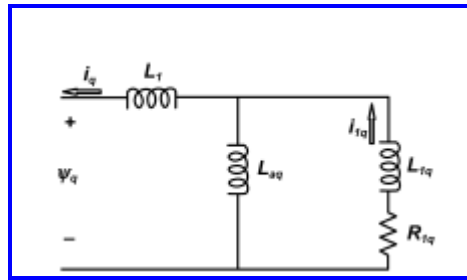
The implication of this fact is that, for the purposes of making an equivalent circuit, it is not possible to make a set of measurements at the generator terminals that will uniquely determine all of the values of the equivalent-circuit parameters. One is always free to pick two parameter values arbitrarily (one parameter plus the field-winding base current for the equivalent circuit of part (b) of Figure 2.4). In spite of these arbitrary choices, the resultant model will have uniquely defined terminal characteristics, an essential feature of a useful model.

It is common practice to choose the value of the armature leakage inductance L_l as the free parameter when making equivalent-circuit models for synchronous machines. It is possible to choose this value totally arbitrarily without affecting the validity of the resultant model. The parameter-determination procedure is such that the remaining model parameter values are calculated in a self-consistent fashion such that the terminal behavior of the model will be the same, independent of the choice of the value of the armature leakage inductance. However, it is common (and indeed recommended) practice to choose a value equal to or close to the manufacturer-supplied leakage-inductance value (which is often based upon an analysis of the flux distribution within the machine when it is operating under rated operating conditions).

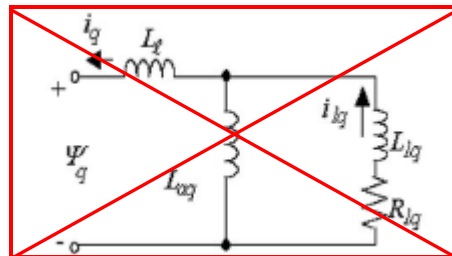
As is discussed in 4.2, the various representations presented here for the direct-axis model are equivalent and can be used interchangeably. This fact is reinforced in 7.4 which presents some of the equations ~~that which~~ translate model parameters from one form to another.

In addition to the d-axis model discussed above, other models with varying numbers of damper windings on the direct axis ~~have been are commonly~~ used by IEEE Std 115 Part II and others ([B3], [B1], [B52]). Table 1 shows ~~some of the most commonly used~~ models in equivalent-circuit form, recommended by an IEEE committee on generator modelling ([B36], Kundur and Dandeno [B52], Canay [B3]) ~~(along with commonly used quadrature-axis models)~~. The model-numbering scheme for the various models is of the form "MODEL N.M," where "N" is an integer ~~that which~~ represents the number of equivalent rotor windings on the direct axis and "M" is an integer ~~that which~~ represents the number of equivalent rotor windings on the quadrature axis. Thus Model 2.1 represents the direct axis of the rotor with two windings (the field winding and a direct-axis damper winding) and the quadrature axis with a single damper winding.

These models range from a “first-order” representation, which includes only the field winding on the rotor direct axis, to a “third-order” representation which includes the field winding and two equivalent damper-winding circuits. Their equivalent forms, flux-current and voltage relationships and transfer-function representations, are similar to those presented for the second-order, single-damper-winding model which has been discussed in some detail in this clause and hence they will not be presented here.



(New)



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Figure 3—Q-axis equivalent circuit including a single q-axis damper winding

4.4 Quadrature-axis model structures

Because there is no rotor winding with terminals on the quadrature axis, the quadrature axis need be represented only as a single-port network. In addition to the quadrature-axis armature winding, varying numbers of damper windings can be included in the quadrature-axis model. Table 1 shows some of the commonly used quadrature-axis model structures.

The flux-current relations for the quadrature-axis models are directly analogous to those presented earlier for the direct-axis. For example, for the model ~~that~~ ~~which~~ includes a single damper winding in the quadrature axis, the equivalent circuit is shown in Figure 3.2 and the flux-current relationship is given by

$$\begin{bmatrix} \psi_q \\ \psi_{lq} \end{bmatrix} = \begin{bmatrix} L_q & M_{qlq} \\ M_{qlq} & L_{lq} \end{bmatrix} \begin{bmatrix} -i_q \\ i_{lq} \end{bmatrix} \quad (24)$$

where

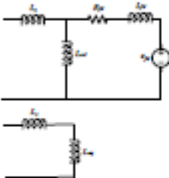
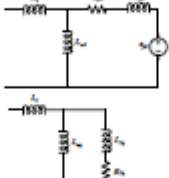
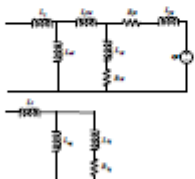
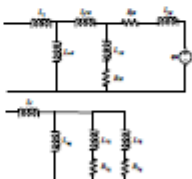
$$\begin{aligned} L_q &= L_{aq} + L_l \\ M_{qlq} &= L_{aq} \\ L_{lq} &= L_{aq} + L_{lq} \end{aligned}$$

(New)

and the voltage equations consist of Equation (9) in combination with an equation for the q-axis damper winding voltage:

$$v_{lq} = 0 = i_{lq} R_{lq} + \frac{d\psi_{lq}}{dt} \quad (25)$$

Table 1—Selection of generator models of varying degrees of complexity

Constant rotor flux linkages	Thevenin equivalent 			
Q-axis D-axis	No equivalent damper circuit	One equivalent damper circuit	Two equivalent damper circuit	Three equivalent damper circuit
Field circuit only	Model 1.0 	Model 1.1 	Not considered	Not considered
Field circuit + one equivalent damper circuit	Not considered	Model 2.1 	Model 2.2 	Model 2.3 
Field circuit + two equivalent damper circuits	Not considered	Not considered	Not considered	Model 3.3 

(New)

CONSTANT ROTOR FLUX LINKAGES	THEVENIN EQUIVALENT			
	Q-AXIS	D-AXIS		
	NO EQUIVALENT DAMPER CIRCUIT	ONE EQUIVALENT DAMPER CIRCUIT	TWO EQUIVALENT DAMPER CIRCUITS	THREE EQUIVALENT DAMPER CIRCUITS
	MODEL 1.0	MODEL 2.1	MODEL 2.2	MODEL 2.3
	NOT CONSIDERED	NOT CONSIDERED	NOT CONSIDERED	NOT CONSIDERED
	NOT CONSIDERED	NOT CONSIDERED	NOT CONSIDERED	NOT CONSIDERED

(Deleted)

Because the quadrature-axis network has but a single port, only a single transfer function is required.

Quadrature-axis operational inductance:

$$L_q(s) \equiv -\frac{\psi_q}{i_q} = L_q \left[\frac{(1+T_{iq}s)}{(1+T_{dq}s)} \right] \quad (26)$$

Note that this transfer function is first order in this case because there is but a single damper winding on the quadrature axis in this form of the model.

The representations for the various forms of the quadrature-axis models found in Table 1 are sufficiently similar that there is no need to present a detailed discussion here. They can be derived in analogous form, simply by changing the number of equivalent damper windings included in the representation.

4.5 Constant-voltage-behind-reactance model

The simplest model that can be used to represent a synchronous machine represents the machine by a constant voltage and a single series reactance. In the steady state, this representation includes the synchronous reactance and the “voltage behind synchronous reactance,” which is proportional to the field current supplied to the generator. In this representation, saliency is neglected and the synchronous reactance is set equal to the direct-axis synchronous reactance of the machine.

Similar models can be made for transient (and subtransient) conditions. The transient model consists of the transient reactance (saliency is again neglected) and the “voltage behind transient reactance,” which is assumed to remain constant for the duration of any transient under study. This reactance, along with open-circuit and short-circuit time constants, is typically found on manufacturer’s data sheets, derived from simple closed-form or finite-element analyses, or it can be obtained from tests (IEEE Std 115-1995). A transient model of this type is assumed to be valid for the initial time period of an electromechanical transient and can be used to roughly estimate the first-swing stability of a synchronous machine.

Since the voltages and currents of these models are not resolved into direct-and quadrature-axis components, this model structure is placed outside the matrix of Table 1. During a transient simulation, the magnitude of the model's internal voltage is kept constant, but the internal angle is changed corresponding to the rotational dynamics of the generator rotor. Advantages of this simple model are that the interfacing of the generator and network equations can be accomplished more quickly during transient simulations and that it requires relatively little data. Thus, this "constant-voltage-behind-transient-reactance" model has virtually replaced Model 1.0 of Table 1 in cases where simple generator models are accepted. However, unlike the case with Model 1.0, exciter action cannot be represented.

4.6 Field-winding per-unit systems

Figure 2-1 presents two forms of the direct-axis equivalent circuit. Part (a) of Figure 2-1 includes an ideal transformer which represents the turns ratio between the field winding and the direct-axis equivalent winding. In this figure, i'_{fd} and e'_{fd} represent the actual field current and voltage applied to the field winding while i_{fd} and e_{fd} represent the field current and voltage as referred to the direct axis through the field to direct-axis armature winding turns ratio, N_{afd} . Part (b) of Figure 2-1 shows the corresponding equivalent circuit in per unit. Consistent with general practice [\(Kamwa and Virouge \[B43\], and Kundur \[B53\]\)](#), proper selection of the per unit bases allow the elimination of the ideal transformer from the equivalent circuit, when it is expressed in per unit. ~~does not include an ideal transformer.~~ Thus, the per-unit field current and voltage in part (b) of Figure 2-1 are simply the referred values of the field current and voltage of part (a) of Figure 2-1 divided by the base current and voltage of the armature winding.

Based upon the equivalent circuit of part (b) of Figure 2 and the associated flux-current relationships in Equation (13) 4, it is clear that the per-unit field current corresponding to 1.0 per-unit direct-axis flux in steady-state open-circuit conditions (and hence 1.0 per-unit open-circuit terminal voltage) is equal to $1.0 / L_{ad}$ (or equivalently $1.0 / X_{ad}$ since L_{ad} and X_{ad} are equal in per unit). In other words, 1.0 per-unit field current will produce an open-circuit per-unit terminal voltage equal to X_{ad} in per unit. This choice of per-unit system for the field current is called ~~commonly referred to as the~~ reciprocal per-unit system (Rankin [B68 B65]). Note that for this choice of field-winding base current, the per-unit field voltage under normal operating conditions (equal to $i_{fd} \times R_{fd}$) is quite small since typically R_{fd} is quite small.

Other choices of base-field current and voltage are possible. The databases of many computer programs define base-field current as that required to produce rated open-circuit terminal voltage on the air-gap line. This is known as the non-reciprocal base. Similarly, ~~the non-reciprocal per unit system used in IEEE Std 115 and IEEE Std 421.5 defines excitation-systems analyses may define~~ base field ~~current (1.0 pu field current) voltage~~ as ~~the current that~~ required to produce rated terminal voltage ~~at the air gap line of the open circuit saturation curve of the machine~~. As is always the case when interconnecting components whose per-unit parameter values are determined on different bases, the user must be careful to perform the appropriate per-unit system conversion. Clearly, for example, if models of the form of part (b) of Figure 2 4 are to be used, all field-winding quantities must be expressed in terms of the reciprocal per-unit system. ~~Equivalently, circuit of part (b) of Figure 2 can also be converted from the reciprocal per unit base to the non-reciprocal per unit base.~~ ~~As long as the conversion of bases is done correctly, the results are identical (cf. Annex G).~~

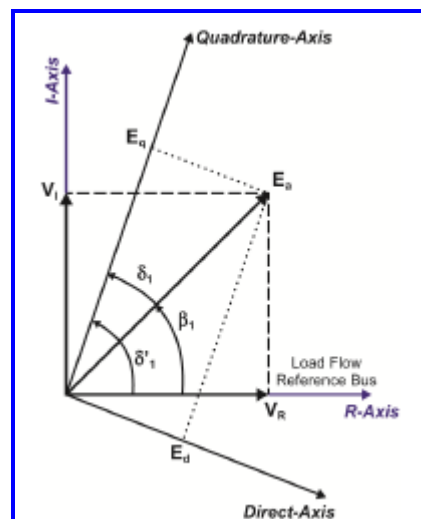
4.7 Generator to power system interfacing

Methods of interfacing the generator and network equations are not presented in this guide in any detail. Kundur and Dandeno [B52 B50] describe one possible approach that permits incorporation of any of the generator stability models discussed in this clause into network computations. Refer to Figure 4 3.

In a typical multi-machine power system stability analysis program, the network is referred to a synchronous reference frame common to the whole interconnected system. The initial angular position for this synchronous reference frame is arbitrary, but usually is tied to the initial (steady state) bus voltage angle of ~~for the network is selected, typically at~~ the so-called “swing” or reference bus in the power flow (steady state) solution. This synchronous frame of reference will maintain a constant angular speed/frequency independently of the simulated dynamic conditions in the system.

The network equations are solved by load-flow methods, assuming that the voltages at the machine buses are known. At any given time step, the fluxes within the machine and its rotor angle are assumed to remain constant and the machine terminal voltages must be found consistently with the internal conditions of the machine (as represented by one of the various models described in this clause). Often this process requires some iteration between the network equations and the machine representation. Once a consistent solution has been found, new values for the machine terminal currents and output power can be determined. These then can be used to solve the machine differential conditions for the rotor angle and fluxes for the next time step, and the process is repeated until the simulation is complete.

The above approach is called alternate solution (alternate network vs. dynamic equations solutions), in contrast with the simultaneous approach which solves the generator differential equations simultaneously in time with the network algebraic equations using an implicit integration methods [B76].



(New)