

IEEE Guide for Synchronous Generator Modeling Practices in Stability Analyses

Sponsor

**Power System Engineering and Electric Machinery Committees
of the
IEEE Power Engineering Society**

Approved March 21, 1991

IEEE Standards Board

Abstract: Categorizes three direct-axis and four quadrature-axis models, along with the basic transient reactance model. Discusses some of the assumptions made in using various models and presents the fundamental equations and concepts involved in generator/system interfacing. Covers, generally, 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 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: Synchronous generator stability models, modeling practices, saturation practices, stability data determination and application

The Institute of Electrical and Electronics Engineers, Inc.

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Foreword

(This Foreword is not a part of IEEE Std 1110-1991, IEEE Guide for Synchronous Generator Modeling Practices in Stability Analyses, but is included for information only.)

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 now reads as follows:

“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 working group has been responsible for two particular IEEE Committee Reports on the subject of machine modeling. The first was published in PA & S in 1980. In 1983, we presented 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 report (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 fifteen years. A Project Authorization Request was made through the Power System Engineering Committee, which was approved by the IEEE Standards Board on Dec. 12, 1985. This occurred at the December 12, 1985 meeting of NesCom, and the request was issued as PAR No. P1110.

In consulting this document, the reader is advised that it is intended to provide advice of a general nature. The primary aim of such a guide is to enable an engineer, who is relatively inexperienced in stability analyses, to perceive some of the important issues in this branch of power system engineering. As such, any reader, experienced or not, should be able to consult specific chapters of interest, without having to examine the entire contents.

The membership of the Joint Working Group has remained to a large extent unchanged since this the first draft of the guide was published in mid-1986. Significant contributions were also made by P. M. Anderson and F. P. DeMello, Working Group members for several years prior to 1986 and up to 1988. Joint Working Group representation from overseas was achieved in the past through Dr. G. Shackshaft. Dr. R. G. Harley joined our Group in 1989. Local associates of the Chairman who have helped substantially during the past four years are Dr. P. Kundur, G. J. Rogers, and J. R. Service, and Dr. A. Semlyen. D. C. Lee assisted in coordinating the drafting of figures. M.E. Coultres, who preceded Mr. Lee as a member, was also most helpful.

Since late 1986, the Chair wishes to acknowledge the assistance given through his association with the Electrical Engineering Department of the University of Toronto. In particular, he appreciates the encouragement and support given by Dr. A. S. Sedra, Dr. G. R. Slemon and Dr. J. D. Lavers of the Electrical Engineering Staff, especially in the logistics of the Chair's activities through more mundane, but essential support in mailing, office space, communications costs, etc.

Appreciation is also extended to Mrs. Linda Espeut of the Electrical Engineering Department and is especially noted for her speedy and accurate assembly of the final drafts of this guide.

The Chair of the working group would like to thank the organizations for which those individuals (who contributed to the development of this document) work.

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IEEE Guide for Synchronous Generator Modeling Practices in Stability Analyses

1. Introduction

1.1

This document has been written to assist the power system analyst in choosing appropriate generator models for power system stability studies.

More complex and advanced control concepts have recently been employed to solve a broad range of stability problems. General experience when conducting such studies has indicated that more detailed generator models are necessary, especially when applying excitation system controls for the enhancement of generator dynamic performance.

Discussions were held in 1984 and 1985 to formulate the guide outline, and to decide what it should contain. At that time, it was felt that computer codes, including generator/network interfacing equations, as well as many other stability program details, all be included. Space limitations, as well as computer program proprietary restrictions, forced the Joint Working Group to abandon this aspect of generator stability modeling.

Included in this guide, however, is a short section on one approach to generator/network interfacing. In addition, details of excitation system generator interfacing considerations are given, as noted below.

Many improvements, particularly in recent years, have occurred in generator modeling, and the objective of this guide is to set forth much of the current wisdom, and discuss the principal issues that ought to be considered in the application of more sophisticated models. These have now become available partly due to better digital simulation capabilities, and also because of enhanced data acquisition procedures.

In this document, the Working Group has also attempted to touch on some of the fundamental analytical steps in the treatment of generator stability representation, as proposed by investigators about fifty years ago. References to several pioneer authors are given in Chapters 2, 4, 5 and 7.

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 the models for harmonics or unbalanced operation. The particular modeling requirements for Subsynchronous Resonance studies have been examined by other IEEE-PES groups, and a second Benchmark Model for SSR Analyses was published in 1985. [3]¹

¹The numbers in brackets correspond with those listed in each Reference section in each Chapter.

Three direct-axis and four quadrature-axis models are categorized in Section 2.1 of Chapter 2, along with the basic “transient reactance” model familiar to many. Principal aspects of the various two-axis models relate to their structure and to the parameter values assigned to the elements of individual models. The general concordance between the more familiar generator reactances and time constants, and the various; direct and quadrature-axis model structures is pointed out in Section 2.1.

Section 2.1 also discusses some of the assumptions made in using various models, including the basic model. It also touches upon the fundamental equations and concepts involved in generator/system interfacing. In Section 2.2, a glossary of terms is given, along with the associated nomenclature used in all the following chapters.

Chapter 3 covers the various attributes of power system stability in a general way, with two basic approaches being recognized. The first is categorized under large-disturbance nonlinear analysis. The second approach considers small disturbances, where the corresponding dynamic equations are linearized.

In Chapter 4, applications of a range of generator models, documented in Chapter 2, are discussed. These applications are also treated in the context of the nature and complexity of large and small power system disturbances that are covered in Chapter 3.

Chapter 5 covers the manner in which generator saturation is treated in stability studies, both in the initialization process, as well as during large disturbance or small disturbance stability analysis procedures. Included in the appendixes of Chapter 5 is the development of saturation functions that are derived either from test data or by the methods of finite elements. The appendixes of Chapter 5 also compare different saturation algorithms for calculating values of excitation and internal power angle, depending upon generator terminal conditions.

After treatment of saturation, the question of parameter determination is thoroughly covered in Chapter 6. Such parameters are found either by test, as in IEEE Std 115-1983 (R1991) [1] or IEEE Std 115A-1987 [2] or are calculated by manufacturers. The detailed translation of data, from specific direct and quadrature axis model structures, with their associated element values, to transient and subtransient reactances and time constants, or to transfer function form is presented for commonly used models. Some of the assumptions made by manufacturers in producing calculated or design parameters are pointed out. In addition, the desirability of a common approach as a basis for such design calculations is recommended.

In Chapter 7, 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. The importance and method of correctly determining generator field resistance is stated. Also included are suggestions for the modeling of negative field currents and other field circuit discontinuities.

1.2 References

[1] IEEE Std 115-1983 (R1991), IEEE Test Procedures for Synchronous Machines (ANSI).²

[2] IEEE Std 115A-1987, IEEE Standard Procedures for Obtaining Synchronous Machine Parameters by Standstill Frequency Response Testing.

[3] IEEE Committee Report, Second Benchmark Model for Computer Simulation of Subsynchronous Resonance, *IEEE Transactions on PAS*, vol. PAS-104, No. 5, May 1985, pp. 1057–1066.

²IEEE publications are available from the Institute of Electrical and Electronics Engineers, Inc., Service Center, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

2. Model Classifications or Categories

2.1 Practical Models Available

The basic approach to generator stability modeling has been to consider an arrangement of three stator windings 120 electrical degrees apart, and a rotating (rotor) structure with an excitation or field winding and one or more equivalent rotor body winding(s). The magnetic axis of the field winding is defined as the direct axis, and an orthogonal axis, called the quadrature axis, is located 90 electrical degrees away. The equivalent rotor windings (or circuits) reflect induced current paths in a round rotor iron body, or in damper bars that are also used in round rotor turbo-generators, as well as in salient pole hydro-generators. One group of equivalent circuits is aligned in the direct axis, and the other group is aligned in the quadrature axis.

R. H. Park [7] developed this concept further by mathematically transforming the three-phase stator quantities (such as voltages, currents and flux linkages) into corresponding two-axis quantities. Park did this by visualizing two fictitious circuits—one in the direct axis aligned with the field axis, and the second in the quadrature axis. Under steady state conditions these fictitious circuits were assumed to rotate in synchronism with the field axis.

The effect of such transformations was to move all the machine time-varying inductance coefficients from the machine flux linkage equations. Time varying three-phase stator voltages, currents, and flux linkages were also transformed into time invariant direct and quadrature axis quantities under steady-state conditions. His treatment is general enough that deviations in speed of the field and rotor structure from steady state could be easily accounted for in the fictitious stator direct and quadrature axis flux linkage and voltage relationships.

The widespread use of direct axis and quadrature axis equations has developed from these concepts. These can also be visualized in terms of direct and quadrature axis equivalent circuits. Alternatively, operational inductance expressions in transfer function form can be used to express the direct and quadrature axis voltage and current relationships.

In considering the equivalent circuits, the model structure for both axes is the basic form or configuration of the model, and its order can be directly observed, ranging usually from first order to third order. Order can be simply defined as the number of rotor circuits in either the d or q axis; this concept is expanded upon in a subsequent paragraph in this section.

Model parameter values have historically been given in terms of reactances and time constants for the direct or quadrature axis. Alternatively, resistance and inductance values can be assigned to the elements of direct or quadrature axis equivalent circuit.

Some of the above points are expanded upon in Section 6.5, where the philosophy behind these modeling approaches is presented. As discussed above, the basic modeling approach usually considered for synchronous machine electrical dynamics is derived from Park's transformations, with corresponding relationships between flux linkages, currents and inductances. This approach is further characterized by a prior knowledge of the stator leakage inductance, and the stator to rotor mutual inductance. To such a fundamental model structure, or configuration in either axis, one may explicitly connect an arbitrary number of rotor circuits (including the field winding in the direct axis). For power system stability studies, based on experience, judgement and intuition, and often a lack of data, it has been found sufficient to limit the number of rotor circuits to a small number (usually three as a maximum).

Consider the matrix shown on Table 1, which can be conveniently chosen for describing model structures ranging from first order to third order in each axis, depending upon the number of inductance/resistance series combinations representing the field and direct axis equivalent rotor circuits, or the number representing quadrature axis equivalent circuits. There are 12 possible combinations of direct and quadrature axis representations, plus one “constant rotor flux linkage” model. The most complex (Model 3.3) has a field winding and two equivalent direct axis rotor iron (damper) windings. The quadrature axis structure of Model 3.3 has three equivalent solid rotor iron circuits, or windings. Some combinations of d and q axis winding configurations are not considered in Table 1, and equivalent circuit structures are not drawn or discussed. Based on experience, as well as on published material [3,4,5,8] it appears there are seven model structures that could be serious candidates for inclusion in large system stability simulations. Six of these model

structures are drawn in Table 1, and the seventh is the constant rotor flux linkage (or alternatively constant voltage behind transient reactance) model.

In Table 1, the field winding in each of the six model structures is identified by the initials *fd*; the direct axis rotor iron body equivalent circuits are identified as *1d*, *2d* according to the number of such circuits. In the quadrature axis, the equivalent circuits are identified as *1q*, *2q* and *3q*, depending on the order of the quadrature axis model structure.

Another approach to any of the models would be to consider the roots of the characteristic equation that defines the linearized model response on open circuit. The roots, for example, in the direct axis for Model 2.2 are usually classified as the inverse of T'_{do} (the direct axis transient open circuit time constant) and the inverse of T''_d (the direct axis subtransient open circuit time constant). If Model 2.2 were used to simulate a terminal fault from an open circuit, the stator currents would be inversely proportional to X''_{do} (for the subtransient period) and inversely proportional to X'_d (for the transient period). Higher order models than 2.2 such as Model 3.3 would possess 3 time constants and 3 values of reactance, and Model 1.1 would only have a single time constant and reactance. Time constant expressions are discussed in Section 5.2, principally in the context of whether they are field or rotor properties.

In discussing the attributes of particular models, a decision was made by the Working Group to limit the complexity of various models to a third order in both axes, Model 3.3. This decision is based on our experience and that of others [3], [5]. This model, which includes one differential leakage inductance branch, is the most complex that appears to be required for large size stability programs. There is a fundamental basis [3], [4] for considering this differential leakage, and additional comments on this requirement are offered in Section 4.1.4 of Chapter Auto. L_{f1d} , as depicted in Fig 1 for example, is a leakage inductance proportional to fluxes that link the field winding and the two direct axis equivalent rotor body circuits. These particular fluxes do not link with the stator circuits.

A popular and widely used structure in many current programs can be described, based on Model 2.2, which considers two windings in each axis, including the direct axis field winding. Parameter values for this model structure have normally been supplied by manufacturers of synchronous machines, or have been, for the direct axis, obtained by tests described in IEEE Std 115-1983 (R1991) [1]. Two time constants and two rotor reactances and resistances have been employed to describe the response of Model 2.2 in each of the d and q axes. The model is shown here in Fig 2, and it is common practice to use it for representing a majority of machines in stability studies.

In Model 2.2, the differential leakage inductance L_{f1d} is proportional to flux that links the field and the one equivalent direct axis rotor body circuit of Fig 2. This flux does not link the stator circuit. (Thus, by definition $L_{f1d} = L_{mf1d} - L_{ad}$, as per the nomenclature of Section 2.2.3)

Direct axis parameters available from generator manufacturers cover all of the element values required in Fig 2, except for L_{f1d} the differential leakage inductance [3] [4]. This value cannot be uniquely determined from stator measurements alone. It should be determined from data based upon both stator and field winding measurements. This is discussed further in Section 6.2, as well as in IEEE Std 115A-1987 [2]. If neither field winding measurements nor design data are available, the value of L_{f1d} is typically set to zero, as in Fig 3. However, it should be recognized that this choice will affect the armature to field winding transfer relationships. When the field winding identity is of significance in a particular study, it is recommended that field winding measurements be included in the model derivation. Models of lower complexity than 3.3 and 2.2 have often been used in the past due to unavailability of higher-order model data, or because they were not considered vital to the stability assessment process.

Model 2.1 with a single q-axis equivalent damper circuit, has had extensive use for representing hydro-generators. Rotor equivalent circuit parameters for Model 2.1 have, on occasion, had to be estimated for older machines. Use of such estimated values is considered good practice rather than neglecting their presence by reverting, or defaulting to Model 1.0.

Model 1.0 is another structure that represents only the field winding effects in the rotor. It is the simplest model to that excitation models can be connected. From this, changes in field flux linkages (E'_q) can be determined. Model 1.0 has had some use in the past, but is not currently recommended for general use.

The simplest model is the classical model that assumes a constant voltage behind transient reactance ($E' = \text{constant}$). It assumes constant flux linkages in each axis, and also that no transient saliency exists, namely $X'_d = X'_q = X'$

$$\text{Then } E' = \sqrt{(E'_q)^2 + (E'_d)^2}$$

Since the voltages and currents of this model are not resolved into direct and quadrature axis components, this model structure is placed outside the matrix of Table 5. During a simulation run, the magnitude of the model's internal voltage is kept constant, but the internal angle is changed to reflect the inertial effects for changes in power. An advantage of this simple model is that the interfacing of generator and network equations can be accomplished more quickly during step-by-step calculations, and the least amount of stability data is needed for it. Thus, the “constant voltage behind transient reactance” model has virtually replaced Model 1.0 in stability procedures and calculations where simple generator models are accepted. Exciter action cannot be represented with this model as it can be with Model 1.0.

Each of the model structures of Table 1 is of a differing order of complexity. Models are constructed by determining the parameter values for the model elements (inductances and resistances) based upon measured or analytically determined data that characterize the generator to be modeled (see Section 6.5). The parameter determination procedure should begin both with the available generator data and a specification of the model structure. Parameters, for models of less complexity (i.e., fewer equivalent rotor windings), cannot be obtained from models of higher complexity by simplification (i.e., eliminating rotor winding elements) from the more complex models. As a result, each model should be based upon the direct application of the above procedures to the desired model structure.

2.1.1 Generator—Power System Interfacing

Methods of interfacing generator and network equations are not presented in this guide in any detail. Reference [6] describes one possible approach that permits incorporation of any of the generator stability models, discussed earlier in this section, into network computations. Figure 4 is illustrative of the method employed.

Park's equations forms one building block of this method, where a d-q reference frame for the stator is rotating in synchronism with the rotor axis. This is also discussed in the introduction to Section 2.1.

The network equations are in phasor form, and in the steady-state load flow are positive sequence quantities, also noted in Section Auto.

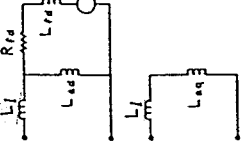
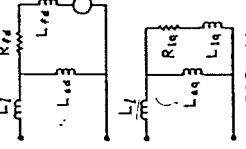
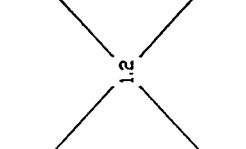
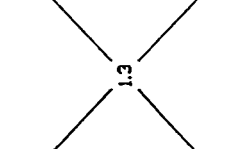
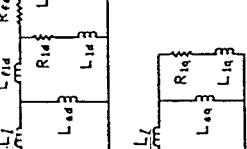
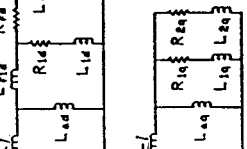
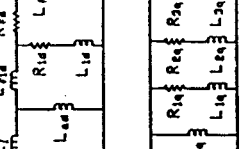
To solve the network equations in terms of Park's representation, two-axis Real (R) and Imaginary (I) voltage phasors are chosen. These are synchronously rotating phasors 90° (electrical) apart, with the real-voltage phasors V_R chosen to be in phase with the “swing” bus voltage in the load flow (usually zero degrees). Thus, the real-voltage phasor V_R is the reference phasor for all the generator terminal voltages in the network. In Fig 4, δ_1' angle is the electrical displacement between system generator #1 rotor position and the reference phasor V_R . Angle δ_1' is comprised of the internal angle δ_1 , of the generator, plus an angle β_1 . The angle β_1 depends on the power system load and generation dispatch. Thus, $\beta^2 \dots \beta_n$ will represent the displacement of all the other n-1 generator terminal voltages with respect to phasor V_R .

Equations used to transform variables from the d, q reference frame to the power system reference frame include, in general,

$$V_R = E_d \sin \delta' + E_q \cos \delta' \quad (1)$$

$$V_I = -E_d \cos \delta' + E_q \sin \delta' \quad (2)$$

Table 1— Selection of Generator Models of Varying Degrees of Complexity

CONSTANT ROTOR FLUX LINKAGES	THEVENIN EQUIV.			
	$E' = \sqrt{(E'_q)^2 + (E'_d)^2}$			
Q - AXIS D - AXIS	NO EQUIV. DAMPER CIRCUIT	ONE EQUIV. DAMPER CIRCUIT	TWO EQUIV. DAMPER CIRCUITS	THREE EQUIV. DAMPER CIRCUITS
FIELD CIRCUIT ONLY	 MODEL 1.0	 MODEL 1.1	 1.2	 1.3
FIELD CIRCUIT + ONE EQUIV. DAMPER CIRCUIT	2.0	 MODEL 2.1	 MODEL 2.2	 MODEL 2.3
FIELD CIRCUIT + TWO EQUIV. DAMPER CIRCUITS	3.0	3.1	3.2	3.3

A second basic equation in this process is as follows taken from Eq 15 in [6]:

$$\begin{bmatrix} V_R \\ V_I \end{bmatrix} = \begin{bmatrix} -R_{RR} & X_{RI} \\ -X_{IR} & -R_{RI} \end{bmatrix} \begin{bmatrix} I_R \\ I_I \end{bmatrix} + \begin{bmatrix} E_R \\ E_I \end{bmatrix} \quad (3)$$

This states that the real and imaginary components of machine terminal voltages are equal to the product of an impedance matrix times the real and imaginary components of stator current plus E_R and E_I . The latter are essentially internal machine voltages. Both E_R and E_I and the impedance matrix elements (the latter including relevant stator and rotor inductances) are affected by δ' , the total electrical angle from the machine rotor position to the system reference phasor.

2.2 Nomenclature and Glossary of Frequently used Terms

2.2.1 Stator Quantities

E_a	Synchronous machine stator terminal voltage in p.u.
E_d	Direct-axis stator voltage in p.u.
E_q	Quadrature axis stator voltage in p.u.
I_a	Synchronous machine stator (armature) current in p.u.
I_d	Direct-axis stator current in p.u.
I_q	Quadrature axis stator current in p.u.

The above capitalized quantities are generally used in equations and phasor diagrams as phasors. (A phasor is a complex number having the form $X = X_0 e^{j\theta}$, where X_0 is the magnitude and θ is the phase angle). This nomenclature is frequently applied to d-q quantities, where the q-axis is considered the imaginary axis. Where lower case letters (e_d , e_q , i_d , i_q) appear in stator voltage, current, or flux equations or otherwise, they are considered scalar quantities.

All model parameter symbols listed below are chosen (to the extent possible) to conform with similar model nomenclature listed in IEEE Std 115A-1987, as well as to the nomenclature of an IEEE Committee Report [3]. Except where noted, such parameters are in per unit referred to the generator stator.

2.2.2 Field or Rotor Quantities

E_{fd}	Field voltage in the non-reciprocal system (dc volts)
e_{fd}	Filed voltage in p.u. in the reciprocal system.
I_{fd}	Field current in the non-reciprocal system (dc amperes).
i_{fd}	Field current in p.u. in the reciprocal system.
R_{fd}	Field resistance in p.u. in the reciprocal system, referred to stator.
r_{fd}	Fields resistance in the physical ohms.
R_{kd}	Direct-axis damper winding or rotor iron equivalent circuit resistances, in p.u., and referred to the stator, where $k=1,2 \dots n$, the winding number.
R_{kq}	Quadrature axis damper winding or rotor iron equivalent circuit resistances in p.u. and referred to the stator, where $k=1,2 \dots n$, the winding number.

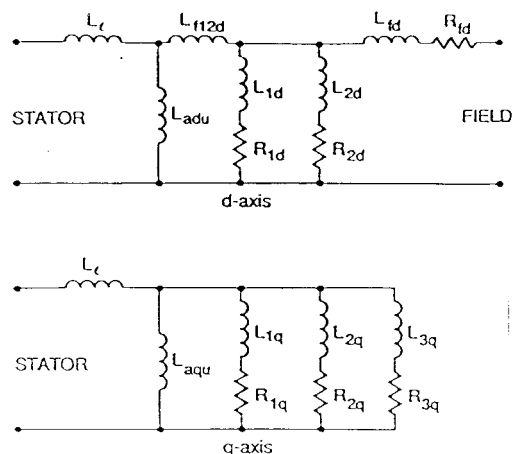


Figure 1—Complete, Third-Order Representation—Both Axes

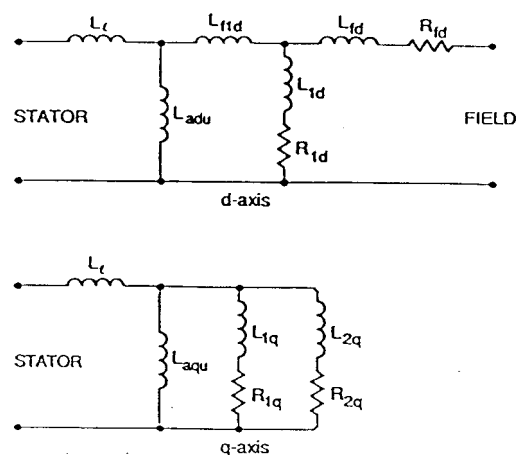
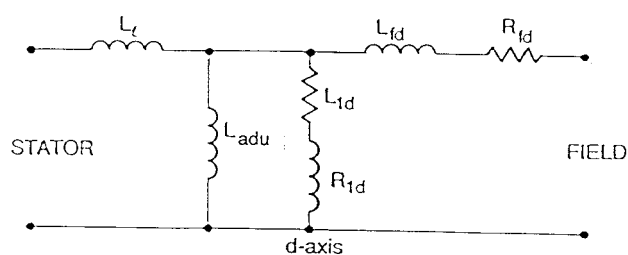


Figure 2—Complete, Second-Order Representation—Both Axes



L_l = STATOR LEAKAGE INDUCTANCE. L_{fd} = FIELD LEAKAGE INDUCTANCE
 L_{1d} = DIRECT AXIS ROTOR IRON EQUIVALENT LEAKAGE INDUCTANCE
 L_{adu} = STATOR TO ROTOR FIELD MUTUAL INDUCTANCE
 R_{fd} = FIELD RESISTANCE. R_{1d} = d-AXIS ROTOR IRON EQUIVALENT RESISTANCE

Figure 3—"Standard" Second-Order Model—D Axis

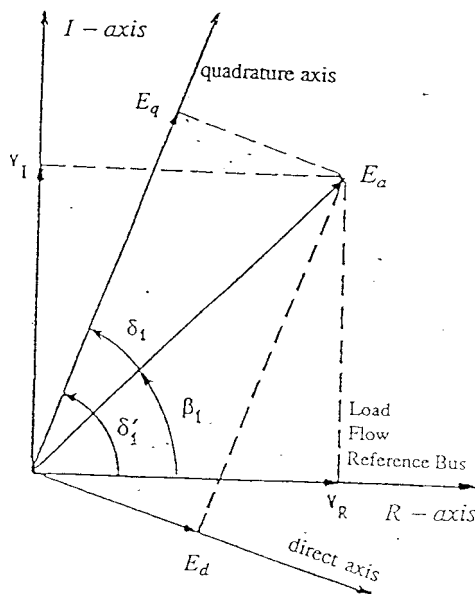


Figure 4—Relationship Between d and q axes and Real and Imaginary Axes

2.2.3 Inductance Quantities—Stator and Rotor

The following inductances are usually referred in p.u. to the stator.

L_{adu}	Direct-axis stator to rotor mutual inductance, unsaturated in p.u.
L_{aqu}	Quadrature-axis stator to rotor mutual inductance, unsaturated in p.u.
L_{du}	Direct axis synchronous inductance (unsaturated) = $L_{adu} + L_l$ in p.u.
L_{qu}	Quadrature axis synchronous inductance (unsaturated) = $L_{aqu} + L_l$ in p.u.
L_l	Stator leakage inductance (both d and q axis), in p.u.
$L_{\beta kd}$	Differential leakage inductances in p.u. proportional to fluxes that link one or more damper windings and the field, but that do not link the stator, $k = 1, 2, \dots, n$, where k is a list of the damper winding to which these fluxes are mutual.
L_{fd}	Field winding leakage inductance.
L_{kd}	Direct-axis equivalent damper winding leakage inductance; $k = 1, 2, \dots, n$.
L_{kq}	Quadrature-axis equivalent damper winding leakage inductance; $k = 1, 2, \dots, n$.
L_{ffd}	Field winding self inductance = $L_{adu} + L_{fd} + L_{f1d}$
L_{mf1d}	Mutual inductance between field winding and a direct axis equivalent winding and equals $L_{f1d} + L_{adu}$. Alternatively, $L_{f1d} = L_{mf1d} - L_{adu}$, for one chosen differential leakage inductance.
L_{11d}	Self-inductance of one equivalent rotor winding = $L_{adu} + L_{ld} + L_{f1d}$
L_{11q}	Self-inductances of another equivalent rotor winding = $L_{aqu} + L_{1q}$
$L_d(s)$	Direct-axis operational inductance, as viewed from the stator terminals.
$L_q(s)$	Quadrature-axis operational inductance, as viewed from the stator terminals.
$G(s)$	Stator to field operational transfer function.

NOTE — Much of the material in this guide uses reactances when describing the relationships between machine fluxes and currents, and this usage arises from the premise that steady-state relationships are being discussed. In generator modeling, $X = \omega_0 \cdot L$, where ω_0 = unity or base speed. Thus, L (inductance) and X (reactance) are often used interchangeably. It seems difficult to settle on, or recommend a specific usage.

In general, reactances, in p.u. are used to describe steady-state, or initial conditions. Inductances are used, by and large, in places that describe changing or transient conditions.

Usually, inductance or reactance values correspond to the unsaturated value of L or X . In some cases the text includes a subscript “ u ” or “ sat ” to clearly distinguish between unsaturated or saturated conditions. The unsaturated condition is implied in the absence of these 2 subscripts.

2.2.4 Commonly Used Symbols in Stability Programs

L_d, L_q	d- and q-axis synchronous inductance, usually quoted unsaturated and in p.u.
L'_d, L'_q	d- and q-axis transient inductance, usually quoted in p.u. and saturated
L''_d, L''_q	d- and q-axis subtransient inductance, usually quoted in p.u. and saturated
	The above 6 quantities are often replaced by using reactance (X) in p.u. namely $X'd$, $X'q$, etc.
T'_{do}, T'_{qo}	d- and q-axis transient open-circuit time constants in seconds.
T''_{do}, T''_{qo}	d- and q-axis subtransient open-circuit time constant in seconds.
T'_d, T'_q	d- and q-axis transient short-circuit time constants in seconds.
T''_d, T''_q	d- and q-axis subtransient short-circuit time constants in seconds.
ψ_d (or λ_d)	Direct-axis stator flux linkages.
ψ_q (or λ_q)	Quadrature-axis stator flux linkages.
ψ_{fd} (or λ_{fd})	Field flux linkages.
$\psi_{1d}\psi_{2d}$ (or $\lambda_{1d}, \lambda_{2d}$)	Direct-axis damper winding or amortisseur flux linkages
$\psi_{1q}, \psi_{2q}, \psi_{3q}$ (or $\lambda_{1q}, \lambda_{2q}, \lambda_{3q}$)	Quadrature axis damper winding or amortisseur flux linkages.

Although flux linkages are denoted in IEEE Std 100-1988 by λ (lambda), common usage in IEEE power literature has been to symbolize flux linkages by ψ (psi), and to use λ for eigenvalue that is defined in Section 2.2.5.

2.2.5 Brief Description of Terms Frequently Used in the Main Body of This Guide

The following terms have been used in this text to describe mathematical procedures or technical concepts. Most of the terms or phrases listed below can be located in IEEE Std 100-1988. A few of the terms listed are not in IEEE Std 100-1988, and can be considered peculiar to the jargon used in this document.

A) Dictionary terms frequently used in this text:

Air Gap	Air Gap Line	Permeability, (Incremental)
Armature	Exciter	
Excitation System	Operational Impedance	
Operational Inductance	Permeability	

B) Definitions of the familiar time constants and reactances for synchronous machines are given in the dictionary under “direct axis” or “quadrature axis” headings.

C) Non-standard or non-defined terms are given below in the context in which they are used.

characteristic equation: This is the relation found by equating to zero the denominator of a transfer function (such as the expression for the operational inductance of a generator as viewed from the stator).

state variables: These are the elements of a set of quantities necessary to completely define the dynamic state of a system, including a power system. The choice of state variables is not necessarily unique for any system. (Also referred to sometimes as dynamic states).

eigenvalue: This is one root of the characteristic equation. The number of eigenvalues in a dynamic system is equal to the order of the characteristic equation, or the number of state variables. The eigenvalues describe the transient response of the system to any disturbance. A transient associated with an eigenvalue takes the exponential form $e^{\lambda_{it}x_i}$,

and this expression is referred to as a mode. The letter x_i denotes the eigenvector associated with the eigenvalue λ_i . Both λ_i and x_i may be real or complex.

NOTE — The use of λ as a symbol for eigenvalue is consistent with the preferred usage of ψ for flux linkages in Section 2.2.4 above.

eigenvector: This vector defines the distribution of the mode, corresponding to a particular eigenvalue, throughout the state variables of the system.

On a more practical basis, the eigenvector can be thought of as a set of coefficients describing the relative magnitudes of the power system dynamic states when some particular mode is the only one that has been excited by a disturbance.

finite element analysis: This is a numerical procedure used to find the magnetic flux distribution in a generator. In its two-dimensional form, the cross section of the generator is divided into a large finite number of geometric elements (frequently triangular). The generator's material properties (rotor steel, stator laminations, air, etc.) are assigned to appropriate elements. Rotor and stator currents are also prescribed. The output of the analysis is the magnetic flux distribution (expressed as the vector potential) in the generator cross-section, from which stator and rotor flux linkages and other quantities of interest can be found. Both nonlinear magnetostatic versions and linear diffusion-equations, which solve for induced currents, are common. Three-dimensional versions have been programmed, but are not in common use.

rotor body: In a turbo-generator, this is the steel forging into which are machined slots for the field winding, amortisseurs, etc. Because it is solid steel, induced currents can flow in it; these are referred to as rotor body currents. In salient pole machines (hydrogenerators) the rotor body is usually a laminated structure (the pole) encircled by the field winding. The poles are then attached to a shaft, and in the case of many poles, a central frame is used to support them. This frame is then connected to the central shaft. Pole-face damper bars or amortisseurs may be embedded in the laminations near the pole face.

saliency: This term is now used for all types of synchronous machines (round-rotor and salient-pole) in which the electromagnetic parameters are significantly different in the direct and quadrature axes. There may be different degrees or amounts of saliency under various conditions, for steady state, transient or subtransient reactances or inductances (calculated or measured) between the direct and quadrature axes. The use of this term arose from consideration of salient-pole machines, including hydro-generators, which all have a pronounced physical difference in the magnetic flux paths for the direct and quadrature axes.

2.3 References

- [1] IEEE Std 115-1983 (R1991), IEEE Test Procedures for Synchronous Machines (ANSI).
- [2] IEEE Std 115A-1987, IEEE Standard Procedures for Obtaining Synchronous Machine Parameters by Standstill Frequency Response Testing
- [3] IEEE Committee Report: Current Usage and Suggested Practices in Power System Stability Simulations for Synchronous Machines, *IEEE Transactions on Energy Conversion*, vol. EC-1, March 1986, pp. 77–93.
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3. Classification of Stability Studies

3.1 Background

The degree of detail and complexity of models required for representing synchronous machines in stability studies depends on the nature of the study, as well as the nature of the power system [2]. A striking tendency of the past 25 years has been that studies of the dynamic performance of such systems can embrace several or even many interconnected power utilities due to the formation of power pools or operating areas. Intra-area, or inter-area studies involving several companies, or several areas or pools, are common, particularly because of changing power transfers arising from the economies of energy interchanges between utilities. As a result, large scale stability programs have been developed for such studies, generally embracing the near-term time frame. Studies of this nature are often concerned with power system operation procedures. On the other hand, detailed examinations of system performance can be concerned with planned additions to power network configurations and with future load and generation patterns expected several years in the future.

Occasionally, very long-term or “broad brush” type studies are performed. However such studies are more concerned with generating station location and transmission network configurations; generator detail is secondary. Such studies are performed to assess the need for future major power system facilities and also fall under the discipline of the power system planning function.

Past system performance is sometimes reviewed and simulated in as much detail as possible to determine possible reasons for misoperation, or for an explanation of past events. However, such a power system analysis forms a small portion of stability studies.

Until recently, all of the stability studies discussed above analyzed power system responses to faults or other similar contingencies, and covered several seconds of simulated time. Such time-domain studies still currently embrace most stability analyses. Lately, power system dynamic responses to small perturbations, involving a linearized model of major system components, including generators and their associated controls, have received increased attention.

For convenience in analysis, and to gain a better understanding of the stability problem, it has been the usual practice to group power system analysis into two general classifications, as noted in Reference [1].

- 1) Large disturbances, where the equations that describe the dynamics of the power system cannot be linearized for the purpose of analysis.
- 2) Small disturbances, where the equations that describe the dynamics of the power system are linearized for the purposes of analysis.

From the first of these two general classifications follows a specific definition of the transient, or large disturbance stability of a power system [1]. The second of these two classifications provides a specific definition of steady state stability of a power system [1]. It is further stated in Reference [1] that steady-state stability is also known as small disturbance stability of a power system.

As a rule, transient stability simulations are highly nonlinear and are studied using step-by-step integration of the differential equations of the dynamic devices that influence system performance. For small disturbance stability, the same equations are linearized so that the more direct methods of stability prediction based on linear system analysis may be applied.

For stability studies involving faults or other sudden changes to the power system configuration, several factors play a significant role in determining how the studies are conducted. These include the severity of the disturbance, and the period in the time domain to be investigated.

For stability studies concerned with a linearized model of the power system, such factors as the nature of the power system responses, including damping of generator oscillations, and the dominant modes or frequencies of power or angular swings, are of prime interest.

The above concepts are discussed accordingly in the following sections.

3.2 Large Disturbances Stability

3.2.1 Short-Term Transient Stability

The traditional transient stability study has been related to the short-term, or transient, response of the power system to a large disturbance such as a fault on the transmission network or sudden loss of generation. It has normally been concerned with the behavior of the system up to about 5 seconds following the disturbance, and depending on the dominant modes of oscillation determined in the analysis, can extend to as many as 10 seconds. The instability is normally due to lack of sufficient generator electrical synchronizing torque, but can also be due to lack of damping torque.

For adequate transient stability performance, the operation of the post-disturbance power system should be stable in the new steady state, and voltages, power and reactive power flows, and relative phase displacements of generators should have stabilized to acceptable values.

Much of the electric utility industry effort and interest related to large disturbances have concentrated on the short-term transient response. The system is designed and operated so as to meet a set of reliability criteria concerning transient stability. The criteria specify certain contingencies that the power system should be able to withstand without loss of synchronism. These contingencies are selected on the basis that they have a certain level of severity and a significant probability of occurrence.

Generator electrical stability characteristics have a significant influence on the short-term transient response of the system and should be adequately represented in transient stability studies. This is discussed in more depth in Chapter 4.

3.2.2 Long-Term Transient Stability

In recent years, the need for studying the response of the system for longer periods has been recognized, and the word long-term stability has been introduced. Time frames associated with such analysis extend beyond the usual 5–10 seconds. In some cases, such studies can cover several minutes of simulated time. [B1]

Some power system analysts have introduced the phrase “mid-term stability,” which could be considered to be the interval between transient stability and long-term stability. This concept embraces periods of time up to as many as 40 s following a disturbance. The definition of “mid-term stability” is avoided in the stability terms of Reference [1]. Comments on such modeling requirements are included in Section Auto under the transient stability headings.

In long-term dynamic response studies, the emphasis is on modeling the sequences of events that follow major system upsets, with the associated slowly changing phenomena. Prime mover and energy supply system dynamics and the influence of automatic generation control, over/under voltage and over/under frequency control and protection schemes, are likely to be significant. Inter-machine synchronizing power oscillations often may be assumed to have damped out, resulting in uniform system frequency. In these cases, the generator electrical characteristics usually do not have a significant influence on long-term dynamic response. On the other hand, longer term effects, such as capacitor switching and restoration of constant mVA loads through tap changer action may render the power system unstable in such a dynamic state, and in these situations, importance is stressed on generator and excitation system representation, and appropriate modeling detail.

3.3 Small Disturbance Stability

Small disturbance (or steady-state) stability is concerned with system response to small changes that continually occur in the operation of the system [B2]. The results are usually given in terms of eigenvalues and eigenvectors. The calculated system response depends in such situations on the type and modeling of excitation control, as well as on the type of generator modeling. In the absence of high initial response excitation control, loss of stability may occur due to lack of sufficient synchronizing torque. This results in monotonic instability, which is also defined in Reference [1].

Generator synchronizing torque is dynamically controlled using high-response, continuously-acting excitation systems. The stability problem, then, often becomes one of ensuring sufficient damping of system oscillations. Instability is normally characterized by oscillations of increasing amplitude.

The generator electrical dynamic response characteristics have a very significant influence on the small disturbance stability of the system. It is, therefore, important to use accurate generator models in such analyses and particularly in design studies of excitation control for enhancing stability. (Generator modeling under these conditions is discussed further in Chapter 4.)

3.4 Classification Based on Dominant Modes of System Response

In the analysis of power system stability of large systems, usually two distinct types of system oscillations are recognized. One type is associated with units at a generating station swinging against the rest of the power system. Such oscillations are referred to as “local mode” or “plant mode” oscillations. The oscillations are localized to one plant or restricted to a small part of the power system. The frequencies of these oscillations are in the range 0.8 to 2.0 Hz. For situations where system stability associated with the plant mode is of primary concern, it is necessary to represent the machines in the local area in detail. Simple models can be used to represent remote machines and system reduction techniques can be used to reduce the size of representation of remote areas.

The other type of oscillation is associated with swinging of many machines in one part of the system against machines in other parts. These are referred to as “inter-area mode” oscillations and have frequencies in the range 0.1 Hz to 0.7 Hz. They are caused by two or more groups of machines connected by relatively weak ties. Analysis of system conditions in which the stability of inter-area swing modes is of primary concern requires detailed representation of the machines throughout all the areas being simulated. In the initial stages of such a study, it is possible to represent all machines by a simple classical model, in order to indicate the frequencies of oscillation, and identify the groups of machines involved in these dominant modes. If this screening process is resorted to, machines in each individual area should be modeled consistently. It generally is questionable practice to retain detailed modeling of machines, including their associated controls, in one area, and then resort to modeling approximations in other areas.

In the final analysis of such multi-area power representations, experience and good judgement are helpful in determining whether the dynamic response of one distinct area can be approximated in the above manner. This decision often can only be taken after initial detailed generator modeling representations of the area under study, and after examination of critical factors such as inter-area flows, or of voltages at key locations in various areas.

3.5 References

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3.6 Bibliography

[B1] Dunlop, R.D., Ewart, D.N., and Schulz, R.P., "Use of Digital Computer Simulations to Assess Long-Term Power System Dynamic Response," *IEEE Transactions on Power Apparatus & Systems*, vol. PAS-94, 1975, pp. 850–857.

[B2] Kundur, P. and Dandeno, P.L., "Practical Application of Eigenvalue Techniques in the Analysis of Power System Dynamic Stability Problems," *Proceedings of the 5th PSCC Conference*, Cambridge, England, 1975.

4. Application of Generator Models in Stability Studies

4.1 General

As noted previously, system stability studies are generally conducted for one of the following purposes:

- 1) Power System Planning, to enable decisions to be made on future transmission and generation requirements.
- 2) Power System Operation, to determine operating limits in the light of various system contingencies.
- 3) Post-disturbance Analysis, to simulate past events that have occurred on the system.

In the initial stages of a planning study, many comparisons of different alternatives are required. In such studies, it may be possible to use simple synchronous machine models, since only a relative measure of the performance of a number of different system configurations is being sought.

In the latter stages of a system study, the behavior of the chosen system alternatives should be explored in detail. In some cases, special controls or protection schemes to maintain the stability of the system may be studied. For these studies, the synchronous generator modeling should be much more complete.

In operating studies, simplified models may be adequate for real-time determination of operating limits and for some contingency analysis studies. For the normal determination of operating limits using contingencies included in system design or operating criteria, more accurate modeling is necessary, again requiring more detailed generator models.

It is often in the simulation of past events that have actually occurred on the system that the most demands are made on the mathematical models used in the simulation.

For planning and operating studies the following seven categories of large disturbances are usually the most significant:

- 1) Stability of one or more generating stations, following a severe nearby fault.
- 2) Excitation system control behavior and its associated stabilization, under all types of disturbances.
- 3) Power transfer limit determination across one or more inter-area interfaces subsequent to disturbances.
- 4) The sudden loss of one or more large generator(s), or deliberate generation tripping to maintain stability.
- 5) Generator and power system performance with delayed fault clearing and the associated transmission line relay performance.
- 6) The effects of large industrial loads, or of deliberate load shedding.
- 7) Inter-area tie-line oscillations of a pronounced magnitude.

For generators adjacent to many of the disturbances noted above, important issues in model application include:

- Calculations of generator power or torque during the fault period, or during the initiating situation.
- The calculations of post-disturbance generator powers, angles and voltages, for periods of up to several seconds of simulated time.

In the case of power-system faults in (1) above, in particular, the effects of unbalanced faults cannot be overlooked, but as at general rule in large-scale studies, calculation of generator balanced electrical torque or power developed across the machine air gap is based on the assumption of a balanced or positive-sequence network. The effect of unbalanced faults on positive-sequence power calculations is obtained by applying an appropriate impedance-to-neutral at the point of fault in the positive-sequence network.

The positive sequence system representation used in stability studies does not allow the effects of dc offsets in armature transients to be modeled. The fundamental frequency rotor losses due to dc offsets and the negative sequence (second harmonic) rotor losses are neglected with the above approach.

Appendix 4A includes a development of the relationships between electrical torque, (T_e) and electrical power (P_e), and comments on neglecting the rate of change of stator flux linkages and/or variations in rotor speed in the torque or power calculations.

4.1.1 Use of the Simplest Model

The “voltage back of transient reactance” model, discussed in Section 2.1, has been widely applied. A general tendency is to represent generators in areas remote from disturbances in this way. If in the transient-stability studies, such “remote” machines suffer sudden or sustained voltage changes of only about 0.1 p.u. or less at their stator terminals, then the use of this simple model may be acceptable. Adjacent machines remote from the disturbance can then be grouped and represented as one machine, as one “voltage behind transient reactance.” In this case, the individual inertias would be totalled and used in the equivalent generator, along with the Thevenin equivalent of all the internal voltages, and the parallel value of all the machine transient reactances.

The question of size of machines being simulated in the remote areas should be seriously considered in decisions on their degree of modeling. Some engineering judgement needs to be exercised as to which machines can logically be ignored. In such cases, they would be balanced against local load. Any generator group consisting of a small percentage of the total area load (5% or less) can be balanced out against local load, or at most, represented in all cases by its transient reactance and the corresponding internal voltages. It may be good practice to also retain an appropriate damping factor for such generator groups.

For simple, yet reasonably accurate reduced order power system analyses, it is important to aggregate machines for which the rotor angle excursions are coherent following some initiating disturbance. For short-time-scale studies (1 to 1-1/2 s) involving “local” stability problems, this coherency criteria may include all generators electrically remote from the disturbance. The reduction of systems for small signal studies is mentioned in Section Auto.

4.1.2 Neglecting Saliency in Second- or Third-Order Models

At one time there was considerable incentive to minimize the number of differential equations required to be solved in stability studies. There is sometimes an incentive in reducing the system size to a prescribed level in terms of the number of load flow busses to be solved at any “time step”. This follows because the number of algebraic equations involved in the iterative process is a direct function of the number of busses to be represented.

As far as the synchronous machine differential equations are concerned, there would be a very small difference in computing time per step if all machine equations were written for a third-order model, as opposed, for example, to a second-order model. With no sub-transient saliency in Model 3.3 for example, (that is if $X_q''' = X_d'''$), that model is computationally more efficient when calculating generator terminal quantities than, for instance, model 2.2 where subtransient saliency, was assumed to be present (i.e. $X_q'' = X_d''$). Simply stated, when E_q''' and E_d''' are replaced by a single voltage E''' , the interfacing of generator and network equations can be accomplished more quickly during step-by-step stability calculations. Refer also to similar comments (on assuming $X'_q = X'_d$) in Section 2.1.

The chief computational limitation on the choice of a Model 3.3 over a Model 2.2 depends on the values of the smallest (effective) time constants associated with Model 3.3. This will likely affect the choice of integration time step. Simulation of high initial response exciters also require small time steps in the 0.005 to 0.01 second ranges. Thus, the

application of such excitation systems to certain types of turbo-generators may dictate the stability analysis integration equations. It should also be noted that elimination of the type of saliency discussed above may slightly distort the values of some quadrature axis elements in Model 2.2, and possibly Model 3.3.

4.1.3 Salient Pole Generators—Stability Model Guidelines

Salient pole generators with laminated rotors are usually constructed with copper damper bars located in the pole faces. These damper bars are connected with continuous end-rings and thus, form a squirrel-cage amortisseur circuit that is effective both in the direct and quadrature axes. Since this amortisseur is the only physical circuit present in the q-axis, a first-order model describes it adequately. Hence, Model 2.1 is recommended for most salient pole generators.

Solid iron pole salient-pole machines may justify a more detailed model structure. Reference [2] discusses various aspects of salient-pole machine modeling. Some of the above considerations are also touched upon in Reference [1]. More information on these particular topics is discussed in [B3].

4.1.4 Round Rotor Generators—Stability Model Guidelines

In round-rotor machines, slots are present over part of the circumference to accommodate the field winding. The tops of these slots contain wedges for mechanical retention of the field turns. These wedges are usually made of a nonmagnetic metal. In some cases, they are segmented and made of nonmagnetic steel, while in other cases the wedges are made of aluminum and may be either segmented or full length. In many constructions, a conductive ring under the field end-winding retaining ring, with fingers extending under the ends of the slot wedges, is used to improve conduction at these connection points.

For infrequent cases where the retaining ring is magnetic, field leakage fluxes and corresponding inductances will be affected, with noticeable differences existing in frequency response data obtained at or near full load, compared with stand-still data [6].

Copper strips are often inserted under the wedges to provide improved conduction between wedge segments and/or to improve amortisseur action. In some cases, a complete squirrel-cage winding is formed, while in other cases the conductive paths contribute only marginally to amortisseur action. The effectiveness of the slot-wedge amortisseur circuit may vary widely depending on the wedge material, segmenting of wedges and the design of the conductive circuit below the wedge. References [5] and [6] discuss the impact of some of the above details on the direct axis rotor model. A third-order model for the direct axis definitely gives a better fit to $L_d(s)$ and $sG(s)$ test data than a second order one. However, in some cases the smallest time constant (T''_{do}) values may be close to the size of the integration equation time steps. In many cases, a second-order model for the direct axis (Model 2.2 or 2.3) will suffice, along with recognition of L_{f1d} , which reflects the differences in mutual coupling between the field, the equivalent rotor wedge and/or damper circuits and the stator.

For turbo-generators therefore, Model 2.2 can usually describe the operational inductance in both direct and quadrature axes adequately, where no conducting strips are placed under the slot wedges, and where the pole face region is without wedges or amortisseur bars.

The pole-face region is often slotted circumferentially, or, on occasion, may be slotted longitudinally for rotor flexing and balancing purposes. In some cases, longitudinal pole face slots may be filled with wedges of either low-conductivity steel or, in the case of machines subject to sub-synchronous resonance (SSR), high-conductivity material to form a quadrature axis amortisseur. The q-axis equivalent circuit model should account for various current paths in the rotor iron along the pole faces. The electrical properties of these paths may be affected by circumferential slotting, or by pole face wedges or damper bars.

However, should the pole-face area have conducting wedges or amortisseur bars, Model 2.3 is recommended. It has also been found, for a range of rotor damper constructions, that a third-order representation such as Model 2.3 or 3.3 gives a better fit between measured and calculated values of $L_q(s)$ including phase angle, and in the 0.1 Hz to 10 Hz range [4]. Three impedance values are thus available to describe the quadrature axis rotor dynamics over the requisite

power system frequency range rather than just two. It would appear that electrical damping from currents in the pole face area would more accurately reflect actual conditions when using a third order quadrature axis model, and this approach is preferable to the use of damping factors. Concordia treats generator damping torques, and the associated damping factors that were used in the past, when adequate quadrature axis operational data was unavailable [B1].

Model 3.3 is also suggested [3] for cases where detailed third-order modeling effects of direct and quadrature axis rotor circuits, and generator torques, are considered important in studying rotor “backswings.” This effect is often critical in special transient stability power limit calculations.

4.1.5 Application of Excitation Controllers Relative to Generator Models

Direct axis generator models play an important role in determining the effect of excitation system performance on generator stability. The largest time constant in the denominator of the transfer function of any direct axis model reflects the impact of the field time constant. Considering all rotor element values, this effective field time constant is increased slightly with higher-order models. An accurate knowledge of the magnitude and phase of $L_d(s)$ and $sG(s)$ over a frequency range from .01 Hz to 10 Hz is useful in determining the impact of excitation system voltage changes on calculation of electrical Torque or Power. Various approaches to excitation system applications are discussed in [B2], [B4], and [B5]. Specific examples of the setting of power system stabilizer (PSS) gains and time constants are given in Reference [7].

4.2 Representation of Generations During Large Disturbances

4.2.1 Short-term Transient Stability Studies

In transient stability studies involving categories (1) through (6) in Section Auto above, and especially for severe fault conditions or excitation system control design, the responses of the generators, exciters and power system itself immediately following the initiating disturbance are of primary interest.

The internal angle and excitation conditions of a generator prior to a disturbance are functions of unit loading and system conditions, and are influenced by the magnetic characteristics of the generator. Saturation of the magnetic paths in generators is discussed more fully in Chapter 5.

For any transient, the depression in system voltages and the corresponding reduction in generator output power due to close-in faults, results in the acceleration of generator rotors. This is normally accompanied by large increases in field voltage through voltage regulator action to compensate for lost synchronizing torque.

Summary of Recommendations:

The following numbered comments summarize the recommendations in the guide for generator stability model selection. These comments relate particularly to the seven stability study categories noted in Section Auto.

Basic considerations in generator model selection would suggest that the power system analyst should use, as a desirable minimum, a second-order model for both the direct and quadrature axes, providing reasonably accurate parameters for these chosen models can be either obtained or can be estimated.

- 1) For turbo-generator representation, a second-order model in both axes (Model 2.2) is nominally required as a minimum. For turbo-generators that also utilize damper bars or conducting wedges in the pole faces, in some cases a second order model may be adequate in the quadrature-axis. A third order model (Model 2.3 or 3.3) may be required for the best results, especially to give good representation of generator damping.
- 2) For excitation system stabilization studies, along with exciter ceiling voltage and response ratio specification studies, a second-order model in the direct axis is a minimum requirement. Improved model detail, in representation of the differential leakage reactance (L_{fd}), along with representation of the field winding terminals is definitely suggested. This is particularly significant for turbo-generators when damper bars or

other conducting materials are used as part of, or under the field slot wedges, or where magnetic retaining rings are employed [6].

- 3) Under the conditions of (2) and (3) of Section Auto, a complete third-order model, Model 3.3, should be considered, provided that appropriate quantities are available. If this type of information cannot be easily obtained from the generator manufacturer, it can be derived from frequency-response measurements.
- 4) For most hydraulic machines, a second-order model for the direct axis is appropriate. For most studies, only a single-order model is required for the quadrature axis (Model 2.1) [B3]. For most studies, only one q-axis transient reactance is provided for such machines (usually called X''_q not X'_q). On occasion, a second-order model (Model 2.2) may be appropriate for the quadrature axis, depending on damper bar, pole-face, and interpolar space construction details. [2]
- 5) In many stability studies, a number of tests may be carried out initially to determine a feeling for the overall dynamic response of the power system. These screening studies are often performed using a simple model such as “voltage behind transient reactance” for virtually all machines. More detailed studies based on recommendations (1) to (4) would then follow. (See also Section 3.4.)

4.2.2 Long-term Transient Stability Studies

Some remarks about the type of investigation as a particular classification of stability have already been made in Section 3.2.2.

As noted in Section 3.2.2, in such a time span, underload tap changing and capacitor switching or line restoration procedures and switching can come into action. However, prime mover (boiler and reactor) or energy supply dynamics are also very much in the picture, to change mechanical power inputs. These latter aspects tend to overshadow the electrical performance of generators, and their associated modeling requirements. In this time frame, they appear to be of secondary importance.

When switching does take place in long-term studies, the program may switch back to a “normal” transient stability study for a few seconds, in which case, the comments of Section 4.2.1 again apply.

4.3 Modeling of Machines for Small Disturbance Stability Studies

While some studies for examining the small-signal stability of a power systems can be made using time domain simulation tools, (such as a transient stability program) this is very time consuming and inefficient. For most small-disturbance or small-signal studies, the system equations are linearized about an initial operating point. Eigenvalue/eigenvector or other linear analysis techniques are then used to assess system stability.

For the generator models, there are two nonlinear functions to account for: magnetic saturation (treated to some extent in Chapter 5) and the torque/power equations. (A third nonlinearity, the “speed voltage” term, has been neglected by using synchronous speed in conjunction with elimination of stator flux derivatives in the equations of Appendix 4A).

Two methods of obtaining linearized equations for small disturbance stability analysis can be used. In one method, the equations are prelinearized when the computer code is written. In the second method, the computer code describes the nonlinear equations and is used for both time simulation, and small signal analysis. Special provision is made to linearize about an operating point by repeated calls from a state matrix building subroutine. From an initial steady state condition, each of the states and inputs is individually perturbed slightly and the effect on the state derivatives and outputs are measured. The state matrices are built one column at a time. When considering this method, the particular computer code being used provides for user selection of the saturation representations. For example, saturation could be linearized based upon total, tangential, or minor hysteresis loop relationships between flux and current.

Occasions for which simpler models may be reverted to would involve one distinct or remote area, as mentioned in Section 3.4.