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

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IEEE Power and Energy Society

Developed by the
Electric Machinery Committee

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

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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

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

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Eli Pajuelo
Uwe Seeger
Jayapalan Senthil
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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.

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Thomas Bishop
William Bloethe
Edson Bortoni da Costa
Gustavo Brunello
Demetrio Bucaneg Jr.
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Gary Donner
Rostyslaw Fostiak
Alexander Glaninger-Katschnig
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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

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],[1] Park ([B65], [B66]), 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.

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], Dandeno et al. [B13]). Other investigators developed alternate techniques for determining machine parameters (Manchur et al. [B58]). 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] The numbers in brackets correspond to those of the bibliography in Annex A.

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] 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 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 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.