

IEEE Guide for Identification, Testing, and Evaluation of the Dynamic Performance of Excitation Control Systems

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Abstract: IEEE Std 421.2-1990, *IEEE Guide for Identification, Testing, and Evaluation of the Dynamic Performance of Excitation Control Systems*, presents dynamic performance criteria, definitions, and test objectives for excitation control systems as applied by electric utilities. It should be specifically noted that the term “excitation control system” refers to the entire control system including the synchronous machine and power system as well as the excitation system.

Keywords: Closed-loop performance, excitation control systems, excitation system specifications, large signal disturbances, small signal disturbances

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Foreword

(This Foreword is not a part of IEEE Std 421.2-1990, IEEE Guide for Identification, Testing, and Evaluation of the Dynamic Performance of Excitation Control Systems.)

This guide presents dynamic performance criteria, definitions, and test objectives for excitation control systems as applied by electric utilities. It should be specifically noted that the term excitation control system refers to the entire control system including the synchronous machine and power system as well as the excitation system.

The Working Group on Excitation Control System Dynamic Performance of the Excitation Systems Subcommittee of the Power Generation Committee adopted many definitions and performance criteria, which are common to all control systems, and derived others specifically related to excitation control systems. In doing this, the material in IEEE Std 421.1-1986, IEEE Standard Definitions for Excitation Systems for Synchronous Machines (ANSI) and IEEE Std 100-1988, IEEE Standard Dictionary of Electrical and Electronics Terms (ANSI) was heavily used. Efforts were made not to conflict with existing definitions and criteria, but to clarify, supplement, and more fully define them as related specifically to excitation control systems. Definitions from these standards, which are reproduced in this standard, are set in italics in Section 3.

In preparing this guide, the working group recognized that both factory testing and field testing of excitation control systems and some of their components are costly and often impractical. Alternator-rectifier excitation systems in which the terminals of the exciter may not be available may preclude field testing of the exciter separately. Compound source excitation systems whose power is derived from the generator currents and voltages present special difficulties. Providing a load which reasonably duplicates the generator field characteristics so that regulation effects and proper waveforms can be adequately simulated may not be economically justifiable. Field tests on units under normal operating conditions are constrained to comply with the operating and security requirements of the power system, which often prohibit large excursions of the excitation control system variables. For many applications, it is necessary to devise practical test procedures for individual components and then by analytical means, to verify the total excitation system performance.

The need for models that accurately simulate the operation of excitation control systems during system disturbances demands effective test methods. However, the practical limitations on tests make it difficult to measure the parameters required for models. One solution is the collection of more complete data during system disturbances. Present instrumentation practices generally do not include the collection of data from enough excitation control system variables to permit the data to be used for model refinement. Improving the quantity and quality of data collected during system disturbances may be the only practical way to obtain the data required to significantly improve the accuracy of large signal models.

This revision incorporates the changes in IEEE Std 421.1-1986, IEEE Standard Definitions for Excitation Systems for Synchronous Machines (ANSI), which substituted a single definition, excitation system nominal response, for several previous definitions that included the phrase “response ratio.” Root locus techniques applicable to excitation control system performance evaluation are added in this revision. The material in IEEE Std 421A-1972, IEEE Guide for Identification, Testing, and Evaluation of the Dynamic Performance of Excitation Control Systems (ANSI), pertaining to power system stabilizers is retained. However, the IEEE Tutorial on Power System Stabilization Via Excitation Control (81EH0175-0 PWR) provides substantial supplemental material. The previous material related to synchronizing and damping torques is omitted.

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IEEE Guide for Identification, Testing, and Evaluation of the Dynamic Performance of Excitation Control Systems

1. Introduction

1.1 Scope

This guide includes criteria, definitions, and test objectives for evaluating the dynamic performance of excitation control systems as applied by electric utilities. The term “excitation control system” (see Fig 1) is used to distinguish the combined performance of the synchronous machine, power system, and excitation system from that of the excitation system alone (see IEEE Std 100-1988, IEEE Standard Dictionary of Electrical and Electronics Terms (ANSI) [1]¹ and IEEE Std 421.1-1986, IEEE Standard Definitions for Excitation Systems for Synchronous Machines (ANSI) [2]). The primary purpose of this guide is to provide a basis for evaluating closed-loop performance of excitation control systems for both large and small signal disturbances; confirming the adequacy of mathematical models of excitation control systems for use in analytical studies of power systems; identifying objectives for tests of excitation control systems and their components; and preparing excitation system specifications and additional standards. Portions of this guide will also serve as educational material for people who are becoming acquainted with excitation control systems.

Traditionally, large signal performance (see 2.1) has been more closely associated with equipment specification and acceptance testing, while small signal performance (see 2.2) has been more closely associated with stability and model studies. Matching actual disturbance data with model simulations requires that both large and small signal performance criteria be considered during design specification and acceptance testing.

¹IEEE publications are available from the Institute of Electrical and Electronics Engineers, IEEE Service Center, 445 Hoes Lane, Piscataway, NJ 08855-1331. The numbers in brackets refer to the references listed in 1.2.

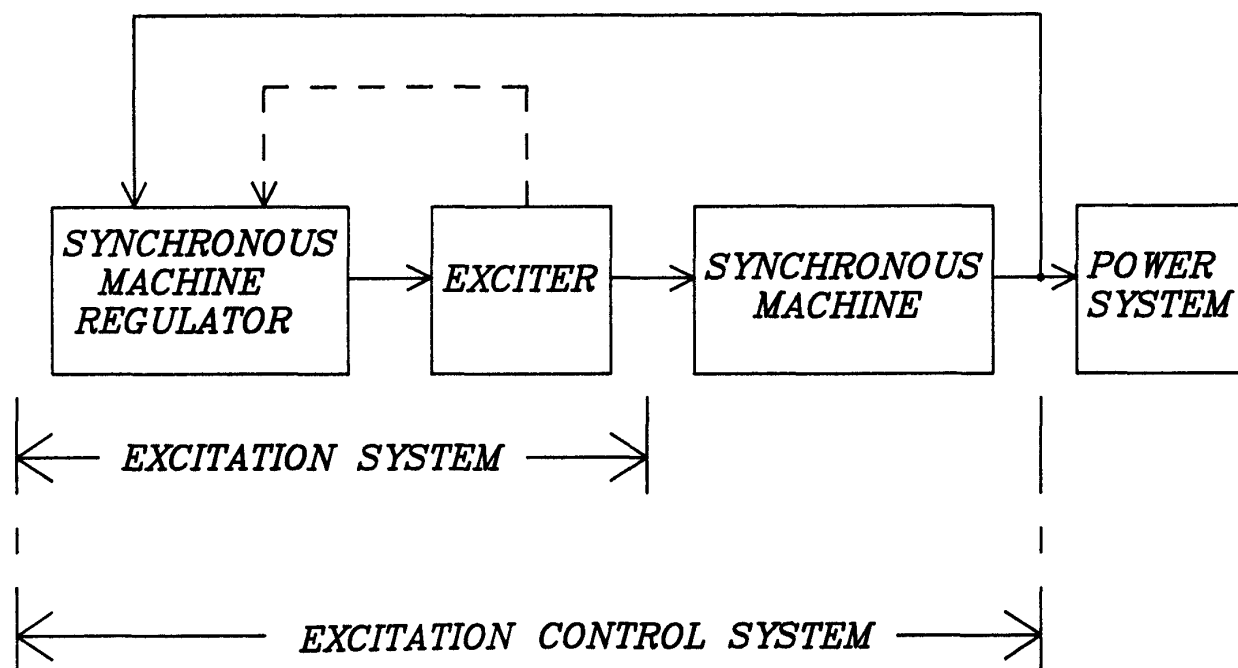


Figure 1—Block Diagram of an Excitation Control System

1.2 References

This guide shall be used in conjunction with the following publications:

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1.3 Definitions

ceiling current: The maximum direct current that the excitation system is able to supply from its terminals for a specified time.

ceiling voltage: The maximum direct voltage that the excitation system is able to supply from its terminals under defined conditions.

system nominal response: The rate of increase of the excitation system output voltage determined from the excitation system voltage response curve, divided by the rated field voltage. This rate, if maintained constant, would develop the same voltage-time area as obtained from the actual curve over the first half-second interval (unless a different time interval is specified).

excitation system voltage response time: The time in seconds for the excitation voltage to attain 95% of the difference between ceiling voltage and rated field voltage under specified conditions.

excitation system voltage time response: The excitation system output voltage expressed as a function of time under specified conditions.

frequency-response characteristic (linear system): In a linear system, the frequency-dependent relation, in both gain and phase difference, between steady-state sinusoidal inputs and the resultant steady-state sinusoidal outputs.

large signal performance: The response to signals that are large enough so that nonlinearities are significant.

power system stabilizer: An element or group of elements that provide an additional input to the regulator to improve the dynamic performance of the power system.

small signal performance: The response to signals that are small enough so that nonlinearities are insignificant.

2. Dynamic Performance Classification

2.1 Large Signal Performance

Large signal performance is the response to signals that are large enough so that nonlinearities are significant.

The purpose of large signal performance criteria is to provide a means of evaluating excitation system performance for severe transients that may include large variations in synchronous machine stator voltages, synchronous machine stator currents, and induced synchronous machine field currents; that is, for transients affecting system transient stability. To assess the ability of the excitation system to improve synchronous machine performance, the criteria must reflect the effects of operation under realistic power system disturbances. With respect to performance testing, it is often impractical to adequately duplicate these effects. In cases where tests can only be made on individual components and only at partial load or open-circuit, analytical means may be used to predict performance under actual operating conditions.

The criteria that assess the large signal performance are quantities such as transient responses, ceiling currents and voltages, voltage response times, and nominal responses derived from time responses (see IEEE Std 100-1988, IEEE Standard Dictionary of Electrical and Electronics Terms (ANSI) [1] and IEEE Std 421.1-1986, IEEE Standard Definitions for Excitation Systems for Synchronous Machines (ANSI) [2]).

2.2 Small Signal Performance

Small signal performance is the response to signals which are small enough that nonlinearities are insignificant. Small signal performance of an excitation control system or its components can be assessed from time responses, frequency responses, or by eigenvalue analysis (see References [9], [10], and [11]).

Small signal performance criteria provide a means of evaluating the response of systems for incremental load changes, incremental voltage changes, and the incremental changes in synchronous machine rotor speed associated with the initial stages of dynamic instability (where oscillations are small enough so that nonlinearities are insignificant). Small signal performance data provide a means for determining or verifying excitation system model parameters for system studies (see References [4] and [8]). The assumption of linearity limits the application of small signal models as noted above.

3. Large Signal Performance Criteria

3.1 General

The following large signal performance criteria relate to excitation control systems and, where applicable, their components. To permit maximum flexibility in the design, manufacture, and application of excitation equipment, some of the performance criteria are defined “under specified conditions.” The applicable conditions may be specified by the manufacturer or, more usually, by the equipment purchaser.

The general nature of several of the following definitions, notably field current and field voltage, permit them to be used to achieve different objectives in different applications. As a result, confusion can also result when they are applied inconsistently. Care must be exercised that the “under specified conditions” clauses are interpreted in a manner consistent with the application.

3.2 Ceiling Current

The maximum direct current which the excitation system is able to supply from its terminals for a specified time (see IEEE Std 100-1988, IEEE Standard Dictionary of Electrical and Electronics Terms (ANSI) [1]).

When sustained overloads or prolonged disturbances are of concern, the ceiling current may be based upon the excitation system thermal duty that identifies the maximum output current and the required time duration. For some applications, the ceiling current will be determined by the requirement that the synchronous machine produce a specific value of steady-state, three-phase, short-circuit current for a specified time.

When a high value of ceiling voltage is required for forcing action, exciter current limiter control circuits may determine the actual ceiling current.

3.3 Ceiling Voltage

The maximum direct voltage that the excitation system is able to supply from its terminals under defined conditions (see IEEE Std 100-1988, IEEE Standard Dictionary of Electrical and Electronics Terms (ANSI) [1]).

Ceiling voltage can be used to evaluate the forcing capability of the excitation system to drive the field current toward the ceiling current value. The ceiling voltage provides an indication of the voltage available to force the field current from rated field current toward ceiling current. The greater the difference between the ceiling voltage and the rated field voltage, the greater the forcing capability. Higher ceiling voltages tend to improve transient stability.

The excitation system ceiling voltage under load may be determined by either a steady-state or transient measurement. It may be determined in a steady-state measurement with the excitation system loaded with a resistance such that ceiling current is attained but not exceeded. It is necessary that the load have adequate inductance so that voltage drop effects, and current and voltage waveforms are reasonably duplicated. It is determined with the exciter output current limiter control circuits inactive. If a transient determination is made, then adequate inductance is required in the load so that the ceiling voltage is measurable at ceiling current before any current limiters operate. The no-load ceiling voltage is determined with the excitation system open-circuited.

For potential source and compound source excitation systems, whose supply depends on the synchronous machine voltage and current, the nature of power system disturbances and specific design parameters of the excitation control system influence the excitation system output. For such systems, the ceiling voltage is defined based upon a specified supply voltage and (if applicable) current.

For excitation systems employing a rotating exciter, the ceiling voltage is determined at rated speed.

Some excitation systems will have both positive and negative values of ceiling voltage. Also, in some special applications, the excitation system may be required to supply both positive and negative field current to the synchronous machine.

3.4 Excitation System Voltage Time Response

The excitation system output voltage expressed as a function of time under specified conditions (see Fig 2 and IEEE Std 100-1988, IEEE Standard Dictionary of Electrical and Electronics Terms (ANSI) [1]).

3.5 Excitation System Voltage Response Time

The time in seconds for the excitation voltage to attain 95% of the difference between ceiling voltage and rated field voltage under specified conditions (see IEEE Std 100-1988, IEEE Standard Dictionary of Electrical and Electronics Terms (ANSI) [1]).

3.6 High Initial Response

For those systems with very short response time relative to the generator field time constant and to power system characteristic swings, the shape of the initial response is not of concern. Those systems whose voltage response time 0.1 second or less are termed “high initial response excitation systems.”

3.7 Excitation System Nominal Response

The rate of increase of the excitation system output voltage determined from the excitation system voltage response curve, divided by the rated field voltage. This rate, if maintained constant, would develop the same voltage-time area as obtained from the actual curve over the first half-second interval (unless a different time interval is specified) (see IEEE Std 100–1988, IEEE Standard Dictionary of Electrical and Electronics Terms (ANSI) [1]). Nominal response is used as a figure of merit related to the ability of an excitation system to respond to transient stability issues and to permit comparisons of excitation systems. The basic underlying concept of nominal response, as related to power system stability, is developed in Appendix A. The half-second interval was selected to associate the nominal response with the excitation system contribution to stability.

The starting point for determining the nominal response is the time the disturbance is initiated; that is, the excitation system nominal response should include any delay time that may be present. Referring to Fig 2, the excitation system nominal response is illustrated by line ac. This line is determined by establishing area $acd = \text{area } abd$.

Nominal response is determined by initially operating the excitation system at rated field current of the synchronous machine and then suddenly creating the three-phase terminal voltage input signal conditions necessary to drive the excitation system voltage to ceiling (see IEEE Std 100–1988, IEEE Standard Dictionary of Electrical and Electronics Terms (ANSI) [1]). If nominal response is used as a figure of merit for comparing different types of excitation systems, misleading results may be obtained if different types of limiters or differing values of inductance are permitted. Nominal response determinations from actual time responses obtained by recording responses during disturbances may be misleading when compared with factory tests because of the influence of fault induced currents.

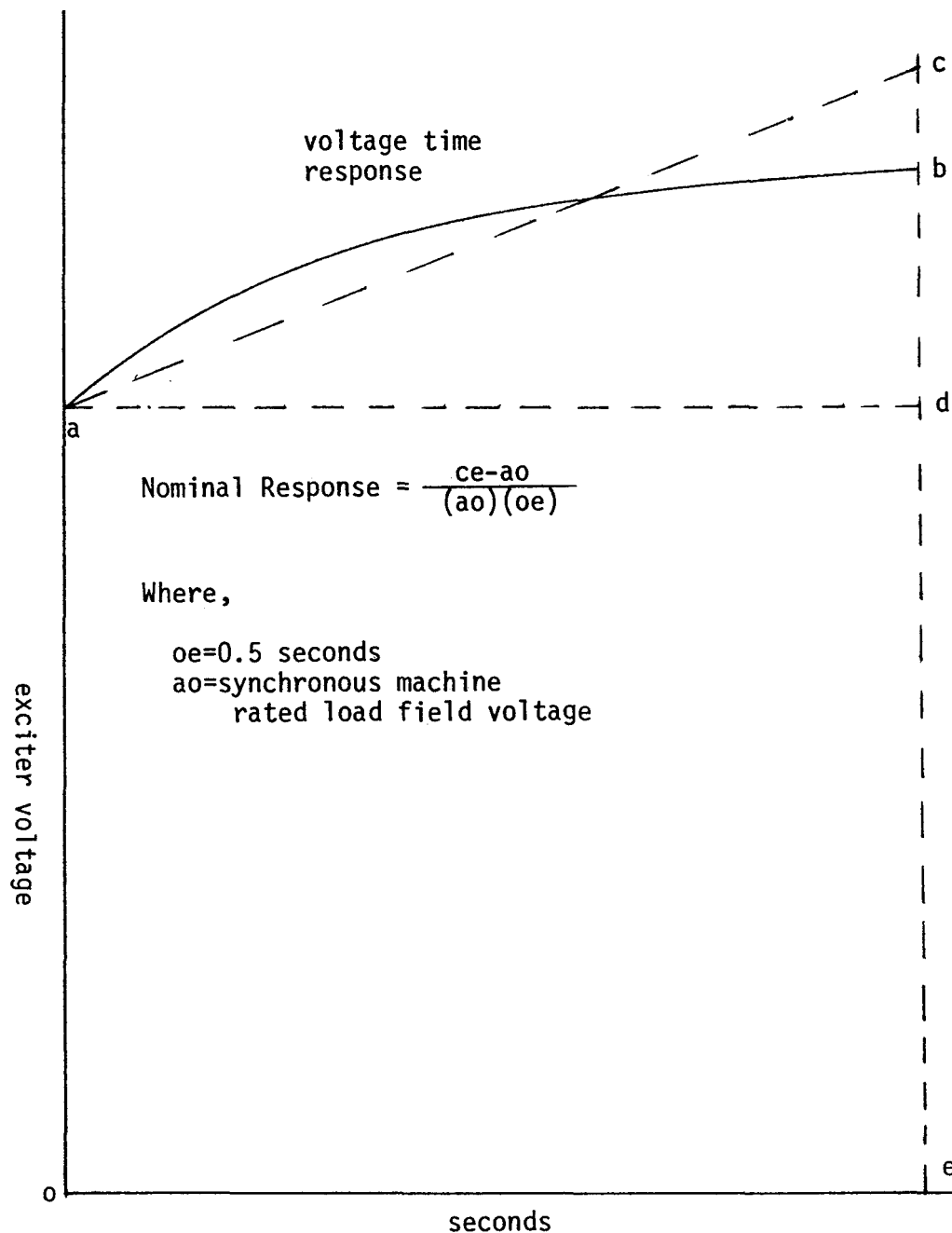


Figure 2—Excitation System Nominal Response

3.8 Transient Responses

Many of the large signal performance criteria provide a single numerical value. Excitation system ceiling voltage and nominal response are two examples. These criteria are useful for comparing performance of different systems, and they are valuable as design criteria that can be used to verify that the manufacturer fulfilled specification requirements. However, these single value criteria do not provide sufficient information in all instances for model parameter selection or verification. A specific response can be achieved in models with different combinations of model parameters. This ambiguity can be reduced by comparing model results with time responses. Although transient

response (see 4.2) is more frequently associated with small signal analysis, it is a useful criteria for large signal performance evaluation, especially for applications involving the refinement or validation of computer models.

Any portion of the excitation control system that is commonly represented in model studies (e.g., synchronous machine regulator, exciter, synchronous machine, excitation system, and excitation control system) may be evaluated using the transient response criteria.

A large signal transient response is a time response with the input and output variables of the component being tested recorded as a function of time. Although transient response is generally associated with a step change in the input variable, it is only necessary that the change in the input variable be large enough and fast enough that the response at the output is classified as a large signal response for the resulting response to be useful. The change to the input variable must be specified. A time response with several variables recorded simultaneously has considerable value in the refinement or validation of large signal computer models.

4. Small Signal Performance Criteria

4.1 General

While the large signal performance criteria can be applied to the excitation control system, individual components of the system, or the excitation system, the small signal performance criteria are commonly used to evaluate the performance of closed-loop excitation control systems.

4.2 Transient Response

A typical transient response of a feedback control system is shown in Fig 3. The principal characteristics of interest are the rise time, overshoot, and settling time as indicated.

4.3 Frequency-Response Characteristic (Linear System)

In a linear system, the frequency-dependent relation, in both gain and phase difference, between steady-state sinusoidal inputs and the resultant steady-state sinusoidal outputs (see IEEE Std 421.1-1986, IEEE Standard Definitions for Excitation Systems for Synchronous Machines [2]). Typical opened-loop frequency response characteristics of an excitation control system with the synchronous machine open-circuited are shown in Fig 4. The principal characteristics of interest are the low frequency gain G , crossover frequency (ω_c), phase margin ϕ_m , and gain margin G_m . The corresponding closed-loop frequency response is shown in Fig 5. Here the parameters of interest are the bandwidth ω_B , the peak value M_p of the gain characteristic, and the frequency ω_m at which the peak value occurs.

Opened-loop frequency response characteristics are useful in determining gain and phase margins, both of which are measures of relative stability. Relative stability of a closed-loop control system can be determined from the properties of the Bode plot of the opened-loop transfer function. However, this method can be used only if the opened-loop transfer function has no poles and zeroes in the right half S-plane (minimum phase characteristics).

Relative stability of a feedback control system is measured in terms of the gain and phase margins. For a minimum phase system, which is stable with the feedback loop open, the gain and phase margins must be positive in order for the system to be stable with the feedback loop closed. Negative gain and phase margins mean that the system will be unstable with the feedback loop closed. In general, a gain margin of 6 dB or more and a phase margin of 40° or more is recommended for most feedback control systems.