

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

IEEE Power and Energy Society

Sponsored by the
Energy Development and Power Generation Committee



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**Energy Development and Power Generation Committee
of the
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Abstract: This guide includes criteria, definitions, and test procedures for evaluating the dynamic performance of excitation control systems for synchronous machines as applied by electric utilities.

Keywords: Closed-loop performance, dynamic performance, excitation control systems, excitation system specifications, IEEE Std 421.2™, large signal disturbances, model, small signal disturbances, stabilizer, synchronous machine

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Introduction

This introduction is not part of IEEE Std 421.2-2014, IEEE Recommended Practice for Overvoltage and Insulation Coordination of Transmission Systems at 1000 kV AC and Above.

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 and Controls Subcommittee of the Energy Development and 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, IEEE Standard Definitions for Excitation Systems for Synchronous Machines and the now discontinued 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 included in Clause 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 a general introduction to the dynamic performance classification section to aid understanding, and the effects of excitation limiters are introduced. Clarifications have been introduced where technology advancements have changed approaches in modelling, such as the introduction of integral control terms whereby open-loop steady-state gain is considered infinite. Additional and improved figures have been introduced and some typical parameters are shown. It is important to note that this document is part of the IEEE 421 series of guides on the various aspects of excitation control systems for synchronous generators and that the IEEE Excitation Systems and Controls Subcommittee has also produced a tutorial on Power System Stabilization via Excitation Control which provides substantial supplemental material.

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1. Introduction

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 Figure 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 421.1TM -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 the closed-loop performance of excitation control systems, including synchronous machines, for both large and small signal disturbances. Confirming the adequacy of mathematical models for ~~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 will also be addressed (see IEEE Std 421.3TM, IEEE Std 421.4TM, and IEEE Std 421.5TM,). Portions of this guide will also serve as educational material for people who are becoming familiar ~~acquainted~~ with excitation control systems. This guide is applicable to excitation systems used on all sizes and types of synchronous machines including those in nuclear power facilities.

Traditionally, large signal performance (see 4.2) has been more closely associated with equipment specification and acceptance testing, while small signal performance (see 4.3) has been more closely associated with stability and model studies. Matching actual disturbance data with model simulations, however, requires that both large and small signal performance criteria be considered during design, specification, and acceptance testing.

¹ IEEE publications are available from The Institute of Electrical and Electronics Engineers (<http://standards.ieee.org/>) ~~IEEE Service Center, 445 Hoes Lane, Piscataway, NJ 08855-1331. The numbers in brackets refer to the references listed in 1-2.~~

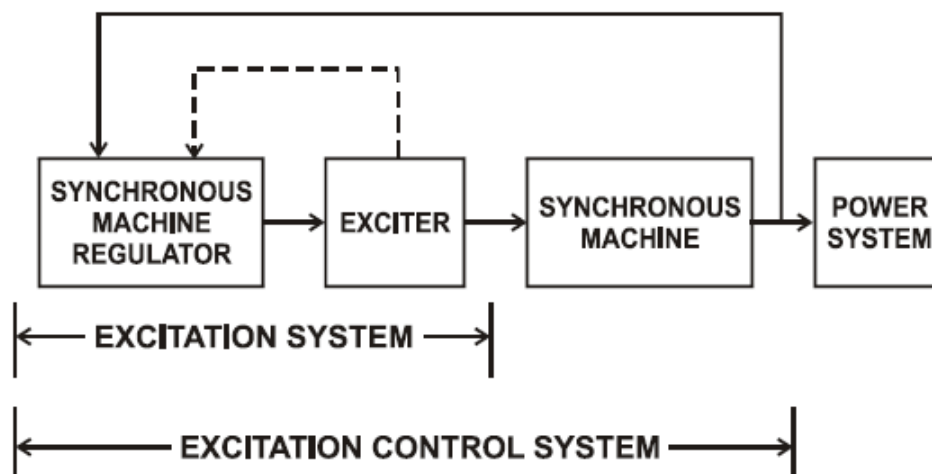


Figure 1 — Block diagram of an excitation control system

2. Normative references

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

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

~~[1] IEEE Std 100-1988, IEEE Standard Dictionary of Electrical and Electronics Terms (ANSI).~~

IEEE Std 421.1TM ~~1986~~, IEEE Standard Definitions for Excitation Systems for Synchronous Machines.¹
(ANSI).

[IEEE Std 421.3TM, IEEE Standard for High-Potential Test Requirements for Excitation Systems for Synchronous Machines.](#)

[IEEE Std 421.4TM, IEEE Guide for the Preparation of Excitation System Specifications.](#)

[IEEE Std 421.5TM, IEEE Recommended Practice for Excitation System Models for Power System Stability Studies.](#)

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

3. Definitions

[For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.² A complete set of excitation system definitions is presented in IEEE Std 421.1TM; however, definitions critical for using this guide are repeated here with additional clarification as needed for the specific application. Additionally, some feedback control system terms from are included.](#)

[air-gap field current:](#) [The synchronous machine field current required to produce rated voltage on the air-gap line of the synchronous machine.](#)

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air-gap field voltage: The synchronous machine field voltage required to produce rated voltage on the air-gap line of the synchronous machine with its field winding at 1) 75 °C for field windings designed to operate at rating with a temperature rise of 60 °C or less; or 2) 100 °C for field windings designed to operate at rating with a temperature rise greater than 60 °C.

NOTE—This defines one per unit excitation system voltage for use in computer representation of excitation systems (IEEE Std 421.5™), however, this value may need to be adjusted in certain simulations to match dynamic responses performed with the field winding temperature at other temperatures.³

automatic voltage regulator (AVR): This term refers to the controller that regulates the synchronous machine terminal voltage. More recent systems frequently include limiters, field current regulator and power system stabilizer with the AVR within the same electronic module. The term *excitation controller* may be used to refer to such an electronic module to emphasize that the included control algorithms adjust machine excitation with a wider purpose than simple regulation of terminal voltage.

ceiling current: The maximum field ~~direct~~ current that the excitation system is designed ~~able~~ to supply. Typically, this is related to the thermal capability of the excitation system equipment or the synchronous machine field circuit capability ~~from its terminals for a specified time.~~

NOTE—There can be separate short-time and steady-state values.

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

dynamic response: The output voltage of a control system or intermediate point in a system expressed as a function of time.

³ Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

excitation control system: The feedback control system that includes the synchronous machine and its excitation system. The term is used to distinguish the performance of the synchronous machine and excitation system in conjunction with the power system from that of the excitation system alone.

excitation limiter: A control function that provides an additional input to the voltage regulator to prevent a current, voltage, or other electrical quantity from exceeding preset limits. Typical excitation limiters include overvoltage (OV), volts/hertz (V/Hz), instantaneous and timed overexcitation limiter (OEL), underexcitation limiter (UEL), and stator overcurrent limiters (SCL). Individual limiters are described in IEEE Std 421.1™.

excitation system nominal response: A figure of merit for non-high initial response excitation systems related to the ability of the excitation system to respond to transient stability issues and to permit comparisons of excitation systems. The nominal response describes the rate of increase of the excitation system output voltage and is determined from the excitation system voltage response curve (see 5.6) ~~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 rated current: The direct current at the excitation system output terminals that the excitation system can supply under defined conditions of its operation. This current is at least that value required by the synchronous machine under the most demanding continuous operating conditions (generally resulting from synchronous machine voltage, frequency, and power factor variations).

excitation system rated voltage: The direct voltage at the excitation system output terminals that the excitation system provides when delivering excitation system rated current under rated continuous load conditions of the synchronous machine with its field winding at (1) 75 °C for field windings designed to operate at rating with a temperature rise of 60 °C or less; or (2) 100 °C for field windings designed to operate at rating with a temperature rise greater than 60 °C.

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.

high initial response (HIR): An excitation system capable of attaining 95% of the difference between ceiling voltage and rated field voltage in 0.1 s or less under specified conditions.

large signal performance: ~~The~~ Response of an excitation control system, excitation system, or elements of an excitation system to signals that are large enough ~~so~~ that nonlinearities must be included in the analysis of the response to obtain realistic results ~~are significant.~~

power system stabilizer (PSS): A function ~~An element or group of elements~~ that provides an additional input to the voltage regulator to improve the damping ~~dynamic performance~~ of ~~the~~ power system oscillations.

NOTE—A number of different quantities may be used as input to the power system stabilizer, such as shaft speed, frequency, electric power, etc., or a combination of these signals.

small signal performance: The response of an excitation control system, excitation system, or elements of an excitation system to signals that are small enough ~~so~~ that nonlinearities can be disregarded in the analysis of the response, and operation can be considered to be linear ~~are insignificant.~~

4. Dynamic performance classification

4.1 Overall

The subclauses below describe methods for tuning and testing excitation system functions as applied to synchronous generators. The techniques and discussions apply directly to analog electronic proportional style controls with feedback from various measured signals and measured with external testing and recording instruments. Actual excitation system equipment and test equipment, however, have evolved from magnetic and rotating devices, through analog electronic implementations to digital control implementations. Both the controls and the test equipment details must be understood and the techniques described below adapted appropriately to achieve the desired tuning goals. Additionally, modern controls may have multiple modes of operation where gains or feedback signals are changed to allow better performance depending on unit conditions such as start-up, on-line at full load, or shut-down. As a result, tests performed in one operating condition, e.g., off-line, may not capture the control gains and time constants which are in service under load. A thorough review of the control gains and time constants settings as well as logic, which may alter these parameters, must be performed prior to embarking on a testing and tuning program.

4.2 Large signal performance

Large signal performance is the response of an excitation control system, excitation system, or elements of an excitation system to signals that are large enough ~~so~~ that nonlinearities must be included in the analysis of the response to obtain accurate results ~~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 power 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 [all of](#) 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 ~~used to that~~ assess the large signal performance [include](#) ~~are~~ quantities such as [dynamic transient](#) responses, ceiling currents and voltages, voltage response times, and nominal responses derived from [dynamic time](#) responses (see ~~IEEE Std 100-1988, IEEE Standard Dictionary of Electrical and Electronics Terms (ANSI) [1] and IEEE Std 421.1TM-1986, IEEE Standard Definitions for Excitation Systems for Synchronous Machines (ANSI) [2]~~).

4.3 Small signal performance

Small signal performance is the response [of an excitation control system, excitation system, or elements of an excitation system](#) to signals ~~that which~~ are small enough that nonlinearities [can be disregarded in the analysis of the response, and operation can be considered to be linear](#) ~~are insignificant~~. Small signal performance of an excitation control system or its components can be assessed from [dynamic time](#) responses, frequency responses, or by eigenvalue analysis. (See [IEEE Std 421.5, Committee Report, 1973 \[B6\], IEEE Tutorial Course \[B23\], Kundur \[B29\], Kundur, et al. \[B30\], for examples](#).) ~~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 [oscillatory 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 [IEEE Std 421.5, Hurley and Baldwin \[B4\], and Dandeno, et al. \[B41\]](#).) ~~References [4] and [8]).~~ The assumption of linearity limits the application of small signal models as noted above.

4.4 Effects of excitation limiters

A modern excitation system used on a synchronous machine may have sufficient excess capability to supply excitation under all operating conditions. The voltage regulator utilizes various auxiliary control and limiting functions that are designed to enhance power system performance and reliability while protecting both the excitation system and the synchronous machine. These limiting functions generally have no effect on the excitation output during normal operating conditions, but protect the exciter and machine during severe unit or power system disturbances in which the excitation system is pushed near or beyond defined operating limits (see Carleton, Bobo, and Burt [B40], Eberly and Schaefer [B42], Overexcitation Limiting Devices [B43], Underexcitation Limiter Models [B44], Nagy [B46], Ribeiro [B47], Rubenstein and Temoshok [B48]).

Typical excitation limiters include overvoltage, volts/hertz, overexcitation (both instantaneous and timed), underexcitation, and stator current limiters. These limiters may act to either decrease or increase the excitation level of the synchronous machine, depending on the type of limiter and the power system circumstances. Where a power system stabilizer (PSS) is applied, limiters should coordinate with PSS functions, and preferably not block the stabilizing signal. (This is more critical for underexcitation limiters as instabilities develop more readily at reduced levels of machine field current.)

5. Large signal performance criteria

5.1 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 [systems 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 [to meet applicable reliability or interconnection requirements](#). ~~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.

[It should be noted that some of the criteria discussed below cannot be directly tested and, thus, might depend on a combination of testing and simulation techniques to be verified.](#)

[When specified in per unit \(pu\), the base value \(1 pu\) of synchronous machine field current is normally considered to be the current required to produce rated terminal voltage on the air-gap line \(see the annex in IEEE Std 421.5 on per unit system\). The corresponding value of synchronous machine base field voltage is the air-gap field voltage as defined in Clause 3 and IEEE Std 421.1.](#)

[Sometimes, the requirements for ceiling current and ceiling voltage may be specified in multiples of the values that produce rated terminal voltage on the synchronous machine open-circuit saturation curve, or in percent above the values required when the synchronous machine is loaded at rated conditions. These values should not be confused with the defined bases for field current and voltage; hence specification of ceiling current and ceiling voltage in this way is discouraged.](#)

[When performing simulations to match dynamic responses obtained with the synchronous machine field at temperatures other than the values given in the definitions in Clause 3, it may be necessary to use different values of base field voltage to get the correct excitation system pu gains. However, all performance measures are based on the use of the specified field winding temperatures. Some simulations may include a field winding temperature \(resistance\) factor that can be adjusted to match responses obtained under various conditions.](#)

5.2 Ceiling current

For some systems, the ability to attain ceiling current is important when the power system is operating at reduced voltage levels or under fault conditions to achieve maximum benefit to power system transient stability. In these cases ceiling current requirements with reduced excitation system supply voltage may need to be specified.

~~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 produces a specific value of steady-state, three-phase, short-circuit armature current for a specified time.

In some excitation systems (especially those that require ~~When~~ a high ~~value of~~ ceiling voltage is ~~required~~ for forcing action), exciter current limiter control functions ~~circuits~~ may determine the actual ceiling current. There may be separate requirements for short-term, mid-term, and sustained ceiling current for some excitation systems. The overexcitation limiter (OEL) and exciter or generator field overcurrent protection should be coordinated with these requirements (see IEEE Std C50.13TM).

Also, in some special applications, the excitation system may be required to supply both positive and negative field current to the synchronous machine. Negative field current can be used in a salient pole synchronous machine, operating as a condenser, to increase the reactive power absorption. This can be useful near high-voltage direct current (HVDC) stations or long transmission lines where extra reactive power absorption is required. A dedicated thyristor bridge connected anti-parallel to the positive field current bridge is necessary to supply the negative field current. The negative field current ceiling requirement will normally be smaller than the positive ceiling value.

5.3 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. A greater ~~the~~ difference between ~~the~~ ceiling voltage and ~~the~~ rated field voltage indicates ~~the~~ greater ~~the~~ forcing capability. Higher ceiling voltages tend to improve power system transient stability.

The no-load ceiling voltage is determined with the excitation system open-circuited (or with a high impedance load so minimal current will flow).

The excitation system ceiling voltage under load may be determined, [as described in 8.2](#), by either a steady-state or transient measurement. [The ceiling voltage is determined considering a specified supply voltage \(usually rated voltage\) and \(if applicable\) synchronous machine current](#) ~~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. [If testing is performed with a different supply voltage and \(if applicable\) current, analytical means may be used to predict the ceiling voltage with the specified supply.](#)

Some excitation systems will have both positive and negative values of ceiling voltage. [Positive ceiling voltage provides an indication of the voltage available to force the field current from rated field current toward ceiling current, while negative ceiling voltage provides an indication of the voltage available to force the field current to zero. Thus, large negative ceiling voltage aids in rapidly demagnetizing the synchronous machine.](#)

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

~~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]).~~

5.4 Excitation System Voltage Response Time

The excitation system voltage response time is the primary means for determining if an excitation system can be classified as high initial response. The voltage response time under load can only be determined by a transient measurement. The time measurement begins at the time the disturbance is initiated and ends when the dynamic response reaches 95% of the difference between ceiling voltage and rated field voltage. Adequate inductance is required in the load so that the time to reach 95% of the difference between ceiling voltage and rated voltage is measurable before the current begins to increase significantly above rated current and before any current limiters operate. The required load characteristics may not be practical to achieve in factory tests.

~~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]).~~

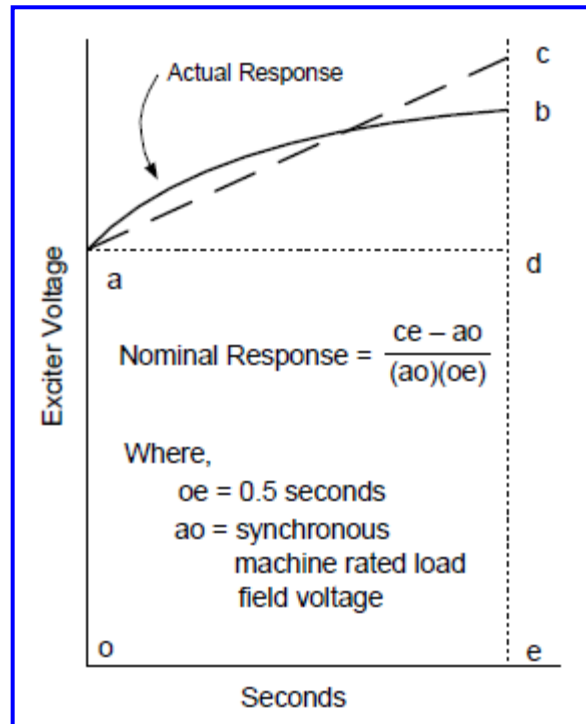
5.5 High initial response (HIR)

For excitation ~~these~~ 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 is 0.1 second or less are termed *high initial response* (HIR) excitation systems. The large signal response characteristics of these systems can be completely described by the ceiling voltage, voltage response time, and ceiling current.

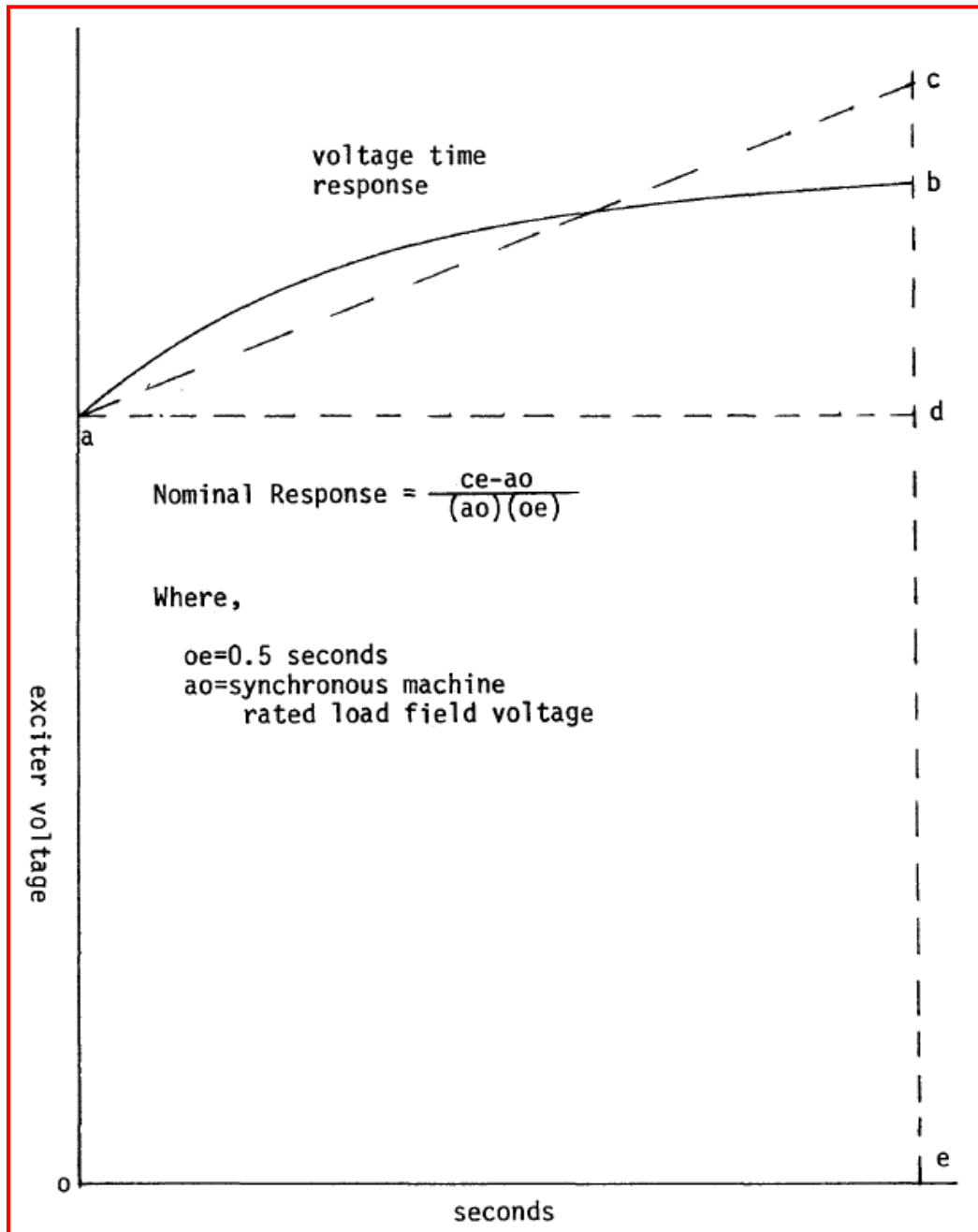
5.6 Excitation system nominal response

~~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]).~~ The nominal response is used as a figure of merit for non-HIR excitation systems to permit comparisons of excitation systems. It is related to the ability of an excitation system to respond to transient stability events ~~issues and to permit comparisons of excitation systems.~~ The basic underlying concept of nominal response, as related to power system stability, is developed in Annex B. The half second interval was selected to associate the nominal response with the excitation system contribution to power system transient stability.

The starting point for determining the nominal response is the time at which the disturbance is initiated; that is, the excitation system nominal response should include any delay time that may be present. Referring to Figure 2, the excitation system nominal response is illustrated by line ac. This line is determined by establishing area acd = area abd. Typical values of nominal response range from 0.2 to 2.0 pu/s with higher numbers representing more contribution to power system transient stability.



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Figure 2 — Excitation system nominal response

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 [421.1](#) ~~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 [dynamic](#) ~~time~~ responses obtained by recording responses during disturbances may be misleading when compared with factory tests because of the influence of fault induced currents [in the generator field winding](#).

5.7 [Large signal dynamic](#) ~~Transient~~ response

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 [match of these values](#) ~~specific response~~ can be achieved [using](#) ~~in~~ models with different combinations of model parameters. ~~This ambiguity can be reduced by~~ Comparing model results with [dynamic](#) ~~time~~ responses [can reduce this ambiguity. Thus, dynamic](#) ~~Although transient~~ response, [also](#) ~~(see 4.2) is more frequently~~ associated with small signal analysis, ~~it~~ is a useful [tool](#) ~~criteria~~ for large signal performance evaluation, especially for applications involving the refinement or validation of computer models.

A large signal [dynamic transient](#) response is a time response with the input and output variables of the component being tested, recorded as a function of time. Although [dynamic 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 result [response](#) to be useful. The change to the input variable must be specified. 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 [dynamic transient](#) response criteria. A [dynamic time](#) response with several variables recorded simultaneously has considerable value in the refinement or validation of large signal computer models.

6. Small signal performance criteria

6.1 General

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

6.2 [Small signal dynamic Transient](#) response

A typical [dynamic transient](#) response ([to a step input](#)) of a feedback control system is shown in Figure 3. The principal characteristics of interest are the [10% to 90%](#) rise time, overshoot, [peak time](#), and settling time as indicated.

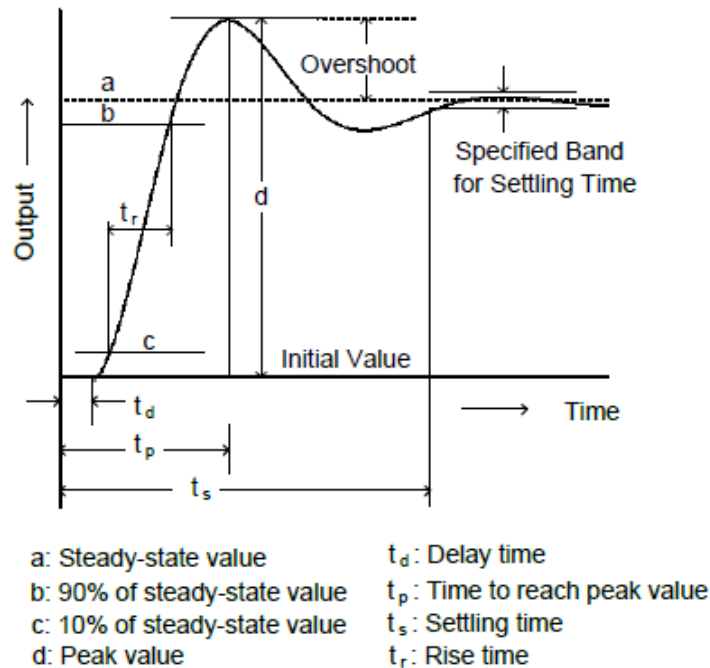


Figure 3 — Typical dynamic response of a feedback control system to a step change in input

6.3 Frequency response characteristic (linear system)

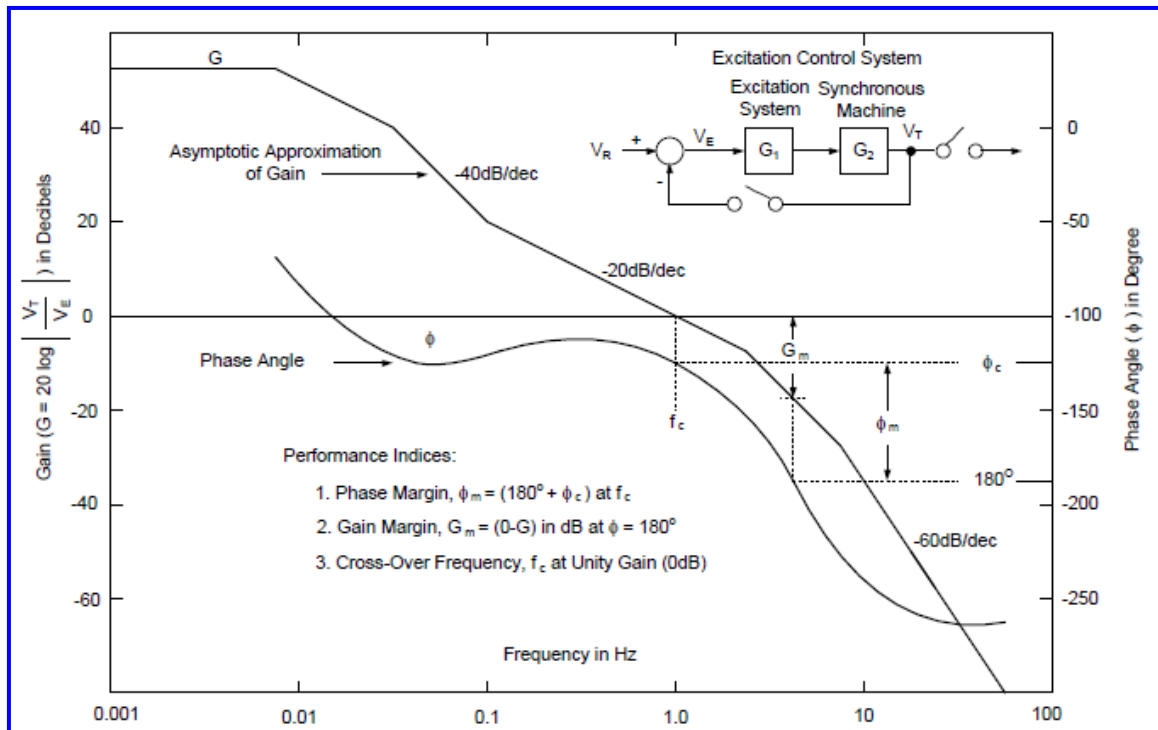
In a linear system, the frequency dependent relation, in both gain and phase difference, between steady-state sinusoidal inputs and the resultant steady-state sinusoidal outputs is called a frequency response. Both open-loop and closed-loop frequency responses are useful for assessing the performance of feedback control systems. For excitation systems, frequency responses of the automatic voltage regulator control loop are of primary interest. (see IEEE Std 421.1-1986, IEEE Standard Definitions for Excitation Systems for Synchronous Machines [2]).

6.3.1 Open-loop frequency response

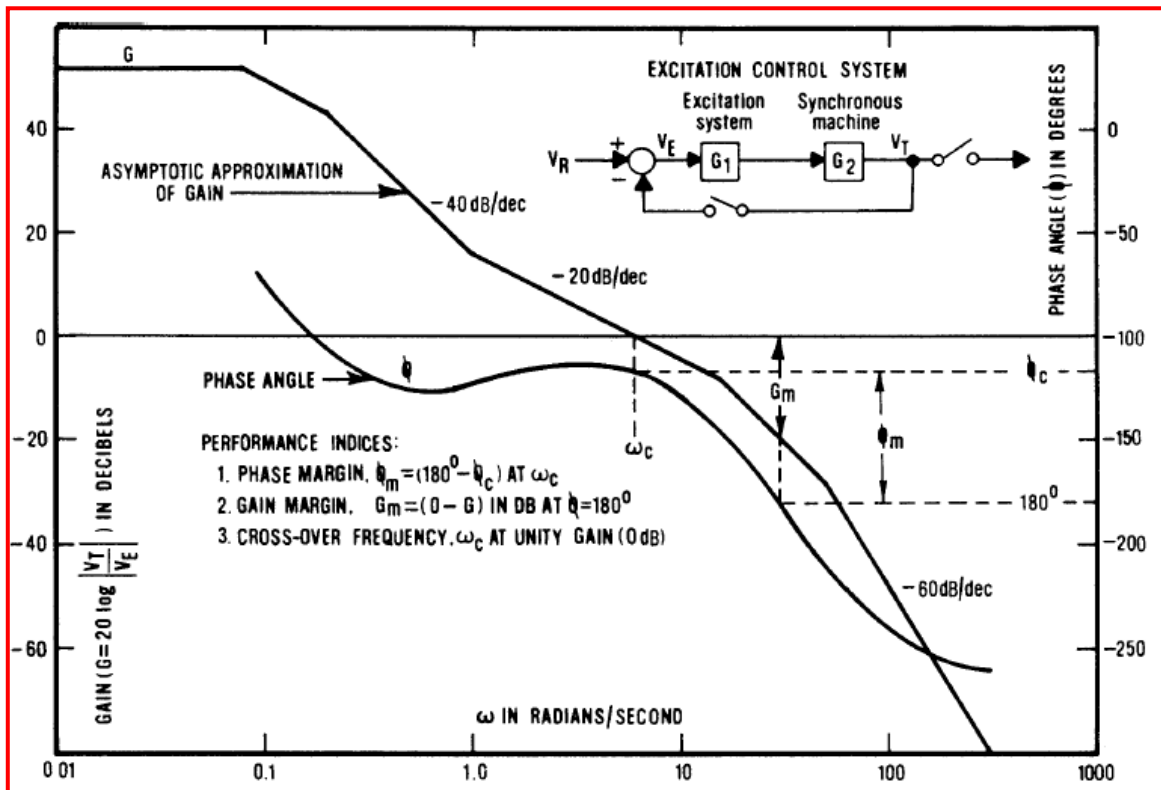
Typical open-loop frequency response characteristics of an excitation control system with the synchronous machine open-circuited ([off-line](#)) are shown in Figure 4. The principal characteristics of interest are the low frequency gain, G , [gain](#) crossover frequency, ω_c , phase margin, ϕ_m , and 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~~

[It is usually not practical to measure the open-loop frequency response characteristics of excitation control systems directly during field testing; however, many analysis techniques and instruments provide the tools for developing the open-loop transfer function of an excitation system from closed-loop measurements.](#)

Open-loop frequency response characteristics are useful in determining gain [margin](#) and phase margin, 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 open-loop transfer function. However, this method can be used only if the open-loop transfer function does not have any poles and/or zeros in the right half s plane (minimum phase characteristics).



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Figure 4 — Typical open-loop frequency response of an excitation control system with the synchronous machine open-circuited

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.

The process of determining stability of non-minimum phase (poles and /or zeros in the right half s