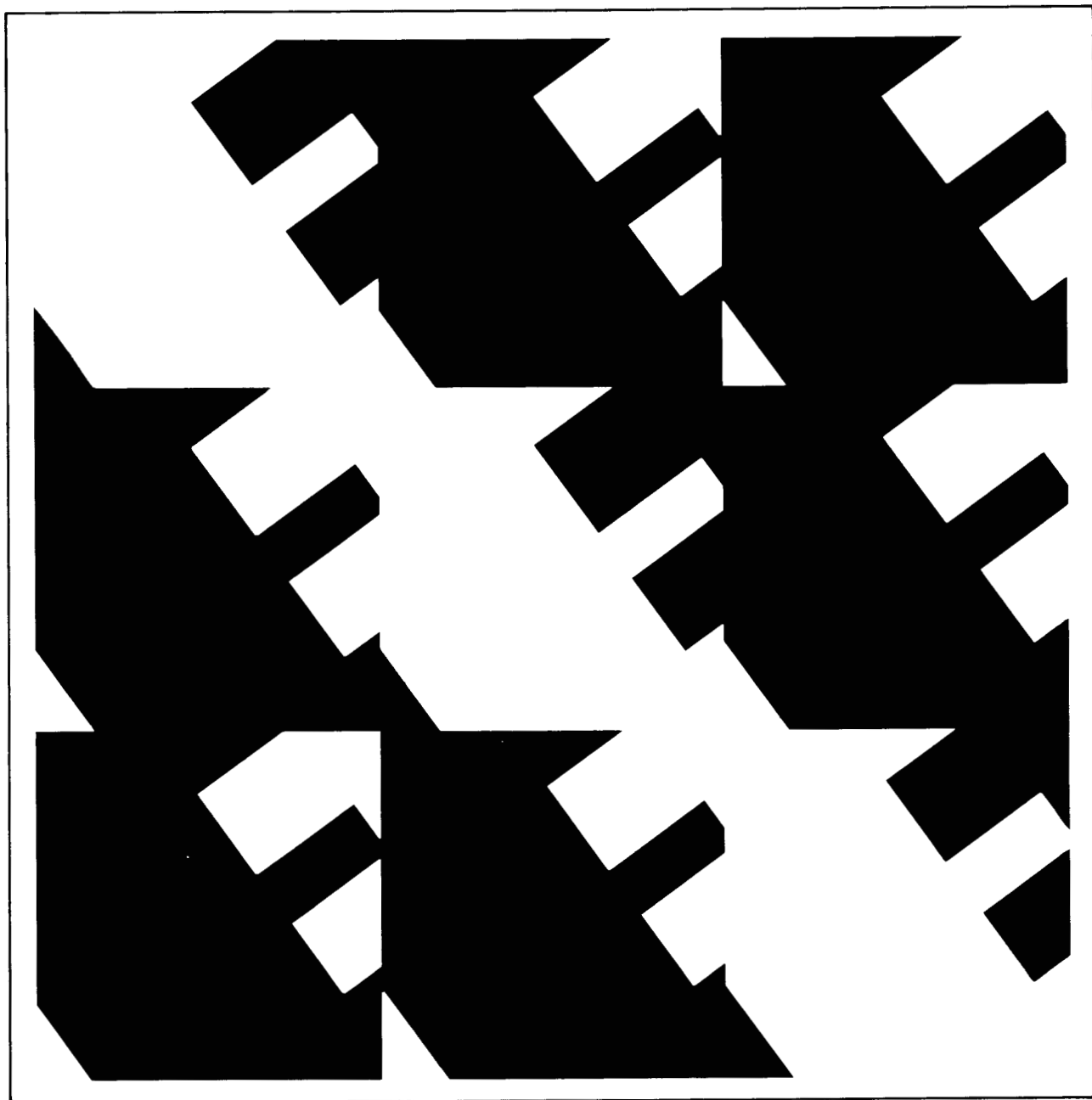


IEEE Guide for Identification, Testing, and Evaluation of the Dynamic Performance of Excitation Control Systems



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

Sponsor
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of the
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Foreword

(This Foreword is not a part of IEEE Std 421A-1978, Guide for Identification, Testing, and Evaluation of the Dynamic Performance of Excitation Control Systems.)

This guide presents dynamic performance criteria, definitions, and test procedures for excitation control systems as applied by electric utilities.

An excitation control system, including the synchronous machine and its excitation system, is a feedback control system. The Working Group on Excitation Control System Dynamic Performance of the Excitation System Subcommittee of the Power Generation Committee therefore adopted many definitions and performance criteria which are common to all feedback control systems and derived others specifically related to excitation control systems. In doing this, the material of IEEE Std 421-1972, IEEE Standard Criteria and Definitions for Excitation Systems for Synchronous Machines and ANSI C85.1-1963, Terminology for Automatic Control and its supplement, ANSI C85.1a-1966, was heavily drawn on. 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.

Prior to this guide, the only excitation system dynamic performance criteria contained in existing standards included excitation system voltage time response, excitation system response ratio, and voltage time response requirements of high initial response excitation systems. (See IEEE Std 421-1972 and IEEE Committee Report, Excitation System Definitions for Synchronous Machines, *IEEE Transactions on Power Apparatus and Systems*). These performance criteria are pertinent to the dynamic performance of excitation systems in response to large signal disturbances but are not indicative of system response to small signals. This guide supplements existing large signal performance criteria with small signal performance criteria and test procedures. These additional criteria and test procedures are essential for fully evaluating the closed-loop performance of excitation control systems and for confirming the adequacy of mathematical models of excitation systems for use in analytical studies of power systems. Furthermore, it should be specifically noted that the term excitation control system refers to the entire feedback control system including the synchronous machine as well as its excitation system. It is the performance of the entire feedback control system which is of paramount importance.

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 are not available preclude field testing of the exciter separately. Compound-rectifier excitation systems whose source of power is derived from the generator currents and voltages present special difficulties. Even 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. 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. (See IEEE Std 421-1972 and IEEE Committee Report.)

Portions of the test procedure for determining excitation control system frequency response and voltage regulator and exciter gain, recommended in this guide, are based on that formulated by the Oscillations Working Group of the Operating Committee of the Western Systems Coordinating Committee, Test Procedures Sub-Work Group. Members of that working group included: F. R. Schleif, *Chairman*, J. N. Haroian, T. Hillesland, L. A. Kenoyer, A. Klopfenstein, R. L. Krahn, J. F. Luini, G. R. Meloy, and J. Schmitt.

Appreciation is expressed to the following former members of the working group who participated in the development of this guide: R. L. Krahn, G. Manchur, and F. R. Schleif.

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

1. Scope

This guide includes criteria, definitions, and test procedures for evaluating the dynamic performance of excitation control systems as applied by electric utilities. Primary purposes are to provide a basis for evaluating closed-loop performance of excitation control systems (including both the synchronous machine and its excitation system) for both large and small signal disturbances; confirming the adequacy of mathematical models of excitation systems for use in analytical studies of power systems; specifying methods for performing tests of excitation control systems and their components; and preparing excitation system specifications and additional standards. Portions of this guide will also serve as an educational means for people becoming acquainted with excitation control systems.

2. Dynamic Performance Classification

2.1 Large Signal Performance. Large signal performance involves changes in control system variables, where the magnitude is sufficiently great that nonlinearities must be included for realistic results.

The purpose of large signal performance criteria is to provide a means of evaluating excitation system performance for severe transients including high generator stator voltages, low generator stator voltages, and high induced generator field currents, that is, for transients associated with questions of system transient stability. To assess the ability of the excitation system to improve generator performance, the criteria must reflect the effects of operation under realistic power system disturbances. Loading and regulation effects are thus of major importance. With respect to perfor-

mance 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 or no load, analytical means may be used to predict performance under actual operating conditions.

The criteria which assess the large signal performance of exciters or excitation systems are real-time quantities (transient response) such as ceiling voltages, time responses, and response times and ratios. These are derived from real-time graphs, such as those shown in Figs 1 and 2.

2.2 Small Signal Performance. Small signal performance of an excitation control system, excitation system, or of the individual components of the excitation system is the response to signals which are small enough that nonlinearities can be disregarded and the operation of the system can be considered to be linear. Small signal performance of a system or its components can be described in terms of real-time parameters (transient response) as for large signal disturbances, or in terms of gain, phase angle, and frequency (frequency response) derived from frequency response graphs such as the ones shown in Figs 3 or 4, or by eigenvalue analysis.

Small signal performance criteria provide a means of evaluating the response of excitation control systems for incremental load changes, incremental voltage changes, and the incremental changes in generator rotor speed associated with the initial stages of dynamic instability (where oscillations are small enough that saturation limits are not reached). Small signal performance data provide a means for determining or verifying excitation system model parameters for system studies [11].¹

¹Numbers in brackets correspond to those of the references listed in Section 7 of this guide.

The assumption of linearity limits the application of small signal models as noted above.

3. Large Signal Performance Criteria

3.1 General. Large signal performance criteria (see 2.1) are as follows for excitation systems and, where applicable, for their components. To permit maximum flexibility in the design, manufacture, and application of excitation equipment, the majority of performance criteria as follows are defined "under specified conditions." The applicable conditions may be specified by the manufacturer or, more usually, by the equipment purchaser.

3.2 Excitation Systems

3.2.1 Excitation System Ceiling Voltage. The maximum dc component of system output voltage that may be attained by an excitation system under specified conditions [1], [2].

NOTE: In some excitation systems, ceiling voltage may have both positive and negative values. Also, in some special applications, the excitation system is capable of supplying both positive and negative field current to the synchronous machine.

3.2.2 Excitation System Nominal Ceiling Voltage. The ceiling voltage attained by an excitation system under the following conditions:

(1) The exciter loaded with a resistor having an ohmic value equal to the resistance of the field winding to be excited and with this field winding at a temperature of 75°C for field windings designed to operate at rating with a temperature rise of 60°C or less; or 100°C for field windings designed to operate at rating with a temperature rise greater than 60°C [1], [2].

NOTE: For rectifier exciters nominal ceiling voltage should be determined with the exciter loaded with a load having resistance as specified above and sufficient inductance so that regulation effects and voltage and current waveforms can be properly duplicated. For test purposes, providing such a load may often be impractical. In such cases, analytical means may be used to predict performance under actual loading conditions.

(2) For excitation systems employing a rotating exciter, the ceiling should be determined at rated speed.

(3) For potential-source rectifier excitation systems, the ceiling should be determined with rated (100 percent) potential applied unless otherwise specified.

(4) In compound-rectifier excitation systems both generator voltage and current inputs are utilized as the source of power for the excitation system. The nominal ceiling voltage will be determined under specified reduced generator terminal voltage and increased generator terminal current conditions as would be encountered during power system faults and other disturbances.

For some applications where relay coordination is a consideration, the ceiling voltage will be determined by a requirement that the generator produce a specific value of steady-state three-phase short circuit current.

3.2.3 Excitation System Voltage Time Response [1], [2]. The excitation system output voltage expressed as a function of time, under specified conditions.

3.2.4 Excitation System Voltage Response Time [1], [2]. The time in seconds for the excitation voltage to attain 95 percent of the difference between ceiling voltage and rated load field voltage under specified conditions.

3.2.5 Excitation System Voltage Response. The rate of increase or decrease of the excitation system output voltage determined from the excitation system voltage-time response curve, which rate if maintained constant, would develop the same voltage-time area as obtained from the curve for a specified period. The starting point for determining the rate of voltage change shall be the initial value of the excitation system voltage time response curve. Referring to Fig 1, the excitation system voltage response is illustrated by line *ac*. This line is determined by establishing the area *acd* equal to area *abd* [1], [2].

NOTES:

(1) The starting point for determining the rate of voltage change shall be the initiation of the disturbance, that is, the excitation system voltage time response should include any delay time that may be present.

(2) A system having an excitation system voltage response time of 0.1 s or less is defined as a high response excitation system [1], [2].

3.2.6 Excitation System Voltage Response Ratio. The numerical value that is obtained when the excitation system voltage response, in volts per second, measured over the first ½ s interval, unless otherwise specified, is divided by the rated load field voltage of the synchronous machine [1], [2]. The basis underlying the concept of response ratio is developed in Appendix A.

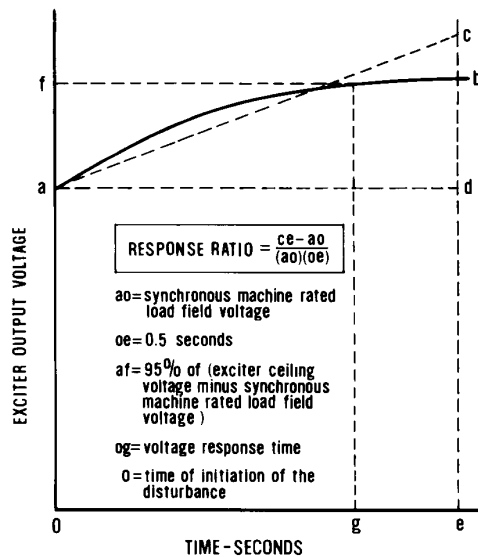


Fig 1
Exciter or Excitation System Voltage Response

NOTES:

(1) Referring to Fig 1, the excitation system response ratio, unless otherwise specified, shall apply only to the increase in excitation system voltage [1], [2].

(2) Response ratio is determined with the exciter voltage initially equal to the rated load field voltage of the synchronous machine to which the exciter is applied, and then suddenly establishing circuit conditions required to obtain nominal exciter ceiling voltage [1], [2]. Excitation system response ratio is determined by suddenly reducing the voltage sensed by the synchronous machine voltage regulator from 100 percent to 80 percent unless otherwise specified.

(3) Unless otherwise specified, excitation system response ratio should be determined with the exciter loaded as specified in 3.2.2. If, for practical considerations, the test is performed at no load, analytical means may be utilized to predict the performance under load.

(4) For excitation systems employing a rotating exciter, the response ratio should be determined at rated speed.

(5) For potential-source rectifier excitation systems, the nature of a power system disturbance greatly affects the available power supply voltages. The ceiling voltage available and the voltage response time are more meaningful parameters. To specify a response ratio implies equivalence with other systems whose output is not adversely affected by such depressed voltage conditions. Therefore, response ratio is not recommended as a specification parameter for these excitation systems.

(6) For compound-rectifier excitation systems, the nature of the power system disturbance and the specific design parameters of the exciter and the synchronous generator influence the performance of the exciter output voltage. For equivalence with rotating exciters, the response ratio should be based on performance under specified reduced generator terminal voltage and increased generator stator current condi-

tions as would be encountered during power system faults and disturbances.

3.3 Excitation System Components

3.3.1 Exciter. All of the large signal performance criteria above, 3.2.1 through 3.2.6, may be applied to the exciter alone as defined in [1]. Historically, the response ratio of the exciter alone has frequently been specified. It is recommended that excitation system response ratio rather than exciter response ratio be used as a large signal performance criterion for excitation control systems.

3.3.2 Voltage Regulator. While IEEE Std 421-1972, Criteria and Definitions for Excitation Systems for Synchronous Machines, recognizes that similar criteria might also be applied to the regulator alone [1], [2], it is recommended that the concept of response ratio not be applied to the regulator.

3.4 Summary. Excitation system response ratio is a well established and useful criterion for evaluating the large signal performance of excitation systems employing rotating exciters. Excitation system response ratio is also applicable to compound-rectifier excitation systems for the reduced terminal voltage and increased terminal current conditions that exist during power system disturbances. For excitation systems with potential-source rectifier exciters, available ceiling voltage and excitation system voltage response time are more meaningful parameters, and it is recommended that these parameters, rather than response ratio, be used as large signal performance criteria for these systems.

4. Small Signal Performance Criteria

4.1 General. Small signal performance criteria (see 2.2) applicable to excitation control systems are given in this section.

4.2 Transient Response. A typical transient response of a feedback control system is shown in Fig 2. The principal characteristics of interest are the rise time, overshoot, and settling time as indicated in Fig 2 [3].

NOTE: In some applications, the time to attain 10 percent of steady-state value is of interest. This time may be appreciable even though the delay time may be very small or even zero.

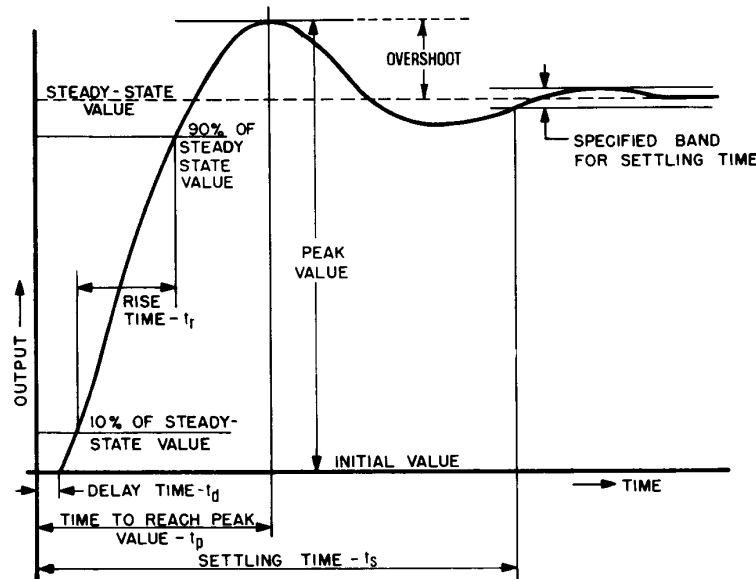


Fig 2

Typical Time Response of a Feedback Control System to a Step Change in Input

4.3 Frequency Response. Typical open-loop frequency response characteristics of an excitation control system with the synchronous machine open-circuited are shown in Fig 3. 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 4. 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 it occurs.

Open-loop frequency response characteristics are useful in determining gain and phase margins, both of which are measures of relative stability for unconditionally stable systems having minimum phase characteristics. Conditionally stable systems and systems having non-minimum phase characteristics (refer to the definitions in Appendix E) require special consideration. In general, a phase margin of 40° or more and a gain margin of 6 dB or more is considered good design practice for most feedback control systems [6], [7], [8].

With respect to the closed-loop frequency response characteristics, the peak value M_p of the amplitude response is also a measure of relative stability. A high value of M_p (>1.6) is indicative of an oscillatory system exhibiting

large overshoot in its transient response. In general, $1.1 \leq M_p \leq 1.6$ is considered good design practice for most feedback control systems [6], [7], [8].

Bandwidth ω_B is a significant closed-loop frequency response performance index because it is indicative of the rise time T_r or speed of the transient response of the system; it measures in part the ability of the system to reproduce input signals, and it approximately describes the filtering or noise-rejection characteristics of the system. In feedback control systems having a step-response exhibiting less than ten percent overshoot, rise time T_r in seconds is related to bandwidth ω_B in Hz by the approximate relationship:

$$T_r \omega_B = 0.30 \text{ to } 0.45$$

In general, the product $T_r \omega_B$ increases as the overshoot in the system transient response increases; values in the range of 0.3 to 0.35 correspond to negligible overshoot; values in the region of 0.45 correspond to systems with about 10 percent overshoot [7].

With respect to excitation systems, the wider the bandwidth, the greater is the potential of the excitation system to contribute positive damping to power system oscillations over a broader frequency range when the excitation

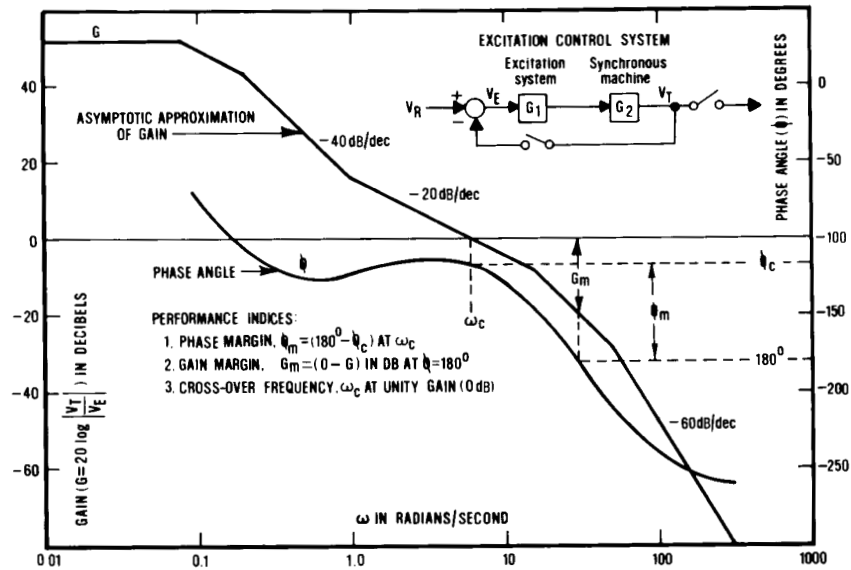


Fig 3
Typical Open-Loop Frequency Response of an Excitation Control System
with the Synchronous Machine Open Circuited

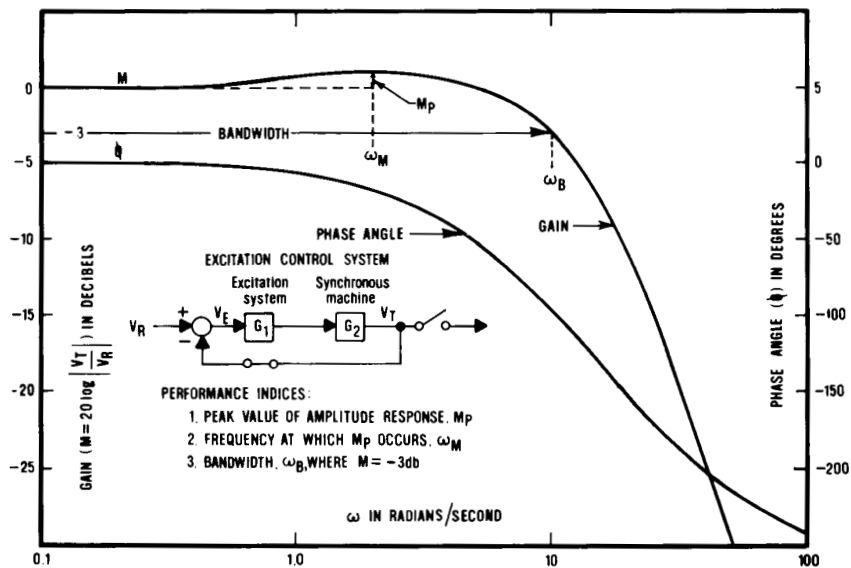


Fig 4
Typical Closed-Loop Frequency Response of an Excitation Control System
with the Synchronous Machine Open Circuited

system is equipped with a properly aligned power system stabilizer as described in 4.5 and 6.3. On the other hand, the wider the bandwidth of the excitation system, the greater is its potential to contribute negative damping at higher (>5 Hz) frequencies encompassing the natural frequencies of the generator mechanical torsional system. This possibility should be thoroughly investigated in specific individual applications as described in 4.7.

Generally accepted values of the performance indices described above characterizing good feedback control system performance are tabulated in Table 1.

4.4 Small Signal Performance Indexes. It is not possible to define such generally acceptable ranges of values for the other small signal performance indexes: rise time, settling time, and bandwidth. These indexes are measures of relative speed of control action. In most feedback control systems, they are primarily determined by the dynamic characteristic of the system element whose output is the ultimately controlled variable. In the case of an excitation control system, the dynamic characteristics of the synchronous machine (field time constant, etc) are the determining factors.

It should be noted that simultaneous optimization of all small signal performance indexes is not possible. For example, low M_p , high gain margin, and high phase margin are not compatible with maximum bandwidth. Those performance indexes which are of primary importance depend on the individual application of each feedback control system, and no universally applicable "best criteria" can be recommended in standards.

Typical ranges of values of small signal performance indexes for an excitation control system are given in Table 2. These data have been derived analytically using the anticipated extreme ranges (longest to shortest) of synchronous machine field time constants and

Table 2
Range of Excitation Control System Small Signal Dynamic Performance Indexes

Performance Index	Range of Expected Values
Excitation system gain	50 – 800 per unit
Gain margin	2 – 20 dB
Phase margin	20 – 80 degrees
M_p	1.0 – 4.0 (0 – 12 dB)
Bandwidth	0.3 – 12 Hz
Overshoot	0 – 80 percent
Rise time	0.1 – 2.5 s
Settling time	0.2 – 10.0 s

excitation system time constants likely to be encountered.

The performance indices of Table 1 are applicable to any feedback control system having a single major feedback loop, that is, a single ultimately controlled variable [6], [7], [8]. As such, they are applicable to an excitation control system with the synchronous machine unloaded. A loaded synchronous machine connected to a power system is a complex multiloop, multivariable, feedback control system.

For a loaded synchronous machine connected to a multimachine interconnected power system, performance indexes such as those of Table 1 lose much of their significance. The loaded generator is a multiloop system, hence analysis and synthesis techniques that are applicable to this type of problem should be used. One approach to assessing the performance of this complex system is to model the system using state-space techniques and calculating the eigenvalues (characteristic equation roots) for the range of excitation system, generator, and system parameters of interest [50]. The state-space model can be derived from known plant and system parameters, operating conditions, and experimental frequency response data, if the later is available. The calculation of eigenvalues gives a direct indication of system stability for the linearized system and serves as an efficient initial step before testing the selected parameters in a more extensive study such as a transient stability study. The quadratic performance index and other indexes that utilize the state space-model are measures of the ability of a multiloop control system to meet specified criteria.

Table 1
Generally Accepted Values of Indexes Characterizing Good Feedback Control System Performance

Gain margin	≥ 6 dB
Phase margin	$\geq 40^\circ$
Overshoot	5 – 15 percent
M_p	1.1 – 1.6 0.8 – 4 dB

When a synchronous machine is connected to a power system, its operating level, and the parameters of the external system greatly influence performance [36], [37], [39]. Fig 5 serves to illustrate some of these effects. Fig 5 shows calculated frequency response characteristics of the transfer function $\Delta VT/\Delta E_{FD}$ for a typical large generator at three operating points: torque angles of 0° , 72° , and 102° , respectively. The characteristics of Fig 5 are calculated for a generator connected to an infinite bus through an external reactance with no voltage regulator or governor action. Torque angle depends on machine characteristics, machine operating point, and on the magnitude of external impedance.

Fig 5 shows that the dynamic characteristics of a generator change dramatically when the torque angle increases. Fig 5 shows that an unloaded generator ($\delta = 0^\circ$) behaves as a simple inductive circuit with a single time constant. The maximum phase lag is 90° , occurring when the frequency ω reaches infinity. Fig 5B and C shows characteristic resonant peaks appearing in the gain function accompanied by a sudden dip in the phase angle. These characteristics are attributable to poorly damped complex poles introduced into the transfer function of the generator by increasing the torque angle.

The highly oscillatory characteristics of a synchronous machine operating at high torque angle can readily lead to instability when the machine is operated in a closed-loop feedback control system with a voltage regulator. It is frequently necessary to apply supplementary control, that is, a power system stabilizer, to compensate for these characteristics to ensure stable operation and improve damping of oscillations arising from system disturbances. Application of power system stabilizers is described in 4.5 and in Appendix C. Suggested procedures for field testing and alignment of power system stabilizers are given in 6.3 and Appendix D.

4.5 Application of Power System Stabilizers. A power system stabilizer is an element or group of elements which provide an additional input to the regulator to improve power system dynamic performance. A number of different quantities may be used as input to the power system stabilizer such as shaft speed, frequency, synchronous machine electrical power, accelerating power, and others. Power

system stabilizers are employed to solve two separate but related problems.

4.5.1 Local Machine-System Oscillations. The use of high initial response excitation systems allows extremely fast terminal voltage regulation. When operating with high regulator gain, the synchronizing torque coefficient is enhanced, and from this point of view wider torque angle operating limits would be expected. As the gain of the voltage regulator is increased, however, negative damping is introduced into the machine torque-speed loop [20]. Depending on the desired gain and the system in which it is employed, the machine-system oscillations (1 to 2 Hz) may become negatively damped. In order to preserve the high synchronizing torque coefficient, and restore the damping torque, power system stabilizers are used.

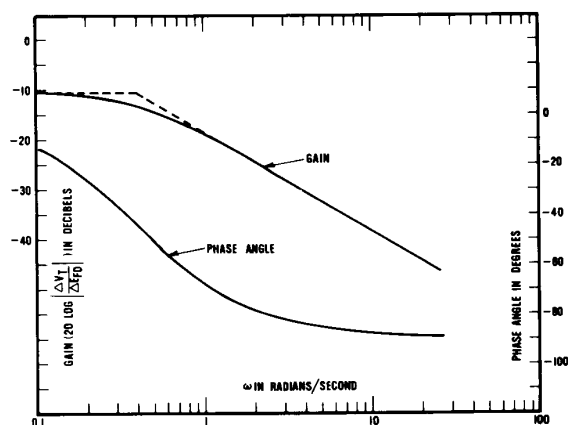
4.5.2 Interarea Oscillations. Conventional excitation systems with a slower response are generally not capable of changing terminal voltage fast enough to significantly affect the damping of the local mode of oscillation.

Interarea oscillations are normally of a much lower frequency (≤ 0.3 Hz) than the local mode. Power system stabilizers can gainfully be employed with many of these systems (as well as with the faster systems) to damp these low-frequency swings.

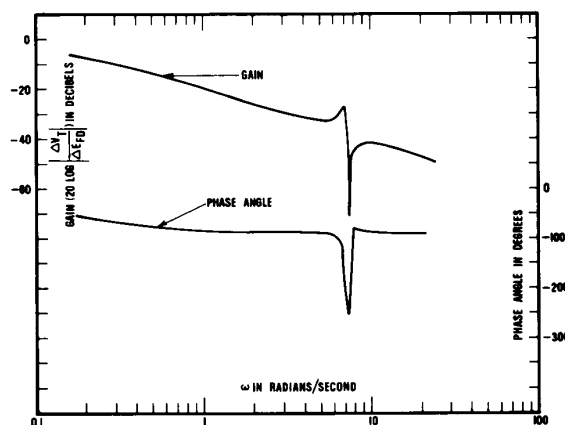
The transfer function of a typical power system stabilizer is shown in Fig 6. The parameter values depend upon the nature of the input signal and the specific application of the stabilizer. Design ranges of typical parameters for power system stabilizers that have been applied in the United States are given in Table 3. Suggested procedures for field testing and alignment of power system stabilizers are given in 6.3 and Appendix D of this guide.

The power system stabilizers control signal transducer should provide a relatively noise free output (the total influence of ripple or random noise should not exceed 10 percent of the dynamic range of the output of the power system stabilizer) proportional to the deviation of the input quantity with time constant $T_Q \leq 0.04$ s.

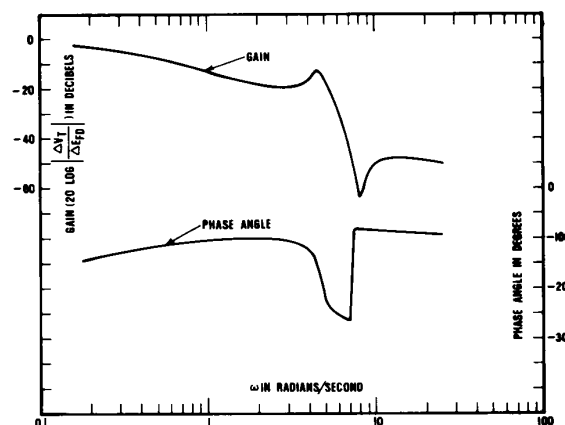
The fundamental function of the signal conditioning network of the power system stabilizer is to compensate for the phase lags of the system being controlled. Phase compensation is generally accomplished by the use of lead-lag functions providing phase lead over the frequency range of interest. With practical



A



B



C

Fig 5

Frequency Response Characteristics of a Typical Synchronous Machine with No Voltage Regulator Nor Governor Action as a Function of Torque Angle
A — Unloaded Machine Operating at 0° Torque Angle; B — Loaded Machine Operating at 72° Torque Angle; C — Loaded Machine Operating at 102° Torque Angle