IEEE Recommended Practice for Excitation System Models for Power System Stability Studies

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Abstract: Excitation system models suitable for use in large-scale system stability studies are presented. Important limiters and supplementary controls are also included. The model structures presented are intended to facilitate the use of field test data as a means of obtaining model parameters. The models are, however, reduced order models and do not represent all of the control loops on any particular system. The models are valid for frequency deviations of ±5% from rated frequency and oscillation frequencies up to 3 Hz. These models would not normally be adequate for use in studies of subsynchronous resonance or other shaft torsional interaction problems. Delayed protective and control features that may come into play in long term dynamic performance studies are not represented. A sample set of data for each of the models, for at least one particular application, is provided.
Keywords: excitation limiters, excitation systems, power system stability

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Introduction

(This introduction is not part of IEEE Std 421.5-2005, IEEE Recommended Practice for Excitation System Models for Power System Stability Studies.)

Excitation system models suitable for use in large-scale system stability studies are presented in this recommended practice. With these models, most of the excitation systems currently in widespread use on large, system-connected synchronous machines in North America can be represented.

In 1968, models for the systems in use at that time were presented by the Excitation System Subcommittee and were widely used by the industry. Improved models that reflected advances in equipment and better modeling practices were developed and published in the *IEEE Transactions on Power Apparatus and Systems* in 1981. These models included representation of more recently developed systems and some of the supplementary excitation control features commonly used with them. In 1992, the 1981 models were updated and presented in the form of recommended practice IEEE Std 421.5-1992. In 2005, this document was further revised to add information on reactive differential compensation, excitation limiters, power factor and var controllers, and new models incorporating proportional, integral, and differential (PID) control.

The model structures presented are intended to facilitate the use of field test data as a means of obtaining model parameters. The models are, however, reduced order models and do not represent all of the control loops on any particular system. The models are valid for frequency deviations of ±5% from rated frequency and oscillation frequencies up to 3 Hz. These models would not normally be adequate for use in studies of subsynchronous resonance or other shaft torsional interaction problems. Delayed protective and control features that may come into play in long-term dynamic performance studies are not represented. A sample set of data for each of the models, for at least one particular application, is provided.

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IEEE Recommended Practice for Excitation System Models for Power System Stability Studies

1. Overview

1.1 Scope

When the behavior of synchronous machines is to be simulated accurately in power system stability studies, it is essential that the excitation systems of the synchronous machines be modeled in sufficient detail (see Byerly and Kimbark [B7][1]). The desired models must be suitable for representing the actual excitation equipment performance for large, severe disturbances as well as for small perturbations.

A 1968 IEEE Committee Report (see [B18]) provided initial excitation system reference models. It established a common nomenclature, presented mathematical models for excitation systems then in common use, and defined parameters for those models. A 1981 report (see IEEE Committee Report [B20]) extended that work. It provided models for newer types of excitation equipment not covered previously as well as improved models for older equipment.

This document, based heavily on the 1981 report, is intended to again update the models, provide models for additional control features, and formalize those models in a recommended practice. To some extent, the model structures presented in this document are intended to facilitate the use of field test data as a means of obtaining model parameters. The models are, however, reduced order models, and they do not represent all of the control loops on any particular system. In some cases, the model used may represent a substantial reduction, resulting in large differences between the structure of the model and the physical system.

The excitation system models themselves do not allow for regulator modulation as a function of system frequency, an inherent characteristic of some older excitation systems. The models are valid for frequency deviations of ±5% from rated frequency and oscillation frequencies up to about 3 Hz. These models would not normally be adequate for use in studies of subsynchronous resonance or other shaft torsional interaction problems. Delayed protective and control functions that may come into play in long-term dynamic performance studies are not represented. See additional information in Annex F.

Where possible, the supplied models are referenced to commercial equipment and vendor names shown in Annex I. This information is given for the convenience of users of this recommended practice and does not

[1]The numbers in brackets correspond to those of the bibliography in Annex J.

constitute an endorsement by the IEEE of these products. The models thus referenced may be appropriate for equivalent excitation systems supplied by other manufacturers.

A sample set of data (not necessarily typical) for each of the models, for at least one particular application, is provided in Annex H. A suffix “A” is used for the designation of models introduced or modified in IEEE Std 421.5-1992, and a suffix “B” is used for models introduced or modified in this latest recommended practice, IEEE Std 421.5-2005.

Modeling work outside of the IEEE is documented in IEC 60034-16:1991 [B17]. Additional background is found in IEEE Committee Report [B19].

2. Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

ANSI C50.10 American National Standard for Rotating Electrical Machinery—Synchronous Machines.[2]

IEEE Std 115™, IEEE Guide: Test Procedures for Synchronous Machines—Part I: Acceptance and Performance Testing; Part II: Test Procedures and Parameter Determination for Dynamic Analysis.[3, 4]

IEEE Std 421.1™, IEEE Definitions for Excitation Systems for Synchronous Machines.

IEEE Std 421.2™, IEEE Guide for Identification, Testing, and Evaluation of the Dynamic Performance of Excitation Control Systems.

IEEE Std 421.3™, IEEE Standard for High Potential-Test Requirements for Excitation Systems for Synchronous Machines.

IEEE Std 421.4™, IEEE Guide for the Preparation of Excitation System Specifications.

IEEE Std C50.13™, IEEE Standard for Cylindrical-Rotor 50 Hz and 60 Hz, Synchronous Generators Rated 10 MVA and above.

3. Representation of synchronous machine excitation systems in power system studies

The general functional block diagram shown in Figure 3-1 indicates various synchronous machine excitation subsystems. These subsystems may include a terminal voltage transducer and load compensator, excitation control elements, an exciter, and in many instances, a power system stabilizer (PSS). Supplementary discontinuous excitation control may also be employed. Models for all of these functions are presented in this recommended practice.

[2]ANSI publications are available from the Sales Department, American National Standards Institute, 25 West 43rd Street, 4th Floor, New York, NY 10036, USA (http://www.ansi.org/).

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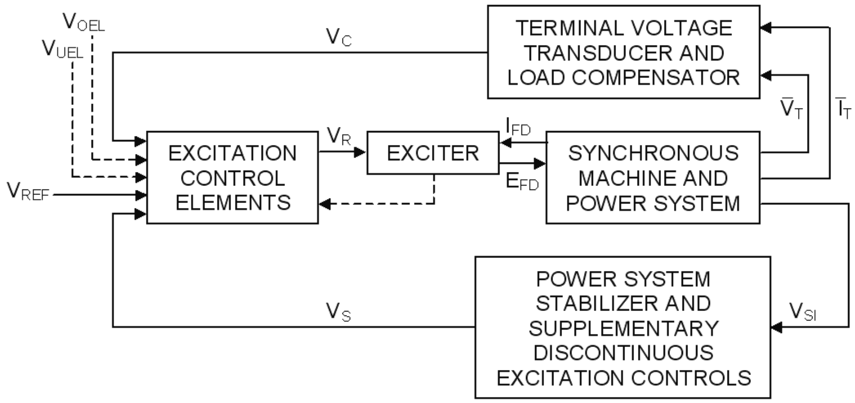


Figure 3-1—General functional block diagram for synchronous machine excitation control system

Excitation control elements include both excitation regulating and stabilizing functions. The terms *excitation system stabilizer* and *transient gain reduction* are used to describe circuits in several of the models encompassed by the excitation control elements shown in Figure 3-1 that affect the stability and response of those systems.

Recently, modeling of field current limiters has become increasingly important, resulting in the addition to this recommended practice of Clause 9 and Clause 10 describing overexcitation and underexcitation limiters (OELs and UELs, respectively). The individual excitation system models in this document show how the output signals from such limiters (V_{OEL} and V_{UEL}) would normally be connected.

The output of the UEL may be received as an input to the excitation system (V_{UEL}) at various locations, either as a summing input or as a gated input, but for any one application of the model, only one of these inputs would be used.

For the OEL some models provide a gate through which the output of the overexcitation limiter or terminal voltage limiter (V_{OEL}) could enter the regulator loop.

In the implementation of all of the models, provision should be made for handling zero values of parameters. For some zero values, it may be appropriate to bypass entire blocks of a model.

The per unit (pu) system used for modeling the excitation system is described in Annex B.

Three distinctive types of excitation systems are identified on the basis of excitation power source, as follows:

a) *Type DC excitation systems,* which utilize a direct current generator with a commutator as the source of excitation system power (see Clause 5)
b) *Type AC excitation systems,* which use an alternator and either stationary or rotating rectifiers to produce the direct current needed for the synchronous machine field (see Clause 6)
c) *Type ST excitation systems*, in which excitation power is supplied through transformers or auxiliary generator windings and rectifiers (see Clause 7)

The following key accessory functions common to most excitation systems are identified and described as follows:

1) Voltage sensing and load compensation (see Clause 4)
2) Power system stabilizer (see Clause 8)

3) Overexcitation limiter (see Clause 9)
4) Underexcitation limiter (see Clause 10)
5) Power factor and var control (see Clause 11)
6) Discontinuous excitation controls (see Clause 12)

In addition, models for some supplementary discontinuous excitation controls are provided.

Most excitation systems represented by the Type AC and ST models allow only positive current flow to the field of the machine, although some systems allow negative voltage forcing until the current decays to zero. Special provisions are made to allow the flow of negative field current when it is induced by the synchronous machine. Methods of accommodating this in the machine/excitation system interface for special studies are described in Annex G.

4. Synchronous machine terminal voltage transducer and current compensator models

Several types of compensation are available on most excitation systems. Synchronous machine active and reactive current compensation are the most common. Either reactive droop compensation and/or line-drop compensation may be used, simulating an impedance drop and effectively regulating at some point other than the terminals of the machine. The impedance or range of adjustment and type of compensation should be specified.

Droop compensation takes its name from the drooping (declining) voltage profile with increasing reactive power output on the unit. Line-drop compensation, also referred to as *transformer-drop compensation,* refers to the act of regulating voltage at a point partway within a generator's step-up transformer or, less frequently, somewhere along the transmission system. This form of compensation produces a rising voltage profile at the generator terminals for increases in reactive output power.

A block diagram of the terminal voltage transducer and the load compensator is shown in Figure 4-1. These model elements are common to all excitation system models described in this document. It is realized that, for some systems, there may be separate and different time constants associated with the functions of voltage sensing and load compensation. The distinction is not recognized in this model, in which only one time constant, T_R, is used for the combined voltage sensing and compensation signal. Single-phase voltage and current sensing will, in general, require a longer time constant in the sensing circuitry to eliminate ripple.

When load compensation is not employed ($R_C = X_C = 0$), the block diagram reduces to a simple sensing circuit. The terminal voltage of the synchronous machine is sensed and is usually reduced to a dc quantity. While the filtering associated with the voltage transducer may be complex, it can usually be reduced, for modeling purposes, to the single time constant T_R shown. For many systems, this time constant is very small and provision should be made to set it to zero.

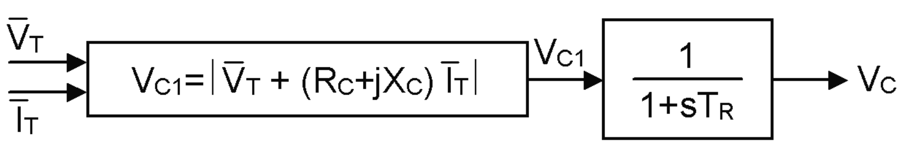


Figure 4-1—Terminal voltage transducer and optional load compensation elements

The terminal voltage transducer output, V_C, is compared with a reference that represents the desired terminal voltage setting, as shown on each of the excitation system models. The equivalent voltage regulator reference signal, V_{REF}, is calculated to satisfy the initial operating conditions. It will, therefore, take on a value unique to the synchronous machine load condition being studied. The resulting error is amplified as described in the appropriate excitation system model to provide the field voltage and subsequent terminal voltage to satisfy the steady-state loop equations. Without load compensation, the excitation system, within its regulation characteristics, attempts to maintain a terminal voltage determined by the reference signal.

When compensation is desired, the appropriate values of R_C and X_C are entered. In most cases, the value of R_C is negligible. The input variables of synchronous machine voltage and current must be in phasor form for the compensator calculation. Care must be taken to ensure that a consistent pu system is utilized for the compensator parameters and the synchronous machine current base.

This type of compensation is normally used in one of the following two ways:

a) When synchronous machines are bused together with no impedance between them, the compensator is used to create artificial coupling impedance so that the machines will share reactive power appropriately. This corresponds to the choice of a regulating point within the synchronous machine. For this case, R_C and X_C would have positive values.

b) When a single synchronous machine is connected through significant impedance to the system, or when two or more machines are connected through individual transformers, it may be desirable to regulate voltage at a point beyond the machine terminals. For example, it may be desirable to compensate for a portion of the transformer impedance and effectively regulate voltage at a point part way through the step-up transformer. For these cases, R_C and X_C would take on the appropriate negative values.

Some compensator circuits act to modify terminal voltage as a function of reactive and real power, instead of reactive and real components of current. Although the model provided will be equivalent to these circuits only near rated terminal voltage, more precise representation has not been deemed worthwhile. These and other forms of compensation are described in Rubenstein and Wakley [B39].

The automatic voltage regulator (AVR) feedback signal can include inputs from other synchronous machines where the machines are connected together on a low-voltage bus and share a common main output transformer. A general form of the AVR feedback signal for unit 1, V_{C1}, is written as shown in Equation (1):

$$V_{C1} = \left\lceil V_T + (R_{C11} + jX_{C11})\overline{I_{T1}} + (R_{C12} + jX_{C12})I_{T2} \right\rceil \qquad (1)$$

V_T = ac voltage phasor common to both of the generators
I_{Ti} = ac current flow out of generator i
R_{Cij} = resistive component of compensation of generator i for current flow out of generator j
X_{Cij} = reactive component of compensation of generator i for current flow out of generator j

The subscripts identify the signals associated with each of the two generators. The first subscript indicates the unit to which the load compensation is connected, while the second subscript indicates the source of the current signal to the compensation. This is the general form of the single machine compensation found on all utility generators (i.e., with R_{C12}, X_{C12} to zero). A similar equation applies to the AVR input for the second unit with appropriate substitution of inputs and subscripts. This can be readily extended to more generators by including additional compensation terms.

In practice, the resistive component of compensation is rarely required on generators synchronized to large grids over high-voltage interconnections. This component of compensation is not even available on some manufacturer's designs. To simplify analysis, the resistive component of compensation is assumed to be zero, and the current signals are resolved into two components as shown in Equation (2):

$$I_T = I_P - jI_Q \tag{2}$$

I_P is the current component in-phase with the terminal voltage and therefore corresponds to the active power flowing from the machine to the system. Similarly, I_Q, corresponds to the reactive component of the current. When the current flowing from the generator lags the voltage, the reactive component of current, I_Q, and the associated reactive power, Q, have positive values. For relatively constant terminal voltage (i.e., changes of no more than a few percent from the nominal level), the amplitude of the active and reactive components of current will be equal to the active and reactive power output of the generator when expressed in pu.

The original compensation equation can now be simplified, as shown in Equation (3):

$$V_{C1} = \left|(V_T + X_{C11}I_{Q1} + X_{C12}I_{Q2}) + j(X_{C11}I_{P1} + X_{C12}X_{P2})\right| \tag{3}$$

$$\approx (V_T + X_{C11}I_{Q1} + X_{C12}I_{Q2})$$

The latter approximation is based on the fact that changes in the active component of current will have little effect on the compensated voltage amplitude. On newer systems, this algebraic equation is an exact representation of the AVR feedback signal, as the reactive component is resolved and multiplied by the compensation and then combined with the terminal voltage signal.

Referring to Equation (3), when the selected compensation is positive and the reactive current lags the voltage, the compensated voltage, V_{C1}, will be greater than the terminal voltage, V_T. When a larger value is presented to the AVR feedback input, the result is a reduction in excitation. Based on this, the type of compensation can be categorized as follows:

$X_{C11} > 0, X_{C12} = 0$ — Commonly referred to as *reactive droop*. The generator terminal voltage will exhibit a declining or drooping characteristic as reactive output increases.

$X_{C11} < 0, X_{C12} = 0$ — Commonly referred to as *transformer-drop* or *line-drop compensation*. The generator terminal voltage will exhibit a rising characteristic as reactive output increases.

$X_{C11} \neq 0, X_{C12} \neq 0$ — Commonly referred to as *cross-current compensation,* although the preferred terminology is *reactive differential compensation*. Through careful selection of the two coefficients (e.g., $X_{C12} = -X_{C11}$), this form of compensation can be used to offset or eliminate the drooping voltage characteristic while enforcing reactive current sharing between synchronous machines sharing a common low-voltage connection.

5. Type DC—Direct current commutator exciters

Few new synchronous machines are being equipped with Type DC exciters, which have been superseded by Type AC and ST systems. However many such systems are still in service. Considering the dwindling percentage and importance of units equipped with these exciters, the previously developed concept (see IEEE Committee Report [B18]) of accounting for loading effects on the exciter by using the loaded saturation curve (see Annex C) is considered adequate.

Digitally based voltage regulators feeding dc rotating main exciters can be represented with the AC Type AC8B model with the parameters K_C and K_D set to 0.

The relationships between regulator limits and field voltage limits are developed in the IEEE Committee Report [B20].

5.1 Type DC1A excitation system model

This model, described by the block diagram of Figure 5-1, is used to represent field-controlled dc commutator exciters with continuously acting voltage regulators (especially the direct-acting rheostatic, rotating amplifier, and magnetic amplifier types).[5] Because this model has been widely implemented by the industry, it is sometimes used to represent other types of systems when detailed data for them are not available or when a simplified model is required.

The principal input to this model is the output, V_C, from the terminal voltage transducer and load compensator model previously described. At the summing junction, terminal voltage transducer output, V_C, is subtracted from the set point reference, V_{REF}. The stabilizing feedback, V_F, is subtracted and the power system stabilizing signal, V_S, is added to produce an error voltage. In the steady state, these last two signals are zero, leaving only the terminal voltage error signal. The resulting signal is amplified in the regulator. The major time constant, T_A, and gain, K_A, associated with the voltage regulator are shown incorporating non-windup limits typical of saturation or amplifier power supply limitations. A discussion of windup and non-windup limits is provided in Annex E. These voltage regulators utilize power sources that are essentially unaffected by brief transients on the synchronous machine or auxiliary buses. The time constants, T_B and T_C, may be used to model equivalent time constants inherent in the voltage regulator, but these time constants are frequently small enough to be neglected and provision should be made for zero input data.

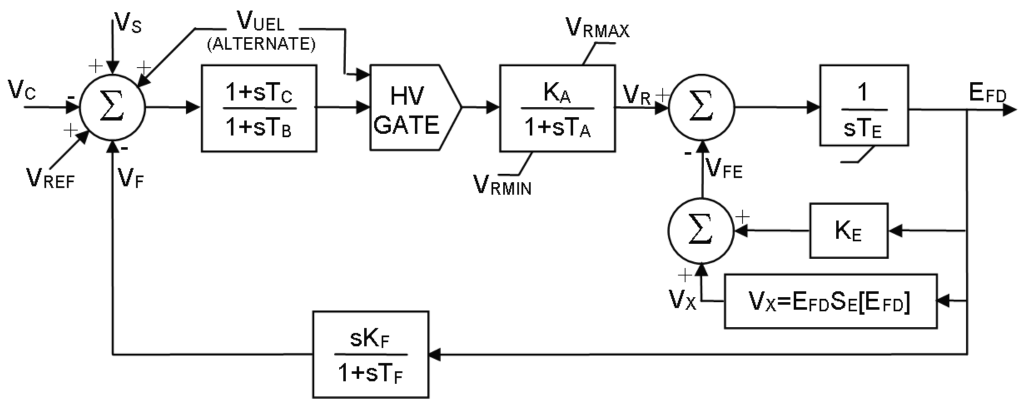


Figure 5-1—Type DC1A—DC commutator exciter

The voltage regulator output, V_R, is used to control the exciter, which may be either separately excited or self-excited as discussed in the IEEE Committee Report [B20]. When a self-excited shunt field is used, the value of K_E reflects the setting of the shunt field rheostat. In some instances, the resulting value of K_E can be negative and allowance should be made for this.

Most of these exciters utilize self-excited shunt fields with the voltage regulator operating in a mode commonly termed *buck-boost*. The majority of station operators manually track the voltage regulator by periodically trimming the rheostat set point so as to zero the voltage regulator output. This may be simulated by selecting the value of K_E so that initial conditions are satisfied with V_R = 0, as described in the IEEE Committee Report [B20]. In some programs, if K_E is entered as zero, it is automatically calculated by the program for self-excitation.

If a nonzero value for K_E is provided, the program should not recalculate K_E, as a fixed rheostat setting is implied. For such systems, the rheostat is frequently fixed at a value that would produce self-excitation near

[5]Examples of excitation systems represented by this model will be made available on the IEEE Web site. Annex I lists examples available at the time of writing this standard.

rated conditions. Systems with fixed field rheostat settings are in widespread use on units that are remotely controlled. A value for $K_E = 1$ is used to represent a separately excited exciter.

The term $S_E[E_{FD}]$ is a nonlinear function with values defined at two or more chosen values of E_{FD}, as described in Annex C. The output of this saturation block, V_X, is the product of the input, E_{FD}, and the value of the nonlinear function $S_E[E_{FD}]$ at this exciter voltage.

A signal derived from field voltage is normally used to provide excitation system stabilization, V_F, via the rate feedback with gain, K_F, and time constant, T_F.

5.2 Type DC2A excitation system model

The model shown in Figure 5-2 is used to represent field-controlled dc commutator exciters with continuously acting voltage regulators having supplies obtained from the generator or auxiliary bus. It differs from the Type DC1A model only in the voltage regulator output limits, which are now proportional to terminal voltage V_T.

It is representative of solid-state replacements for various forms of older mechanical and rotating amplifier regulating equipment connected to dc commutator exciters.

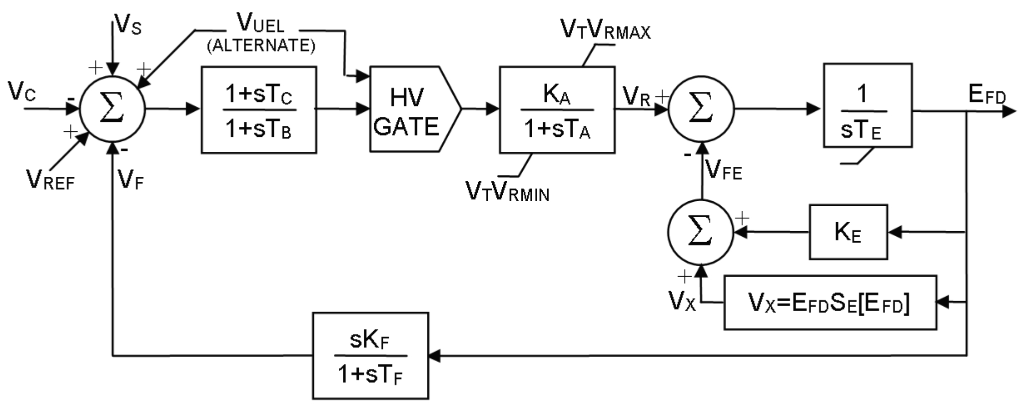


Figure 5-2Type DC2A—DC commutator exciter with bus-fed regulator

5.3 Type DC3A excitation system model

The systems discussed in the previous subclauses are representative of the first generation of high gain, fast-acting excitation sources. The Type DC3A model is used to represent older systems, in particular those dc commutator exciters with non-continuously acting regulators that were commonly used before the development of the continuously acting varieties.

These systems respond at basically two different rates, depending upon the magnitude of voltage error. For small errors, adjustment is made periodically with a signal to a motor-operated rheostat. Larger errors cause resistors to be quickly shorted or inserted and a strong forcing signal applied to the exciter. Continuous motion of the motor-operated rheostat occurs for these larger error signals, even though it is bypassed by contactor action. Figure 5-3 illustrates this control action.

The exciter representation is similar to that of systems described previously. Note that no excitation system stabilizer is represented.

Depending upon the magnitude of voltage error, $V_{REF} - V_C$, different regulator modes come into play. If the voltage error is larger than the fast raise/lower contact setting, K_V (typically 5%), V_{RMAX} or V_{RMIN} is applied to the exciter, depending upon the sign of the voltage error. For an absolute value of voltage error less than K_V, the exciter input equals the rheostat setting V_{RH}. The rheostat setting is notched up or down, depending upon the sign of the error. The travel time representing continuous motion of the rheostat drive motor is T_{RH}. A non-windup limit (see Annex E) is shown around this block, to represent the fact that when the rheostat reaches either limit, it is ready to come off the limit immediately when the input signal reverses. Additional refinements, such as dead band for small errors, have been considered, but were not deemed justified for the relatively few older machines using these voltage regulators.

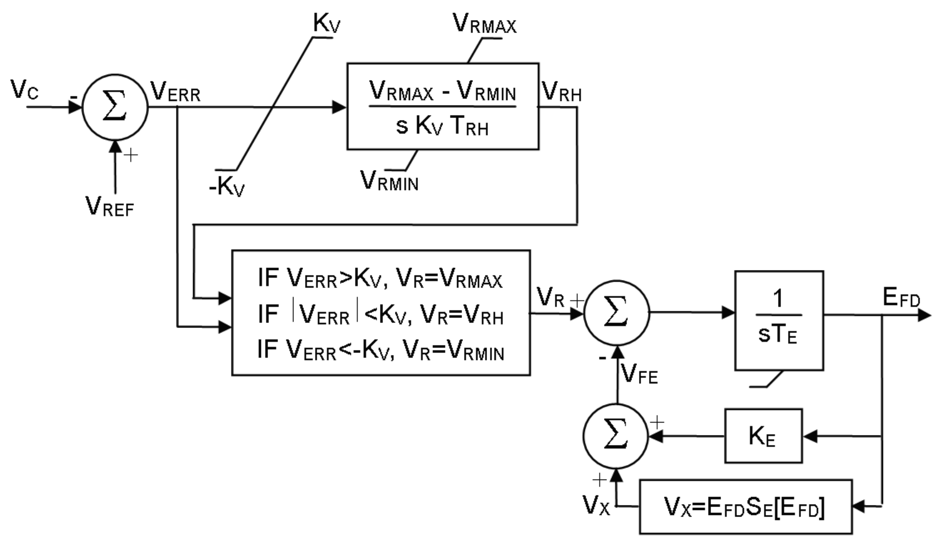


Figure 5-3—Type DC3A—DC commutator exciter with non-continuously acting regulators

The model assumes that the quick raise/lower limits are the same as the rheostat limits. It does not account for time constant changes in the exciter field as a result of changes in field resistance (as a result of rheostat movement and operation of quick action contacts).

5.4 Type DC4B excitation system model

These excitation systems utilize a field-controlled dc commutator exciter with a continuously acting voltage regulator having supplies obtained from the generator or auxiliary bus. The replacement of the controls only as an upgrade (retaining the dc commutator exciter) has resulted in a new model. The block diagram of this model is shown in Figure 5-4. This excitation system typically includes a proportional, integral, and differential (PID) generator voltage regulator (AVR). An alternative rate feedback loop (K_F, T_F) for stabilization is also shown in the model if the AVR does not include a derivative term. If a PSS control is supplied, the appropriate model is the Type PSS2B model.

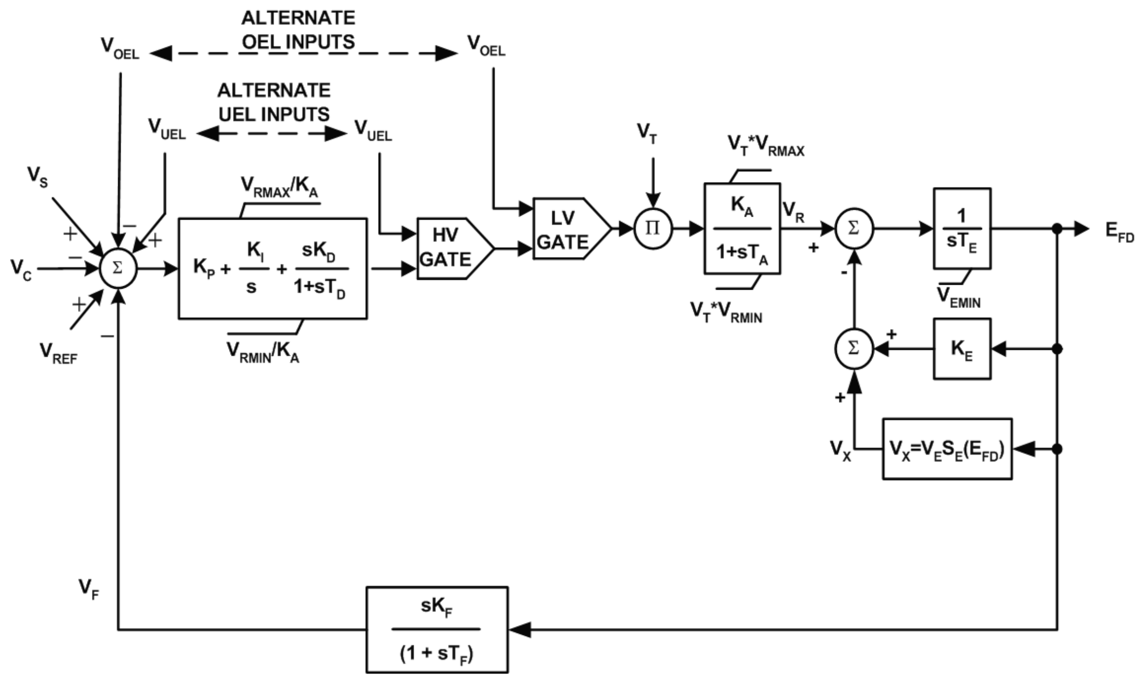


Figure 5-4—Type DC4B—DC commutator exciter with PID style regulator

6. Type AC—Alternator-supplied rectifier excitation systems

These excitation systems use an ac alternator and either stationary or rotating rectifiers to produce the dc field requirements. Loading effects on such exciters are significant, and the use of generator field current as an input to the models allows these effects to be represented accurately. These systems do not allow the supply of negative field current, and only the Type AC4A model allows negative field voltage forcing. Modeling considerations for induced negative field currents are discussed in Annex G. If these models are being used to design phase lead networks for PSSs, and the local mode is close to 3 Hz or higher, a more detailed treatment of the ac machine may be needed. However, the models will be satisfactory for large-scale simulations.

In these models, a signal, V_{FE}, proportional to exciter field current is derived from the summation of signals from exciter output voltage, V_E, multiplied by $K_E + S_E[V_E]$, (where $S_E[V_E]$ represents saturation as described in Annex C) and I_{FD} multiplied by the demagnetization term, K_D. In some of the models, the exciter field current signal, $V_{FE,}$ is used as the input to the excitation system stabilizing block with output, V_F.

6.1 Type AC1A excitation system model

The model shown in Figure 6-1 represents the field-controlled alternator-rectifier excitation systems designated Type AC1A. These excitation systems consist of an alternator main exciter with non-controlled rectifiers. The exciter does not employ self-excitation, and the voltage regulator power is taken from a source that is not affected by external transients. The diode characteristic in the exciter output imposes a lower limit of zero on the exciter output voltage, as shown in Figure 6-1.

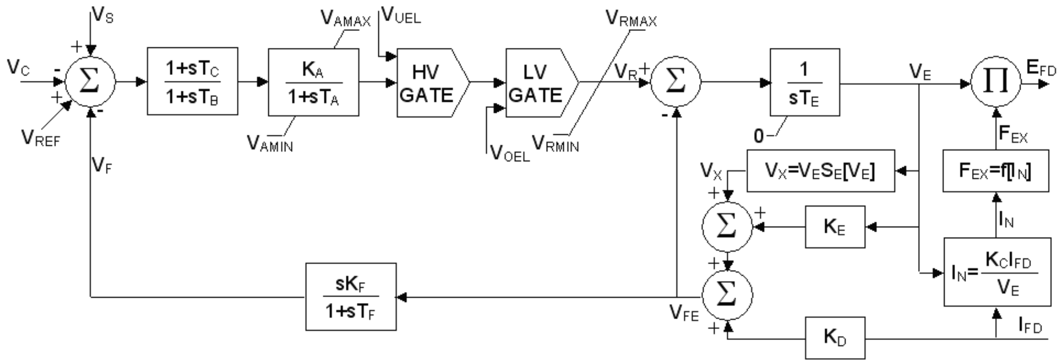


Figure 6-1—Type AC1A—Alternator-rectifier excitation system with non-controlled rectifiers and feedback from exciter field current

For large power system stability studies, the exciter alternator synchronous machine can be represented by the simplified model shown in Figure 6-1. The demagnetizing effect of load current, I_{FD}, on the exciter alternator output voltage, V_E, is accounted for in the feedback path that includes the constant, K_D. This constant is a function of the exciter alternator synchronous and transient reactances, see Ferguson, Herbst, and Miller [B12] and Gayek [B13].

Exciter output voltage drop due to rectifier regulation is simulated by inclusion of the constant K_C (which is a function of commutating reactance) and the rectifier regulation curve, F_{EX}, as described in Annex D.

6.2 Type AC2A excitation system model

The model shown in Figure 6-2, designated as Type AC2A, represents a high initial response field-controlled alternator-rectifier excitation system. The alternator main exciter is used with non-controlled rectifiers. The Type AC2A model is similar to that of Type AC1A except for the inclusion of exciter time constant compensation and exciter field current limiting elements.

The exciter time constant compensation consists essentially of a direct negative feedback, V_H, around the exciter field time constant, reducing its effective value and thereby increasing the small signal response bandwidth of the excitation system. The time constant is reduced by a factor proportional to the product of gains, K_B and K_H, of the compensation loop and is normally more than an order of magnitude lower than the time constant without compensation.

To obtain high initial response with this system, a very high forcing voltage, V_{RMAX}, is applied to the exciter field. A limiter sensing exciter field current serves to allow high forcing but limit the current. By limiting the exciter field current, exciter output voltage, V_E, is limited to a selected value, which is usually determined by the specified excitation system nominal response. Although this limit is realized physically by a feedback loop as described in Annex F, the time constants associated with the loop can be extremely small and can cause computational problems. For this reason, the limiter is shown in the model as a positive limit on exciter voltage back of commutating reactance, which is in turn a function of generator field current. For small limiter loop time constants, this has the same effect, but it circumvents the computational problem associated with the high gain, low time constant loop.

The limits on V_E are used to represent the effects of feedback limiter operation, as described in Annex F.

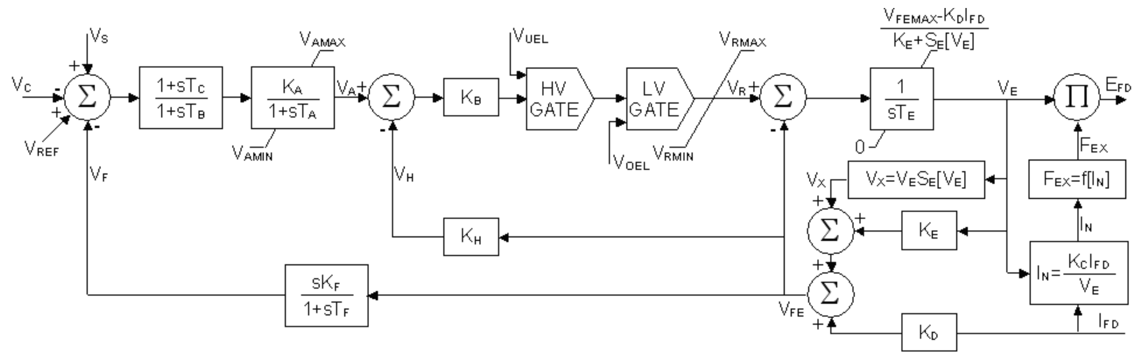


Figure 6-2—Type AC2A—High initial response alternator-rectifier excitation system with non-controlled rectifiers and feedback from exciter field current

6.3 Type AC3A excitation system model

The model shown in Figure 6-3, represents the field-controlled alternator-rectifier excitation systems designated Type AC3A. These excitation systems include an alternator main exciter with non-controlled rectifiers. The exciter employs self-excitation, and the voltage regulator power is derived from the exciter output voltage. Therefore, this system has an additional nonlinearity, simulated by the use of a multiplier whose inputs are the voltage regulator command signal, V_A, and the exciter output voltage, E_{FD}, times K_R. This model is applicable to excitation systems employing static voltage regulators.

For large power system stability studies, the exciter alternator synchronous machine model is simplified.

The demagnetizing effect of load current (I_{FD}) on the dynamics of the exciter alternator output voltage, V_E, is accounted for. The feedback path includes the constant K_D, which is a function of the exciter alternator synchronous and transient reactances.

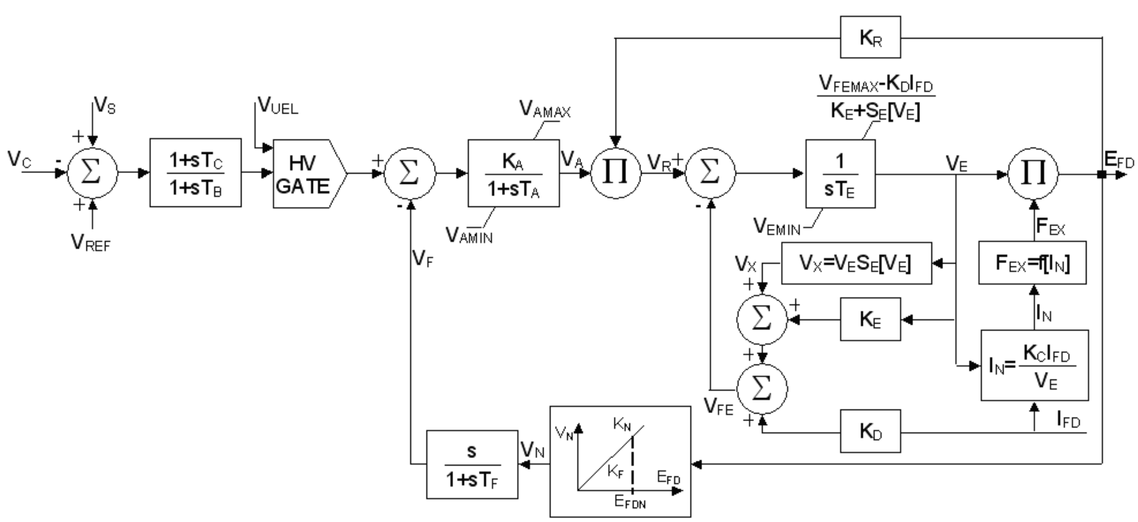


Figure 6-3—Type AC3A—Alternator-rectifier exciter with alternator field current limiter

Exciter output voltage drop due to rectifier regulation is simulated by inclusion of the constant, K_C (which is a function of commutating reactance), and the regulation curve, F_{EX}, as described in Annex D.

The excitation system stabilizer in this model has a nonlinear characteristic. The gain is K_F with exciter output voltage less than E_{FDN}. When exciter output exceeds E_{FDN}, the value of this gain becomes K_N.

The limits on V_E are used to represent the effects of feedback limiter operation, as described in Annex F.

6.4 Type AC4A excitation system model

The Type AC4A alternator-supplied controlled-rectifier excitation system illustrated in Figure 6-4 is quite different from the other type ac systems. This high initial response excitation system utilizes a full thyristor bridge in the exciter output circuit.

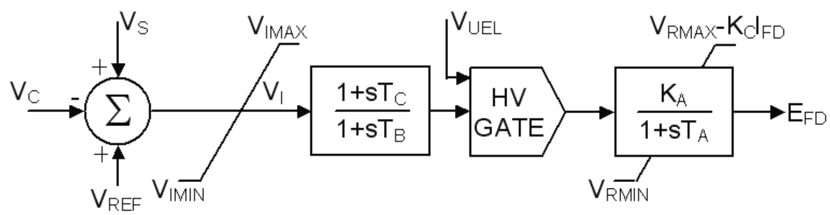


Figure 6-4—Type AC4A alternator-supplied controlled-rectifier exciter

The voltage regulator controls the firing of the thyristor bridges. The exciter alternator uses an independent voltage regulator to control its output voltage to a constant value. These effects are not modeled; however, transient loading effects on the exciter alternator are included. Exciter loading is confined to the region described as mode 1 in Annex D, and loading effects can be accounted for by using the exciter load current and commutating reactance to modify excitation limits. The excitation system stabilization is frequently accomplished in thyristor systems by a series lag-lead network rather than through rate feedback. The time constants, T_B and T_C, allow simulation of this control function. The overall equivalent gain and the time constant associated with the regulator and/or firing of the thyristors are simulated by K_A and T_A, respectively.

6.5 Type AC5A excitation system model

The model shown in Figure 6-5, designated as Type AC5A, is a simplified model for brushless excitation systems. The regulator is supplied from a source, such as a permanent magnet generator, which is not affected by system disturbances.

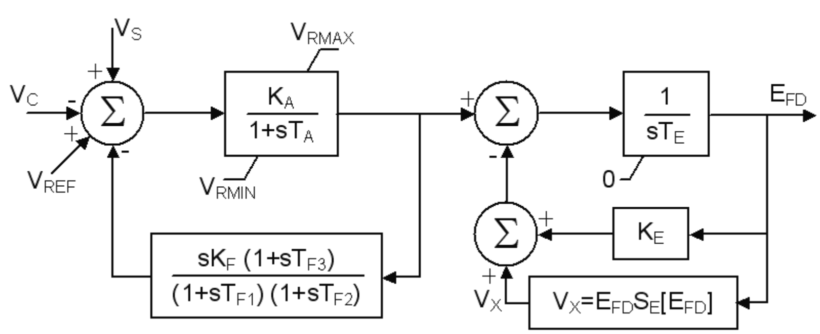


Figure 6-5—Type AC5A—Simplified rotating rectifier excitation system representa-

Unlike other ac models, this model uses loaded rather than open circuit exciter saturation data in the same way as it is used for the dc models (Annex C).

Because the model has been widely implemented by the industry, it is sometimes used to represent other types of systems when either detailed data for them are not available or simplified models are required.

6.6 Type AC6A excitation system model

The model shown in Figure 6-6 is used to represent field-controlled alternator-rectifier excitation systems with system-supplied electronic voltage regulators. The maximum output of the regulator, $V_{R,}$ is a function of terminal voltage, V_T. The field current limiter included in the original model AC6A remains in the 2005 update of this document, although overexcitation and underexcitation limiters are now described more fully in Clause 9 and Clause 10 respectively.

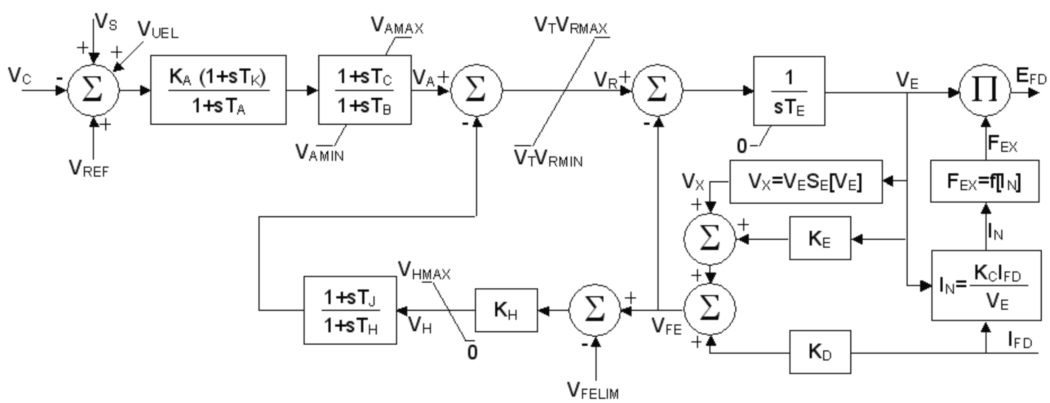


Figure 6-6—Type AC6A—Alternator-rectifier excitation system with non-controlled rectifiers and system-supplied electronic voltage regulator

6.7 Type AC7B excitation system model

These excitation systems consist of an ac alternator with either stationary or rotating rectifiers to produce the dc field requirements. Upgrades to earlier ac excitation systems, which replace only the controls but retain the ac alternator and diode rectifier bridge, have resulted in this new model, as shown in Figure 6-7. Some of the features of this excitation system include a high bandwidth inner loop regulating generator field voltage or exciter current (K_{F2}, K_{F1}), a fast exciter current limit, V_{FEMAX}, to protect the field of the ac alternator, and the PID generator voltage regulator (AVR). An alternative rate feedback loop (K_F, T_F) is provided for stabilization if the AVR does not include a derivative term. If a PSS control is supplied, the Type PSS2B or PSS3B models are appropriate.

6.8 Type AC8B excitation system model

The block diagram of the AC8B model is shown in Figure 6-8. The AVR in this model consists of PID control, with separate constants for the proportional (K_{PR}), integral (K_{IR}), and derivative (K_{DR}) gains. The values for the constants are chosen for best performance for each particular generator excitation system. The representation of the brushless exciter (T_E, K_E, $S_{E,}$ K_C, K_D) is similar to the model Type AC2A. Sample data for this model is shown in Annex H. The Type AC8B model can be used to represent static voltage regulators applied to brushless excitation systems. Digitally based voltage regulators feeding dc rotating main exciters can be represented with the AC Type AC8B model with the parameters K_C and K_D set to 0. For thyristor power stages fed from the generator terminals, the limits V_{RMAX} and V_{RMIN} should be a function of terminal voltage: $V_T \times V_{RMAX}$ and $V_T \times V_{RMIN}$. This may be accommodated in simulation programs using an additional logic state to identify bus or PMG fed systems from terminal fed systems.

The limits on V_E are used to represent the effects of feedback limiter operation, as described in Annex F.

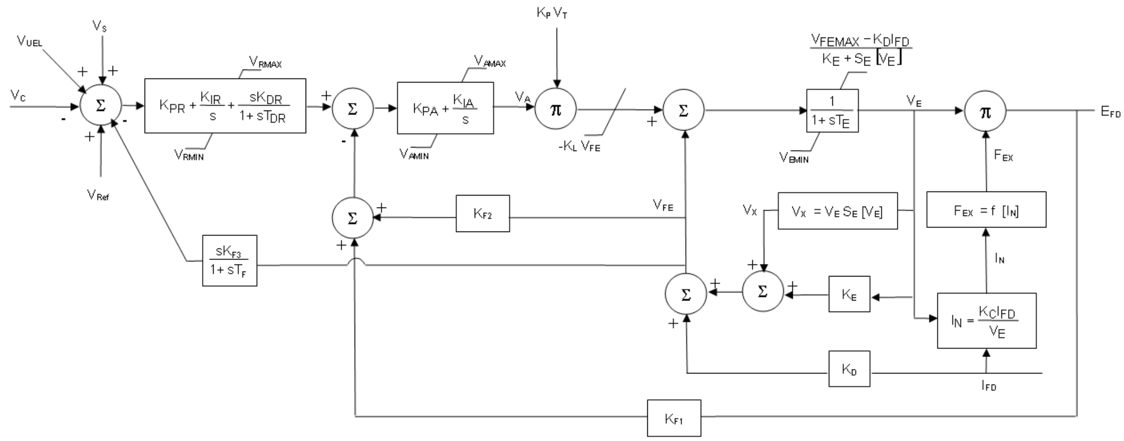


Figure 6-7—Type AC7B—Alternator-rectifier excitation system

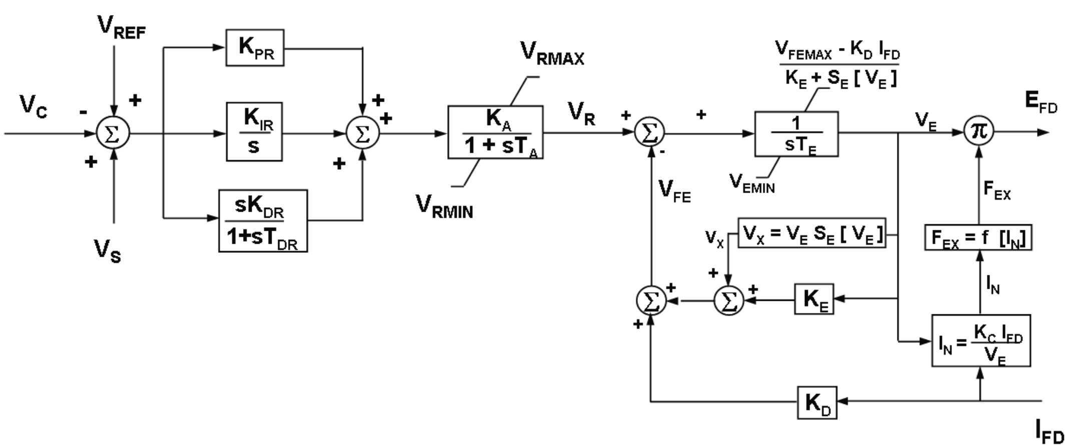


Figure 6-8—Type AC8B—Alternator-rectifier excitation system

7. Type ST—Static excitation systems

In these excitation systems, voltage (and also current in compounded systems) is transformed to an appropriate level. Rectifiers, either controlled or non-controlled, provide the necessary direct current for the generator field.

While many of these systems allow negative field voltage forcing, most do not supply negative field current. For specialized studies where negative field current must be accommodated, more detailed modeling is required, as discussed in Annex G.

For many of the static systems, exciter ceiling voltage is very high. For such systems, additional field current limiter circuits may be used to protect the exciter and the generator rotor. These frequently include both instantaneous and time delayed elements, but only the instantaneous limits are included here, and these only for the ST1A and ST6B models. The original ST1A model remains unchanged including an exciter field current limiter but limiters are now described more fully in Clause 9 and Clause 10 of this document.

7.1 Type ST1A excitation system model

The computer model of the Type ST1A potential-source controlled-rectifier excitation system shown in Figure 7-1 is intended to represent systems in which excitation power is supplied through a transformer from the generator terminals (or the unit's auxiliary bus) and is regulated by a controlled rectifier. The maximum exciter voltage available from such systems is directly related to the generator terminal voltage (except as noted, as follows).

In this type of system, the inherent exciter time constants are very small, and exciter stabilization may not be required. On the other hand, it may be desirable to reduce the transient gain of these systems for other reasons. The model shown is sufficiently versatile to represent transient gain reduction implemented either in the forward path via time constants, T_B and T_C (in which case K_F would normally be set to zero), or in the feedback path by suitable choice of rate feedback parameters, K_F and T_F. Voltage regulator gain and any inherent excitation system time constant are represented by K_A and T_A, respectively.

The time constants, T_{C1} and T_{B1}, allow for the possibility of representing transient gain increase, in which case T_{C1} would be greater than T_{B1}.

The way in which the firing angle for the bridge rectifiers is derived affects the input-output relationship, which is assumed to be linear in the model by choice of a simple gain, K_A. For many systems a truly linear relationship applies. In a few systems, the bridge relationship is not linearized, leaving this nominally linear gain a sinusoidal function, the amplitude of which may be dependent on the supply voltage. As the gain is normally set very high, a linearization of this characteristic is normally satisfactory for modeling purposes. The representation of the ceiling is the same whether the characteristic is linear or sinusoidal.

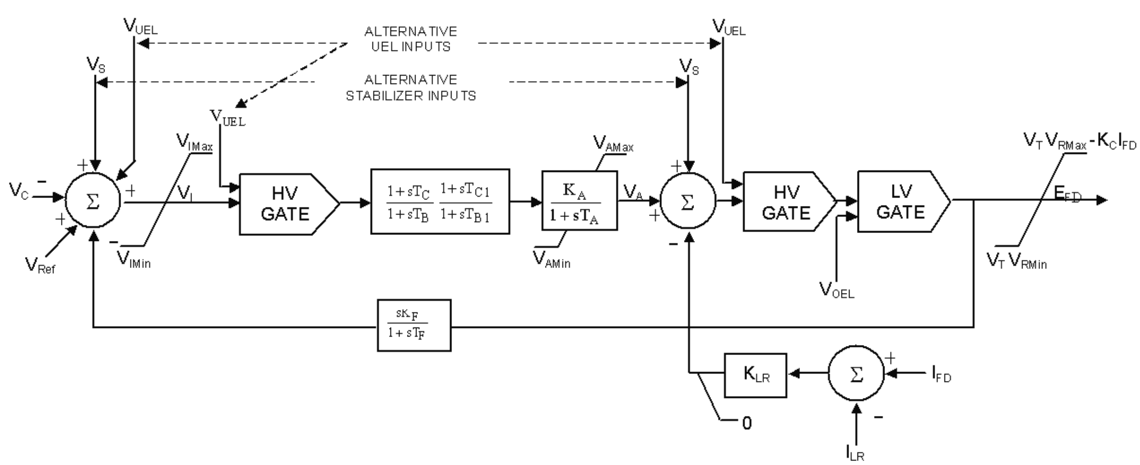


Figure 7-1—Type ST1A—Potential-source, controlled-rectifier exciter

In many cases, the internal limits on V_I can be neglected. The field voltage limits that are functions of both terminal voltage and synchronous machine field current should be modeled. The representation of the field voltage positive limit as a linear function of synchronous machine field current is possible because operation of the rectifier bridge in such systems is confined to the mode 1 region as described in Annex D. The negative limit would have a similar current-dependent characteristic, but the sign of the term could be either positive or negative depending upon whether a constant firing angle or constant extinction angle is chosen for the limit. As field current is normally low under this condition, the term is not included in the model.

As a result of the very high forcing capability of these systems, a field current limiter is sometimes employed to protect the generator rotor and exciter. The limit start setting is defined by I_{LR} and the gain is represented by K_{LR}. To permit this limit to be ignored, provision should be made to allow K_{LR} to be set to zero. This limiter is described here to maintain consistency with the original ST1A model. However, this document describes overexcitation and underexcitation limiters more fully in Clause 9 and Clause 10, respectively.

While for the majority of these excitation systems, a fully controlled bridge is employed, the model is also applicable to systems in which only half of the bridge is controlled, in which case the negative field voltage limit is set to zero ($V_{RMIN} = 0$).

7.2 Type ST2A excitation system model

Some static systems utilize both current and voltage sources (generator terminal quantities) to comprise the power source. These compound-source rectifier excitation systems are designated Type ST2A and are modeled as shown in Figure 7-2. It is necessary to form a model of the exciter power source utilizing a phasor combination of terminal voltage, V_T, and terminal current, I_T. Rectifier loading and commutation effects are accounted for as described in Annex D. E_{FDMAX} represents the limit on the exciter voltage due to saturation of the magnetic components. The regulator controls the exciter output through controlled saturation of the power transformer components. T_E is a time constant associated with the inductance of the control windings.

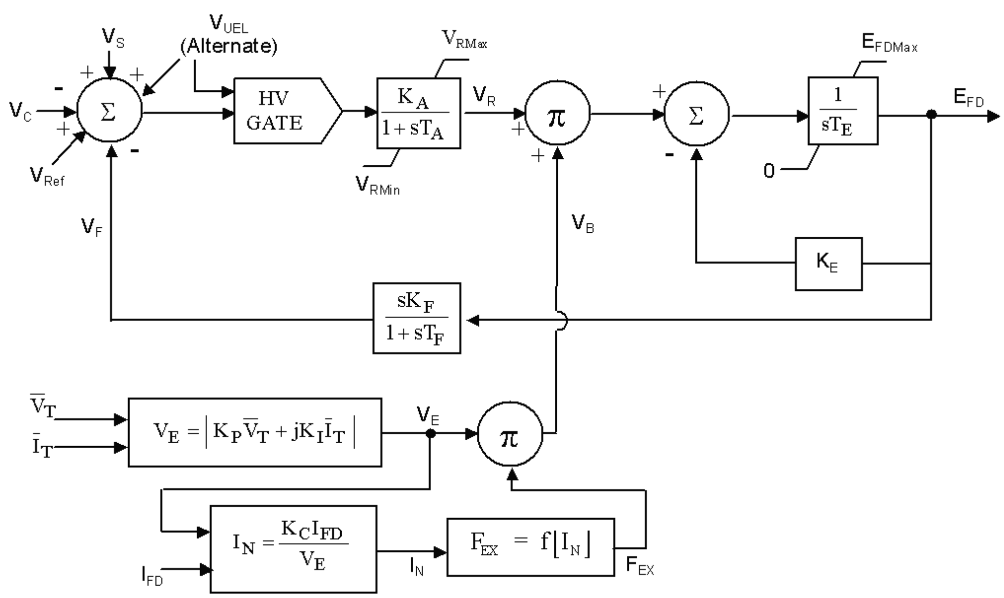


Figure 7-2—Type ST2A—Compound-source rectifier exciter

7.3 Type ST3A excitation system model

Some static systems utilize a field voltage control loop to linearize the exciter control characteristic as shown in Figure 7-3. This also makes the output independent of supply source variations until supply limitations are reached.

These systems utilize a variety of controlled-rectifier designs: full thyristor complements or hybrid bridges in either series or shunt configurations. The power source may consist of only a potential source, either fed from the machine terminals or from internal windings. Some designs may have compound power sources utilizing both machine potential and current. These power sources are represented as phasor combinations of machine terminal current and voltage and are accommodated by suitable parameters in the model shown.

The excitation system stabilizer for these systems is provided by a series lag-lead element in the voltage regulator, represented by the time constants T_B and T_C. The inner loop field voltage regulator is comprised of the gains K_M and K_G and the time constant T_M. This loop has a wide bandwidth compared with the upper limit of 3 Hz for the models described in this recommended practice. The time constant T_M may be increased for study purposes, eliminating the need for excessively short computing increments while still retaining the required accuracy at 3 Hz. Rectifier loading and commutation effects are accounted for as discussed in Annex D. The limit, V_{BMAX}, is determined by the saturation level of power components.

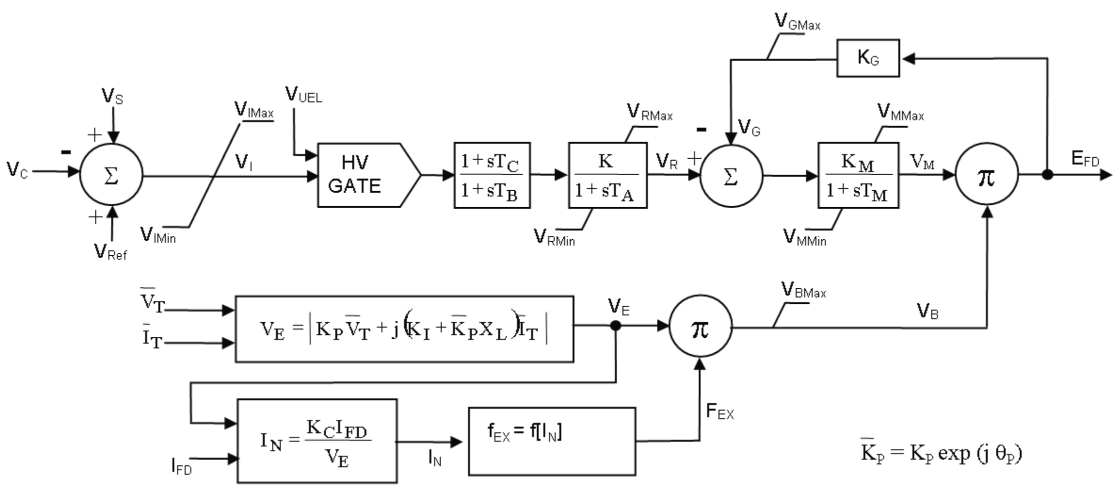


Figure 7-3—Type ST3A—Potential- or compound-source controlled-rectifier exciter with field voltage control loop

7.4 Type ST4B excitation system model

This model is a variation of the Type ST3A model, with a proportional plus integral (PI) regulator block replacing the lag-lead regulator characteristic that was in the ST3A model. Both potential- and compound-source rectifier excitation systems are modeled as shown in Figure 7-4. The PI regulator blocks have non-windup limits that are represented as described in Annex A. The voltage regulator of this model is typically implemented digitally, so the model is identified with the suffix “B.”

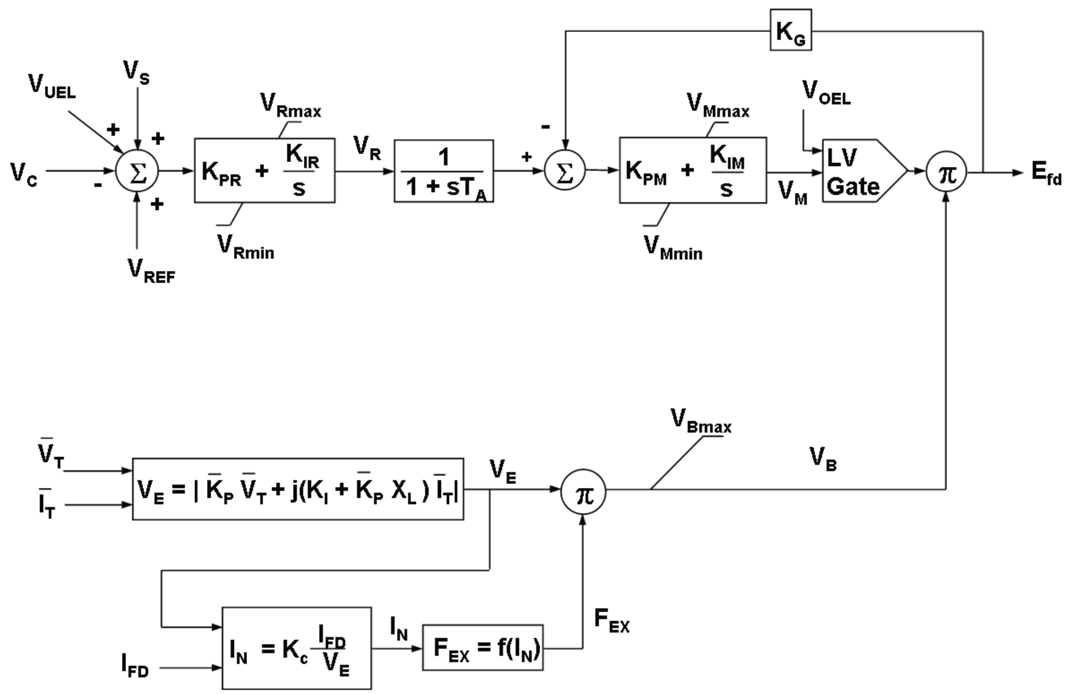


Figure 7-4—Type ST4B—Potential- or compound-source controlled-rectifier exciter

The other features of the regulator are a low value gate for the OEL limit function, and the UEL and V/Hz control are summed into the input to the regulator. This means that on a unit with PSS control, the PSS will be active if the unit goes into UEL limit control, unlike some previous designs that had take-over type limiters. The description of rectifier regulation, F_{EX}, may be found in Annex D. There is flexibility in the power component model to represent bus-fed exciters (K_I and X_L both equal to zero), compound static systems ($X_L = 0$), and potential- and compound-source systems where X_L is not zero. The appropriate PSS model to use with the ST4B excitation model is Type PSS2B.

7.5 Type ST5B excitation system model

The Type ST5B excitation system shown in Figure 7-5 is a variation of the Type ST1A model, with alternative overexcitation and underexcitation inputs and additional limits. The corresponding stabilizer models that can be used with these models are the Type PSS2B, PSS3B, or PSS4B. Sample data for the model is provided in Annex H.

7.6 Type ST6B excitation system model

The AVR shown in Figure 7-6 consists of a PI voltage regulator with an inner loop field voltage regulator and pre-control. The field voltage regulator implements a proportional control. The pre-control and the delay in the feedback circuit increase the dynamic response. If the field voltage regulator is not implemented, the corresponding parameters K_{FF} and K_G are set to 0. V_R represents the limits of the power rectifier. The ceiling current I_{FD} limitation is included in this model. The power for the rectifier, V_B, may be supplied from the generator terminals or from an independent source. Inputs are provided for external models of the overexcitation limiter (V_{OEL}), underexcitation limiter (V_{UEL}), and PSS (V_S). Sample data for the model is provided in Annex H.

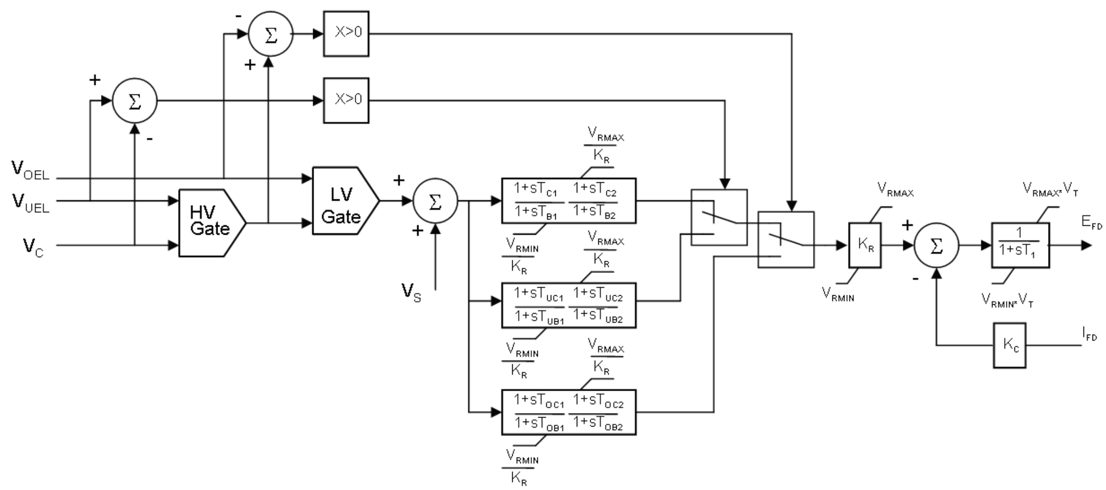


Figure 7-5—Type ST5B—Static potential-source excitation system

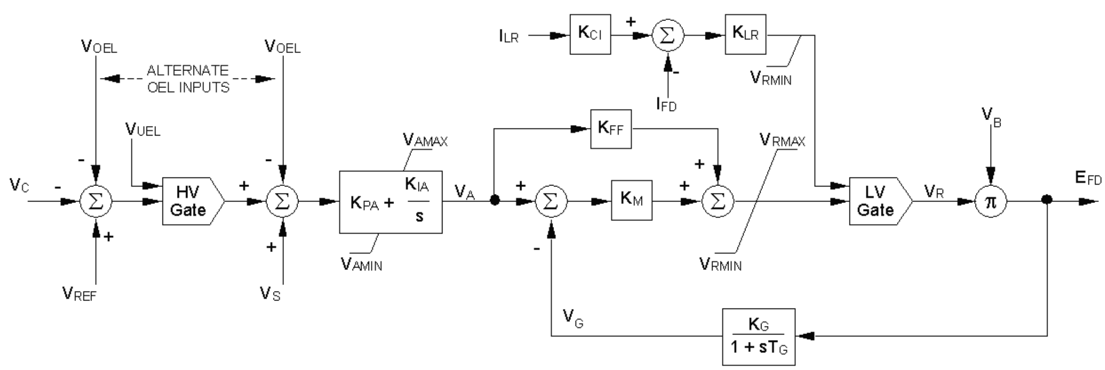


Figure 7-6—Type ST6B—Static potential-source excitation system with field current limiter

7.7 Type ST7B excitation system model

The model ST7B in Figure 7-7 is representative of static potential-source excitation systems. In this system, the AVR consists of a PI voltage regulator. A phase lead-lag filter in series allows introduction of a derivative function, typically used with brushless excitation systems. In that case, the regulator is of the PID type. In addition, the terminal voltage channel includes a phase lead-lag filter.

The AVR includes the appropriate inputs on its reference for overexcitation limiter (OEL1), underexcitation limiter (UEL), stator current limiter (SCL), and current compensator (DROOP). All these limitations, when they work at voltage reference level, keep the PSS (VS signal from Type PSS1A, PSS2A, or PSS2B) in operation. However, the UEL limitation can also be transferred to the high value (HV) gate acting on the output signal. In addition, the output signal passes through a low value (LV) gate for a ceiling overexcitation limiter (OEL2).

All control loops in the diagram, including limitation functions, are built to obtain a non-windup behavior of any integrator (see Annex E). Sample data for the model are provided in Annex H.

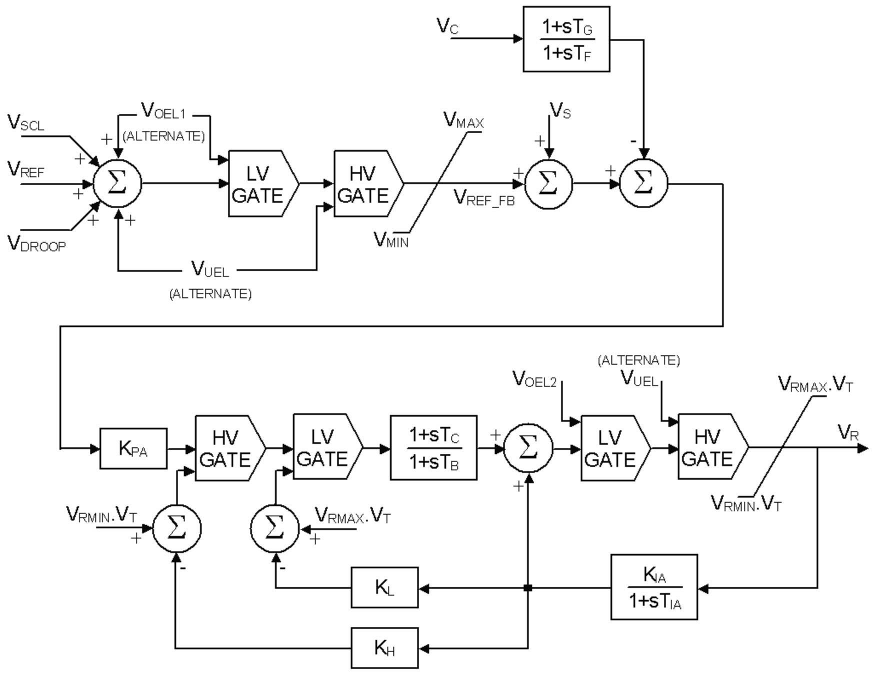


Figure 7-7—Type ST7B—Static potential-source excitation system

8. Power system stabilizers

PSSs are used to enhance damping of power system oscillations through excitation control. Commonly used inputs are shaft speed, terminal frequency, and power. Where frequency is used as an input, it will normally be terminal frequency, but in some cases a frequency behind a simulated machine reactance (equivalent to shaft speed for many studies) may be employed.

The stabilizer models provided in the following subclauses are generally consistent with the excitation models, with the range of frequency response outlined in the scope. They may not be applicable for investigation of control modes of instability, which normally occur above 3 Hz.

Stabilizer parameters should be consistent with the type of input signal specified in the stabilizer model. Parameters for stabilizers with different input signals may look very different while providing similar damping characteristics.

PSSs can be installed on synchronous machines operating as synchronous condensers or machines operating as pumped-storage units. In these cases the stabilizer will need to have the ability to switch between different sets of parameters depending on the mode of operation at a particular time.

8.1 Type PSS1A power system stabilizer model

Figure 8-1 shows the generalized form of a PSS with a single input. Some common stabilizer input signals, V_{SI}, are speed, frequency, and power.

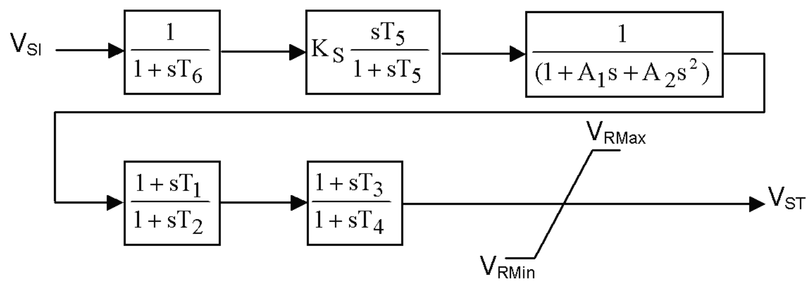


Figure 8-1—Type PSS1A—Single-input PSS

T_6 may be used to represent a transducer time constant. Stabilizer gain is set by the term K_S and signal washout is set by the time constant T_5.

In the next block, A_1 and A_2 allow some of the low-frequency effects of high-frequency torsional filters (used in some stabilizers) to be accounted for. When not used for this purpose, the block can be used to assist in shaping the gain and phase characteristics of the stabilizer, if required. The next two blocks allow two stages of lead-lag compensation, as set by constants T_1 to T_4.

Stabilizer output can be limited in various ways, not all of which are shown in Figure 22. This model shows only simple stabilizer output limits, V_{STMAX} and V_{STMIN}. For some systems, the stabilizer output is removed if the generator terminal voltage deviates outside a chosen band, as shown in the supplementary discontinuous excitation control model Type DEC3A of Figure 11-3. In other systems, the stabilizer output is limited as a function of generator terminal voltage as included in the Type DEC1A model of Figure 11-1.

The stabilizer output, V_{ST}, is an input to the supplementary discontinuous control models. Where the discontinuous control models are not used, $V_S = V_{ST}$.

8.2 Type PSS2B power system stabilizer model

This stabilizer model, shown in Figure 8-2, is designed to represent a variety of dual-input stabilizers, which normally use combinations of power and speed or frequency to derive the stabilizing signal.

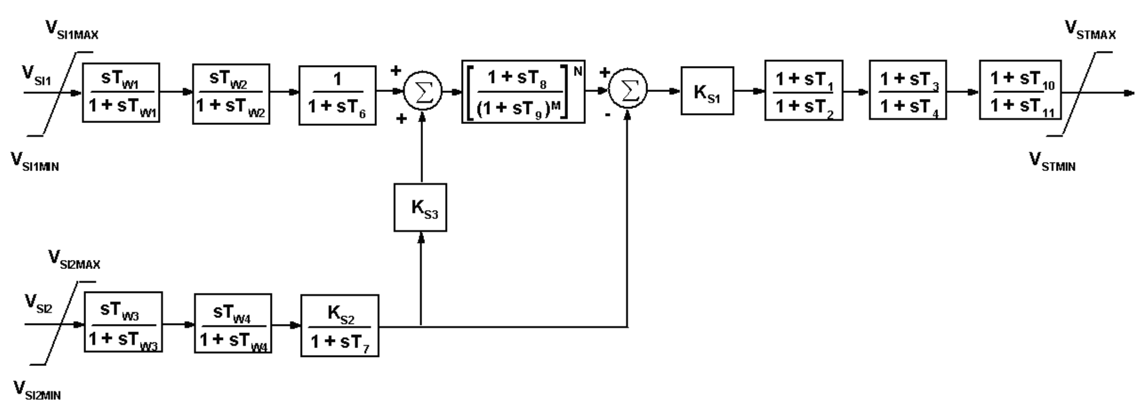


Figure 8-2—Type PSS2B—Dual-input PSS

In particular, this model can be used to represent two distinct types of dual-input stabilizer implementations as described as follows:

a) Stabilizers that, in the frequency range of system oscillations, act as electrical power input stabilizers. These use the speed or frequency input for the generation of an equivalent mechanical power signal, to make the total signal insensitive to mechanical power change.

b) Stabilizers that use a combination of speed (or frequency) and electrical power. These systems usually use the speed directly (i.e., without phase-lead compensation) and add a signal proportional to electrical power to achieve the desired stabilizing signal shaping.

While the same model is used for the two types of dual-input stabilizers described in the preceding items a) and b), the parameters used in the model for equivalent stabilizing action will be very different. For each input, two washouts can be represented (T_{W1} to T_{W4}) along with a transducer or integrator time constants (T_6, T_7). For the first type of dual-input stabilizer, K_{S3} would normally be 1 and K_{S2} would be equal to $T_7/2H$, where H is the inertia constant of the synchronous machine. V_{SI1} would normally represent speed or frequency and V_{SI2} would be a power signal. The indices M and N allow a "ramp-tracking" or simpler filter characteristic to be represented. To model all existing field uses of the ramp-tracking filter, the indices M and N should allow integers up to 5 and 4, respectively. Typical values of M = 5, N = 1 or M = 2, N = 4 are in use by several utilities. Phase compensation is provided by the two lead-lag or lag-lead blocks (T_1 to T_4). Output limiting options are similar to those described for the PSS1A model.

For many types of studies, the simpler single-input PSS1A model, with appropriate parameters, may be used in place of the two-input PSS2B model.

The PSS2B model shown in Figure 8-2 is a slight variation of the PSS2A model from the 1992 recommended practice. An additional block with lag time constant T_{11} and lead time constant T_{10} can be used to model stabilizers which incorporate a third lead-lag function.

8.3 Type PSS3B power system stabilizer model

The PSS model PSS3B shown in Figure 8-3 has dual inputs of electrical power ($V_{SI1} = P_E$) and rotor angular frequency deviation ($V_{SI2} = \Delta\omega$). The signals are used to derive an equivalent mechanical power signal. By combining this signal with electrical power, a signal proportional to accelerating power is produced. The time constants T_1 and T_2 represent the transducer time constants, and the time constants T_{W1} to T_{W3} represent the washout time constants for electric power, rotor angular speed, and derived mechanical power, respectively. In this model, the stabilizing signal V_{ST} results from the vector summation of processed signals for electrical power and angular frequency deviation.

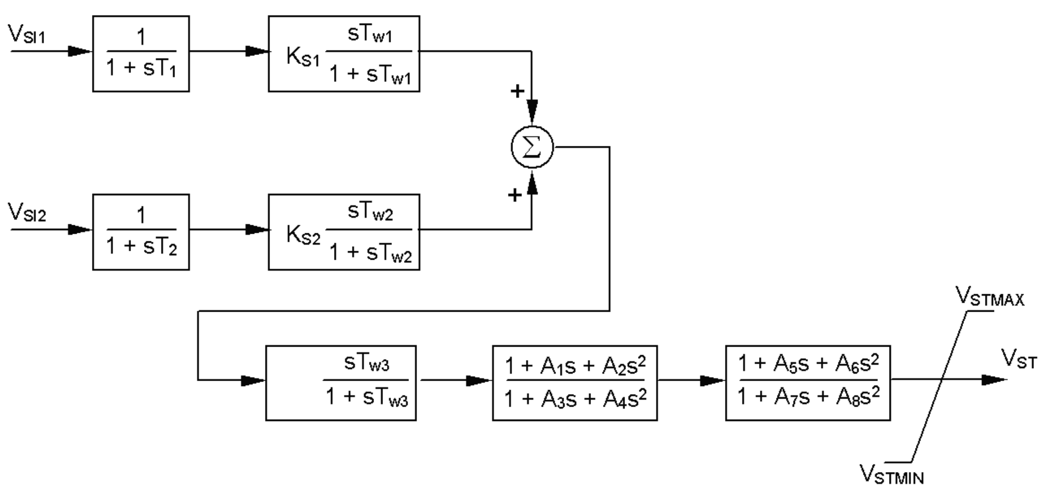


Figure 8-3—Type PSS3B—Dual-input PSS

The desired amplitude and phase for the stabilizing signal is obtained by matching the polarity and magnitude of the gain constants K_{S1} and K_{S2}. Phase compensation is provided by the two subsequent filters A_1 to A_8. The maximum allowed influence of the stabilizing signal on the AVR may be adjusted with the limit values V_{STMAX} and V_{STMIN}.

8.4 Type PSS4B power system stabilizer model

The PSS4B model represents a structure based on multiple working frequency bands as shown in Figure 8-4a. Three separate bands, respectively dedicated to the low-, intermediate- and high-frequency modes of oscillations, are used in this delta-omega (speed input) PSS.

The low band is typically associated with the power system global mode, the intermediate with the inter-area modes, and the high with the local modes. Each of the three bands is composed of a differential filter, a gain, and a limiter. Their outputs are summed and passed through a final limiter V_{STMIN}/V_{STMAX} resulting in PSS output V_{ST}.

The PSS4B measures the rotor speed deviation in two different ways. $\Delta\omega_{L-I}$ feeds the low and intermediate bands, while $\Delta\omega_H$ is dedicated to the high-frequency band. The equivalent model of these two speed transducers is shown in Figure 8-4b. Tuneable notch filters $N_i(s)$, optionally used for turbo-generators torsional modes, are defined as shown in Equation (4).

$$N_i(s) = \frac{s^2 + \omega_{ni}^2}{s^2 + B_{wi}s + \omega_{ni}^2} \tag{4}$$

with ω_{ni} the filter frequency, and B_{wi} its 3 dB bandwidth.

Sample data sets are shown in H.21, which also contains a brief description of the tuning philosophy used in the PSS4B model.

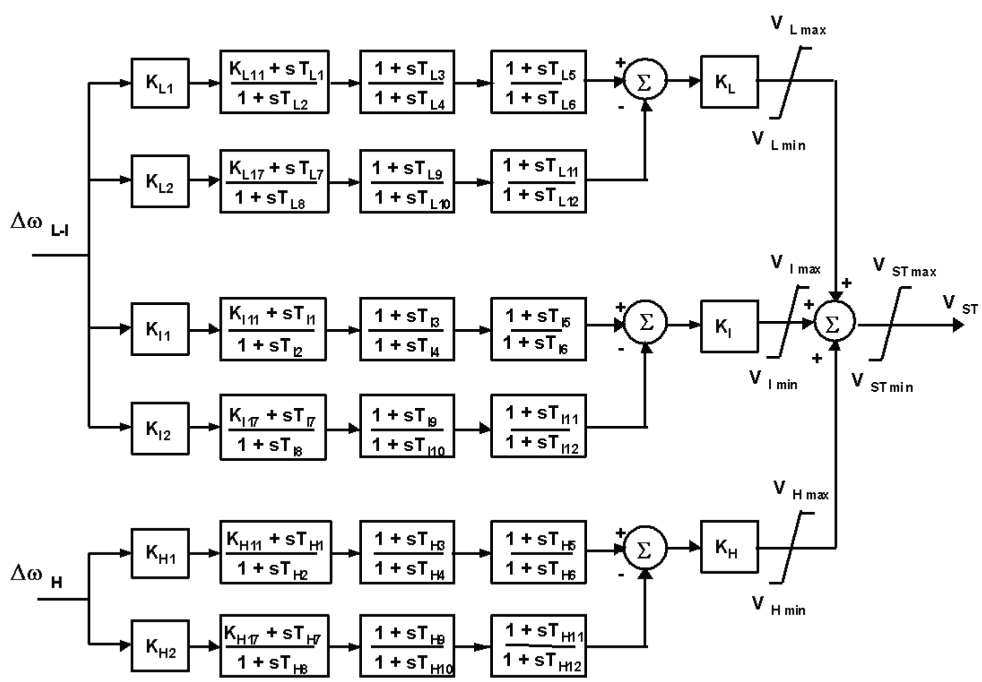


Figure 8-4a—Type PSS4B—Multi-band PSS

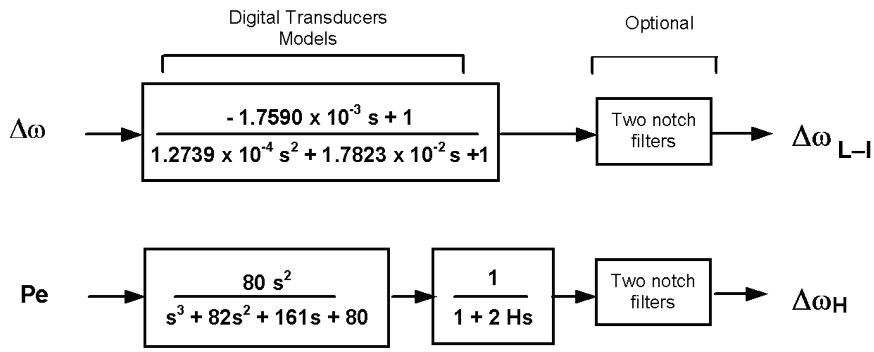


Figure 8-4b—Type PSS4B—MB-PSS speed deviation transducers

9. Overexcitation limiters

Overexcitation limiters (OELs), also referred to as *maximum excitation limiters* and *field current limiters,* have been provided with excitation systems for many years, but until recently, OELs have not been modeled in power system dynamic simulations. The possibility of voltage collapse in stressed power systems increases the importance of modeling these limiters in studies of system conditions that cause machines to operate at high levels of excitation for a sustained period, such as voltage collapse or system-islanding. Such events typically occur over a long time frame compared with transient or small-signal stability simulations. Although OEL modeling will not be required in every system study, most of the effort required to implement these models will be the collection of limiter data and prototype testing. The extra computational time required to process these models is expected to be minimal (see Ribeiro [B37]). Reference material may be found in Girgis and Vu [B14], IEEE Task Force on Excitation Limiters [B25], Murdoch et al. [B33], Murdoch et al. [B34], Shimomura et al. [B40], and Van Cutsem and Vournas [B43].

An OEL model for long system studies should represent the stable, slowly changing dynamics associated with long-term behavior, but not the fast dynamics that must be examined during their design and tuning. In simulations of the variable time step or quasi-steady-state type, in which the calculation time step may be increased from a fraction of a cycle to several seconds, differential equations for fast dynamics may be replaced by algebraic equations. OEL operation, as well as tap changing, capacitor bank switching, and load shedding, are essential to long-term simulations. In the simplest form, a limiter model might consist of a single constant representing the field current limit and a flag to warn that the limit has been exceeded, so that simulation results after this point in time may not be valid.

9.1 Field winding thermal capability

The limiting action provided by OELs must offer proper protection from overheating due to high field current levels while simultaneously allowing maximum field forcing for power system stability purposes. Limiting is typically delayed for some period to allow fault clearing.

OEL operating characteristics typically attempt to remain within the field overload capability for round-rotor synchronous machines given in ANSI C50.13-1989 [B3]. The standard specifies allowable levels of field voltage rather than field current. In simulation, a constant field resistance is normally assumed and field voltage and current, as a percentage of rated values, are equivalent in the steady state. The rotor capability is defined by Equation (5) where *A*, *B,* and *C* are constants 33.75, 2, and 1 respectively, and field current is expressed as a percentage of rated (see ANSI C50.13-1989 [B3]). This relationship is plotted in Figure 9-1.

$$\text{time} = A/(I_{FD}^{B} - C) \tag{5}$$

The OEL characteristic must also co-ordinate with over excitation protection, volts-per-hertz limiters and terminal voltage limiters, and protections (see IEEE Std C37.102™-1995 [B23]).

Some OELs utilize a temperature or pressure recalibration feature, in which the OEL characteristic is shifted depending upon the generator cooling gas temperature or pressure. Since this is typically a slowly acting effect, it is not represented in the OEL model, and the OEL model should reflect the limiting characteristic at the initial operating condition.

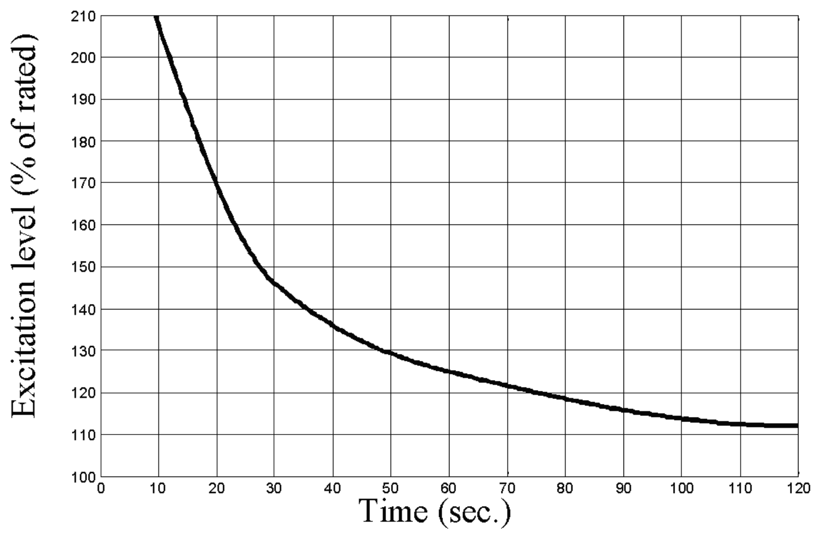


Figure 9-1—Field voltage short-time capability

9.2 OEL types

Limiting devices built to prevent field current from exceeding the machine capability are of several forms, but all operate through the same sequence of events: Detect the overexcitation condition, allow it to persist for a defined time-overload period, and then reduce the excitation to a safe level. Although ideally the quantity to measure to determine an overexcitation condition should be field winding temperature, limiters in use today measure field current, field voltage, or exciter field current or voltage. Therefore the detection stage of these limiters is a comparison of the measured current or voltage with a defined pickup level. The variation in limiter designs appears in the latter two stages. The allowed overexcitation period may be fixed or vary inversely with the excitation level. The excitation level may be reduced by instantaneously lowering the reference set point, by ramping or stepping down the reference set point, or by transferring control from the AVR to a lower manually controlled field voltage set point.

A simple form of OEL has a fixed pickup point, a fixed time delay, and instantly reduces the excitation set point to a safe value. A more common type of overexcitation limiter provided by many manufacturers combines instantaneous and inverse-time pickup characteristics and switches from an instantaneous limiter with a setting of about 160% of rated field current to a timed limiter with a setting of about 105% of rated field current. The field current set point is not ramped down, but decreases almost instantly when this type of limiter switches. The inverse-time curve, the instantaneous limiter value, and the timed limiter value are all adjustable on this type of limiter.

Other manufacturers provide overexcitation limiters that ramp down the limiter set point from the instantaneous value to the timed limiter setting. The ramp rate can be constant (see Kundur [B28]) or proportional to the level of overexcitation (see Morison, Gao, and Kundur [B32]).

Some, typically older, excitation systems do not have continuously acting overexcitation limiters. These systems switch from automatic voltage regulation to a fixed field set point if excitation is high for too long. The excitation set point may be positioned to produce the maximum continuous field current or it may be positioned near the normal unity power factor position. See Taylor [B41]. In these types of systems, the AVR output signal is permanently overridden.

9.3 OEL model

The model described herein is intended to represent the significant features of OELs necessary for some large-scale system studies. It is the result of a pragmatic approach to obtain a model that can be widely applied with attainable data from generator owners. An attempt to include all variations in the functionality of OELs and duplicate how they interact with the rest of the excitation systems would likely result in a level of application insufficient for the studies for which they are intended.

In actual systems, an OEL may monitor and limit one of several variables (main field current or voltage, exciter field current or voltage, etc.). While this design choice affects the fast dynamic response characteristics of the OEL, it is not of great concern when examining the long-term response. Therefore, it is generally sufficient to treat main field current as the input parameter. Since most simulation programs assume a constant field resistance, in the steady state the values of E_{FD} and I_{FD} will be equivalent in a non-reciprocal pu system (see IEEE Std 1110™-2002 [B22]). The model in Figure 27 assumes that the measured/limited quantity is main field current, I_{FD}, although E_{FD} could be used as well. Systems that limit the field of a rotating exciter can also be based on the corresponding level of main field current.

Unfortunately, the choice of generator field voltage as the limited variable introduces a dependency on field resistance, which can change by over 20% with temperature changes from 25 °C to 75 °C. The field voltage limit point should then reflect a “hot” field temperature, or if field resistance is included in the model, the generator should be modeled with a higher field resistance, appropriate for the hot field condition.

In simulation programs, the normalized value of field current will most likely be the field current on the air-gap line of the machine saturation curve at rated terminal voltage. Since OEL settings are usually based on the field current under rated MVA, rated voltage conditions, the field current must be converted to the base value of I_{Rated}. This parameter sets the pu base for the other variables in the limiter model. Thus, limiter models for varying sizes and types of machines can have similar parameters. It should be emphasized that the 1.0 pu base, used within the OEL model, is based on the rated machine excitation level and not on the air-gap line as used in the generator model.

The limiting characteristic parameters are then selected. The timed-limit pickup, I_{TFPU}, is usually near 1.05 pu of the rated value. The instantaneous limit value, I_{INST}, is normally near 1.5 pu. In some systems, hysteresis between pickup and dropout is included in the design, so the value of I_{FDLIM} can be set to the same level as I_{TFPU}. In some systems, the value of I_{FDLIM} must be set a few percent higher in order to avoid limit cycling.

Digital systems define the inverse-time limiter characteristic using an equation with variable parameters, and may adhere to standard curve definitions, such as in Equation (5) or those found in IEEE Std C37.112™-1996 [B24]. However, the inverse-time characteristics of older systems are dependent on the designs and may vary in shape. Most types of systems can be adequately modeled by a curve fit using the characteristic Equation (5) where *A*, *B,* and *C* are constants (see IEEE Std C37.112-1996 [B24]).

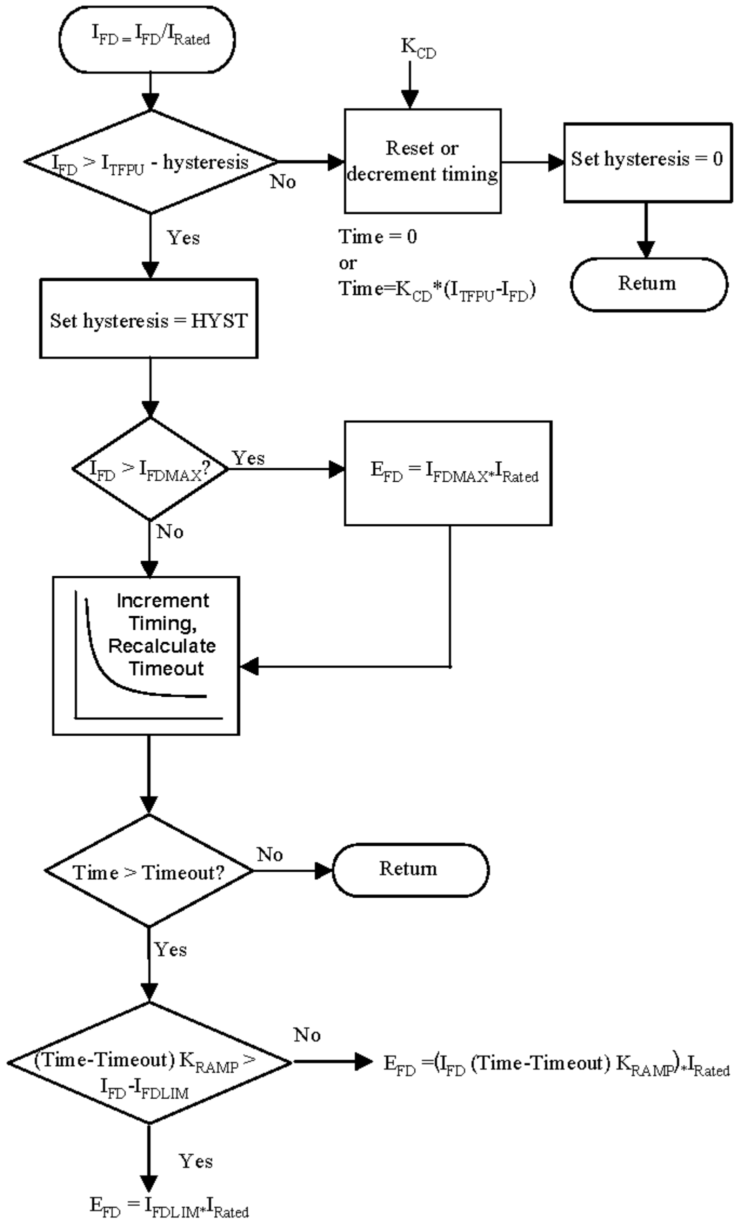


Figure 9-2—Overexcitation limiter with selectable pickup and limiting characteristics

The level of I_{FD} is compared to the pickup level, I_{TFPU}, and if I_{FD} is less than the pickup level, the OEL will not be active. In this case, the timer should be reset or decremented by the appropriate amount. Some OELs will automatically reset the timing device after the limiter has dropped out, i.e., the level of I_{FD} is less than I_{TFPU}. Other designs will slowly reverse the timer back to zero, to account for the cooling of the field winding. If the limiter picks up again before the timer is fully reset, the OEL will act much quicker. In the model, the cooldown rate is proportional to the difference between I_{TFPU} and I_{FD} and a gain set by K_{CD}.

More sophisticated designs incorporate a hysteresis feature, which will not allow the limiter to drop out until the excitation level is below a defined amount less than the pickup level. This helps to prevent limit cycling. The hysteresis should be initialized to zero and only set to the constant value *HYST* after the limiter has picked up. It should be reset to zero after the limiter has dropped out. A permanent limit condition, such as transferring to manual control, can be achieved by setting *HYST* to a sufficiently large value, such as I_{TFPU}.

If an instantaneous maximum limit or ceiling level is represented, the parameter I_{FDMAX} is used. The level of I_{FD} is then clamped to the maximum value I_{FDMAX}.

While the level of I_{FD} remains above I_{TFPU}, the limiter timing is incremented according to the appropriate timing characteristic. A fixed time limiter should simply increment the time regardless of the level of overexcitation. For inverse-time applications, the time-overexcitation condition should be integrated according to the appropriate relationship [e.g., Equation (5)] to account for variation in the level of overexcitation while the limiter is timing. When the limiter timing reaches time-out, the level of I_{FD} is reduced to the value I_{FDLIM}. Most limiters accomplish this quickly, in one step, although some limiters will ramp the excitation down. The ramp rate is set by the parameter K_{RAMP}. A one-step reduction in field current will result for a sufficiently large value of K_{RAMP}. The value of I_{FD} should remain at the limited value until system conditions result in a value of I_{FD} that is less than the pickup level, I_{TFPU} minus the hysteresis, *HYST*. Again, as the pu system of excitation level of the OEL model is not the same as the generator and excitation system models, the value of I_{FDLIM} must be converted to the corresponding level of E_{FD} in the generator model by multiplying by I_{Rated}. In most cases, windup of the limiter is appropriate, as implied in Figure 9-2 by continued time incrementing for high field current.

This model does not incorporate the necessary stability control functions of actual OELs. Therefore, it is not designed to interact with any of the excitation system models included in this document. It is intended that the synchronous machine field voltage, E_{FD}, is altered directly by auctioneering the excitation system model output with the output signal of this OEL model, as if there were a low value gate at the output of the excitation system model. The output signal of this OEL model is not, in general, equivalent to the signal V_{OEL} found in other parts of this document. The output signal should not enter any internal point in an excitation system model, as it then would require additional signal compensation and detailed tuning to match actual equipment response. These details have been purposely eliminated from this model. If it is desired to represent a dynamic V_{OEL} signal that impacts the stability of the excitation control system, a more detailed OEL model must be used, such as detailed in IEEE Task Force on Excitation Limiters [B25].

Since the action of this limiter model will override the output of an excitation system model, if the simulated system voltage conditions improve during an imposed OEL limit to the point that the OEL may drop out of control, there may be additional lag time before the excitation system model resumes control due to windup of the excitation system model.

Sample data is provided in Annex H.

10. Underexcitation limiters

A UEL acts to boost excitation for one or more of the following purposes (see Berube, Hajagos, and Beaulieu [B6]):

a) To prevent operation that jeopardizes stability of the synchronous machine or could lead to loss of synchronism due to insufficient excitation.

b) To prevent operation that would lead to overheating in the stator end region of the synchronous machine, typically defined by the extreme underexcited region of the machine capability curve.

c) To prevent loss-of-excitation relays from operating during underexcited operation.

The UEL typically senses either a combination of voltage and current of the synchronous machine or a combination of real and reactive power. The UEL output is applied in the voltage regulator to either a summing junction to add to the normal voltage control or a HV gate to override the normal action of the voltage regulator. Depending upon the implementation of the UEL function to control excitation, the action of the UEL could take the PSS out of service and/or cause interactions, which may not normally occur during normal operation when the UEL characteristic is not reached.

Although UEL designs utilize various types of input sensing and signal processing, their limiting characteristics are usually plotted in terms of real and reactive power on MVAR vs. MW axes. However in many cases, the specified limit in terms of MW and MVAR is terminal voltage dependent, such as would occur with UELs that sense apparent impedance at the generator terminals. In an attempt to encompass a wide range of UEL applications, two UEL models have been developed, as follows:

1) Circular characteristic (Type UEL1)
2) Single- or multiple-segment straight-line characteristic (Type UEL2)

Some UELs utilize a temperature or pressure recalibration feature, in which the UEL characteristic is shifted depending upon the generator cooling gas temperature or pressure. Since this is typically a slowly acting effect, it is not represented in the UEL models, and selection of the UEL model constants should reflect the limiting characteristic at the initial operating condition.

The V_F input to both models allows provision for an excitation system stabilizer signal from the voltage regulator, which can be used for damping of oscillations. Similarly, the lag and lead functions represented by T_{U1} through T_{U4} may be appropriately adjusted in certain applications to provide damping.

Additional information may be found in Anderson, Simmons, and Woodrow [B1], Berdy [B5], Carleton, Bobo, and Burt [B8], Cawson and Brown [B9], Estcourt et al. [B11], Heffron and Phillips [B15], IEEE Std C37.102-1995 [B23], IEEE Task Force on Excitation Limiters [B25], Landgren [B30], Nagy [B35], Ribeiro [B37], and Rubenstein and Temoshok [B38].

10.1 Circular characteristic UEL (Type UEL1 model)

The Type UEL1 model shown in Figure 10-1 has a circular limit boundary when plotted in terms of machine reactive power vs. real power output. The phasor inputs of I_T and V_T are synchronous machine terminal output current and voltage with both magnitude and phase angle of these ac quantities sensed.

Figure 10-2 shows a typical UEL1 limiting characteristic plotted on MVAR vs. MW axes. K_{UR} determines the radius of the UEL limit such that V_{UR} has a predetermined magnitude and is also proportional to the magnitude of machine terminal voltage V_T. K_{UC} determines the center of the UEL limit. When K_{UC} multiplied by the phasor quantity V_T is summed with the phasor quantity $-jI_T$, the resulting magnitude V_{UC} determines whether or not the machine operating point has reached the UEL limit. Absorbing more reactive power (Q_T) or sending more real power (P_T) increases V_{UC} and results in the machine operating point moving toward the circular UEL limit.

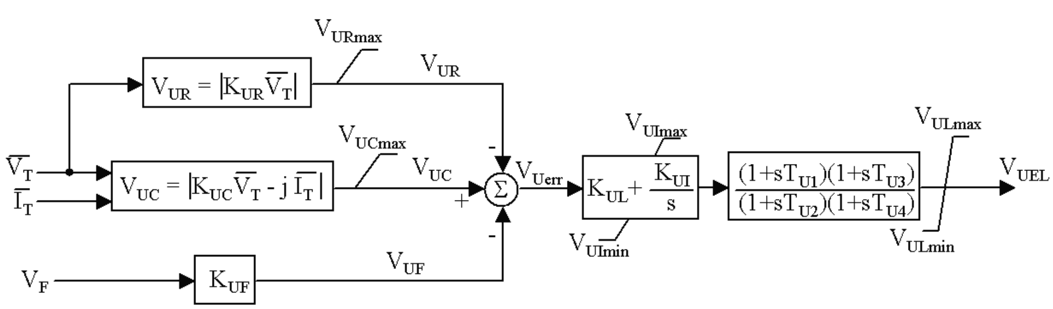


Figure 10-1—Type UEL1 model for circular characteristic underexcitation limiter

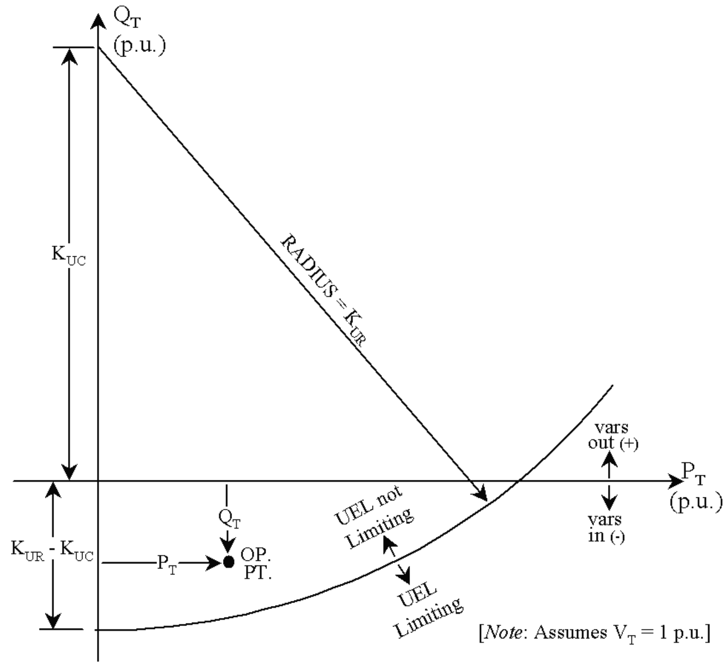


Figure 10-2—Type UEL1 circular limiting characteristic

Since the Type UEL1 model derives the operating point using I_T and compares it with a radius and center proportional to V_T, this model essentially represents a UEL that utilizes a circular apparent impedance characteristic as its limit. Since generator loss of excitation relays often utilize a similar circular impedance characteristic, this type of UEL generally allows close coordination with a loss of excitation relay. Also, the UEL limit boundaries in terms of P and Q vary with V_T^2, just as the steady-state stability limit varies with V_T^2, so the UEL limit changes as terminal voltage variations alter the steady-state stability limit.

Under normal conditions when the UEL is not limiting, $V_{UC} < V_{UR}$ and the UEL error signal V_{Uerr} shown in Figure 10-1 is negative. When conditions are such that the UEL limit is exceeded, $V_{UC} > V_{UR}$ and the UEL error signal V_{Uerr} becomes positive. This will drive the UEL output in the positive direction, and if the gain is sufficient, the UEL output will take over control of the voltage regulator to boost excitation to move the operating point back toward the UEL limit.

Sample data is provided in H.23.

10.2 Piecewise linear UEL (Type UEL2 model)

Figure 10-3 shows the Type UEL2 model. For this model, the UEL limit has either a straight-line or multi-segment characteristic when plotted in terms of machine reactive power output (Q_T) vs. real power output (P_T). The UEL limit can be unaffected by terminal voltage V_T by setting the exponential constant $k1 = k2 = 0$ (such that $F1 = F2 = 1$). If instead the UEL senses the real and reactive components of machine current I_T, the UEL limit characteristic can be made proportional to V_T by using $k1 = k2 = 1$. Similarly, if the UEL is configured to limit based on the real and reactive components of the apparent impedance looking from the machine terminals, the UEL limit characteristic can be made proportional to V_T^2 using $k1 = k2 = 2$ in the model.

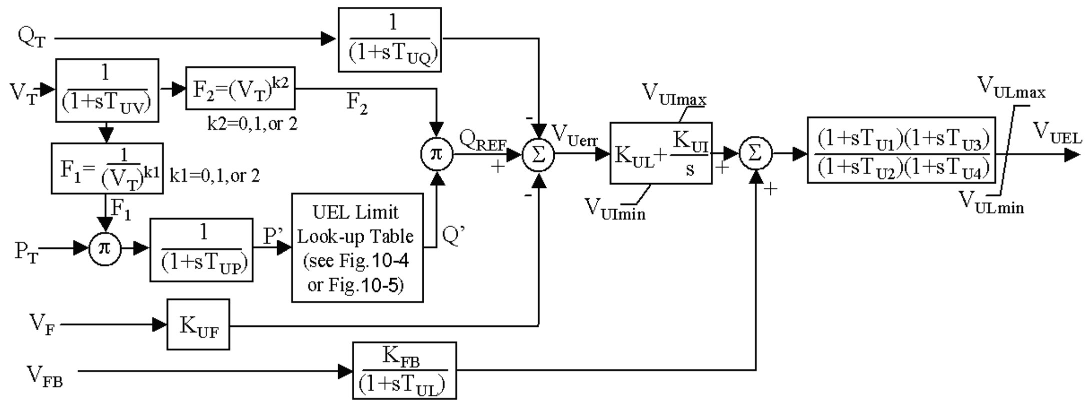


Figure 10-3—Type UEL2 model for straight-line or multi-segment underexcitation limiter

In the UEL2 model in Figure 10-3, after the real power P_T is modified by $F1$ (applying the appropriate effect of terminal voltage V_T), the resulting normalized value P' is sent to the UEL look-up table to determine the corresponding normalized value of the reactive power Q' at the UEL limit characteristic.

This normalized limit value Q' is then multiplied by $F2$ to determine the UEL limit reference Q_{REF}, which is compared with the machine reactive power Q_T. Note that the UEL limit characteristic specified in Table 10-1 utilizes normalized values of real and reactive power (P' and Q'), which are valid at rated terminal voltage (V_T = 1.0 pu). The functions $F1$ and $F2$ provide the appropriate adjustments so that the effects of terminal voltage, if any, on the UEL limit are properly taken into account.

Figure 10-4 shows the normalized UEL limit characteristic for a UEL in which the limit is comprised of a single straight line. When the points ($P0$, $Q0$) and ($P1$, $Q1$) are specified, they define two points on the straight-line UEL characteristic. In the example shown in Figure 10-4 these point are located on the intercepts of the P and Q axes such that $P0 = 0$ and $Q1 = 0$, but the points would not need to be defined in this manner. Note that the P and Q values used to specify the UEL limit are those values that would be applicable with V_T = 1.0 pu. For any value of P', the corresponding value of Q' can readily be determined by linear interpolation.

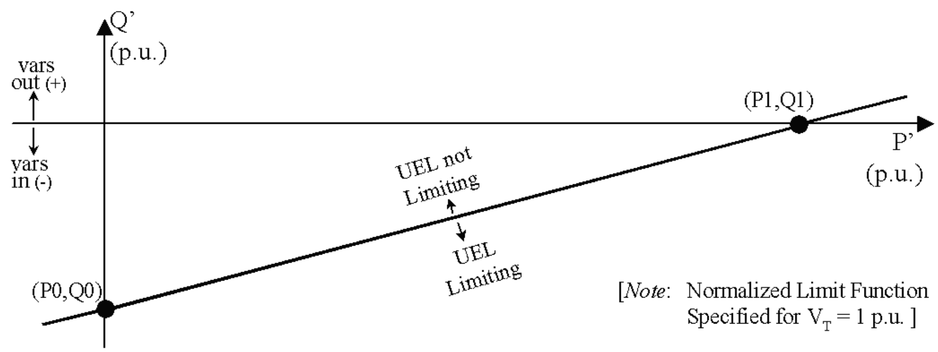


Figure 10-4—Type UEL2 straight-line normalized limiting characteristic

Figure 10-5 shows a UEL limit characteristic for a UEL in which the limit is comprised of multiple straight-line segments, showing up to six segments, although some systems may use more or fewer segments. By defining the endpoints of each of the segments in terms of *P* and *Q* values (at V_T = 1.0 pu), the UEL characteristic is determined. The UEL characteristic can be comprised of any number of straight-line segments from 1 to 6. The data requirements to define the UEL characteristic vs. the number of UEL segments are defined in Table 1.

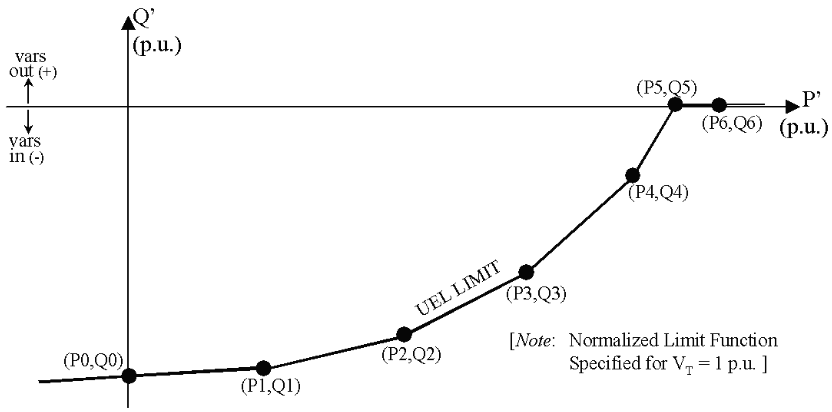


Figure 10-5—Example of Type UEL2 multi-segment normalized limiting characteristic using six segments

Table 10-1—UEL set point look-up table requirements

Segment endpoint values required	Number of UEL segments					
	1	2	3	4	5	6
*P*0, *Q*0	X	X	X	X	X	X
*P*1, *Q*1	X	X	X	X	X	X
*P*2, *Q*2		X	X	X	X	X
*P*3, *Q*3			X	X	X	X
*P*4, *Q*4				X	X	X
*P*5, *Q*5					X	X
*P*6, *Q*6						X

Note that the *P* and *Q* values used to specify the UEL limit are those values that would be applicable with V_T = 1.0 pu. Between the indicated segment endpoints, the UEL characteristic is defined by a straight line. For any value of *P*′, the corresponding value of *Q*′ can readily be determined by linear interpolation. The UEL characteristic beyond each of the defined endpoints is a straight line that is a continuation of the segment defined by the first two (for negative values of *P*) or last two (for positive values of *P*) endpoints. For example, in Figure 10-5 the UEL characteristic for negative values of *P* is an extension of the segment defined by the points (*P*0, *Q*0) and (*P*1, *Q*1). Also in this example, it can be seen that beyond point (*P*5, *Q*5) a UEL limit continuing along the $Q' = 0$ axis can be represented by defining the point ($P6$, $Q6$) such that $Q5 = Q6 = 0$ and $P6>P5$. If the point ($P6$, $Q6$) was not defined in this example, then the UEL characteristic would extend to the upper right with the same slope as the line segment defined by the points ($P4$, $Q4$) and ($P5$, $Q5$).

Under normal conditions when the UEL is not limiting, the UEL error signal V_{Uerr} shown in Figure 10-3 is negative, since the reactive power Q_T will be greater than the limit value Q_{REF}. When conditions are such that the UEL limit is exceeded, V_{Uerr} becomes positive. This will drive the UEL output in the positive direction, and if the gain is sufficient, the UEL output will take over control of the voltage regulator to boost excitation to move the operating point back toward the UEL limit.

The input V_{FB} allows provision for the feedback signal necessary in non-windup integrator function, depending on the chosen representation (see Annex E). Sample data is provided in H.24.

11. Power factor and reactive power controllers and regulators

Excitation systems for synchronous machines are sometimes supplied with an optional means of automatically adjusting generator output reactive power (var) or power factor (pf) to a user-specified value. This can be accomplished with either a reactive power or power factor controller or regulator, as described in Hurley, Bize, and Mummert [B16] A reactive power or power factor controller is defined as a *var/pf controller* in IEEE Std 421.1[6] as "A control function that acts through the reference adjuster to modify the voltage regulator set point to maintain the synchronous machine steady-state power factor or reactive power at a predetermined value." A var/pf regulator is defined as "A synchronous machine regulator that functions to maintain the power factor or reactive component of power at a predetermined value."

The use of a var/pf controller or regulator has its origin in industrial applications of synchronous motors and generators, in which the synchronous machine is typically tied directly to a plant distribution bus. In many of these industrial applications, the machine voltage is expected to follow any variations in the utility-fed system voltage, in which case machine terminal voltage regulation may not be desirable. Var/pf controllers and regulators are often used in these types of industrial applications.

In this sense, each synchronous machine on a power system might be placed into one of the two following categories:

a) *Voltage supporting machines:* Synchronous machines that would be expected to aid in the regulation of system voltage. Most generators and synchronous condensers should be in this category, particularly larger machines or any machines that deliver power directly to the transmission system. These machines should typically regulate voltage, in which case specification of a var/pf controller or regulator would not be appropriate.
b) *Voltage following machines:* Synchronous machines that would not be expected to aid in the regulation of system voltage, but whose voltage would be expected to follow the variations of incoming system voltage. This category would tend to include small synchronous machines that are connected to distribution systems whose incoming voltage is regulated by the utility with load tap changing transformers or other such devices (see ANSI C50.13-1989 [B3]). These machines will typically be the ones that could justifiably be specified to include a var/pf controller or regulator.

It is in the interest of maintaining proper grid voltage stability and voltage support that as many machines as possible be operated as voltage supporting, rather than voltage following machines.

Var/pf controllers and regulators are popular with small independent power producers, since they eliminate one of the labor-intensive operating activities. When applied to large machines or machines connected to the

[6]Information on references can be found in Clause 2.

transmission system, however, they reduce the amount of voltage regulation, which may adversely affect power system stability. If improperly configured, var/pf controllers and regulators can also contribute to system overvoltage or undervoltage conditions. Many utilities are developing policies to limit the use of such controls or at least ensure that each application is reviewed in detail.

At the distribution level, the situation is somewhat different. Distribution systems were not originally designed to rely on voltage regulation from generation sources; instead other means such as capacitor banks, load tap changing transformers, or feeder voltage regulators were relied upon. Although introduction of voltage regulation can improve the voltage profile and dynamic response of distribution systems, coordination with existing controls could be a problem where multiple voltage controlling devices are located on a single feeder. Under these circumstances, var/pf controls provide an alternative mode of operation that could be easier to coordinate (see Ontario Hydro [B36]).

In the case of a controller, the AVR is equipped with a slow, outer-loop control, which uses the error between the desired and measured pf, var, or reactive current signal to raise or lower the AVR's set point, in order to maintain the desired unit reactive output. This is the same as if the unit were under the control of an attentive operator. The var or pf controller tends to perform the right action during a disturbance because the voltage regulator will react immediately and the var or pf will slowly integrate its set point back to normal after the voltage regulator corrective action occurs. A var/pf controller will allow dynamic voltage support during faults. A var/pf regulator will *not* allow dynamic voltage support during faults. So a controller, instead of a regulator, is used where dynamic voltage support during faults is desired.

In the case of a var/pf regulator, the var/pf regulator eliminates the AVR terminal voltage feedback loop and, instead, directly controls the unit's field voltage to regulate pf or var to the user's reference set point. These types of regulators typically utilize a reference adjuster and error detection methods similar to that with a voltage regulator, except for the sensed feedback signal. This regulator could be implemented as a separate device or as part of a programmable logic control system used to control different aspects of the generator's operation. For motors, continuous acting control may typically be implemented using a regulator so as to increase the machines pull-out torque when subjected to pulse type loads. For generators, one must be careful in applying var/pf regulators.

Since var/pf regulators function similar to a voltage regulator, the var/pf regulators can be modeled using the same models as most of the excitation systems. The only change to these models is that the terminal voltage input, V_C, is replaced by the quantity being regulated, i.e., power factor or vars. The controller functions require a new set of models to simulate how they modify the reference signal, V_{REF}, and consequently the machine terminal voltage so as to keep the controlled quantity near a set value over an extended time period. Included in the controller is a time delay. This allows the machine to provide voltage support until the time delay has been exceeded. In addition, this time delay allows a synchronous generator to support voltage while a synchronous motor is being started. The following subclauses deal with these new models. Sample data is provided in H.24.

11.1 Voltage adjuster

The model that is shown in Figure 11-1 is used to represent the voltage adjuster in either a power factor or var control system. The output of the model is the V_{REF} signal that is to be used as the V_{REF} input in any of the other previously presented models. The inputs to this model are the raise or lower signals from one of the following controller models and a signal indicating if the adjuster should be raised at a fast rate. In the model, when both inputs V_{CR} and V_{CL} are low, the output remains fixed. When only V_{CR} is high, the RAISE ADJUSTER contact oscillates with an on time of T_{ON}, and an off time of T_{OFF}. The output ramps up at the set slew rate [ADJ_SLEW/($V_{ADJMAX} - V_{ADJMIN}$)], while the Raise command line is active, and pauses while the Raise command line is inactive. When only V_{CL} is high, the LOWER ADJUSTER contact oscillates with an on time of T_{ON}, and an off time of T_{OFF}. The output ramps down at the set slew rate, while the Lower command line is active, and pauses while the Lower command line is inactive. When both V_{ADJF} and V_{CR}

are on, the RAISE ADJUSTER contact is on continuously and the output ramps up. When both V_{ADJF} and V_{CL} are on, the LOWER ADJUSTER contact is on continuously and the output ramps down. *ADJ_SLEW* is the time required for the output to go between the limits V_{ADJMIN} and V_{ADJMAX}, when both V_{ADJF} and V_{CR} are on.

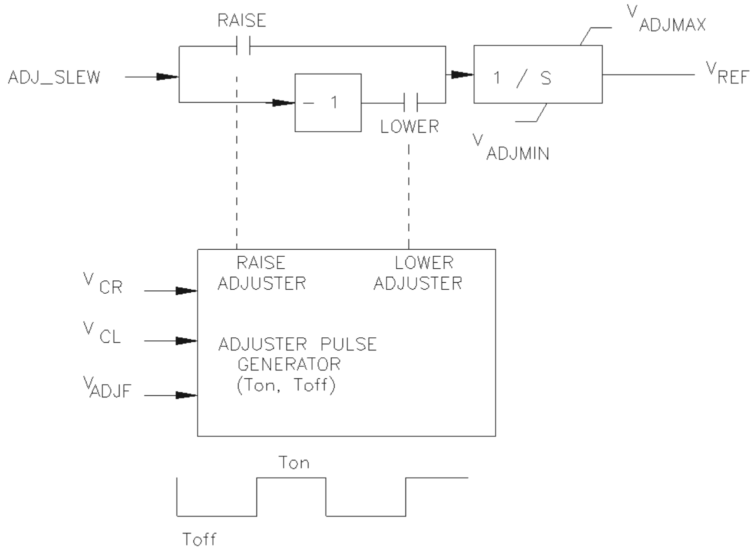


Figure 11-1—Voltage adjuster model

11.2 PF controller Type I

The model that is shown in Figure 11-2 is used to represent a Type I pf controller that operates by moving the voltage reference directly. The pf controller generates Adjuster Raise (V_{CR}) or Adjuster Lower (V_{CL}) signals, which may be used as inputs to the voltage adjuster model. This function operates after a time delay to raise or lower this reference set point until the generator power factor is within the set dead-band value. Both outputs are low when V_{PFE} is between $-V_{PFC\_BW}$ and V_{PFC_BW}. When V_{PFE} exceeds V_{PFC_BW} for a time greater than T_{PFC} seconds, the output V_{CR} is held high until V_{PFE} drops below V_{PFC_BW}. When V_{PFE} is more negative than $-V_{PFC\_BW}$ for a time greater than T_{PFC} seconds, the output V_{CL} is held high until V_{PFE} becomes less negative than $-V_{PFC\_BW}$.

Since the power factor of a unit varies from 0 to 1 as excitation is increased from maximum underexcited to unity power factor, and then from 1 to 0 as excitation is further increased to maximum overexcitation, a dummy variable PF_{NORM} has been created internally to the controller. In the underexcited state, PF_{NORM} equals the power factor. In the overexcited state, PF_{NORM} equals 2.0 minus the power factor. A separate input variable *OVEX* is set to 0 when the unit is underexcited and then set to 1 when the unit is overexcited.

11.3 Var controller Type I

The model shown in Figure 11-3 is used to represent a Type I var controller that operates by moving the voltage reference directly. The var controller generates Adjuster Raise (V_{CR}) or Adjuster Lower (V_{CL}) signals, which may be used as inputs to the voltage adjuster model. This function operates after a time delay to raise or lower this reference set point until the generator reactive power (var) is within the set dead-band value. Both outputs are low when V_{VARE} is between $-V_{VARC\_BW}$ and V_{VARC_BW}. When V_{VARE} exceeds V_{PFBW} for a time greater than T_{VARC} seconds, the output V_{CR} is held high until V_{VARE} drops below V_{VARC_BW}. When V_{VARC_BW} is more negative than $-V_{VARC\_BW}$ for a time greater than T_{VARC} seconds, the output V_{CL} is held high until $V_{VARE\ VAR}$ becomes less negative than $-V_{VARC\_BW}$.

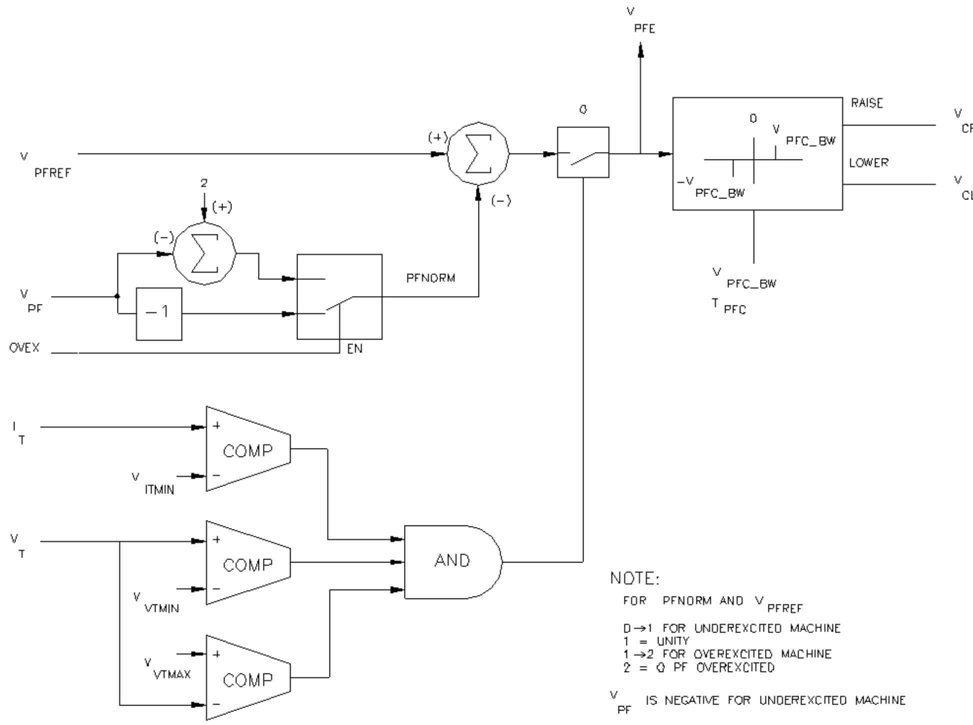


Figure 11-2—PF controller Type I model

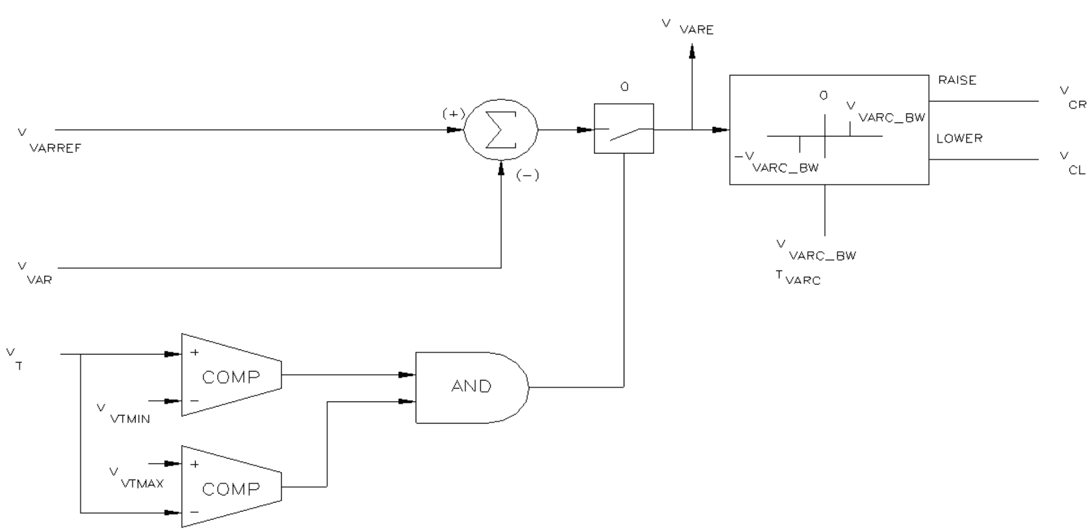


Figure 11-3—Var controller Type I model

11.4 PF controller Type II

The Type II pf controller is a summing point type controller and makes up the outside loop of a two-loop system. This controller is implemented as a slow PI type controller. The voltage regulator forms the inner loop and is implemented as a fast controller. As shown in Figure 11-4, the pf controller generates the pf controller signal (V_{PF}), which is used as input to the voltage regulator loop. The resulting control makes the generator power factor reach the desired power factor set point smoothly. No dead band and time delay is used. The controller response time depends on the PI controller gains. In the overexcitation or underexcitation state, the integral action is disabled to allow the limiter to play its role. Non-windup limit (V_{CLMT}) is used for bounding the pf controller output voltage V_{PF}.

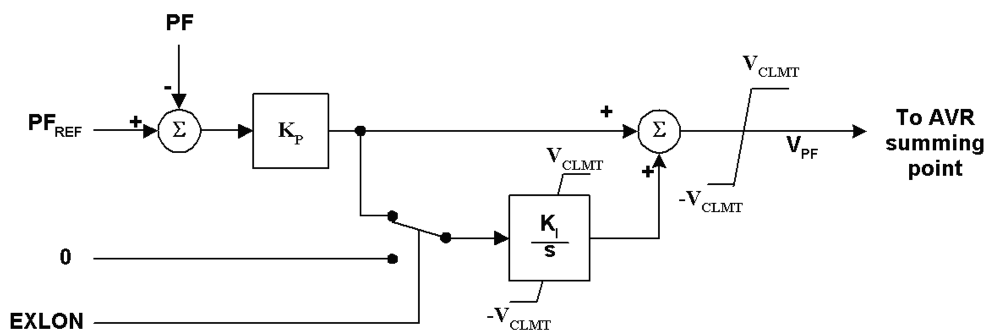


Figure 11-4—PF controller Type II model

11.5 Var controller Type II

The Type II var controller is a summing point type controller. It makes up the outside loop of a two-loop system. As shown in Figure 11-5, this controller is implemented as a slow PI type controller, and the voltage regulator forms the inner loop and is implemented as a fast controller. The var controller generates the var controller signal (V_{VAR}), which may be used as input to the voltage regulator loop. The resulting control makes generator reactive power reach the desired var set point smoothly. No dead band and time delay is used. The controller response time depends on the PI controller gains. In the overexcitation or underexcitation state, the integral action is disabled to allow the limiter to play its role. Non-windup limit (V_{CLMT}) is used for bounding the var controller output voltages V_{VAR}.

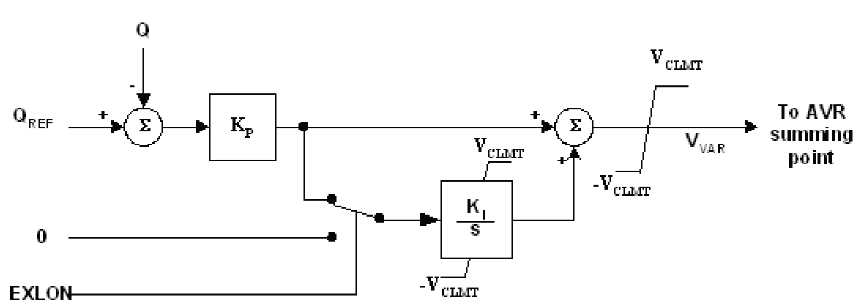


Figure 11-5—Var controller Type II model

12. Supplementary discontinuous excitation control

12.1 General

In some particular system configurations, continuous excitation control with terminal voltage and power system stabilizing regulator input signals does not ensure that the potential of the excitation system for improving system stability is fully exploited. For these situations, discontinuous excitation control signals may be employed to enhance stability following large transient disturbances, see Bayne, Kundur, and Watson [B4], Lee and Kundur [B31], and Taylor [B42].

12.2 Type DEC1A discontinuous excitation control

The Type DEC1A discontinuous excitation control model, shown in Figure 12-1, is used to represent a scheme that boosts generator excitation to a level higher than that demanded by the voltage regulator and stabilizer immediately following a system fault. The scheme, which has been applied to a number of large synchronous generators with bus-fed static exciters (ST1A), adds a signal proportional to rotor angle change to the terminal voltage and power system stabilizing signals. This angle signal is used only during the transient period of about 2 s because it results in steady-state instability if used continuously. The objective of such a control is to maintain the field voltage and hence the terminal voltage high, until the maximum of the rotor angle swing is reached. This control is used specifically for instances where both local and inter area oscillations are present in the transient, and where the back swing of the local mode would otherwise bring the excitation off ceiling before the true peak of the angular swing is reached. Excessive terminal voltage is prevented by the use of a terminal voltage limiter circuit.

The effect of this discontinuous control, in addition to increasing generator terminal voltage and air-gap power, is to raise the system voltage level and hence load power, contributing to unit deceleration.

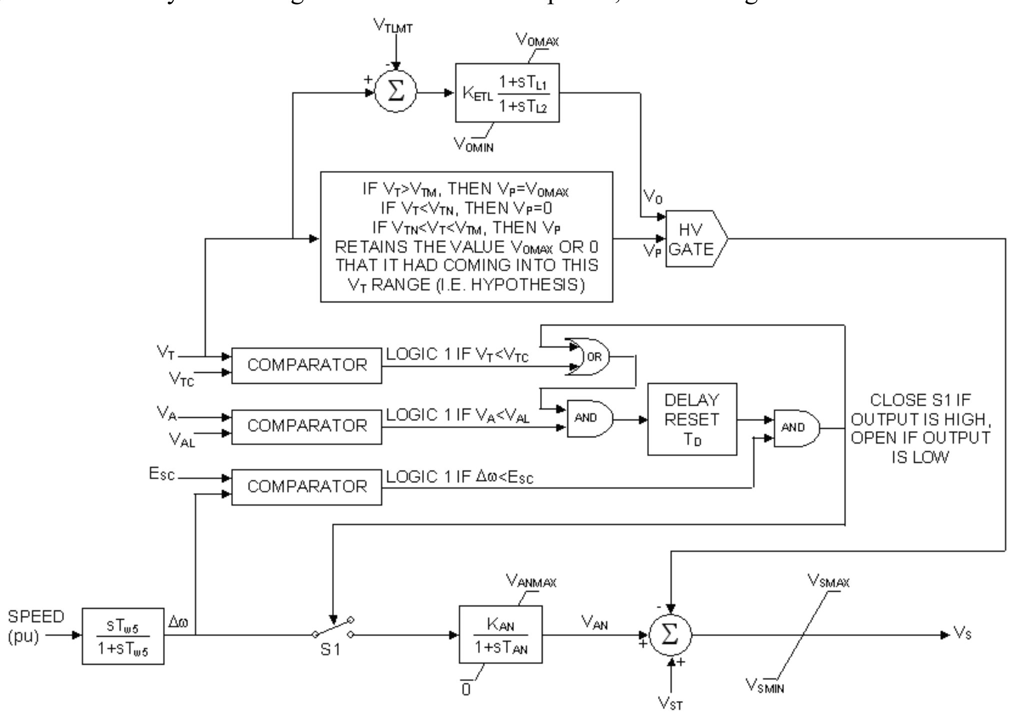


Figure 12-1—Type DEC1A discontinuous excitation controller transient excitation boosting with dual action terminal voltage limiter

As shown in Figure 12-1, the speed (or equivalent) PSS signal provides continuous control to maintain steady-state stability under normal operating conditions. For the discontinuous control, a signal proportional to change in the angle of the synchronous machine is obtained by integrating the speed signal. It is not a perfect integrator, i.e., the signal is reset with the time constant, T_{AN}.

The speed change is integrated only during the transient period following a severe system fault. The relay contact, S_1, which introduces the signal, is closed if the following conditions are satisfied:

a) A drop in terminal voltage in excess of a preset value

b) Regulator output at positive ceiling

c) Rise in speed above a preset value

The relay contact, S_1, is opened when either

1) The speed change drops below a threshold value, or

2) Regulator output comes off ceiling.

The output of the integrator block then decays exponentially with a time constant, T_{AN}.

The use of a fast-acting terminal voltage limiter is essential for satisfactory application of this discontinuous excitation control scheme. A dual voltage limiter is used to provide fast response and a high degree of security, without the risk of exciting shaft torsional oscillations. One of the limiters is fast acting and uses a discrete or bang-bang type of control with hysteresis to limit the generator terminal voltage. The second limiter uses a continuous control action and is slower acting, but limits to a lower terminal voltage. It takes over control of terminal voltage from the first limiter after an initial delay and limits the terminal voltage to a lower value for sustained overexcitation conditions, such as those that could be caused by malfunction of PSS or discontinuous excitation controls. By overriding the action of the discrete limiter, the slower limiter prevents sustained terminal voltage and resulting power oscillations inherent to the action of the bang-bang limiter should the unit be operating continuously against the limit for any reason.

The outputs of the PSS, V_{ST}, the terminal voltage limiter, and the angle signal are combined, and overall limits are applied to the new signal, V_S, which goes to the summing junction of the voltage regulator.

12.3 Type DEC2A discontinuous excitation control

A model for the DEC2A discontinuous excitation control is shown in Figure 12-2. This system provides transient excitation boosting via an open-loop control as initiated by a trigger signal generated remotely. The trigger initiates a step of amplitude, V_K, which may be conditioned by the small time constant, T_{D1}. The high pass filter block with time constant, T_{D2}, produces a decaying pulse that should temporarily raise generator terminal voltage and hence system voltage. The limiter freezes the filter block output if terminal voltage exceeds a fixed level. The output is released when terminal voltage drops below this level and filter block output drops below its value at the time the output was frozen (bumpless clipping using digital logic).

This transient excitation boosting is implemented at the Grand Coulee third powerhouse, with the control initiated for outage of the Pacific 3100 MW HVDC Intertie, see Taylor [B42]. For this disturbance, the inter area mode swing center is about 1300 km from the power plant, and normal voltage regulator field boosting was minimal.

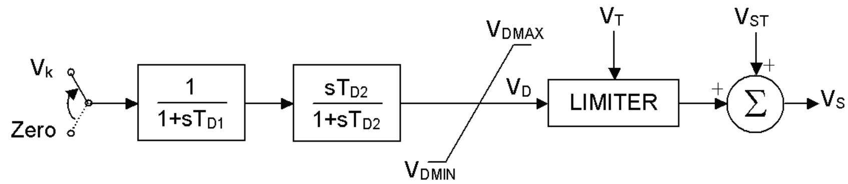


Figure 12-2—Type DEC2A—Discontinuous excitation controller open-loop transient excitation boosting

12.4 Type DEC3A discontinuous excitation control

In some systems, the stabilizer output is disconnected from the regulator immediately following a severe fault to prevent the stabilizer from competing with action of voltage regulator during the first swing. This is accomplished in the DEC3A model by opening the output of the stabilizer for a set time, T_{DR}, if the terminal voltage drops below a set value of, V_{TMIN} (see Figure 12-3).

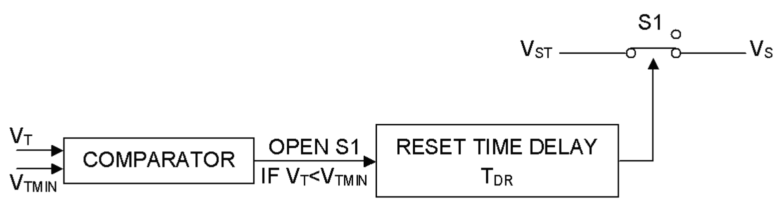


Figure 12-3—Type DEC3A discontinuous excitation controller temporary interruption of stabilizing signal

Annex A

(normative)

Nomenclature

Maximum and minimum limits of parameters are not shown explicitly in the nomenclature, but are represented by the appropriate subscript (max or min) on the variable. A score line above a parameter is used to indicate that it is a phasor.

A_{1-8}	PSS signal conditioning frequency filter constants
ADJ_SLEW	Voltage adjuster travel time
E_{FD}	Exciter output voltage
E_{FD1}, E_{FD2}	Exciter voltages at which exciter saturation is defined (dc commutator exciters and Type AC5A models only)
E_{FDN}	Value of E_{FD} at which feedback gain changes (Type AC3A)
E_{SC}	Speed change reference (Type DEC1A)
EXLON	Indication that overexcitation limiter is active
F_1, F_2	UEL terminal voltage multiplying factors
F_{EX}	Rectifier loading factor, a function of I_N
HV GATE	Model block with two inputs and one output, the output always corresponding to the higher of the two inputs.
HYST	OEL pickup/drop-out hysteresis
I_{FD}	Synchronous machine field current
I_{FDLIM}	OEL timed field current limit
I_{FDMAX}	OEL instantaneous field current limit
I_{LR}	Exciter output current limit reference
I_N	Normalized exciter load current
I_{Rated}	Rated field current
I_T, $\overline{I_T}$	Synchronous machine terminal current
I_{TFPU}	OEL timed field current limiter pickup level
k_1	UEL terminal voltage exponent applied to real power input to UEL limit look-up table
k_2	UEL terminal voltage exponent applied to reactive power output from UEL limit look-up table
K_A	Voltage regulator gain
K_{AN}	Discontinuous controller gain (Type DEC1A)
K_B	Second stage regulator gain

K_B, K_I, K_H	Low, intermediate, and high band gains (Type PSS4B)
K_C	Rectifier loading factor proportional to commutating reactance
K_{CD}	OEL cooldown gain
K_{CI}	Exciter output current limit adjustment (Type ST6B)
K_D	Demagnetizing factor, a function of exciter alternator reactances
K_E	Exciter constant related to self-excited field
K_{ETL}	Terminal voltage limiter gain (Type DEC1A)
K_F, K_{F1}, K_{F2}, K_N	Excitation control system stabilizer gains
K_{FB}	Gain associated with optional integrator feedback input signal to UEL
K_{FF}	Pre-control gain constant of the inner loop field regulator (Type ST6B)
K_G	Feedback gain constant of the inner loop field regulator (Type ST3A, ST6B)
K_H	Exciter field current feedback gain (Type AC2A), exciter field current limiter gain (Type AC6A)
K_{H1}, K_{H2}	High band differential filter gains (Type PSS4B)
K_{H11}, K_{H17}	High band first lead-lag blocks coefficients (Type PSS4B)
K_I	Potential circuit gain coefficient
K_{I1}, K_{I2}	Intermediate band differential filter gains (Type PSS4B)
K_{I11}, K_{I17}	Intermediate band first lead-lag blocks coefficients (Type PSS4B)
K_L, K_I, K_H	Low, intermediate, and high band gains (Type PSS4B)
K_{L1}, K_{L2}	Low band differential filter gains (Type PSS4B)
K_{L11}, K_{L17}	Low band first lead-lag blocks coefficients (Type PSS4B)
K_{LR}	Exciter output current limiter gain
K_M	Forward gain constant of the inner loop field regulator (Type ST3A, ST6B)
K_N	Excitation system stabilizer gain (Type AC3A)
K_P	Potential circuit gain coefficient
K_{PA}, K_{IA}	Voltage regulator proportional and integral gains (Type ST6B, AC7B)
K_{PM}, K_{IM}	Voltage regulator proportional and integral gains (Type ST4B)
K_{PR}, K_{IR}, K_{DR}	Voltage regulator proportional, integral, and derivative gains (Type ST4B, AC7B, AC8B)
K_R	Constant associated with regulator and alternator field power supply (Type AC3A)
K_{RAMP}	OEL ramped limit rate
K_S	PSS gain (Type PSS1A)
K_{S1}, K_{S2}, K_{S3}	PSS gains (Type PSS2B, PSS3B)

K_{UC}	UEL center setting
K_{UF}	UEL excitation system stabilizer gain
K_{UI}	UEL integrator gain
K_{UL}	UEL proportional gain
K_{UR}	UEL radius setting
K_V	Fast raise/lower contact setting (Type DC3A)
LV GATE	Model block with two inputs and one output, the output always corresponding to the lower of the two inputs.
M	Integer filter constant (Type PSS2A)
N	Integer filter constant (Type PSS2A)
OVEX	Indication of synchronous machine being overexcited
P'	Synchronous machine normalized real output power (for $V_T = 1.0$ pu)
$P_{0–6}$	Real power values for endpoints in UEL2 model
pf	Power factor
PFNORM	Voltage representing power factor (between 0 and 2)
PF_{REF}	PF controller reference voltage (determined to satisfy initial conditions)
P_T	Synchronous machine real output power
Q'	Synchronous machine normalized reactive output power (for $V_T = 1.0$ pu)
Q	Synchronous machine reactive power
$Q_{0–6}$	Reactive power values for endpoints in UEL2 model
Q_{REF}	Reference value of reactive power for UEL limiter
Q_{REF}	Var controller reference voltage (determined to satisfy initial conditions)
Q_T	Synchronous machine reactive output power
R_C	Resistive component of load compensation
S_E	Exciter saturation function
$S_E[E_{FD1}$ or $E_{FD2}]$	Exciter saturation function value at the corresponding exciter voltage, E_{FD}
$S_E[V_{E1}$ or $V_{E2}]$	Exciter saturation function value at the corresponding exciter voltage, V_E, back of commutating reactance
T_1, T_2	PSS transducer time constants (Type PSS3B)
T_1, T_3, T_{10}	PSS lead compensating time constants
T_2, T_4, T_{11}	PSS lag compensating time constants
T_5	PSS washout time constant
T_6, T_7	PSS transducer time constants

T_8	PSS filter time constant
T_A, T_B, T_C, T_{B1}, T_{C1}, T_K	Voltage regulator time constants
T_{AN}	Discontinuous controller time constant (Type DEC1A)
T_{D1}	Discontinuous controller time constant (Type DEC2A)
T_{D2}	Discontinuous controller washout time constant (Type DEC2A)
T_{DR}	Reset time delay (Type DEC3A); lag time constant (Type AC7B, AC8B)
T_E	Exciter time constant, integration rate associated with exciter control
T_F	Excitation control system stabilizer time constant
T_{F2}, T_{F3}	Excitation control system stabilizer time constants (Type AC5A)
T_G	Feedback time constant of inner loop field voltage regulator (Type ST6B)
T_H, T_J	Exciter field current limiter time constants
T_{H1}, T_{H2}, …, T_{H12}	High band time constants (Type PSS4B)
T_{I1}, T_{I2}, …, T_{I12}	Intermediate band time constants (Type PSS4B)
T_K	Regulator lead time constant (Type AC6A)
T_L, T_I, T_H	Low, intermediate, and high band time constants (Type PSS4B)
T_{L1}, T_{L2}, …, T_{L12}	Low band time constants (Type PSS4B)
T_M	Forward time constant of inner loop field regulator (Type ST3A)
T_{OFF}	Time adjuster change signal is off
T_{ON}	Time adjuster change signal is on
T_{PFC}	PF controller time delay
T_R	Regulator input filter time constant
T_{RH}	Rheostat travel time (Type DC3A)
T_{U1}, T_{U3}	UEL lead time constants
T_{U2}, T_{U4}	UEL lag time constants
T_{UL}	Time constant associated with optional integrator feedback input signal to UEL
T_{UP}	UEL real power filter time constant
T_{UQ}	UEL reactive power filter time constant
T_{UV}	UEL voltage filter time constant
T_{VARC}	Var controller time delay
T_{W1}, T_{W2}, T_{W3}, T_{W4}, T_{W5}	PSS and DEC washout time constants
V_A	Regulator internal voltage

V_{ADJF}	Voltage adjuster change permissive input command
V_{ADJMAX}	Maximum voltage adjuster output
V_{ADJMIN}	Minimum voltage adjuster output
V_{AL}	Regulator voltage reference (Type DEC1A)
$V_{AMAX, AMIN}$	Maximum and minimum voltage regulator outputs
V_{AN}	Internal signal (Type DEC1A)
V_B	Available exciter voltage
V_C	Output of terminal voltage transducer and load compensation elements
V_{C1}	Signal proportional to compensated terminal voltage
V_{CL}	Voltage adjuster lower input command
V_{CLMT}	Maximum pf/var controller output
V_{CR}	Voltage adjuster raise input command
V_D	Discontinuous controller internal voltage (Type DEC2A)
V_E	Exciter voltage back of commutating reactance
V_{E1}, V_{E2}	Exciter alternator output voltages back of commutating reactance at which saturation is defined
V_{EMIN}	Minimum exciter voltage output
V_{ERR}	Voltage error signal Type DC3A model
V_F	Excitation system stabilizer output
V_{FB}	UEL optional integrator feedback input signal
V_{FE}	Signal proportional to exciter field current
V_{FELIM}, V_{FEMAX}	Exciter field current limit reference
V_G	Inner loop voltage feedback
V_H	Exciter field current feedback signal
VH_{MIN}, VH_{MAX}	High band output limits (Type PSS4B)
V_I	Internal signal within voltage regulator
VI_{MAX}, VI_{MIN}	Intermediate band output limits (Type PSS4B)
V_{IMAX}, V_{IMIN}	Voltage regulator input limits
V_{ITMIN}	Minimum machine terminal current needed to enable pf/var controller
V_K	Discontinuous controller input reference (Type DEC2A)
VL_{MIN}, VL_{MAX}	Low band output limits (Type PSS4B)
V_M	Output factor of converter bridge corresponding to firing angle command to thyristors (Type ST3A, ST4B)

V_N	Rate feedback input variable
V_O, V_P	Limiter signals (Type DEC1A)
V_{OEL}	Overexcitation limiter output (Type AC1A, AC2A, ST1A)
V_{PF}	PF/var controller signal proportional to power factor
V_{PF}	PF controller output
V_{PFC_BW}	PF controller bandwidth
V_{PFE}	PF controller error
V_{PFREF}	PF controller reference voltage (determined to satisfy initial conditions)
V_R	Voltage regulator output
$V_{RMAX, RMIN}$	Maximum and minimum voltage regulator outputs
V_{REF}	Voltage regulator reference voltage (determined to satisfy initial conditions)
V_{RH}	Voltage determined by rheostat setting (Type DC3A)
V_S	Combined PSS and possibly discontinuous control output after any limits or switching, as summed with terminal voltage and reference signals (in pu equivalent of terminal voltage)
V_{SI}, V_{SI1}, V_{SI2}	PSS inputs (speed, power, or frequency deviation)
V_{ST}	PSS output (in pu equivalent of terminal voltage)
V_{STMIN}, V_{STMAX}	PSS output limits
V_T, $\overline{V}_T$	Synchronous machine terminal voltage
V_{TC}	Terminal voltage level reference (Type DEC1A)
V_{TM}, T_{TN}	Voltage limits (Type DEC1A)
V_{TMIN}	Terminal undervoltage comparison level (Type DEC3A)
V_{UC}	UEL center plus operating point phasor magnitude
V_{UEL}	Underexcitation limiter output
V_{Uerr}	UEL error signal
V_{UImax}, V_{UImin}	UEL integrator output limits
V_{ULmax}, V_{ULmin}	UEL output limits
V_{UR}	UEL radius phasor magnitude
V_{VAR}	Synchronous machine reactive power output
V_{VAR}	Var controller output
V_{VARC_BW}	Var controller bandwidth
V_{VARE}	Var controller error
V_{VARREF}	Var controller reference voltage (determined to satisfy initial conditions)
V_{VTMAX}	Maximum machine terminal voltage for pf/var controller to be enabled

V_{VTMAX}	Maximum machine terminal voltage for var controller to be enabled
V_{VTMIN}	Minimum machine terminal voltage needed to enable pf/var controller
V_{VTMIN}	Minimum machine terminal voltage needed to enable var controller
V_X	Signal proportional to exciter saturation
X_C	Reactance component of load compensation
X_L	Reactance associated with potential source
θ_P	Potential circuit phase angle (degrees)

Annex B

(normative)

Per unit system

Synchronous machine currents and voltages in system studies are represented by pu variables. In the pu system used here, one pu synchronous machine terminal voltage is defined to be rated voltage, and one pu stator current is rated current; one pu generator field current is that current required to produce rated synchronous machine terminal voltage on the air-gap line, and one pu field voltage is the corresponding field voltage, see IEEE Committee Report [B19].

Excitation system models must interface with synchronous machine models at both the stator and field terminals. Signals that are summed with the pu synchronous machine terminal voltage at the input to the voltage regulator must, of necessity, be normalized to the same base. The exciter output current must be in pu on the field current base of the synchronous machine, and exciter output voltage must be in pu on the synchronous machine field voltage base. Note that these bases for field voltage and current may be different from those used internally in the model of the synchronous machine, and base conversion of these two quantities may be required at the interface.

The base field voltage in this pu system depends directly on the field resistance base. A reference temperature of the field winding was defined with respect to insulation class in ANSI C50.10. In IEEE Std 421.1, two temperatures on which to calculate base field resistance (75 °C and 100 °C) are defined, and these are related to temperature rise rather than insulation class. For modeling purposes, both the base resistance and the temperature assumed for its calculation should be specified. This allows recalculation, per the equations in IEEE Std 115, of a new base resistance value for any desired operating temperature.

In the past, several different bases have been used to normalize regulator output voltage. Similar excitation systems having essentially the same performance characteristics can have quite different parameters depending on the choice of this base, see IEEE Committee Report [B18].

Annex C

(normative)

Exciter saturation and loading effects

The exciter saturation function $S_E[E_{FD}]$ is defined as a multiplier of pu exciter output voltage to represent the increase in exciter excitation requirements due to saturation. Figure C.1 illustrates the calculation of a particular value of $S_E[E_{FD}]$. At a given exciter output voltage, the quantities *A*, *B,* and *C* are defined as the exciter excitation required to produce that output voltage on the constant-resistance-load saturation curve, on the air-gap line, and on the no-load saturation curve, respectively. The constant-resistance-load saturation curve is used in defining S_E for all dc-commutator exciters and for ac exciters represented by the simplified AC5A model. For the loaded saturation representation, $S_E[E_{FD}]$ is given by Equation (C.1):

$$S_E[E_{FD}] = \frac{A - B}{B} \tag{C.1}$$

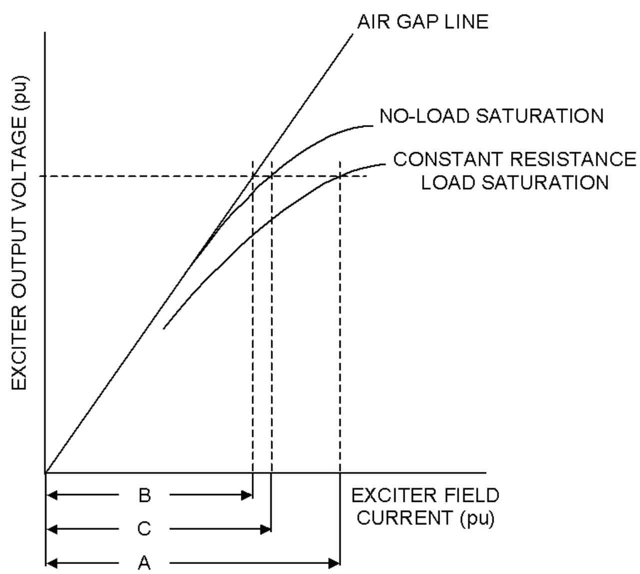


Figure C.1—Exciter saturation characteristics

Note that when exciter field resistance is significantly different from exciter base resistance, an adjusted value of S_E, may be used as described in Annex A of the IEEE Committee Report [B20].

The no-load saturation curve is used in defining $S_E[V_E]$ for alternator-rectifier exciters (except for Type AC5A). Here $S_E[V_E]$ is given by Equation (C.2):

$$S_E[V_E] = \frac{C - B}{B} \tag{C.2}$$

The no-load saturation curve for alternator-rectifier exciters is used because exciter regulation effects are accounted for by inclusion of a demagnetizing factor, K_D, and commutating reactance voltage drops in the model (see Annex D).

Different computer programs have represented the exciter saturation characteristic with different mathematical expressions. In general, the saturation function can be defined adequately by two points. To be consistent, the procedure suggested is to establish two voltages at which to specify S_E and then use these data for computer input. The form of the saturation function is not defined here, but rather considered to be a part of the particular computer program used.

In general, the following would be specified:

Saturation function designation	DC-commutator exciter voltage	Alternator-rectifier exciter voltage
$S_E[E_{FD1}]$	E_{FD1}	
$S_E[E_{FD2}]$	E_{FD2}	
$S_E[V_{E1}]$		V_{E1}
$S_E[V_{E2}]$		V_{E2}

Since saturation effects are most significant at higher voltages, the voltage, E_{FD1}, for which $S_E[E_{FD1}]$ is specified, should be near the exciter ceiling voltage, and the voltage, E_{FD2}, for which $S_E[E_{FD2}]$ is specified, should be at a lower value, commonly near 75% of E_{FD1}. In providing saturation data, the voltages E_{FD1} and E_{FD2} should be specified along with the corresponding saturation data.

Similarly, for the alternator-rectifier exciters, the voltage, V_{E1}, for which $S_E[V_{E1}]$ is specified, should be near the exciter open circuit ceiling voltage and the voltage V_{E2}, for which $S_E[V_{E2}]$ is specified, should be a lower value, commonly near 75% of V_{E1}. In providing saturation data, the voltages, V_{E1} and V_{E2}, should be specified along with the corresponding saturation data.

In some cases, e.g., a self-excited dc exciter, the ceiling voltage may not be precisely known because it depends on K_E. In such cases, $S_E[E_{FD1}]$ corresponds to a specified value of exciter voltage near its expected maximum value.

Annex D

(normative)

Rectifier regulation

All ac sources that supply rectifier circuits have an internal impedance that is predominantly inductive. The effect of this impedance alters the process of commutation and causes a very nonlinear decrease in rectifier average output voltage as the rectifier load current increases. The three-phase full-wave bridge circuits commonly employed have three distinct modes of operation. The rectifier load current determines the equations characterizing these three modes. Figure D.1 shows the rectifier regulation characteristics determined by the equations shown in Figure D.2. For small values of K_C, only Mode 1 operation need be modeled, as is done in the Type ST1A model shown in Figure 7-1.

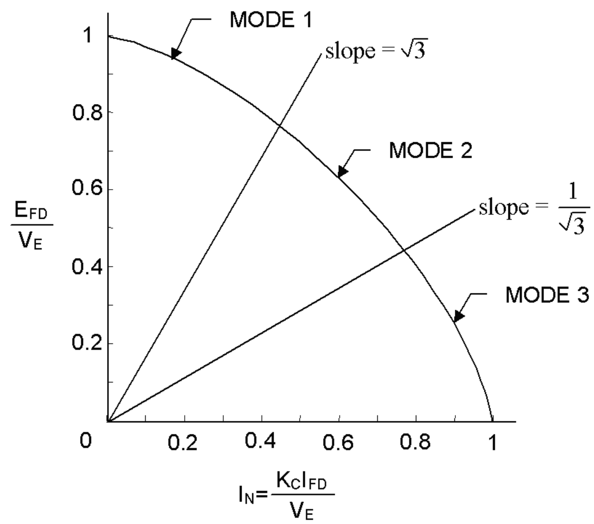


Figure D.1—Rectifier regulation characteristic

The quantities E_{FD}, I_{FD}, V_E and K_C are all in pu on the synchronous machine field base. For computer simulation purposes, the curve of Figure D1 is defined by three segments as shown by the equations in Figure D.2.

Note that I_N should not be greater than 1. However, if I_N is greater than 1 for any reason, the model should set $F_{EX} = 0$. If $I_{FD} < 0$ or $I_N < 0$, the condition should be flagged. The considerations of Annex H would then apply. Further information may be found in ANSI C34.2-1968 [B2], Krause, Wasynczuk, and Sudhoff [B27], and Witzke, Kresser, and Dillard [B44].

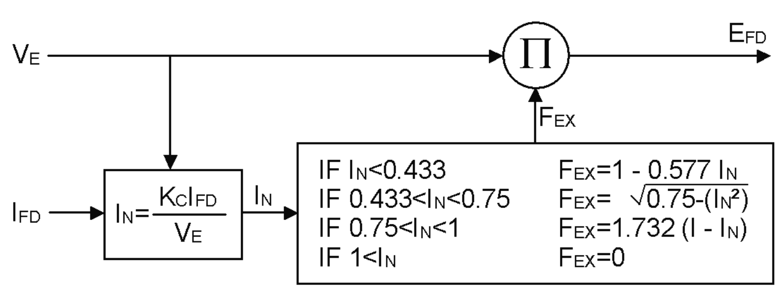


Figure D.2—Rectifier regulation equations

Annex E

(normative)

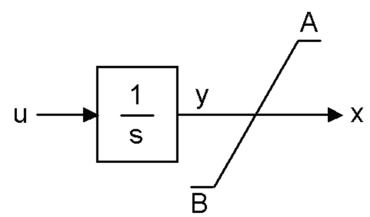
Representation of limits

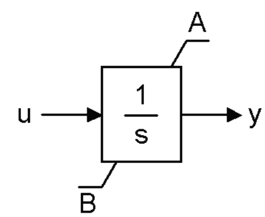
E.1 General

Two distinct types of limiters, windup and non-windup, are represented in the models. Implementation of the two types of limiters for three types of model blocks is described as follows.

E.2 Simple integrator

The functions of these two types of limits, as applied to simple integrator blocks, are illustrated in Figure E.1 and Figure E.2. Note the difference in block diagram notation of the two types of limiters. With the non-windup limiter (see Figure E.2), starting from a limited condition with $y = A$ or $y = B$, the output, y, of the block will begin to change in value as soon as the input to the block changes sign. This is not the case with the windup limiter (see Figure E.1), where the integrator output, y, must first integrate back to the limiter setting before the output, x, can come off the limit.





$$dy/dt = u$$

If $A \geq y \geq B$, then $x = y$

If $y > A$, then $x = A$

If $y < B$, then $x = B$

Figure E.1—Integrator with windup limiter

If $A \geq y \geq B$, then $dy/dt = u$

If $y > A$, then dy/dt is set to 0

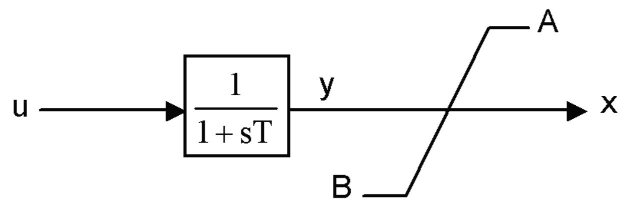
If $y < B$, then dy/dt is set to 0

Figure E.2—Integrator with non-windup limiter

E.3 Simple time constant

Figures E.3 and E.4 show the designation of windup and non-windup limits on single time constant blocks. The equations and part (b) of Figure E.4 show how these limits are implemented. It should be noted that in the case of a windup limit, the variable, y, is not limited. Therefore when the output variable, x, hits a limit, it cannot come off the limit until y comes within the limits.

In the case of the non-windup limit, the variable, y, is limited. To be at a limit $y = A$ or $y = B$ implies input $u > A$ or $u < B$ respectively. With this limiter, the output comes off the limit as soon as the input, u, reenters the range within the limits defined by $B \leq u \leq A$.



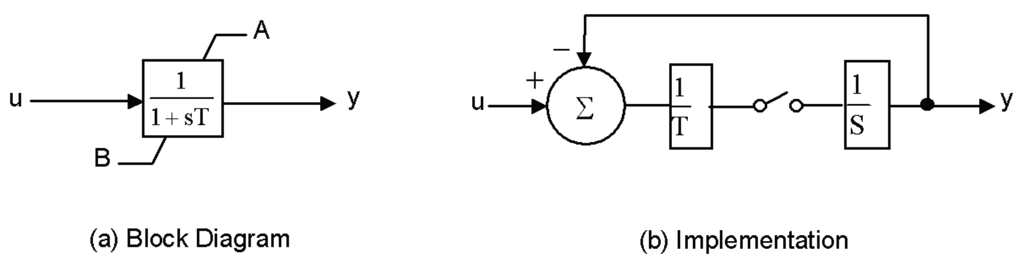
$$dy/dt = (u - y)\ /T$$

If $B \le y \le A$, then $x = y$

If $y > A$, then $x = A$

If $y < B$, then $x = B$

Figure E.3—Simple time constant—Windup limiter



$$f = (u - y)/T$$

If $y = A$, and $f > 0$, then dy/dt is set to 0

If $y = B$, and $f > 0$, then dy/dt is set to 0

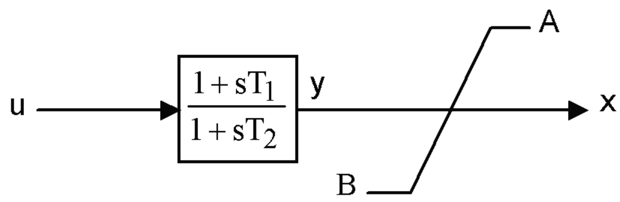
Otherwise, $B < y < A$, and $dy/dt = f$

Figure E.4—Simple time constant—Windup limiter

E.4 Lag-lead block

A block diagram representation and equations for a windup limiter applied to a lag-lead block are provided in Figure E.5.

Figure E.6 shows the block diagram representation for a non-windup limiter applied to a lag-lead block, along with equations and a diagram showing how it is realized. Other models of non-windup limiting of a lag-lead block are possible, but this one is considered to most accurately represent the behavior of most electronic implementations of lag-lead functions.



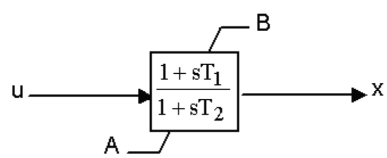
If $T_1 = T_2$, then $y = u$

If $B \le y \le A$, then $x = y$

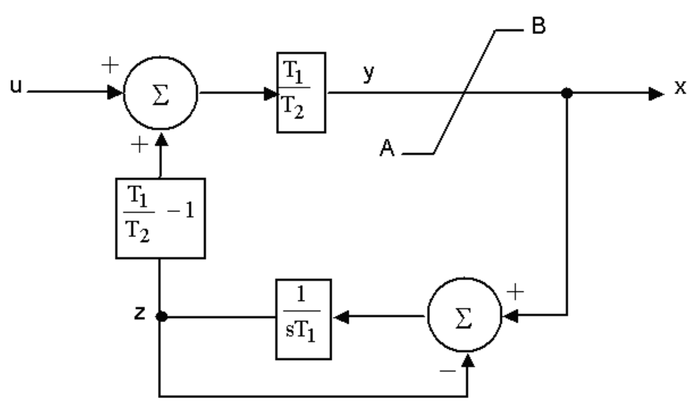
If $y > A$, then $x = A$

If $y < B$, then $x = B$

Figure E.5—Lag-lead with windup limiter



(a) Model



(b) Implementation

$T_2 > T_1$, $T_1 > 0$, $T_2 > 0$

If $y > A$, then $x = A$

If $y < B$, then $x = B$

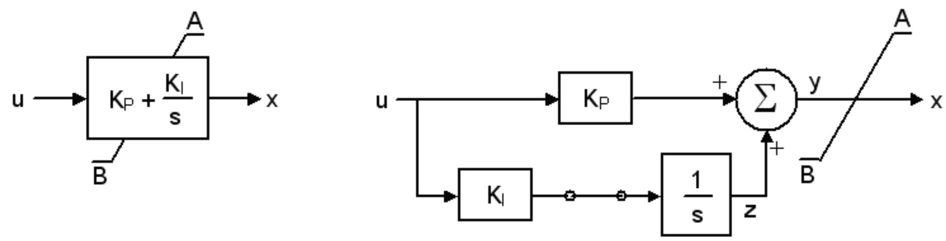
If $A \ge y \ge B$, then $x = y$

Figure E.6—Lag-lead with non-windup limiter

E.5 Proportional-integral block

The use of proportional plus integral regulator blocks in the models ST4B, ST6B, and AC7B requires some definition of the non-windup modeling required to implement the computer models (see Figure E.7).

The ST7B model implements a non-windup proportional-integral function as represented on Figure E.8. If a nonlinearity is acting (that means a saturation is reached or a LV or HV comparator imposes another signal as the output signal), then the low-pass filter output follows the PI output signal, insuring a non-windup behavior of the PI function integrator.



$y > A$, then $x = A$ and $dz/dt = 0$

$y < B$, then $x = B$ and $dz/dt = 0$

Figure E.7—Non-windup proportional-integral block

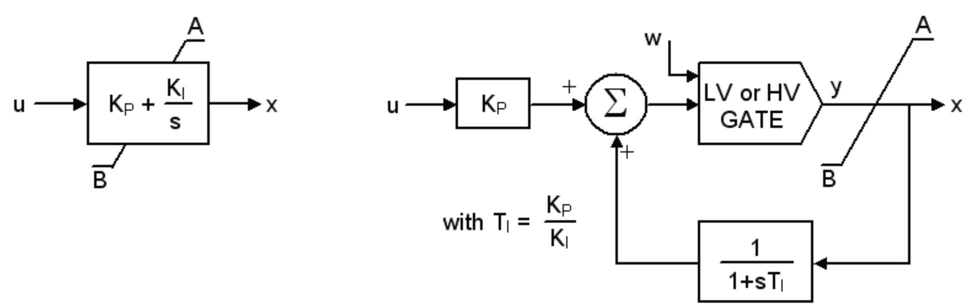


Figure E.8—Non-windup proportional-integral block

Annex F

(informative)

Avoiding computational problems by eliminating fast feedback loops

F.1 General

The models represented in the body of this report are reduced order models, which do not contain all of the feedback loops of the physical system.

The models are valid for oscillation frequencies up to about 3 Hz. This annex discusses the elimination of fast feedback loops. Direct simulation of these loops could result in computational problems for the typical power system stability program. The computation problems are avoided by simulating the loops indirectly as limiters.

F.2 Maximum field current limiter loop for the AC2A system

The recommended model for the Type AC2A system is shown in Figure 6-2. The upper limiter on the exciter voltage (V_E) is not a physical limit. The physical system contains a fast feedback loop that limits the exciter field current. This loop is shown in Figure F.1.

The output of the field current limiter loop, V_L, is normally the higher of the two parameters entering the low value gate. As such, it has no effect on the excitation system output. As the field current, V_{FE}, increases, the output of the loop decreases. As the field current increases to approximately V_{LR}, the output of the loop becomes the lower of the two parameters entering the gate and an error signal is produced to decrease the field current.

The effective time constant for the field current limiter loop is approximately 1.0 ms and direct simulation of this loop would require time steps smaller than those normally used in stability studies. The recommended model in Figure 6-2 simulates the loop as an upper limit on the exciter voltage.

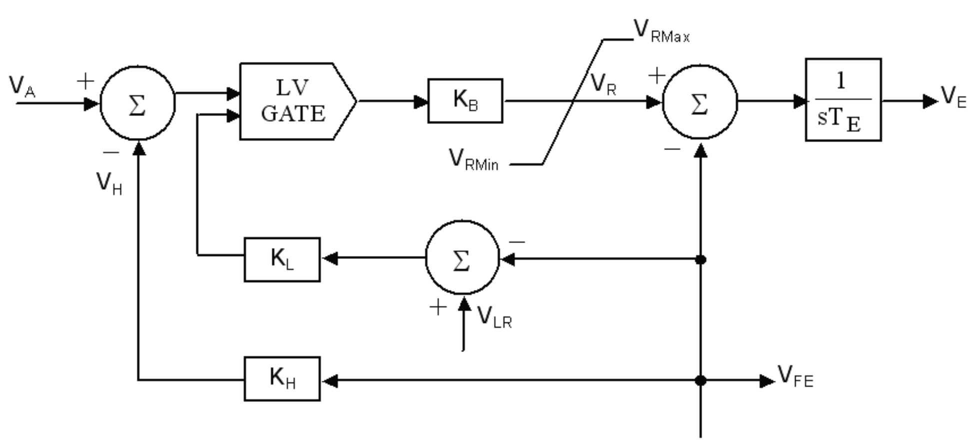


Figure F.1—Maximum field current limiter loop for the Type AC2A high initial response alternator-rectifier excitation system with non-controlled rectifiers and feedback from exciter field current

F.3 Derivation of maximum exciter voltage for the AC2A system

The equations representing the steady-state position of the exciter voltage can be obtained from Figure 6-2 and Figure F.1 as shown in Equation (F.1) and Equation (F.2):

$$V_{FE} = V_R = (V_{LR} - V_{FE})\,(K_L\,K_B) \qquad \text{(F.1)}$$

$$V_{FE} = (K_E + S_E)\,V_E + K_D\,I_{FD} \qquad \text{(F.2)}$$

Solving Equation (F.1) for V_{FE}, then substituting V_{FEMAX} for V_{FE} [see Equation (F.3)]:

$$V_{FEMAX} = \frac{V_{LR}K_LK_B}{1 + K_LK_B} \cong V_{LR} \qquad \text{(F.3)}$$

Solving Equation (F.2) for V_E, then substituting V_{FEMAX} and V_{EMAX} for V_{FE} and V_E, respectively [see Equation (F.4)]:

$$V_{EMAX} = \frac{V_{FEMAX} - K_DI_{FD}}{K_E + S_E} \qquad \text{(F.4)}$$

F.4 Minimum field voltage limiter loop for the AC3A system

The recommended model for the Type AC3A system is shown in Figure 6-3. The lower limiter on the exciter voltage (V_E) is not a physical limit. The physical system contains a fast feedback loop that limits the field voltage. This loop is shown in Figure F.2.

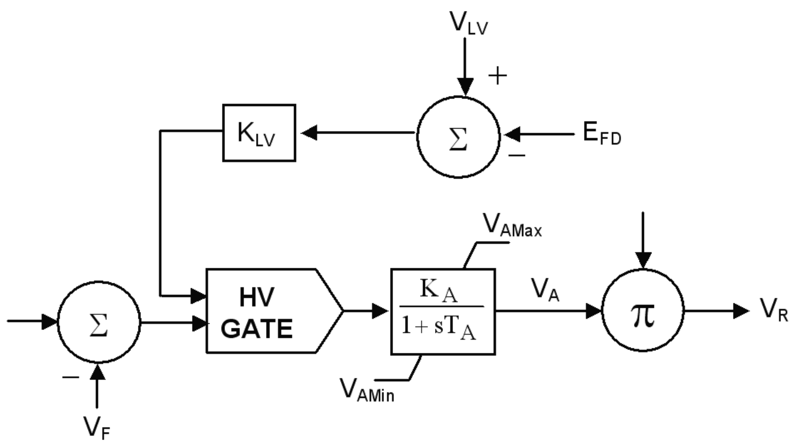


Figure F.2—Minimum field voltage limiter loop for the Type AC3A alternator-rectifier exciter

The output of the field limiter loop is normally the lower of the two parameters entering the high value gate. As such, it has no effect on the excitation system output. As the field voltage drops, the output of the loop increases. As the field voltage decreases to approximately V_{LV}, the output of the loop becomes the greater of the two parameters entering the gate and an error signal is produced to boost the field voltage.

The field voltage limiter loop is a fast loop with a natural frequency of oscillation greater than 4 Hz. Direct simulation of this loop in a stability study would require time steps smaller than those normally used in stability studies. The recommended model in Figure 6-3 simulates the loop as a lower limiter on the exciter voltage.

F.5 Derivation of minimum exciter voltage for the AC3A system

The equations representing the steady-state position of the exciter voltage can be obtained from Figure 6-3 and Figure F.2 as shown in Equation (F.5), Equation (F.6), and Equation (F.7):

$$V_{FE} = V_R = (K_A\, K_R\, E_{FD}\, K_{LV})\,(V_{LV} - E_{FD}) \tag{F.5}$$

$$V_{FE} = (K_E + S_E)\, V_E + K_D\, I_{FD} \tag{F.6}$$

$$E_{FD} = F_{EX}\, V_E \tag{F.7}$$

Solving Equation (F.5), Equation (F.6), and Equation (F.7) for $E_{FD,}$ then substituting E_{FDMIN} for E_{FD} [see Equation (F.8), Equation (F.9), and Equation (F.10)]:

$$E_{FDMIN} = \frac{G_1 V_{LV} - K_D I_{FD}}{G_2} \tag{F.8}$$

where

$$G_1 = K_A\, K_{LV}\, K_R\, E_{FDMIN} \tag{F.9}$$

$$G_2 = G_1 + \frac{K_E + S_E}{F_{EX}} \tag{F.10}$$

Since G_1 is very large (70 to 1000), E_{FDMIN} can be approximated as shown in Equation (F.11):

$$E_{FDMIN} \cong V_{LV} \tag{F.11}$$

The minimum steady-state limit for the exciter voltage can be obtained by substituting Equation (F.11) into Equation (F.7).

$$V_{EMIN} \cong \frac{F_{LV}}{F_{EX}}$$

F.6 Maximum field current limiter loop for the AC3A system

The recommended model for the AC3A system is shown in Figure 6-3. The upper limiter on the exciter voltage, V_E, is not a physical limit. The physical system contains a fast feedback loop that limits the exciter field current. This loop is shown in Figure F.3.

The output of the field current limiter loop is normally zero. As the field current (V_{FE}) increases, the output of this loop decreases. When the field current time, $K_{FA,}$ exceeds E_{TX}, the output of the loop comes off its limit and an error signal to decrease the excitation is produced, thus limiting the field current.

The field current limiter loop is a fast loop with a natural frequency of oscillation greater than 4 Hz. Direct simulation of this loop in a stability study would require time steps smaller than those normally used in stability studies. The recommended model in Figure 6-3 simulates the loop as an upper limiter on the exciter voltage.

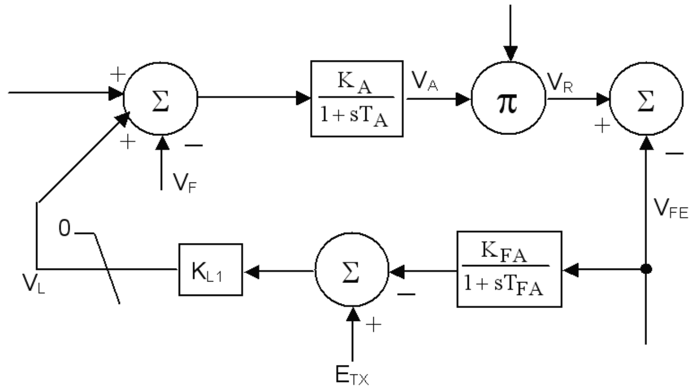


Figure F.3—Maximum field current limiter loop for the Type AC3A alternator-rectifier exciter with alternator field current limiter

F.7 Derivation of maximum exciter voltage for the AC3A system

The equations representing the steady-state position of the exciter voltage can be obtained from Figure 6-3 and Figure F.3, as shown in Equation (F.12), Equation (F.13), Equation (F.14), Equation (F.15), and Equation (F.16):

$$V_L = K_{L1}\,(E_{TX} - K_{FA}\,V_{FE}) \quad \text{(F.12)}$$

$$V_{FE} = V_R = (K_A\,K_R\,E_{FD})(V_L + V_S + V_{ERR} - V_F) \quad \text{(F.13)}$$

$$V_{FE} = (K_E + S_E)\,V_E + K_D\,I_{FD} \quad \text{(F.14)}$$

$$E_{FD} = F_{EX}\,V_E \quad \text{(F.15)}$$

$$V_{ERR} = V_{REF} - V_C \quad \text{(F.16)}$$

The exciter stabilizer output, V_F, will be zero in the steady state. The output decays to zero, however, with a relatively long time constant, T_F, which is approximately 1.0 s. The other time constants in the system vary from 0.01 s to 0.02 s with the exception of T_E, which is approximately 1.0 s. Although T_E is large, the effective time constant is quite small due to the large gains K_A and K_R.

By combining these equations, setting V_F equal to zero, and substituting V_{FEMAX} for V_{FE} [see Equation (F.17) and Equation (F.18)]:

$$V_{FEMAX} = (K_{L1}E_{TX} + V_S + V_{ERR})\frac{G_1}{1 + G_1 K_{FA} K_{L1}} \quad \text{(F.17)}$$

where

$$G_1 = K_A\,K_R\,F_{EX}\,V_{EMAX} \quad \text{(F.18)}$$

The typical values of the parameters when the field voltage is near ceiling follow:

$K_{L1}\ E_{TX}$ = 0.93

V_S = 0.0 to 0.10

V_{ERR} = 0.0 to 1.0

G_1 = 1000

$G_1\ K_{FA}\ K_{L1}$ = 56

Assuming the above typical values, Equation (F.17) can be simplified, as shown in Equation (F.19).

$$V_{FEMAX} = \frac{K_{L1}E_{TX} + V_S + V_{ERR}}{K_{FA}K_{L1}} \tag{F.19}$$

Solving Equation (F.14) for V_E, then substituting V_{EMAX} for V_E [see Equation (F.20)]:

$$V_{EMAX} = \frac{V_{FEMAX} - K_D I_{FD}}{S_E + K_E} \tag{F.20}$$

Annex G

(normative)

Paths for flow of induced synchronous machine negative field current

G.1 General

AC and ST type exciters cannot deliver negative field current because they have rectifiers at their output. Under some conditions a negative current may be induced in the field of the synchronous machine (see de Mello, Leuzinger, and Mills [B10]). If this current is not allowed to flow, a dangerously high voltage may result. In some cases, damper windings or solid iron rotor effects may limit the maximum voltage experienced by the field winding and rectifiers under such conditions, but in other cases circuitry is provided to allow negative field currents to flow, bypassing the exciter itself. These take the form of either “crowbar” circuits (field shorting) or nonlinear resistors (varistors) as shown in Figure G.1.

In the case of the crowbar, a resistor is inserted across the field of the synchronous machine by thyristors that are triggered on the overvoltage produced when the field current attempts to reverse and is blocked by the rectifiers on the output of the exciter.

Varistors are nonlinear resistors that are connected permanently across the field of the synchronous machine. During normal conditions, the resistance of these devices is very high and little current flows through them. The varistor current increases very rapidly as the voltage across it is increased beyond a threshold level and thus limits the voltage seen by the field winding and the rectifiers on the output of the exciter.

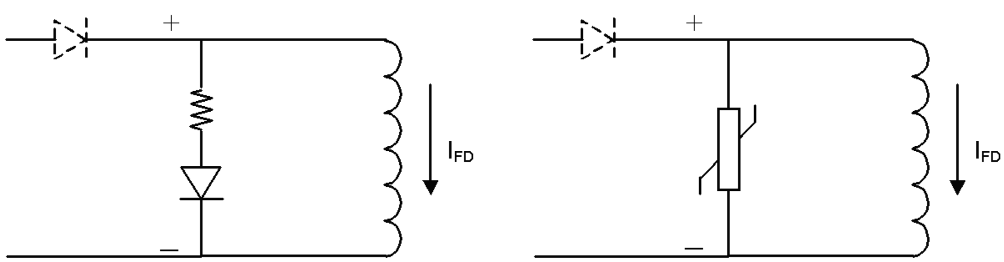


Figure G.1—Bypass circuits for induced negative field current

For some machines, no special field shorting circuitry is provided. For these machines, the amortisseur windings and solid iron rotor current paths are sufficient to limit the maximum voltage attained when the rectifiers block to a level that is below the withstand capabilities of the field winding and the rectifiers.

For some special studies, it is desirable to have the capability to represent the various methods of handling negative synchronous machine field currents (see Kundur and Dandeno [B29]). Although these techniques apply as much to the treatment of the synchronous machine equations as they do to the excitation system, a brief description of how each of the three regimes can be represented is given in the following subclauses.

G.1.1 Crowbar

When the field current of the synchronous machine becomes negative, set the field voltage, E_{FD}, to zero and increase the field circuit resistance by an amount equal to the value of the crowbar field discharge resistor. When the field current becomes positive, restore the field resistance to its normal value to allow field voltage to again be the same as the output voltage of the excitation system.

Systems with crowbar circuits often detect crowbar current and use this to initiate a unit trip.

G.1.2 Varistor

The treatment of the varistor is similar to that of the crowbar, except that the resistance added is nonlinear. The varistor characteristic may be represented by an equation of the form shown in Equation (G.1):

$$V = K\,I^a \tag{G.1}$$

If there are n varistors in parallel, the varistor characteristic may be expressed in terms of the field current as shown in Equation (G.2):

$$V = K\left(\frac{I_{fd}}{n}\right)^a \tag{G.2}$$

The effective resistance introduced by the varistor is then given in terms of the magnitude of I_{fd} by Equation (G.3):

$$R_v = \frac{V}{I_{fd}} = \frac{K}{n^a}(I_{fd})^{a-1} \tag{G.3}$$

G.1.3 No special provision for handling negative field current

Where no paths for negative field current are provided external to the synchronous machine, conditions in the machine during blocking of field current may be simulated by increasing the field leakage inductance of the synchronous machine model to a very large value. The field leakage inductance is restored to its normal value when the field current is positive. Paths for induced rotor currents are provided entirely by the amortisseur and rotor body circuits. It is important, therefore, to ensure that the synchronous machine model includes their effects.

Accurate representation of conditions where negative field currents might be encountered requires detailed generator modeling as well as the representation of the paths for the flow of induced currents described above.

Annex H

(informative)

Sample data

The data presented below must be considered as *sample* data only, not *representative* or *typical* data. Depending upon the parameters used, any one model may represent many different designs and many levels of performance for any one design. In this annex, consistent sets of data are provided which are considered neither typical nor representative of systems using that model. Unless specified otherwise, time constants are in seconds and all other parameters are in pu.

H.1 Sample data for a Type DC1A excitation system

Exciter	DC1A fast response exciter with stabilizer	
	K_A	46.0
	T_A	0.06
	T_B	0
	T_C	0
	T_E	0.46
	K_F	0.1
	T_F	1.0
	$S_E[E_{FD1}]$	0.33
	$S_E[E_{FD2}]$	0.10
	E_{FD1}	3.1
	E_{FD2}	2.3
	K_E	Computed
	V_{RMAX}	1.0
	V_{RMIN}	–0.9

Stabilizer	Type PSS1A with speed input	
	K_S	3.15
	T_1	0.76
	T_2	0.1
	T_3	0.76
	T_4	0.1
	$T_5$1	0.0
	V_{STMAX}	0.09
	V_{STMIN}	–0.09

H.2 Sample data for a Type DC2A excitation system

H.2.1 Separately excited main exciter

The generator connected to this excitation system has been up rated and has a very flat saturation curve at normal operating points. Therefore, the excitation system gain is relatively high.

Excitation		
	K_A	300
	T_A	0.01
	T_B	0
	T_C	0
	T_E	1.33
	K_E	1.0
	K_F	0.1
	T_F	0.675
	$S_E[E_{FD1}]$	0.279
	$S_E[E_{FD2}]$	0.117
	E_{FD1}	3.05
	E_{FD2}	2.29
	V_{RMAX}	4.95
	V_{RMIN}	–4.9

Stabilizer	Type PSS1A with terminal frequency or speed (to represent internally compensated frequency) input	
	K_S	1.4 pu
	T_1	0.5
	T_2	0.06
	T_3	0.5
	T_4	0.06
	T_5	30.0
	T_6	0.016
	V_{STMAX}	0.05
	V_{STMIN}	–0.05

H.3 Sample data for a Type DC3A excitation system

Terminal voltage transducer: $T_R = 0$; $R_C = 0$; $X_C = 0$

Exciter and regulator	Alternative 1 (self-excited)	Alternative 2 (separately excited)
K_E	0.05	1.0
T_E	0.5	1.4
K_V	0.05	0.05
V_{RMAX}	1.0	5.7
V_{RMIN}	0.0	–1.1
T_{RH}	20.0	20.0
$S_E[E_{FD1}]$	0.267	0.27
$S_E[E_{FD2}]$	0.068	0.07
E_{FD1}	3.375	4.5
E_{FD2}	3.15	3.38

H.4 Sample data for a Type DC4B excitation system

Description	Parameter	Value	Units
Regulator proportional gain	K_P	80	pu
Regulator integral gain	K_I	20	pu
Regulator derivative gain	K_D	20	pu
Regulator derivative filter time constant	T_D	0.01	s
Regulator output gain	K_A	1	pu
Regulator output time constant	T_A	0.2	s
Max controller output	V_{RMAX}	2.7	pu
Exciter field time constant	T_E	0.8	pu
Exciter field proportional constant	K_E	1.0	pu
Exciter minimum output voltage	V_{EMIN}	0	pu
Exciter flux at S_{E1}	E_1	1.75	pu
Saturation factor at E_1	S_{E1}	0.08	
Exciter flux at S_{E2}	E_2	2.33	pu
Saturation factor at E_2	S_{E2}	0.27	
Rate feedback gain	K_F	0	pu
Rate feedback time constant	T_F	0	s

H.5 Sample data for a Type AC1A excitation system

$T_R = 0$	$K_F = 0.03$	$V_{AMIN} = -14.5$
$R_C = 0$	$T_F = 1.0$	$V_{RMAX} = 6.03$
$X_C = 0$	$K_E = 1.0$	$V_{RMIN} = -5.43$
$K_A = 400$	$T_E = 0.80$	$S_E[V_{E1}] = 0.10$
$T_A = 0.02$	$K_D = 0.38$	$V_{E1} = 4.18$
$T_B = 0$	$K_c = 0.20$	$S_E[V_{E2}] = 0.03$
$T_C = 0$	$V_{AMAX} = 14.5$	$V_{E2} = 3.14$

H.6 Sample data for a Type AC2A excitation system

$T_R = 0$	$K_H = 1.0$	$V_{AMIN} = -8.0$
$R_C = 0$	$K_F = 0.03$	$V_{RMAX} = 105$
$X_C = 0$	$T_F = 1.0$	$V_{RMIN} = -95$
$K_A = 400$	$K_E = 1.0$	$V_{FEMAX} = 4.4$
$T_A = 0.01$	$T_E = 0.60$	$S_E[V_{E1}] = 0.037$
$T_B = 0$	$K_D = 0.35$	$V_{E1} = 4.4$
$T_c = 0$	$K_c = 0.28$	$S_E[V_{E2}] = 0.012$
$K_B = 25$	$V_{AMAX} = 8.0$	$V_{E2} = 3.3$

H.7 Sample data for a Type AC3A excitation system

$T_R = 0$	$V_{LV} = 0.790$	$K_R = 3.77$
$T_C = 0$	$V_{E\,MAX} = 6.24 = V_{E1}$	$K_{LV} = 0.194$
$T_B = 0$	$V_{E\,MIN} = 0.1$	$K_C = 0.104$
$T_A = 0.013$	$S_E[V_{E1}] = 1.143$	$K_D = 0.499$
$T_E = 1.17$	$V_{E2} = 0.75\ V_{E\,MAX}$	$K_E = 1.0$
$T_F = 1.0$	$S_E[V_{E2}] = 0.100$	$K_F = 0.143$
$V_{A\,MAX} = 1.0$	$E_{FDN} = 2.36$	$K_N = 0.05$
$V_{A\,MIN} = -0.95$	$K_A = 45.62$	$V_{FEMAX} = 16$

H.8 Sample data for a Type AC4A excitation system

$T_R = 0$	$V_{IMAX} = 10$	$K_A = 200$
$T_C = 1.0$	$V_{IMIN} = -10$	$K_C = 0$
$T_B = 10$	$V_{R\,MAX} = 5.64$	
$T_A = 0.015$	$V_{R\,MIN} = -4.53$	

H.9 Sample data for a Type AC5A excitation system

Terminal voltage transducer: $T_R = 0$; $R_C = 0$; $X_C = 0$

$K_A = 400$	$K_E = 1.0$	$K_F = 0.03$
$T_A = 0.02$	$S_E[E_{FD1}] = 0.86$	$T_{F1} = 1.0$
$V_{RMAX} = 7.3$	$E_{FD1} = 5.6$	$T_{F2} = T_{F3} = 0$
$V_{RMIN} = -7.3$	$S_E[E_{FD2}] = 0.5$	
$T_E = 0.8$	$E_{FD2} = 0.75 \times E_{FD1}$	

H.10 Sample data for a Type AC6A excitation system

Terminal voltage transducer: $T_R = 0.02$; $R_C = 0$; $X_C = 0$

Exciter

$K_A = 536$	$T_J = 0.02$	$V_{HMAX} = 75$
$T_A = 0.086$	$K_D = 1.91$	$V_{FELIM} = 19$
$T_B = 9.0$	$K_C = 0.173$	$S_E[V_{E1}] = 0.214$
$T_C = 3.0$	$K_E = 1.6$	$V_{E1} = 7.4$
$T_K = 0.18$	$V_{AMAX} = 75$	$S_E[V_{E2}] = 0.044$
$K_H = 92$	$V_{AMIN} = -75$	$V_{E2} = 5.55$
$T_E = 1.0$	$V_{RMAX} = 44$	
$T_H = 0.08$	$V_{RMIN} = -36$	

Type PSS2A stabilizer parameters with speed and electrical power input

$K_{S1} = 20$	$M = 2$
$K_{S2} = 1.13 = T_7/2H$	$N = 4$
$K_{S3} = 1$	$V_{STMAX} = 0.20$
$T_1 = T_3 = 0.16$	$V_{STMIN} = -0.066$
$T_2 = T_4 = 0.02$	$T_6 = 0$
H = synchronous machine inertia constant	$T_7 = 10.0$
$T_{W1} = T_{W2} = T_{W3} = 10$	$T_8 = 0.3$
$T_{W4} = 0$	$T_9 = 0.15$

H.11 Sample data for a Type AC7B excitation system

Data set 1: Alternator-rectifier excitation system

$T_R = 0.0$	$K_{IA} = 59.69$	$K_D = 0.02$
$K_{PR} = 4.24$	$V_{Amax} = 1.0$	$K_E = 1.0$
$K_{IR} = 4.24$	$V_{Amin} = –0.95$	$K_{F1} = 0.212$
$K_{DR} = 0.0$	$K_P = 4.96$	$K_{F2} = 0.0$
$T_{DR} = 0.0$	$K_L = 10.0$	$S_{Emax} = 0.44$
$V_{Rmax} = 5.79$	$T_E = 1.1$	$V_{Emax} = 6.30$
$V_{Rmin} = –5.79$	$V_{FEmax} = 6.9$	$S_{E\,0.75max} = 0.075$
$K_{PA} = 65.36$	$K_C = 0.18$	$V_{E\,0.75max} = 3.02$

Data set 2: DC exciter

$T_R = 0.0$	$K_{IA} = 0.0$	$K_E = 1.0$
$K_{PR} = 170.0$	$V_{Amax} = 10.0$	$K_{F1} = 0.0$
$K_{IR} = 130.0$	$V_{Amin} = 0.0$	$K_{F2} = 0.0$
$K_{DR} = 60.0$	$K_P = 1.0$	$V_{FEmax} = 99.0$
$T_{DR} = 0.03$	$K_L = 0.0$	$S_{Emax} = 1.5$
$V_{Rmax} = 10.0$	$T_E = 1.0$	$V_{Emax} = 4.5$
$V_{Rmin} = 0.0$	$K_C = 0.0$	$S_{E\,0.75max} = 1.36$
$K_{PA} = 1.0$	$K_D = 0.0$	$V_{E\,0.75max} = 3.38$

H.12 Sample data for a Type AC8B excitation system

$K_{PR} = 80$	$V_{RMAX} = 35$	$SE_{(E1)} = 0.3$
$K_{IR} = 5$	$V_{RMIN} = 0$	$E_1 = 6.5$
$K_{DR} = 10$	$K_E = 1.0$	$SE_{(E2)} = 3.0$
$T_{DR} = 0.1$	$T_E = 1.2$	$E_2 = 9.0$
$V_{FEmax} = 6.0$	$K_C = 0.55$	$K_D = 1.1$

H.13 Sample data for a Type ST1A excitation system

Data set 1: Bus-fed thyristor excitation system with no transient gain reduction, dual-input stabilizer, and discontinuous excitation control.

Terminal voltage transducer: $T_R = 0.02$; $R_C = 0$; $X_C = 0$

Exciter

$K_A = 210.0$	$T_{B1} = 0$	$K_F = 0$
$T_A = 0$	$V_{RMAX} = 6.43$	$T_F = 0$ (not used)
$T_C = 1.0$	$V_{RMIN} = -6.0$	$K_{LR} = 4.54$
$T_B = 1.0$	$K_C = 0.038$	$I_{LR} = 4.4$
$T_{C1} = 0$	V_{IMAX}, V_{IMIN} (not represented)	

Stabilizer Type PSS2A with speed deviation and electrical power as inputs

V_{SI1} = speed input in pu	$T_{w4} = 0$
V_{SI2} = electrical power input in pu	$M = 2$
$K_{S1} = 20$	$N = 4$
$K_{S2} = 1.13 = T_7/2H$	$V_{STMAX} = 0.20$
$K_{S3} = 1$	$V_{STMIN} = -0.066$
$T_1 = T_3 = 0.16$	$T_6 = 0$
$T_2 = T_4 = 0.02$	$T_7 = 10$
H = synchronous machine inertia constant	$T_8 = 0.3$
$T_{W1} = T_{W2} = T_{W3} = 10$	$T_9 = 0.15$

Discontinuous excitation control data (DEC1A)

$V_{TLMT} = 1.1$	$E_{SC} = 0.0015$	$T_D = 0.03$
$V_{OMAX} = 0.3$	$K_{AN} = 400$	$T_{L1} = 0.025$
$V_{OMIN} = 0.1$	$T_{AN} = 0.08$	$T_{L2} = 1.25$
$K_{ETL} = 47$	$T_{W5} = 5.0$	$V_{TM} = 1.13$
$V_{TL} = 0.95$	$V_{STMAX} = 0.2$	$V_{TN} = 1.12$
$V_{AL} = 5.5$	$V_{STMIN} = -0.066$	

NOTE—If the preceding stabilizer data is used without the discontinuous control, then the system is most accurately represented by leaving the slower acting terminal voltage limited function of the DEC1A model in service [i.e., use DEC1A and set $K_{AN} = 0$; set V_{TM} and V_{TN} high (e.g., 2.0) so that the fast-acting limiter is inactive].[7]

[7]Notes in text, tables, and figures are given for information only and do not contain requirements needed to implement the recommended practice.

Data set 2: Bus-fed thyristor excitation system with transient gain reduction and speed input stabilizer:

Terminal voltage transducer: $T_R = 0.04$; $R_C = 0$; $X_C = 0$

Exciter		
$K_A = 190$	$T_{B1} = 0$	$V_{IMIN} = –999$ (not represented)
$T_A = 0$	$V_{RMAX} = 7.8$	$K_F = 0$
$T_C = 1.0$	$V_{RMIN} = –6.7$	$T_F = 1$ (not used)
$T_B = 10.0$	$K_C = 0.08$	$K_{LR} = 0$
$T_{C1} = 0$	$V_{IMAX} = 999$	$I_{LR} = 0$ (not represented)

Stabilizer	Type PSS1A (with speed deviation as input)	
$K_S = 16.7$	$T_3 = 0.15$	$T_6 = 0$
$T_1 = 0.15$	$T_4 = 0.03$	$V_{STMAX} = 0.10$
$T_2 = 0.03$	$T_5 = 1.65$	$V_{STMIN} = –0.066$

H.14 Sample data for a Type ST2A excitation system

$T_R = 0$	$V_{R\,MAX} = 1.0$	$K_F = 0.05$
$T_E = 0.5$	$V_{R\,MIN} = 0$	$K_P = 4.88$
$T_A = 0.15$	$K_E = 1.0$	$K_I = 8.0$
$T_F = 1.0$	$K_A = 120$	$K_C = 1.82$

$E_{FD\,MAX} = 2.75$ times direct axis synchronous reactance of the synchronous machine in pu

H.15 Sample data for a Type ST3A excitation system

Data set 1: Potential source

Exciter		
$T_A = 0$	$V_{I\,MIN} = –0.2$	$K_G = 1.0$
$T_R = 0$	$V_{M\,MAX} = 1.0$	$K_M = 7.93$
$T_M = 0.4$[a]	$V_{M\,MIN} = 0$	$K_A = 200$
$T_B = 10.0$	$V_{R\,MAX} = 10.0$	$K_P = 6.15$
$T_C = 1.0$	$V_{R\,MIN} = -10.0$	$\theta_P = 0^o$
$X_L = 0.081$	$V_{G\,MAX} = 5.8$	$K_I = 0$
$V_{I\,MAX} = 0.2$	$E_{FD\,MAX} = 6.9$	$K_C = 0.20$

[a] T_M may be increased to 1.0 s for most studies to permit longer computing time increments, up to 0.02 s.

Stabilizer	Type PSS1A (Input signal: speed or frequency)	
$A_1 = 0.061$	$T_3 = 0.3$	$V_{STMAX} = 0.05$
$A_2 = 0.0017$	$T_4 = 0.03$	$V_{STMIN} = –0.05$
$T_1 = 0.3$	$T_5 = 10$	
$T_2 = 0.03$	$K_S = 5$	

Data set 2: Compound power source

Exciter		
$T_A = 0$	$V_{I\,MIN} = –0.2$	$K_G = 1.0$
$T_R = 0$	$V_{M\,MAX} = 1.0$	$K_M = 7.04$
$T_M = 0.4$[a]	$V_{M\,MIN} = 0$	$K_A = 200$
$T_B = 6.67$	$V_{R\,MAX} = 10.0$	$K_P = 4.37$
$T_C = 1.0$	$V_{R\,MIN} = –10.0$	$\theta_P = 20^o$
$X_L = 0.09$	$V_{G\,MAX} = 6.53$	$K_I = 4.83$
$V_{I\,MAX} = 0.2$	$E_{FD\,MAX} = 8.63$	$K_C = 1.10$

[a] T_M may be increased to 1.0 s for most studies to permit longer computing time increments, up to 0.02 s.

Stabilizer	Type PSS1A (Input signal: speed or frequency)	
$A_1 = 0.061$	$T_3 = 0.3$	$V_{STMAX} = 0.05$
$A_2 = 0.0017$	$T_4 = 0.03$	$V_{STMIN} = –0.05$
$T_1 = 0.3$	$T_5 = 10$	
$T_2 = 0.03$	$K_S = 5$	

H.16 Sample data for a Type ST4B potential- or compound-source controlled-rectifier excitation system

Data set 1: Potential source

Exciter		
$T_R = 0.0$	$K_{PM} = 1.0$	$K_I = 0.0$
$K_{PR} = 10.75$	$K_{IM} = 0.0$	$X_L = 0.124$
$K_{IR} = 10.75$	$V_{Mmax} = 99$	$K_C = 0.113$
$T_A = 0.02$	$V_{Mmin} = –99$	$V_{Bmax} = 11.63$
$V_{Rmax} = 1.0$	$K_G = 0.0$	
$V_{Rmin} = –0.87$	$K_P = 9.3/0°$	

Stabilizer	Type PSS2B	
$K_{S1} = 20.0$	$T_7 = 10.0$	V_{SI1} = speed pu
$K_{S2} = 0.99$	$T_8 = 0.5$	V_{SI2} = electrical power pu
$K_{S3} = 1.0$	$T_9 = 0.1$	$V_{STMAX} = 0.1$
$T_1 = 0.15$	$T_{10} = 0.0$	$V_{STMIN} = -0.1$
$T_2 = 0.025$	$T_{11} = 0.033$	$T_{W1} = T_{W2} = T_{W3} = 10.0$
$T_3 = 0.15$	$N = 1$	$T_{W4} = 0.0$
$T_4 = 0.02$	$M = 5$	
$T_6 = 0.0$		

Data set 2: Compound source		
$T_R = 0.0$	$K_{PM} = 0.0$	$K_I = 8.8$
$K_{PR} = 20.0$	$K_{IM} = 14.9$	$X_L = 0.0$
$K_{IR} = 20.0$	$V_{mmax} = 1.0$	$K_C = 1.8$
$T_A = 0.02$	$V_{Mmin} = -0.87$	$V_{Bmax} = 8.54$
$V_{Rmax} = 1.0$	$K_G = 1.0$	
$V_{Rmin} = -0.87$	$K_P = 5.5/0°$	

H.17 Sample data for a Type ST5B potential-source controlled-rectifier excitation system

$T_{B1} = 6.0$	$T_{UB2} = 0.05$	$K_R = 200.0$
$T_{C1} = 0.8$	$T_{UC2} = 0.1$	$T_1 = 0.004$
$T_{B2} = 0.01$	$T_{OB1} = 2$	$V_{Rmax} = 5.0$
$T_{C2} = 0.08$	$T_{OC1} = 0.1$	$V_{Rmin} = -4.0$
$T_{UB1} = 10$	$T_{OB2} = 0.08$	$K_C = 0.004$
$T_{UC1} = 2$	$T_{OC2} = 0.08$	

H.18 Sample data for a Type ST6B potential-source controlled-rectifier excitation system with field current limiter

$K_{PA} = 18.038$	$T_G = 0.02$ s	$K_{CI} = 1.0577$
$K_{IA} = 45.094$ s^{-1}	$T_R = 0.012$ s	$K_{LR} = 17.33$
$K_{FF} = 1$	$V_{AMAX} = 4.81$	$I_{LR} = 4.164$
$K_M = 1$	$V_{AMIN} = -3.85$	$V_{RMAX} = 4.81$
$K_G = 1$		$V_{RMIN} = -3.85$

H.19 Sample data for a Type ST7B static potential-source excitation system

$K_{PA} = 40$	$T_G = 1$ s	$V_{MAX} = 1.1$
$K_{IA} = 1$	$T_F = 1$ s	$V_{MIN} = 0.9$
$T_{IA} = 3$ s	$V_{RMAX} = 5$	$K_L = 1$
$T_B = 1$ s	$V_{RMIN} = –4.5$	$K_H = 1$
$T_C = 1$ s		

H.20 Sample data for a Type PSS3B dual input PSS

Data set 1

$K_{S1} = 1.0$	$T_3 = 0.02$	V_{SI1} = Electrical power pu
$K_{S2} = 0.0$	$T_4 = 1.5$	V_{SI2} = Rotor angular speed pu
$T_1 = 0.02$	$V_{STMAX} = 0.10$	(Parameters not shown unused)
$T_2 = 1.5$	$V_{STMIN} = –0.10$	

Data set 2

$T_1 = 0.012$ s	$A_1 = 0.359$ s	$A_8 = 0$ s^2
$T_2 = 0.012$ s	$A_2 = 0.586$ s^2	$V_{STMAX} = 0.1$ pu
$K_{S1} = –0.602$	$A_3 = 0.429$ s	$V_{STMIN} = –0.1$ pu
$K_{S2} = 30.12$	$A_4 = 0.564$ s^2	
$T_{w1} = 0.3$ s	$A_5 = 0.001$ s	
$T_{w2} = 0.3$ s	$A_6 = 0$ s^2	
$T_{w3} = 0.6$ s	$A_7 = 0.031$ s	

H.21 Sample data for a Type PSS4B—Multi-band power system stabilizer

A typical data set uses a subset of the full model parameters. The unlisted parameters default to zero (blocks not used).

Although the PSS4B differential filters parameters may be used in various ways, a simple setting method based on three symmetrical band-pass filters respectively tuned at F_L, F_I, and F_H is most often used. Their time constants and branch gains are derived from Equation (H.1), Equation (H.2), Equation (H.3), and Equation (H.4) for the low band case. This method allows for sensitivity studies with only six parameters—F_L, F_I, F_H, K_L, K_I, K_H—involved.

$$T_{L2} = T_{L7} = \frac{1}{2\pi F_L \sqrt{R}} \tag{H.1}$$

$$T_{L1} = T_{L2} / R \tag{H.2}$$

$$T_{L8} = T_{L7} \times R \tag{H.3}$$

$$K_{L1} = K_{L2} = (R^2 + R) / (R^2 - 2R + 1) \quad \text{(H.4)}$$

R is a constant here equal to 1.2.

Band gains and central frequencies corresponding to this data set are respectively:

$K_L = 7.5$

$K_I = 30.0$

$K_H = 120.0$

$F_L = 0.07$ Hz

$F_I = 0.7$ Hz

$F_H = 8.0$ Hz

F_H is set to a high value to provide phase lead up to 4 Hz.

$K_L = 7.5$	$K_I = 30.0$	$K_H = 120.0$
$K_{L1} = 66.0$	$K_{I1} = 66.0$	$K_{H1} = 66.0$
$K_{L2} = 66.0$	$K_{I2} = 66.0$	$K_{H2} = 66.0$
$K_{L11} = 1.0$	$K_{I11} = 1.0$	$K_{H11} = 1.0$
$K_{L17} = 1.0$	$K_{I17} = 1.0$	$K_{H17} = 1.0$
$T_{L1} = 1.730$	$T_{I1} = 0.1730$	$T_{H1} = 0.01513$
$T_{L2} = 2.075$	$T_{I2} = 0.2075$	$T_{H2} = 0.01816$
$T_{L7} = 2.075$	$T_{I7} = 0.2075$	$T_{H7} = 0.01816$
$T_{L8} = 2.491$	$T_{I8} = 0.2491$	$T_{H8} = 0.02179$
$VL_{MAX} = +0.075$	$VI_{MAX} = +0.60$	$VH_{MAX} = +0.60$
$VL_{MIN} = -0.075$	$VI_{MIN} = -0.60$	$VH_{MIN} = -0.60$
$V_{STMAX} = +0.15$		
$V_{STMIN} = -0.15$		

H.22 Sample data for OEL model

I_{TFPU}	1.05 pu
I_{FDMAX}	1.50 pu
I_{FDLIM}	1.05 pu
$HYST$	0.03 pu
K_{CD}	1.0 pu

K_{RAMP} 10.0 pu/s

NOTE—I_{FD} must be based on I_{Rated}.

H.23 Sample data for a Type UEL1 underexcitation limiter model

The following is a set of sample data for a Type UEL1 model for one manufacturer's brushless or static excitation system, as applied to the HV gate input of a Type AC1A (Figure 6-1) or Type ST1A (Figure 7-1) excitation system model. The limiter setting is based upon the steady-state stability limit for a generator synchronous reactance Xd = 1.76 pu and an external reactance Xe = 0.30 pu:

K_{UC} = 1.38 pu

K_{UR} = 1.95 pu

T_{U2} = 0.05 s

K_{UL} = 100 pu

K_{UI} = 0

K_{UF} = 3.3 pu

$T_{U1} = T_{U3} = T_{U4} = 0$

$V_{URmax} = V_{UCmax}$ = 5.8 pu

V_{ULMAX} = 18 pu

V_{ULMIN} = –18 pu

H.24 Sample data for a Type UEL2 under excitation limiter model

The following is a set of sample data for a four-segment Type UEL2 model for one manufacturer's bus-fed static excitation system, as applied to the voltage error summing junction of a Type ST1A (Figure 7-1) excitation system model:

$Q0$ = –0.31 pu

$P0$ = 0 pu

$Q1$ = –0.31 pu

$P1$ = 0.3 pu

$Q2$ = –0.28 pu

$P2$ = 0.6 pu

$Q3$ = –0.21 pu

$P3$ = 0.9 pu

$Q4$ = 0 pu

$P4$ = 1.02 pu

k = 2

T_{UV} = 5.0 s

T_{UP} = 5.0 s

$K_{UF} = K_{FB} = 0$

K_{UL} = 0.8 pu

K_{UI} = 0.5 pu

$T_{U1} = T_{U2} = T_{U3} = T_{U4} = T_{UQ} = T_{UL} = 0$

$V_{ULmax} = V_{UImax}$ = 0.25 pu

$V_{ULmin} = V_{UImin} = 0$

H.25 Sample data for power factor and reactive power controllers

Following is a list of sample data for each of the models presented in Clause 11.

Voltage adjuster model (Figure 11-1)			
Variable	**Definition**	**Scale**	**Sample value**
V_{CL}	Adjuster lower signal	—	
V_{CR}	Adjuster raise signal	—	
V_{ADJF}	Set high to provide a continuous raise or lower	—	
V_{REF}	Voltage regulator reference	pu	
ADJ_SLEW	Rate at which output of adjuster changes	s/pu	300.0
V_{ADJMAX}	Maximum output of the adjuster	pu	1.1
V_{ADJMIN}	Minimum output of the adjuster	pu	0.9
T_{AON}	Time that adjuster pulses are on	s	0.1
T_{AOFF}	Time that adjuster pulses are off	s	0.5

PF controller model (Figure 11-2)			
Variable	**Definition**	**Scale**	**Sample value**
V_{PFREF}	PF controller reference 0 = 0 pf underexcited 1 = Unity pf 2 = 0 pf overexcited	—	
V_{PF}	Synchronous machine power factor 0 = 0 pf underexcited 1 = Unity pf 2 = 0 pf overexcited	—	
$OVEX$	Overexcitation Flag 0 (False) = underexcited 1 (True) = overexcited	True/false	
I_T	Synchronous machine line current	pu	
V_T	Synchronous machine line voltage	pu	
V_{PFE}	Power factor error	—	
V_{CL}	Adjuster lower signal	—	
V_{CR}	Adjuster raise signal	—	
V_{PFC_BW}	PF controller dead band	—	0.05
T_{PFC}	PF controller time delay	s	5.0

Var controller model (Figure 11-3)			
Variable	**Definition**	**Scale**	**Sample value**
V_{VARREF}	Var controller reference 0 = 0 pf underexcited 1 = Unity pf 2 = 0 pf overexcited	—	
V_{VAR}	Synchronous machine power factor 0 = 0 pf underexcited 1 = Unity pf 2 = 0 pf overexcited	—	
V_T	Synchronous machine line voltage	pu	
V_{VARE}	Var error	—	
V_{CL}	Adjuster lower signal	—	
V_{CR}	Adjuster raise signal	—	
V_{VARC_BW}	Var controller dead band	—	0.02
T_{VARC}	Var controller time delay	s	5.0

PF controller model Type II (Figure 11-4)			
Variable	**Definition**	**Scale**	**Sample value**
PF_{REF}	Power factor reference	pu	
PF	Power factor measured	pu	
V_{REF}	Voltage regulator reference	pu	
V_{CLMT}	Maximum output of the pf controller	pu	0.1
K_P	Proportional gain of the pf controller	pu	1
K_I	Integral gain of the pf controller	pu	1
V_{PF}	Output of the pf controller		
V_S	Generator sensing voltage		
$EXLON$	Overexcitation or under excitation flag 0 = FALSE, 1 = TRUE		

Var controller model Type II (Figure 11-5)			
Variable	**Definition**	**Scale**	**Sample value**
Q_{REF}	Reactive power reference	pu	
Q	Reactive power measured	pu	
V_{REF}	Voltage regulator reference	pu	
V_{CLMT}	Maximum output of the pf controller	pu	0.1
K_P	Proportional gain of the pf controller	pu	1
K_I	Integral gain of the pf controller	pu	1
V_{PF}	Output of the var controller		
V_S	Generator sensing voltage		
EXLON	Overexcitation or under excitation flag 0 = FALSE, 1 = TRUE		

Annex I

(informative)

Manufacturer model cross reference

The following information is given for the convenience of users of this recommended practice and does not constitute an endorsement by the IEEE of these products.

At the time IEEE Std 421.5-2005 was approved, the following examples of equivalent excitation systems were supplied by other manufacturers. The IEEE will make available at no charge to the users of this recommended practice, IEEE Std 421.5-2005, an up-to-date listing of examples of equivalent excitation systems supplied by other manufactures. This list will be made available at the IEEE Web site.

Type	Examples
DC1A	Regulex is a trademark of Allis Chalmers Corp. Amplidyne and GDA are trademarks of General Electric Co. Westinghouse Mag-A-Stat, Rototrol, Silverstat, and TRA. AB and KC are trademarks of Asea Brown Boveri Inc. The type KC may be modeled with some approximations.
DC2A	Westinghouse PRX-400. General Electric SVR. Eaton Cutler Hammer/Westinghouse type WDR retrofit.
DC3A	GFA 4 is a trademark of General Electric Co. Westinghouse BJ30.
DC4B	Basler DECS or Eaton/Cutler Hammer ECS2100 applied to a dc commutator exciter.
AC1A	Westinghouse Brushless Excitation System; Cutler Hammer Westinghouse WDR brushless exciter retrofit.
AC2A	Westinghouse High Initial Response Brushless excitation system.
AC3A	ALTERREX is a trademark of General Electric Co.
AC4A	ALTHYREX is a trademark of General Electric Co.; General Electric Rotating Thyristor Excitation system.
AC5A	This model can be used to represent small excitation systems such as those produced by Basler and Electric Machinery.
AC6A	Stationary diode systems such as those produced by C.A. Parsons.
AC7B	Basler DECS and EATON ECS2100 applied to ac/dc rotating exciters; Brush PRISMIC A50-B, GE EX2000/2100, SIEMENS RG3, and THYRISIEM brushless excitation. Voltage regulator replacements for GE Alterrex (Type AC3A model) or dc exciters. DECS is a trademark of Basler Electric Co. Brush and PRISMIC are trademarks of FKI plc. RG3 and THYRISIEM are registered trademarks of Siemens AG.
AC8B	Basler DECS and Brush PRISMIC A30 and A10.
ST1A	Silcomatic (a trademark of Canadian General Electric Co.). Westinghouse Canada Solid State Thyristor Excitation System; Westinghouse Type PS Static Excitation System with Type WTA, WTA-300, and WHS voltage regulators. Static excitation systems by ALSTOM, ASEA, Brown Boveri, GEC-Eliott, Hitachi, Mitsubishi, Rayrolle-Parsons, and Toshiba. General Electric Potential Source Static Excitation System. Basler Model SSE. UNITROL (a registered trademark of Asea Brown Boveri, Inc.); THYRIPOL (a registered trademark of Siemens AG.); Westinghouse WDR and MGR.
ST2A	General Electric static excitation systems, frequently referred to as the SCT-PPT or SCPT.

ST3A	General Electric Compound Power Source and Potential Power Source GENERREX excitation systems. GENERREX is a trademark of General Electric Co.
ST4B	Basler DECS applied to static excitation, Brush PRISMIC A50-S and A50-A, General Electric EX2000/2100 bus-fed potential source and static compound source and Generrex-PPS or -CPS; Canadian General Electric SILCOmatic 5 or EATON ECS2100 static excitation system.
ST5B	UNITROL D, P, F, and 5000 (trademarks of Asea Brown Boveri); Brush DCP.
ST6B	THYRIPOL (a trademark of Siemens AG) and EATON ECS2100 static excitation systems.
ST7B	ALSTOM excitation systems—Eurorec, Microrec K4.1, ALSPA P320 (ALSPA P320 is a trademark of ALSTOM).
PSS2B	The PSS2B model is a standard option available in Eaton Cutler-Hammer, GE, and ABB UNITROL P, F and 5000, Basler and ALSTOM ALSPA P320 excitation systems, and the stand-alone Basler PSS-100 and Brush PRISMIC T20 stabilizers.
PSS3B	The PSS3B model is mainly used with the Siemens THYRIPOL and ABB UNITROL-M and -D excitation systems.
PSS4B	Multi-band PSS ABB type MB-PSS.

Annex J

(informative)

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