



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

IEEE Power Engineering Society

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**Energy Development and Power Generation Committee
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IEEE Power Engineering Society**

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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 $\pm 5\%$ 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 $\pm 5\%$ 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 $\pm 5\%$ 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

¹The 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 115TM, 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 421.1TM, IEEE Definitions for Excitation Systems for Synchronous Machines.

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

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

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

IEEE Std C50.13TM, 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.

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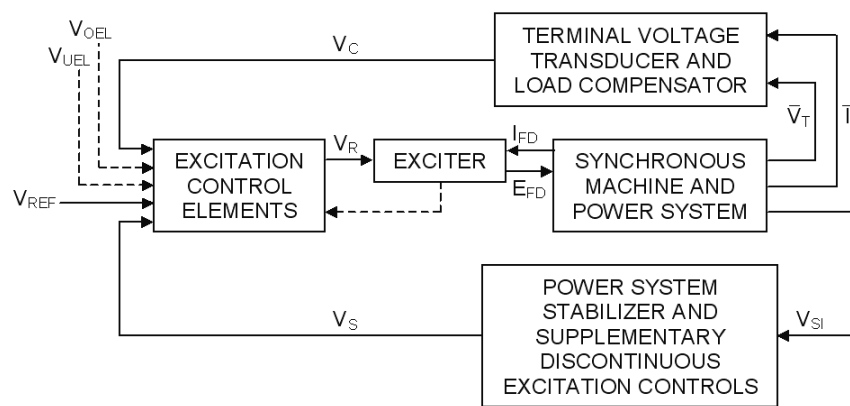


Figure 3-1—General functional block diagram for synchronous machine excitation control system

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:

- Type DC excitation systems*, which utilize a direct current generator with a commutator as the source of excitation system power (see Clause 5)
- 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)
- 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:

- Voltage sensing and load compensation (see Clause 4)
- 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.

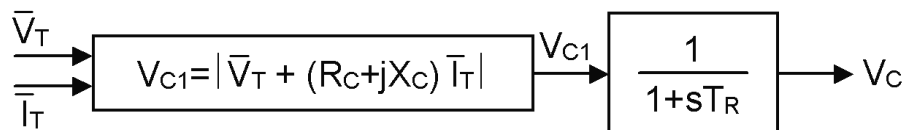


Figure 4-1—Terminal voltage transducer and optional load compensation elements

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):

$$V_{C1} = \left[V_T + (R_{C11} + jX_{C11})\overline{I_{T1}} + (R_{C12} + jX_{C12})I_{T2} \right] \quad (1)$$

- 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):

$$I_T = I_P - jI_Q \quad (2)$$

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):

$$\begin{aligned} V_{C1} &= |(V_T + X_{C11}I_{Q1} + X_{C12}I_{Q2}) + j(X_{C11}I_{P1} + X_{C12}I_{P2})| \\ &\approx (V_T + X_{C11}I_{Q1} + X_{C12}I_{Q2}) \end{aligned} \quad (3)$$

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 <i>reactive droop</i> . 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 <i>transformer-drop</i> or <i>line-drop compensation</i> . 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 <i>cross-current compensation</i> , although the preferred terminology is <i>reactive differential compensation</i> . 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.

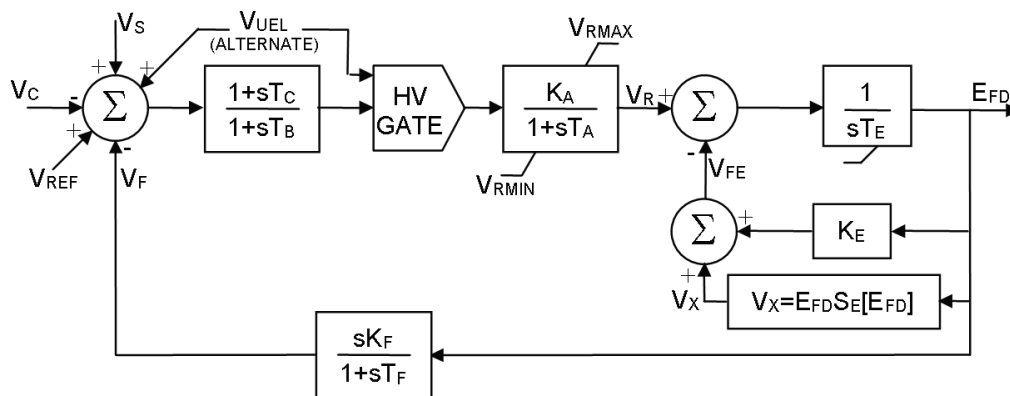


Figure 5-1—Type DC1A—DC commutator exciter

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

⁵Examples 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.

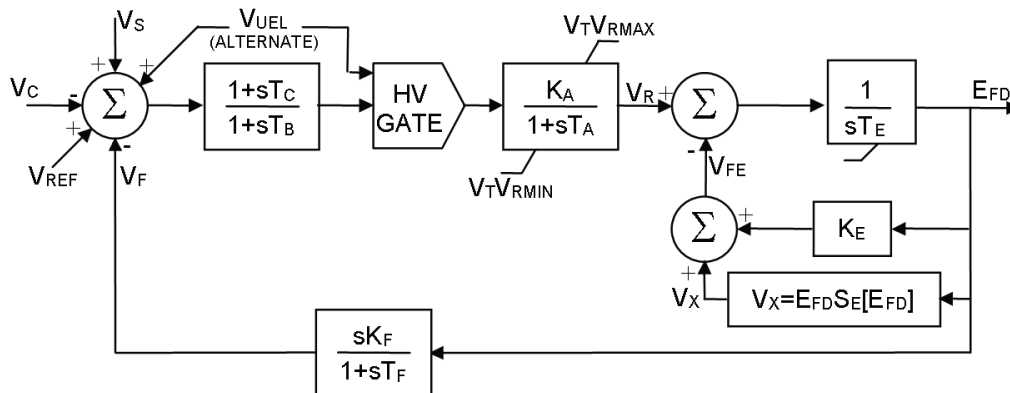


Figure 5-2 Type DC2A—DC commutator exciter with bus-fed regulator

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.

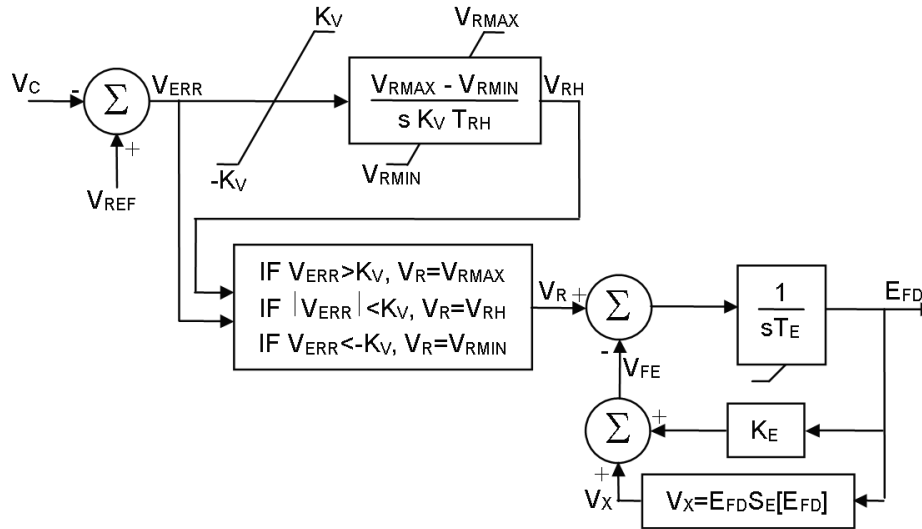


Figure 5-3—Type DC3A—DC commutator exciter with non-continuously acting regulators

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.

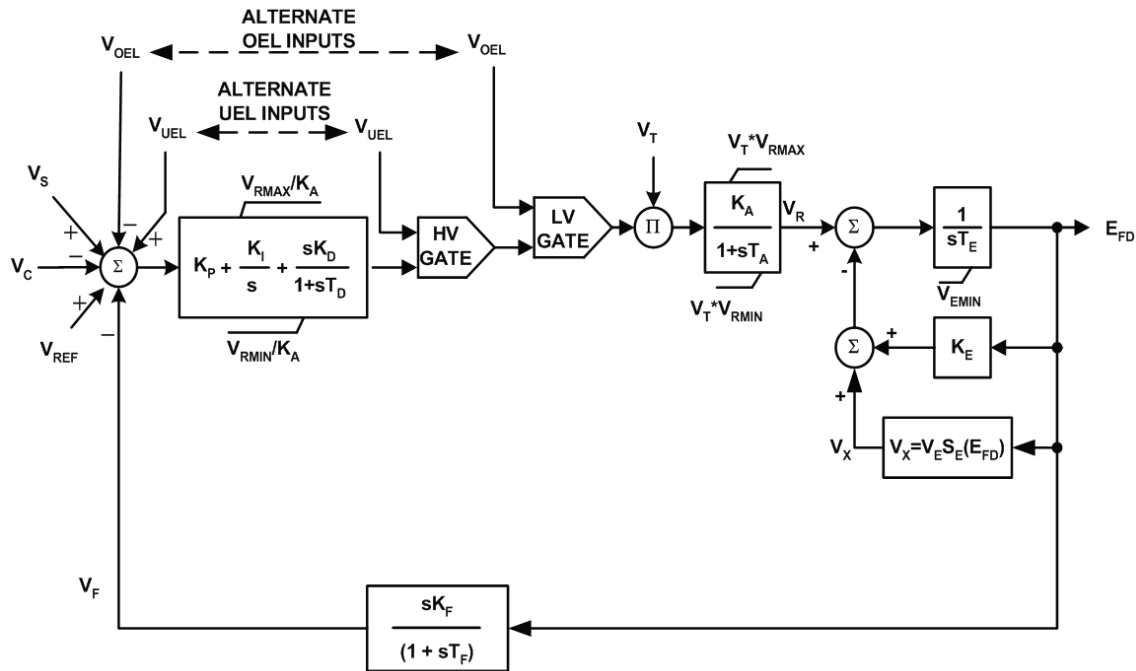


Figure 5-4—Type DC4B—DC commutator exciter with PID style regulator

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.

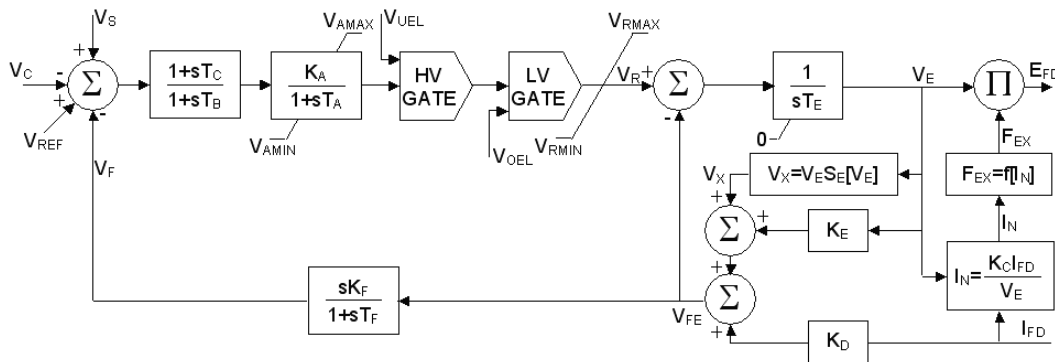


Figure 6-1—Type AC1A—Alternator-rectifier excitation system with non-controlled rectifiers and feedback from exciter field current

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.

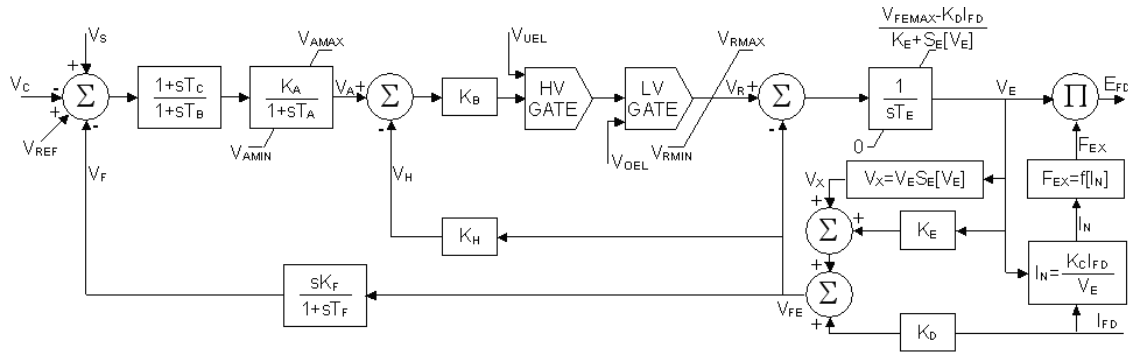


Figure 6-2—Type AC2A—High initial response alternator-rectifier excitation system with non-controlled rectifiers and feedback from exciter field current

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.

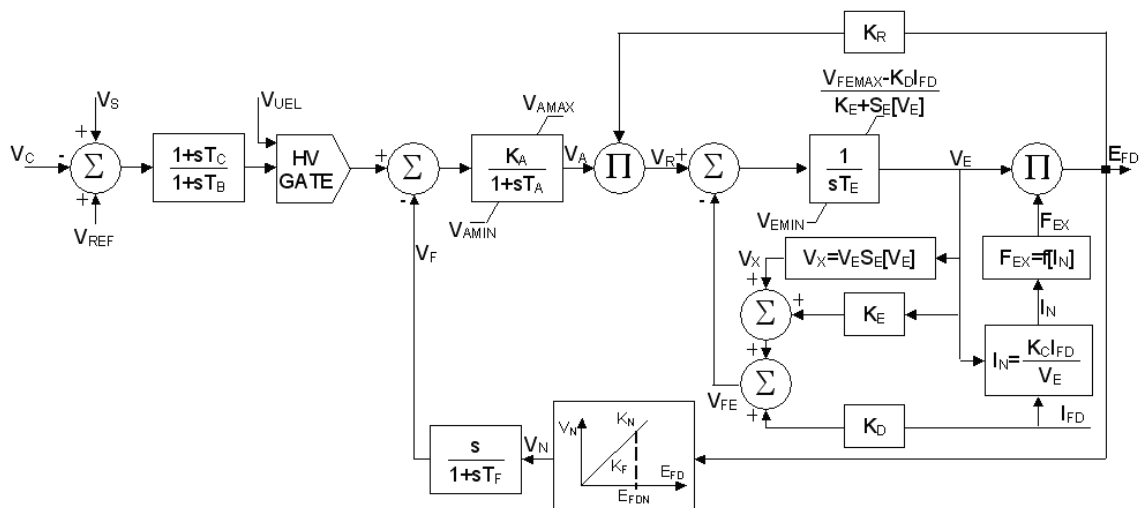


Figure 6-3—Type AC3A—Alternator-rectifier exciter with alternator field current limiter

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.

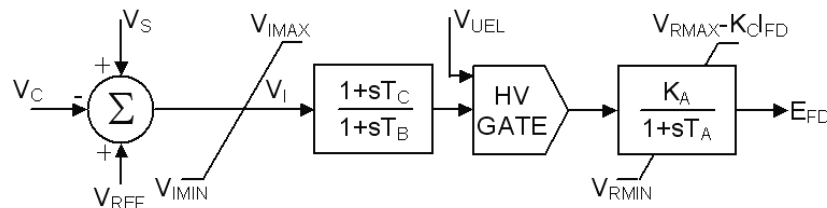


Figure 6-4—Type AC4A alternator-supplied controlled-rectifier exciter

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.

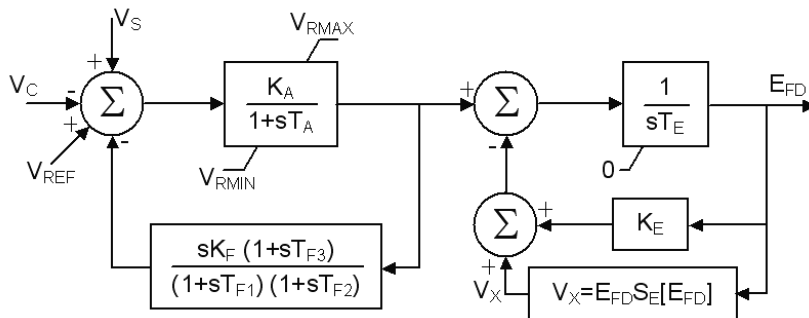


Figure 6-5—Type AC5A—Simplified rotating rectifier excitation system representa-

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.

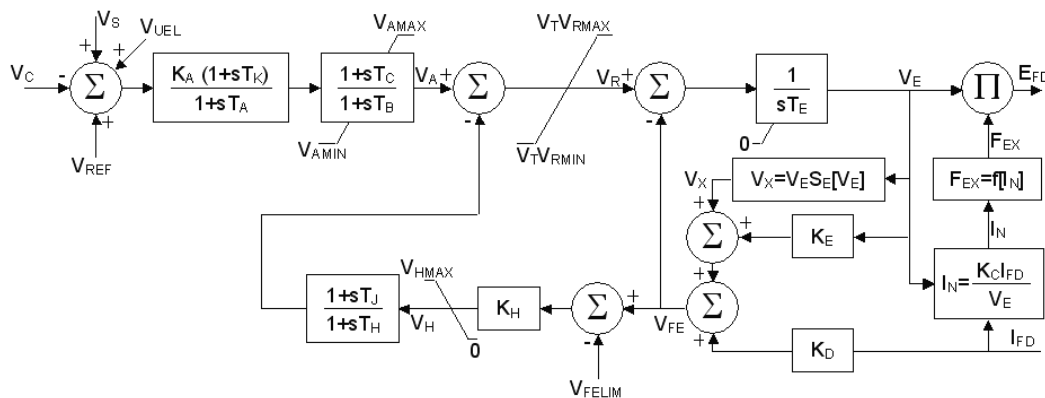


Figure 6-6—Type AC6A—Alternator-rectifier excitation system with non-controlled rectifiers and system-supplied electronic voltage regulator

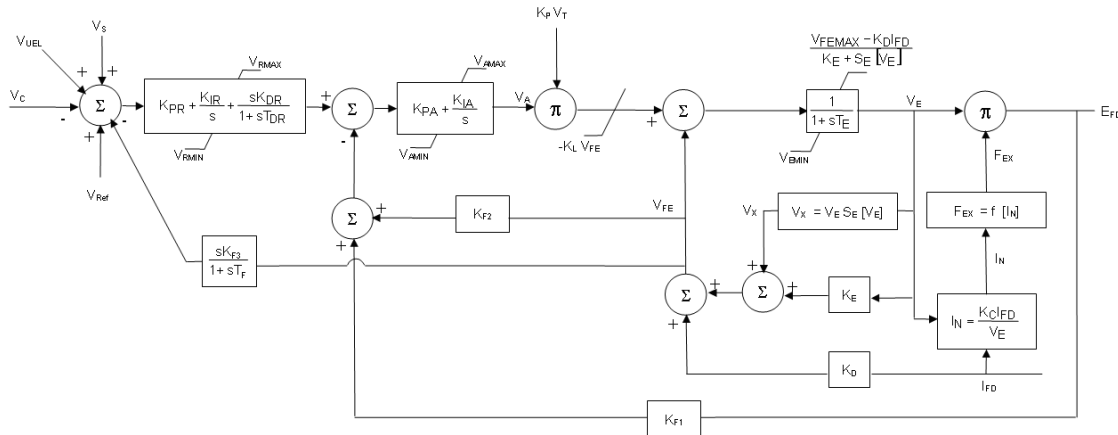
6.7 Type AC7B excitation system model

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

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

[illegible]

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.

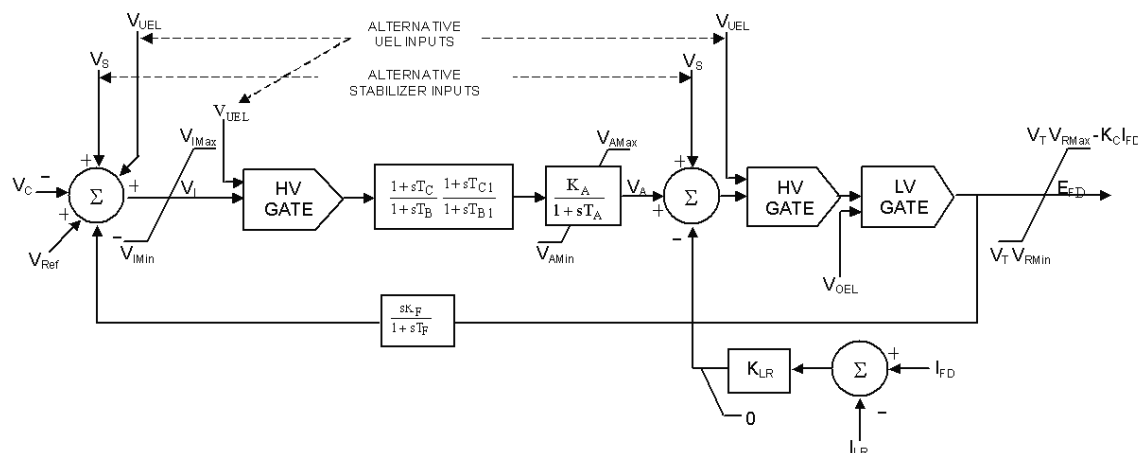


Figure 7-1—Type ST1A—Potential-source, controlled-rectifier exciter

In many cases, the internal limits on V_f 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.

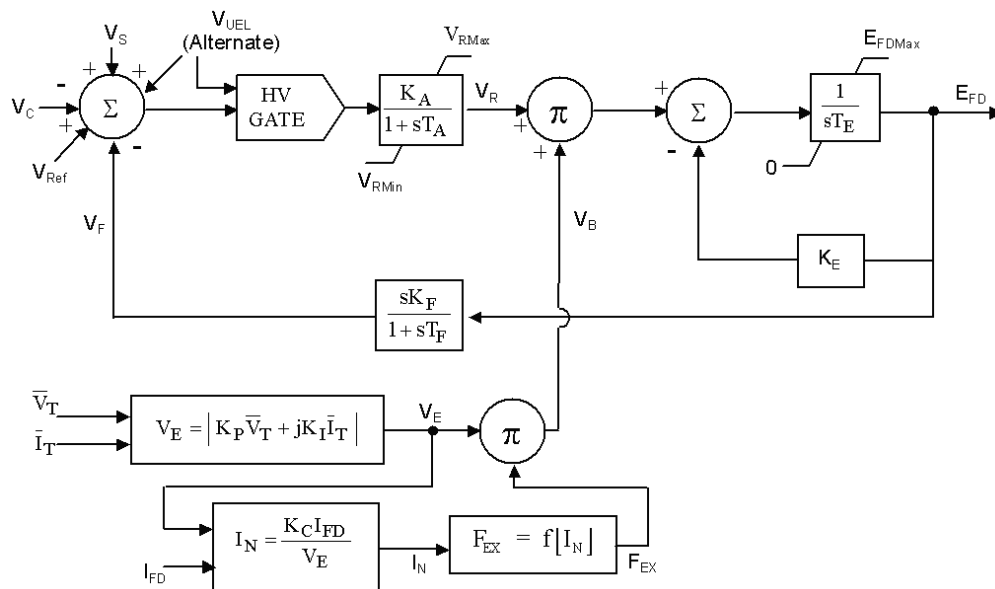


Figure 7-2—Type ST2A—Compound-source rectifier exciter

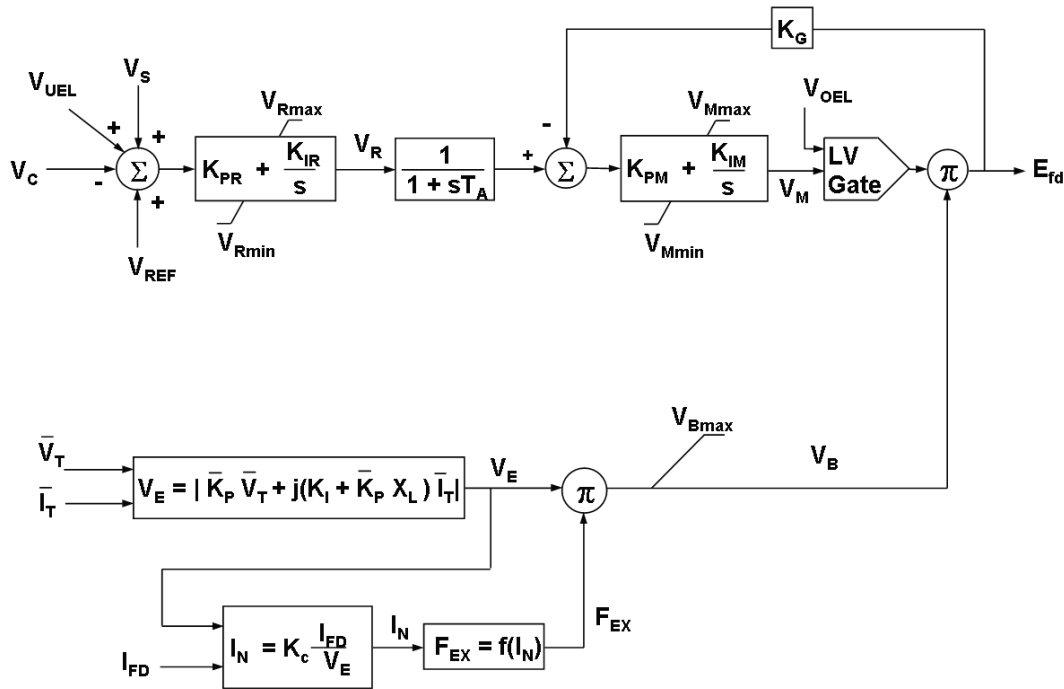


Figure 7-4—Type ST4B—Potential- or compound-source controlled-rectifier exciter

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.