

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. With these models, most of the excitation systems currently in widespread use on large, system-connected synchronous machines in North America can be represented. They include updates of models published in the IEEE Transactions on Power Apparatus and Systems in 1981 as well as models for additional control features such as discontinuous excitation controls.

Keywords: excitation systems, power system stability

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Foreword

(This foreword is not a part of IEEE Std 421.5-1992, 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 this recommended practice, the 1981 models are again updated, and models for additional control features such as discontinuous excitation controls are provided.

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

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 [12]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 [6]) 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 [7]) 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 of 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 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.

A sample set of data (not necessarily typical) for each of the models, for at least one particular application, is provided in Appendix I. A suffix, "A," is used with the version of all models described in this report to differentiate them from previous models.

¹The numbers in brackets correspond to those of the references in Section 2.

2. References

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

- [1] ANSI C50.10-1990, American National Standard for Synchronous Machines — Rotating Electrical Machinery.²
- [2] IEEE Std 100-1988, IEEE Standard Dictionary of Electrical and Electronics Terms (ANSI).³
- [3] IEEE Std 115-1983, IEEE Test Procedures for Synchronous Machines (ANSI).
- [4] IEEE Std 421.1-1986, IEEE Standard Definitions for Excitation Systems for Synchronous Machines (ANSI).
- [5] Bayne, J. P., Kundur, P., and Watson, W. “Static Exciter Control to Improve Transient Stability,” *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-94, pp. 1141–1146, July 1975.
- [6] “Computer Representation of Excitation Systems,” IEEE Committee Report, *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-87, no. 6, pp. 1460–1464, June 1968.
- [7] “Excitation System Models for Power System Stability Studies,” IEEE Committee Report, *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-100, PP. 494–509, Feb. 1981.
- [8] Ferguson, R. W., Herbst, H., and Miller, R. W. “Analytical Studies of the Brushless Excitation System,” *AIEE Transactions on Power Apparatus and Systems (Part III)*, vol. 79, pp. 1815–1821, Feb. 1960.
- [9] Gayek, H. W. “Transfer Characteristics of Brushless Aircraft Generator Systems,” *IEEE Transactions on Aerospace*, vol. 2, no. 2, pp. 913–928, Apr. 1964.
- [10] Lee, D. C. and Kundur, P. “Advanced Excitation Controls for Power System Stability Enhancement,” CIGRE Paper: 38-01, Paris, France, 1986.
- [11] Rubenstein, A. S. and Wakley, W. W. “Control of Reactive kVA With Modern Amplidyne Voltage Regulators,” *AIEE Transactions on Power Apparatus and Systems (Part III)*, pp. 961–970, 1957.
- [12] *Stability of Large Electric Power Systems*. R. T. Byerly and E. W. Kimbark, Ed., New York: IEEE Press, 1974.
- [13] Taylor, C. W. “Transient Excitation Boosting on Static Exciters in an AC/DC Power System,” Invited Paper-08, Symposium of Specialists in Electric Operational Planning, Rio de Janeiro, Aug. 1987.

3. Representation of Synchronous Machine Excitation Systems in Power System Studies

The general functional block diagram shown in Fig 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. Supplementary discontinuous excitation control may also be employed. Models for all of these functions are presented in this recommended practice.

²ANSI publications are available from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA.

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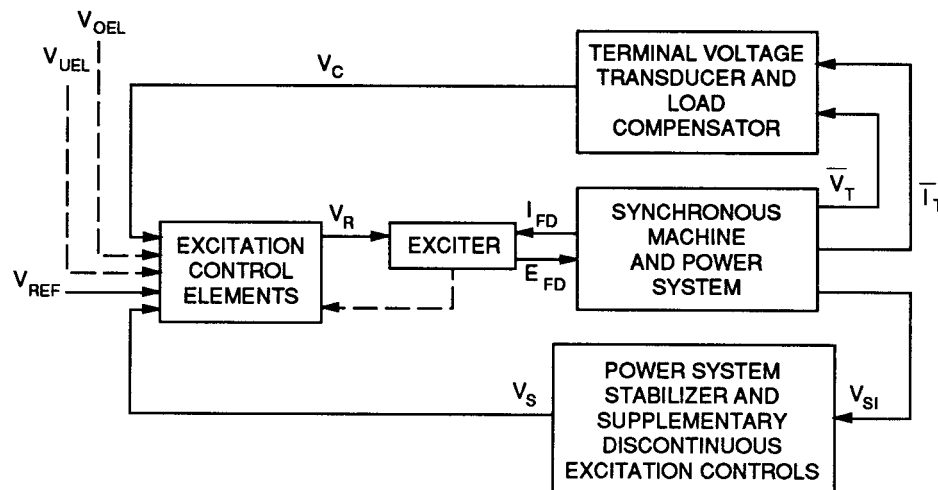


Figure 1—General Functional Block Diagram for Synchronous Machine Excitation Control System

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 block “excitation control elements” in Fig 1 that affect the stability and response of those systems.

Field current limiters are not normally represented in large system studies, but they are becoming increasingly important in the representation of bus-fed static systems employing fast-acting limiters. As a result, they have been included in that model.

The models in this standard do not include underexcitation limiters (UELs). They do show how outputs, V_{UEL} , of such limiters would normally be connected to the various excitation system models. The output of the UEL may be received as an input to the excitation system 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.

Terminal voltage and terminal V/Hz limiters are not normally represented in excitation system models. Some models, however, do provide a gate through which the output of a terminal voltage limiter, V_{OEL} , could enter the regulator loop. A terminal voltage limiter function is also included with one of the supplementary discontinuous excitation control models.

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 system used for modeling the excitation system is described in Appendix B.

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

- 1) *Type DC excitation systems*, which utilize a direct current generator with a commutator as the source of excitation system power
- 2) *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
- 3) *Type ST excitation systems*, in which excitation power is supplied through transformers or auxiliary generator windings and rectifiers

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

- 1) Voltage sensing and load compensation
- 2) Power system stabilizer

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

The type AC and ST excitation systems 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 Appendix G.

4. Synchronous Machine Terminal Voltage Transducer and Load Compensator Models

A block diagram of the terminal voltage transducer and the load compensator is shown in Fig 2. 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.

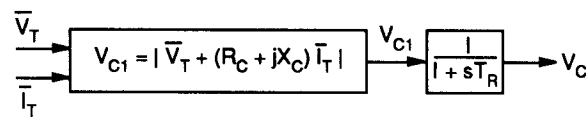


Figure 2—Terminal Voltage Transducer and Optional Load Compensation Elements

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.

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 per unit 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:

- 1) When units are bused together with no impedance between them, the compensator is used to create an artificial coupling impedance so that the units 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.
- 2) When a single unit is connected through a significant impedance to the system, or when two or more units 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 [11].

5. Type DC — Direct Current Commutator Exciters

Few type DC exciters are now being produced, having been superseded by type AC and ST systems. There are, however, many such systems still in service. Considering the dwindling percentage and importance of units equipped with these exciters, the previously developed concept (see [6]) of accounting for loading effects on the exciter by using the loaded saturation curve (Appendix C) is considered adequate.

The relationships between regulator limits and field voltage limits are developed in [7].

5.1 Type DC1A Excitation System Model

This model, described by the block diagram of Fig 3, 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). Examples include

- | | |
|----------------------|--|
| (1) Allis Chalmers | — Regulex ^{TM4} regulator |
| (2) General Electric | — Amplidyne ⁵ regulator |
| | — GDA regulator |
| (3) Westinghouse | — Mag-A-Stat ^{TM6} regulator |
| | — Rototrol TM regulator |
| | — Silverstat TM regulator |
| | — TRA TM regulator |
| (4) Brown Boveri | — Type AB regulator |
| | — Type KC ^{TM7} regulators (with some approximations) |

⁴Regulex is a trademark of Allis Chalmers Corp.

⁵Amplidyne is a trademark of General Electric Co.

⁶Mag-A-Stat, Rototrol, Silverstat, and TRA are trademarks of Westinghouse Elec. Corp.

⁷KC is a trademark of Asea Brown Boveri Inc.

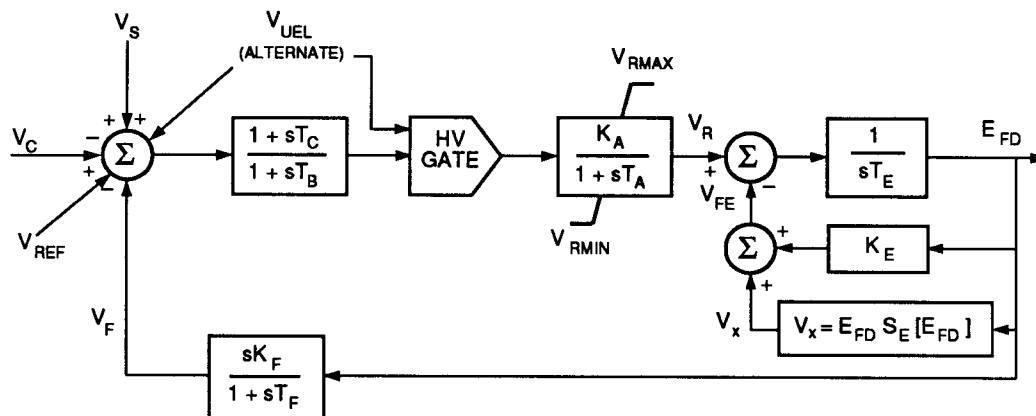


Figure 3—Type DC1A — DC Commutator Exciter

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 described above. 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 nonwindup limits typical of saturation or amplifier power supply limitations. A discussion of windup and nonwindup limits is provided in Appendix E. These voltage regulators utilize power sources that are essentially unaffected by brief transients on the synchronous machine or auxiliaries 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.

The voltage regulator output, V_R , is used to control the exciter, which may be either separately-excited or self-excited as discussed in [7]. 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 such that initial conditions are satisfied with $V_R = 0$, as described in [7]. In some programs, if K_E is not provided, it is automatically calculated by the program for self-excitation.

If a value for K_E is provided, the program should not recalculate K_E because a fixed rheostat setting is implied. For such systems, the rheostat is frequently fixed at a value that would produce self-excitation near rated conditions. Systems with fixed field rheostat settings are in widespread use on units that are remotely controlled. A value of $K_E = 1$ is used to represent a separately excited exciter.

The term $S_E[E_{FD}]$ is a nonlinear function with a value defined at any chosen E_{FD} , as described in Appendix 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 Fig 4 is used to represent field controlled dc commutator exciters with continuously acting voltage regulators having supplies obtained from the generator or auxiliaries bus. It differs from the type DC1A model only in the voltage regulator output limits, which are now proportional to terminal voltage, V_T .

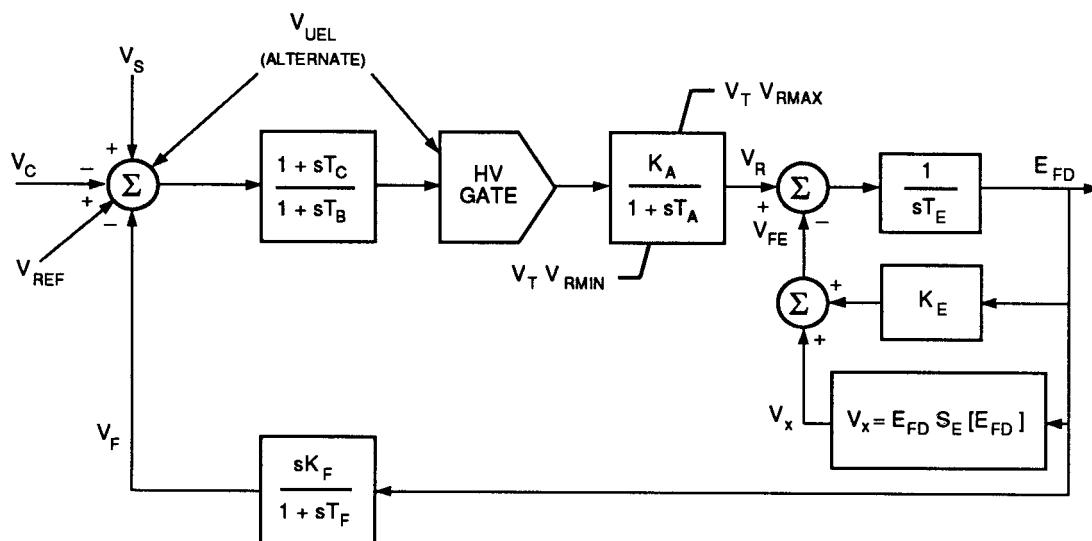


Figure 4—Type DC2A—DC Commutator Exciter With Bus-Fed Regulator

It is representative of solid state replacements for various forms of older mechanical and rotating amplifier equipment.

Regulators represented by this model include

- (1) Westinghouse — Type PRX-400^{TM8}
- (2) General Electric — Type SVR

5.3 Type DC3A Excitation System Model

The systems discussed in the previous sections 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 noncontinuously acting regulators that were commonly used before the development of the continuously acting varieties. Some examples of these systems are

- (1) General Electric — GFA4^{TM9} regulator
- (2) Westinghouse — BJ30^{TM10} regulator

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 to be 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. Fig 5 illustrates this control action.

⁸PRX-400 is a trademark of Westinghouse Elec. Corp.

⁹GFA4 is a trademark of General Electric Co.

¹⁰BJ30 is a trademark of Westinghouse Elec. Corp.

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

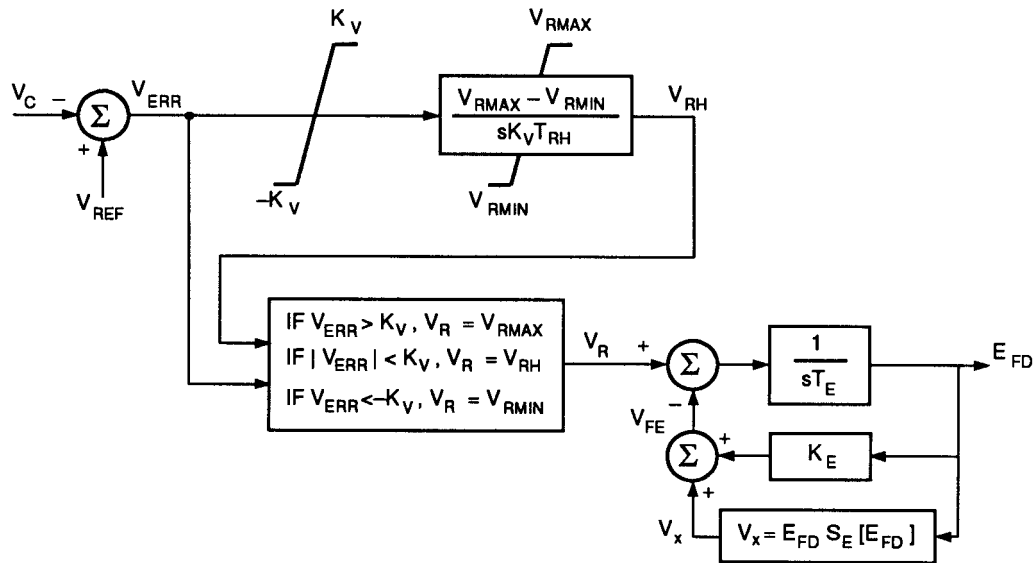


Figure 5—Type DC3A—DC Commutator Exciter With Noncontinuously Acting Regulators

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 and down, depending upon the sign of the error. The travel time representing continuous motion of the rheostat drive motor is T_{RH} . A nonwindup limit (see Appendix 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.

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).

6. Type AC — Alternator Supplied Rectifier Excitation Systems

These excitation systems use an ac alternator and either stationary or rotating rectifiers to produce the direct current needed for the generator field. 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 Appendix G.

6.1 Type AC1A Excitation System Model

The model shown in Fig 6 represents the field controlled alternator-rectifier excitation systems designated as type AC1A. These excitation systems consist of an alternator main exciter with noncontrolled rectifiers. The exciter does not employ self-excitation, and the voltage regulator power is taken from a source that is not effected by external transients. The diode characteristic in the exciter output imposes a lower limit of zero on the exciter output voltage, as shown in Fig 6. This model is applicable for simulating the performance of the Westinghouse brushless excitation system.

For large power system stability studies, the exciter alternator synchronous machine can be represented by the simplified model shown in Fig 6. 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 [8] and [9].

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 Appendix D.

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

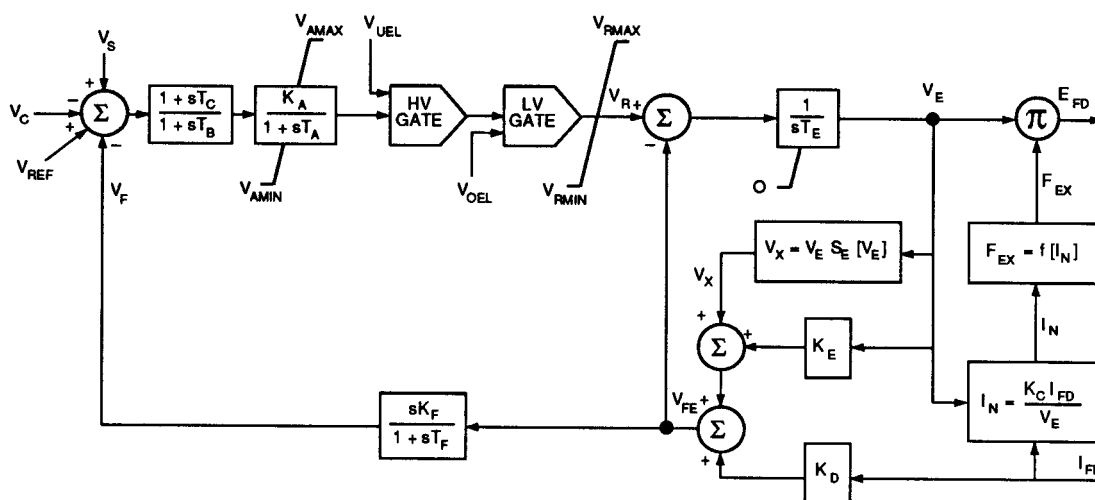


Figure 6—Type AC1A—Alternator-Rectifier Excitation System With Noncontrolled Rectifiers and Feedback From Exciter Field Current

6.2 Type AC2A Excitation System Model

The model shown in Fig 7, designated as type AC2A, represents a high initial response field controlled alternator-rectifier excitation system. The alternator main exciter is used with noncontrolled 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. This model is applicable for simulating the performance of the Westinghouse high initial response brushless excitation system.

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 limits the current. By limiting the exciter field current, exciter output voltage, E_E , is limited to a selected value that is usually determined by the specified excitation system nominal response. Although this limit is realized physically by a feedback loop as described in Appendix 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.

6.3 Type AC3A Excitation System Model

The model shown in Fig 8 represents the field controlled alternator-rectifier excitation systems designated as type AC3A. These excitation systems include an alternator main exciter with noncontrolled 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, V_{FD} , times K_R . This model is applicable to systems such as the General Electric ALTEREX™¹¹ 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.

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 Appendix D.

In the model, 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 Appendix C) and I_{FD} multiplied by the demagnetization term, K_D .

The excitation system stabilizer also 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 Appendix F.

6.4 Type AC4A Excitation System Model

The type AC4A alternator supplied controlled rectifier system illustrated in Fig 9 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.

¹¹ ALTEREX is a trademark of General Electric Co.

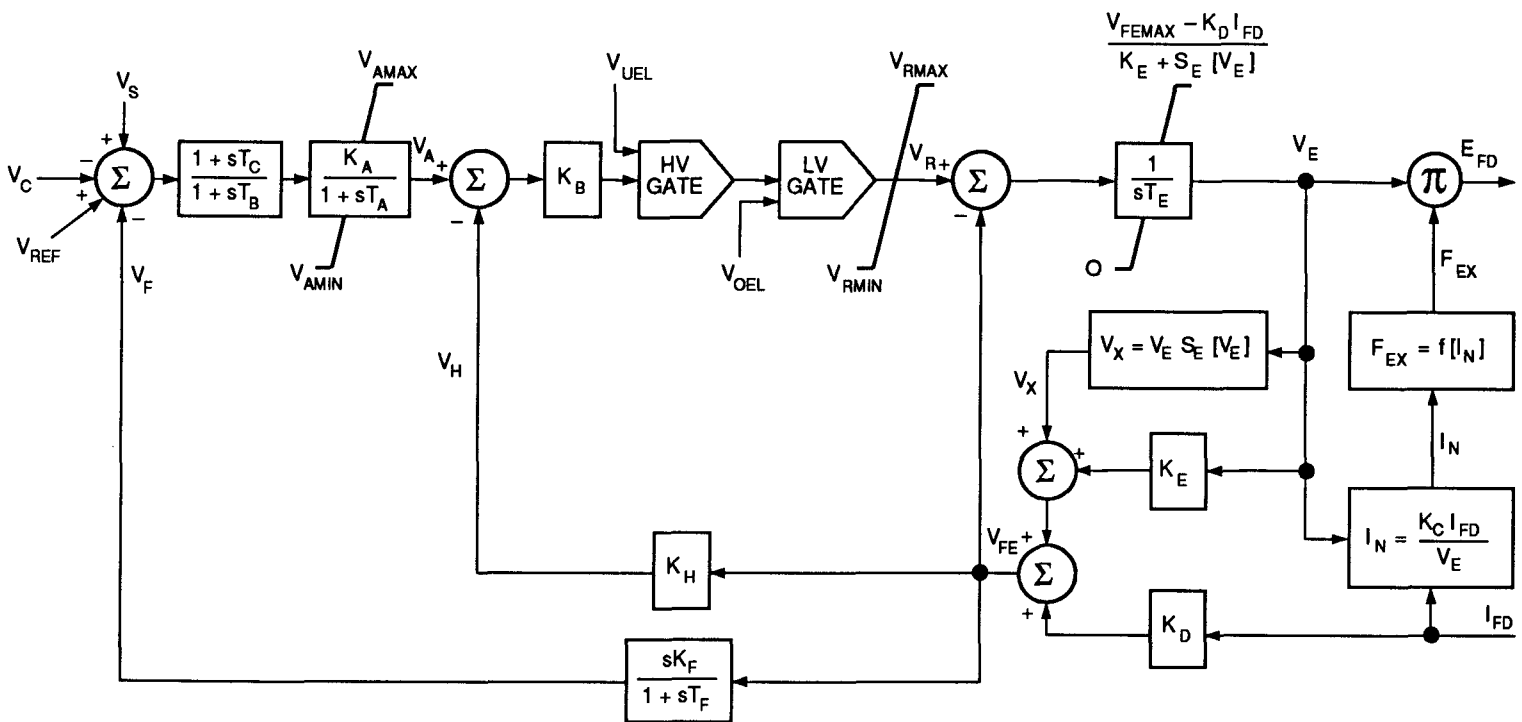


Figure 7—Type AC2A — High Initial Response Alternator-Rectifier Excitation System With Noncontrolled Rectifiers and Feedback From Exciter Field Current

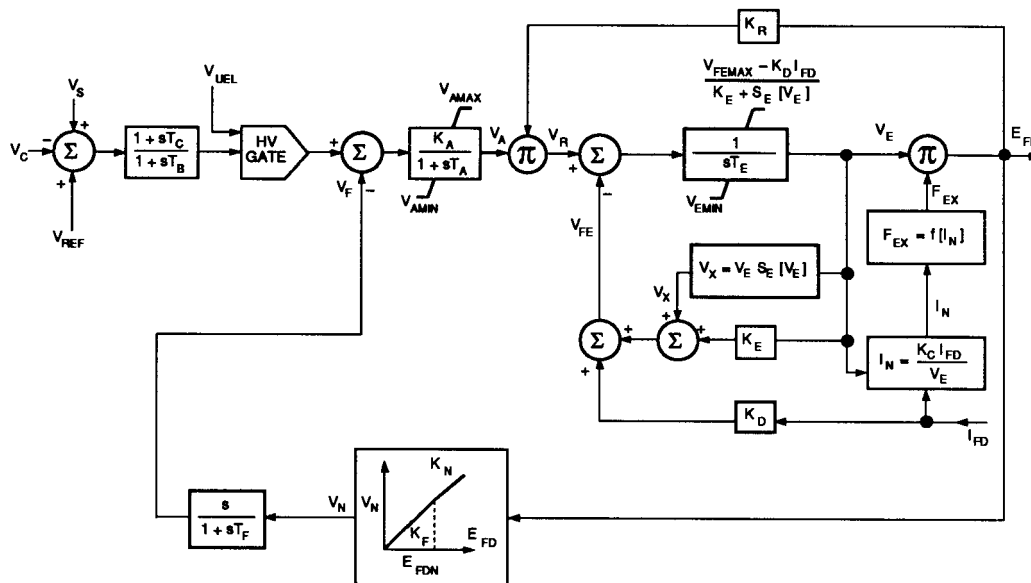


Figure 8—Type AC3A — Alternator-Rectifier Exciter With Alternator Field Current Limiter

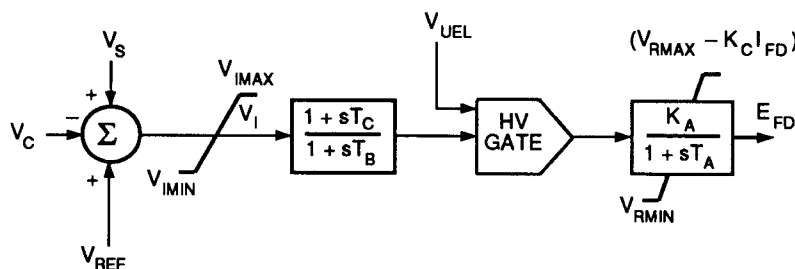


Figure 9—Type AC4A — Alternator Supplied Controlled-Rectifier Exciter

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 Appendix 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.

Systems to which this stimulation model applies include the General Electric ALTHYREX^{TM12} and rotating thyristor excitation systems.

6.5 Type AC5A Excitation System Model

The model shown in Fig 10 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, that is not affected by system disturbances.

¹²ALTHYREX is a trademark of General Electric Co.