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

Sponsor

Energy Development and Power Generating Committee of the Power Engineering Society

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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 ±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.

[1]The 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.

[2]ANSI publications are available from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA.
[3]IEEE publications are available from the Institute of Electrical and Electronics Engineers, Service Center, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

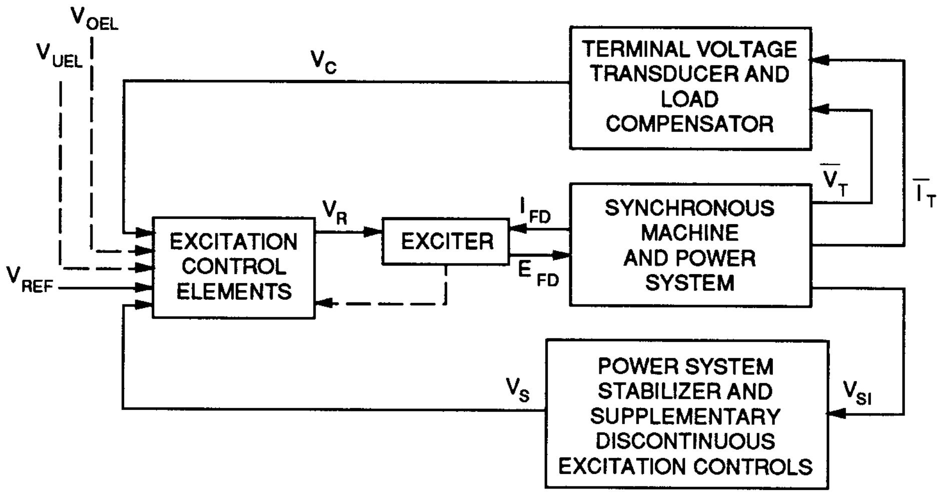

Figure 1—General Functional Block Diagram for Synchronous Machine Excitation Control System

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.

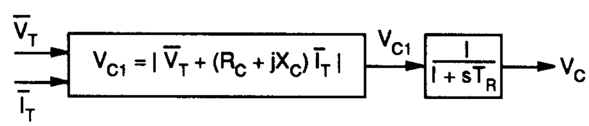

Figure 2—Terminal Voltage Transducer and Optional Load Compensation Elements

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™[4] regulator
(2) General Electric	— Amplidyne[5] regulator
	— GDA regulator
(3) Westinghouse	— Mag-A-Stat™[6] regulator
	— Rototrol™ regulator
	— Silverstat™ regulator
	— TRA™ regulator
(4) Brown Boveri	— Type AB regulator
	— Type KC™[7] regulators (with some approximations)

[4]Regulex is a trademark of Allis Chalmers Corp.
[5]Amplidyne is a trademark of General Electric Co.
[6]Mag-A-Stat, Rototrol, Silverstat, and TRA are trademarks of Westinghouse Elec. Corp.
[7]KC is a trademark of Asea Brown Boveri Inc.

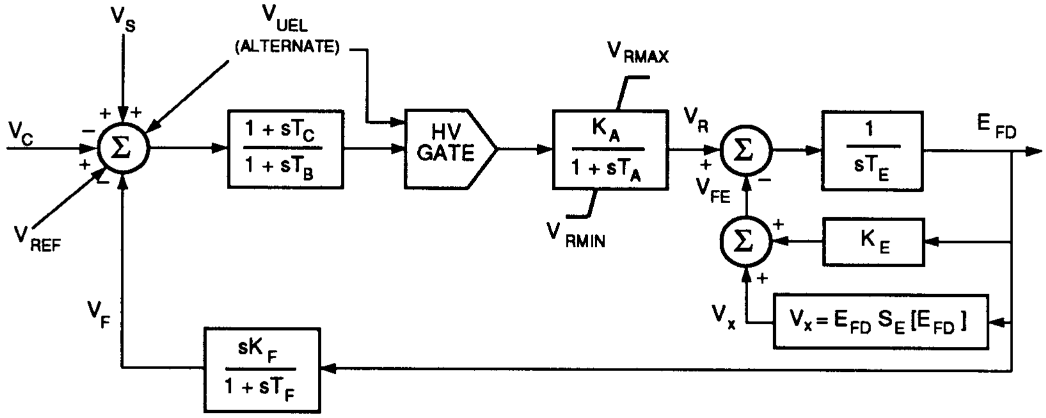

Figure 3—Type DC1A — DC Commutator Exciter

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.

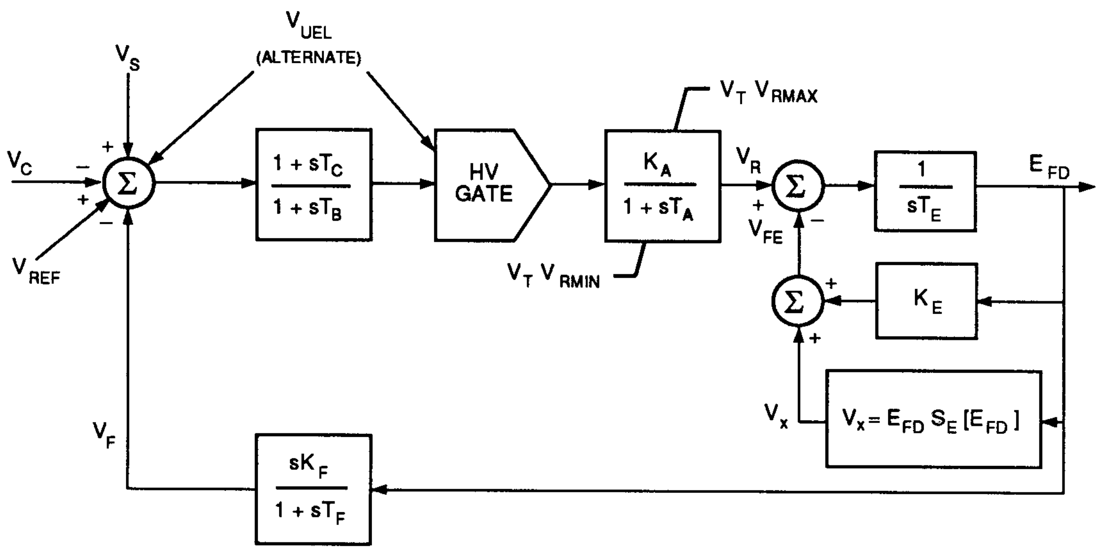

Figure 4—Type DC2A—DC Commutator Exciter With Bus-Fed Regulator

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™[8]
(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™[9] regulator
(2) Westinghouse — BJ30™[10] 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.

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[8]PRX-400 is a trademark of Westinghouse Elec. Corp.
[9]GFA4 is a trademark of General Electric Co.
[10]BJ30 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.

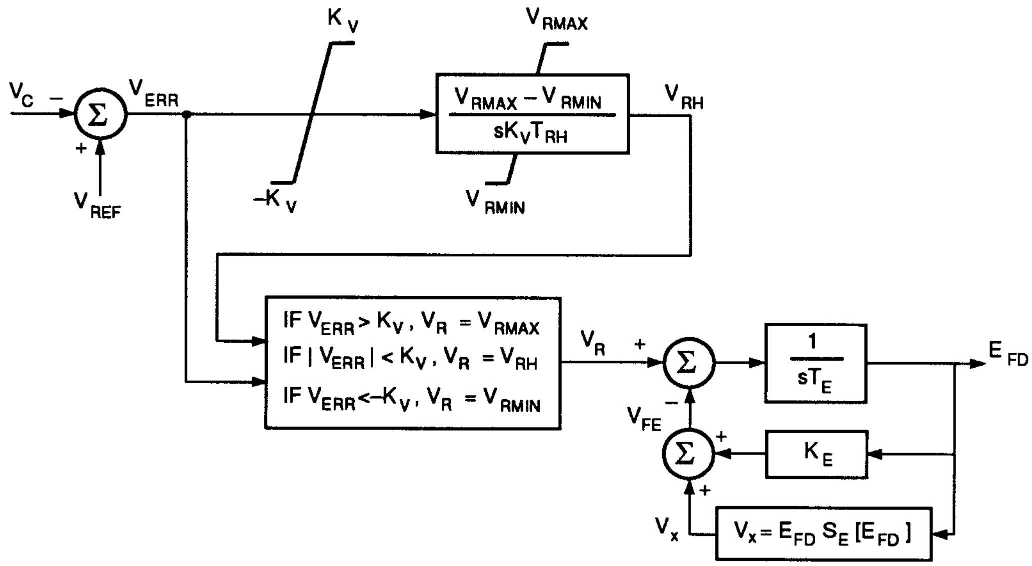

Figure 5—Type DC3A—DC Commutator Exciter With Noncontinuously Acting Regulators

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.

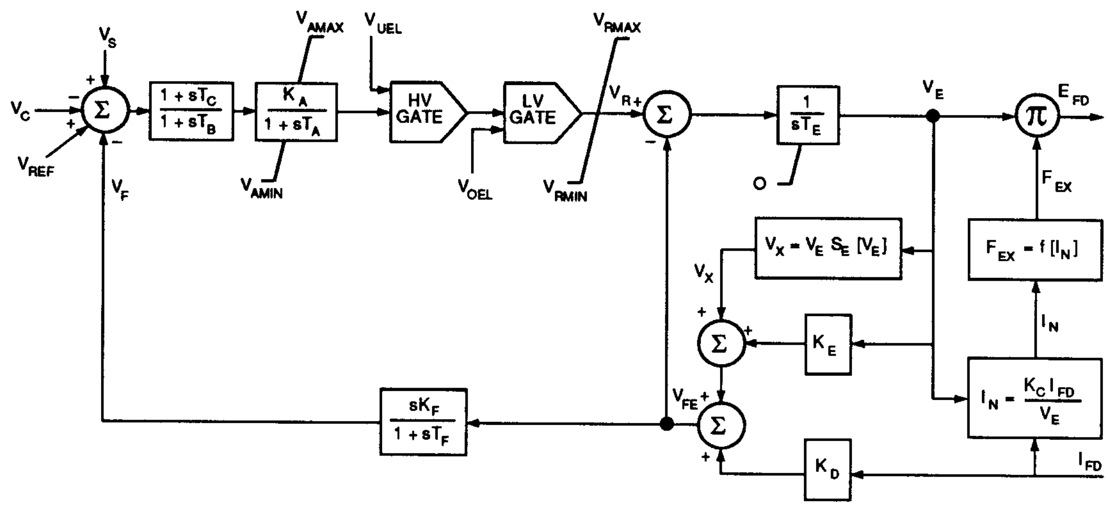

Figure 6—Type AC1A—Alternator-Rectifier Excitation System With Noncontrolled Rectifiers and Feedback From Exciter Field Current

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.

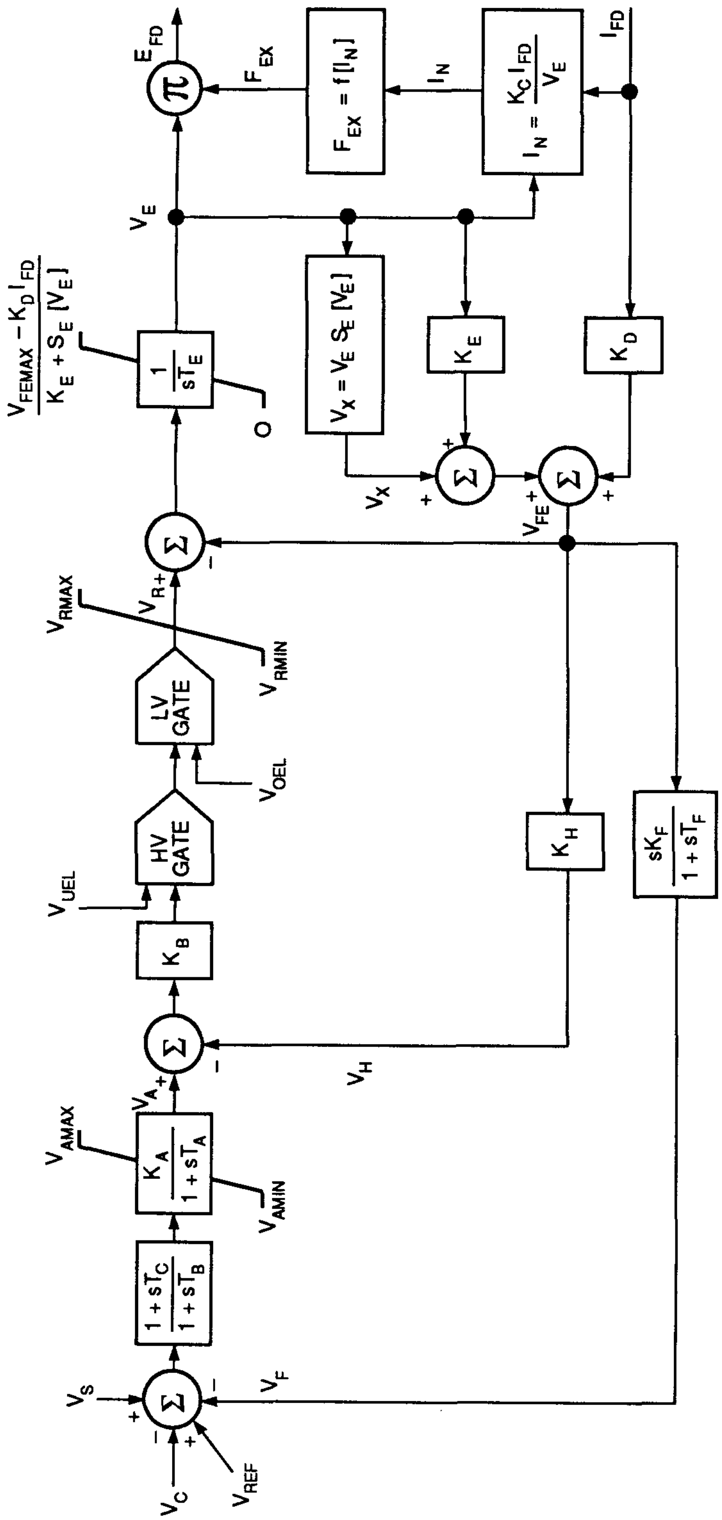

Figure 7—Type AC2A — High Initial Response Alternator-Rectifier Excitation System With Noncontrolled Rectifiers and Feedback From Exciter Field Current

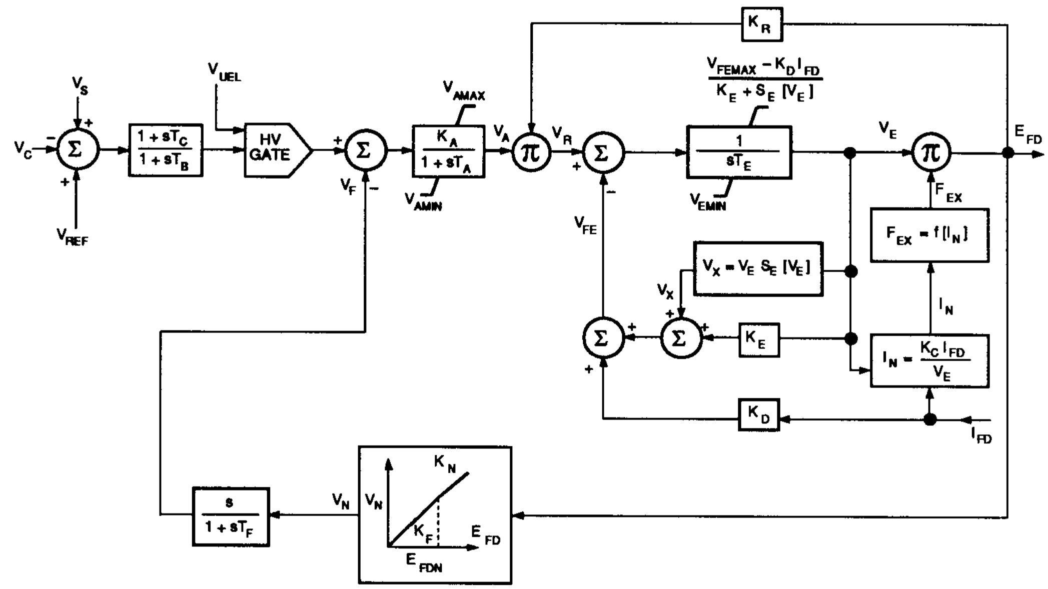

Figure 8—Type AC3A — Alternator-Rectifier Exciter With Alternator Field Current Limiter

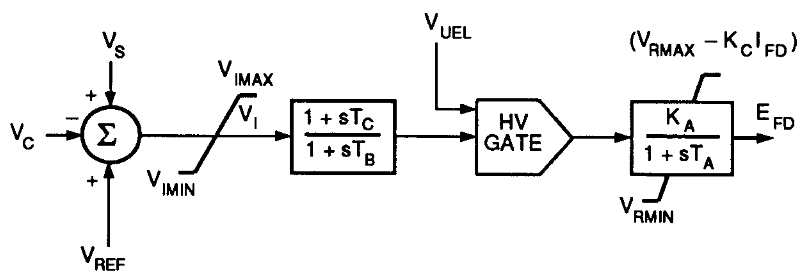

Figure 9—Type AC4A — Alternator Supplied Controlled-Rectifier Exciter

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™ [12] 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.

[12] ALTHYREX is a trademark of General Electric Co.

This model can be used to represent small excitation systems such as those produced by Basler and Electric Machinery.

Note that, 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 (see Appendix 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.

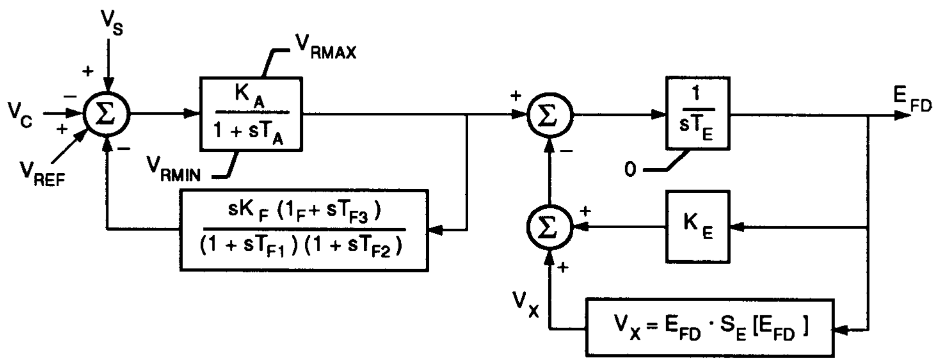

Figure 10—Type AC5A—Simplified Rotating Rectifier Excitation System Representation

6.6 Type AC6A Excitation System Model

The model shown in Fig 11 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, and the model includes an exciter field current limiter. It is particularly suitable for representation of stationary diode systems such as those produced by C.A. Parsons.

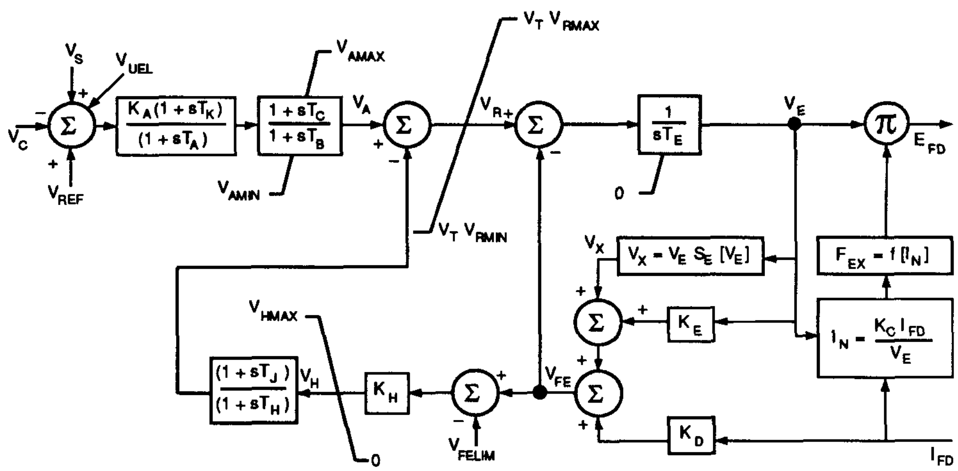

Figure 11—Type AC6A—Alternator-Rectifier Excitation System With Noncontrolled Rectifiers and System-Supplied Electronic Voltage Regulator

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 noncontrolled, 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 Appendix 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; however, only the instantaneous limits are included here, and these are shown only for the ST1A Model.

7.1 Type ST1A Excitation System Model

The computer model of the type ST1A potential-source controlled-rectifier exciter excitation system shown in Fig 12 is intended to represent systems in which excitation power is supplied through a transformer from the generator terminals (or the unit auxiliaries 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 below).

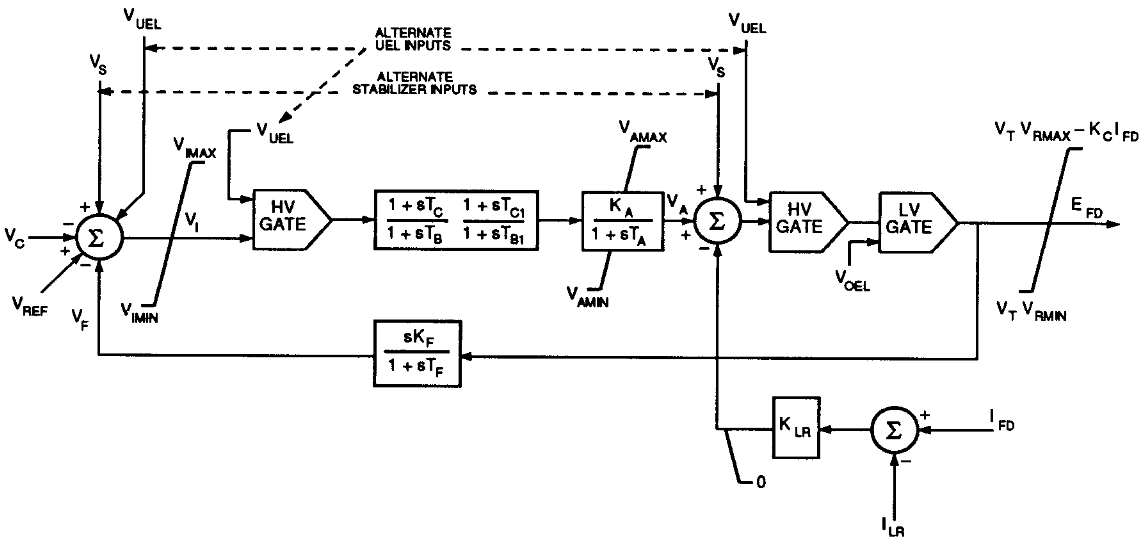

Figure 12—Type ST1A — Potential-Source Controlled-Rectifier Exciter

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, with T_{C1} normally being 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.

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 Appendix D. The negative limit would have a similar current dependent characteristic, but the sign of the term could be either positive of negative depending upon whether 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.

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 ceiling is set to zero ($V_{RMIN} = 0$).

Examples of type ST1A excitation systems are:

1) Canadian General Electric Silcomatic™[13] Excitation System
2) Westinghouse Canada Solid State Thyristor Excitation System
3) Westinghouse Type PS Static Excitation System with Type WTA™[14], WHS™, or WTA-300™ Regulators
4) ASEA Static Excitation System
5) Brown Boveri Static Excitation System
6) Rayrolle-Parsons Static Excitation System
7) GEC-Eliott Static Excitation System
8) Toshiba Static Excitation System
9) Mitsubishi Static Excitation System
10) General Electric Potential Source Static Excitation System
11) Hitachi Static Excitation System
12) Basler Model SSE Excitation System
13) ABB UNITROL®[15] Excitation System

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 Fig 13. 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 Appendix 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.

One example of such a system is the General Electric static excitation system, frequently referred to as the SCT-PPT or SCPT system.

[13]Silcomatic is a trademark of General Electric Co.
[14]WTA, WHS, and WTA-300 are trademarks of Westinghouse Elec. Corp.
[15]UNITROL is a registered trademark of Asea Brown Boveri, Inc.

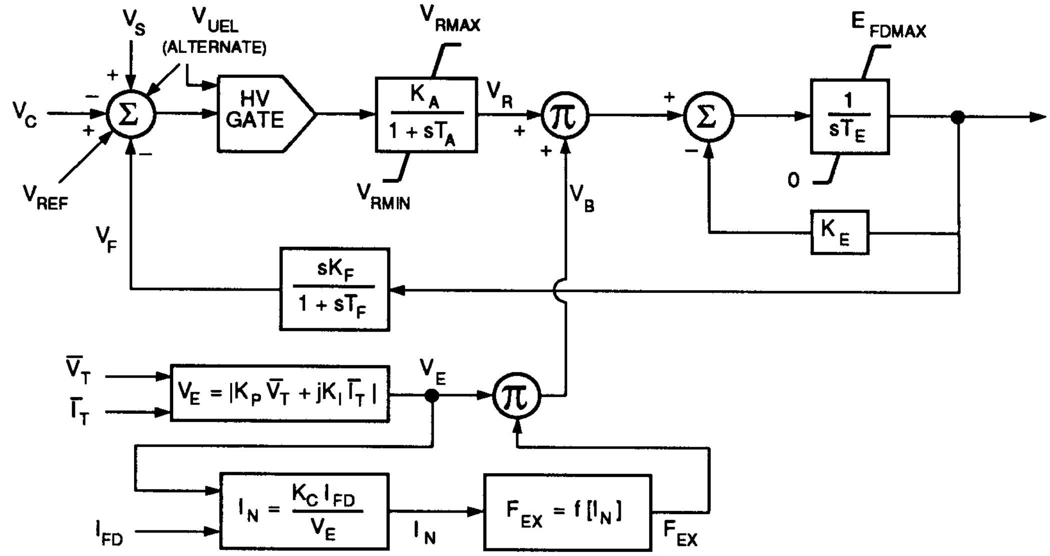

Figure 13—Type ST2A — Compound-Source Rectifier Exciter

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 Fig 14. This also makes the output independent of supply source variations until supply limitations are reached.

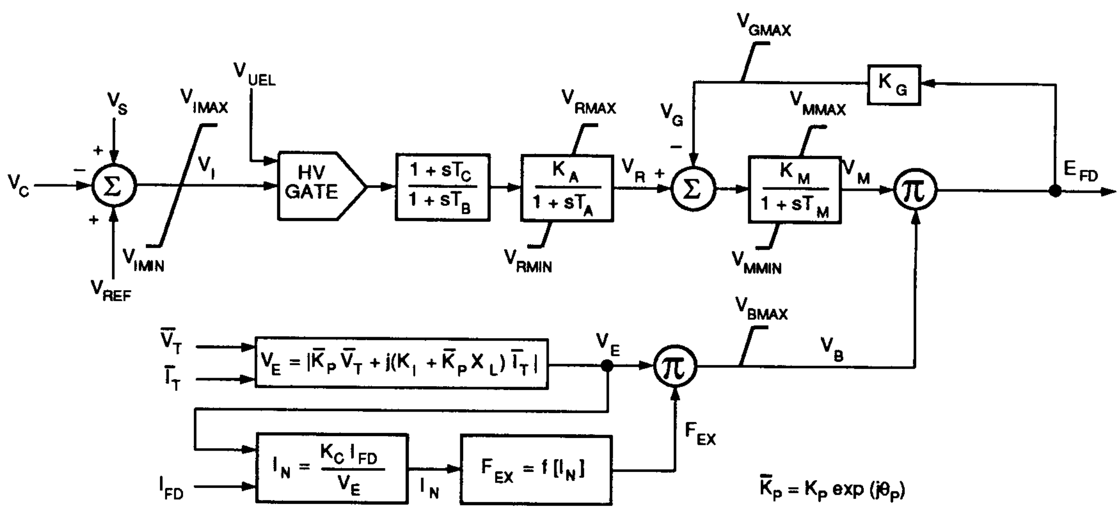

Figure 14—Type ST3A — Potential or Compound-Source Controlled-Rectifier Exciter With Field Voltage Control Loop

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 standard. 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 Appendix D. The V_{BMAX} limit is determined by the saturation level of power components.

Systems of this type include General Electric Compound Power Source GENERREX™[16] and Potential Power Source GENERREX excitation systems.

8. Power System Stabilizers

Power system stabilizers 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 below are generally consistent with the excitation models, within the range of frequency response outlined in the scope. They may not be applicable for investigation of control modes of instability that 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.

For pumping units, the stabilizer can be used with the synchronous machine operating in either the generating or pumping modes, but different parameters would normally be required for operation in the two modes.

8.1 Type PSS1A Power System Stabilizer

Fig 15 shows the generalized form of a power system stabilizer with a single input. Some common stabilizer input signals (V_{SI}) are speed, frequency, and power.

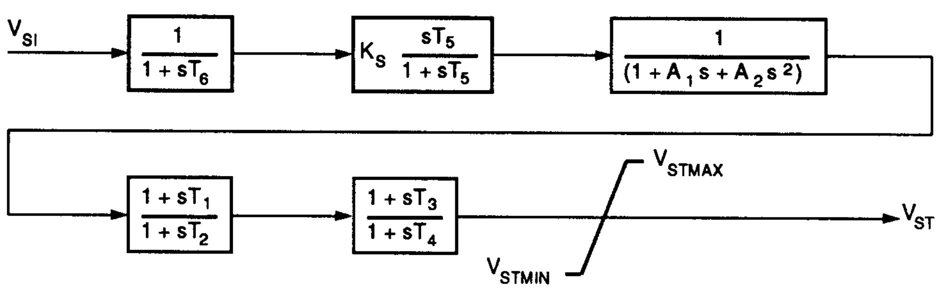

Figure 15—Type PSS1A — Single Input Power System Stabilizer

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.

[16]GENERREX is a trademark of General Electric Co.

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 Fig 15. 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 Fig 19. In other systems, the stabilizer output is limited as a function of generator terminal voltage as included in the type DEC1A model of Fig 17.

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 PSS2A Power System Stabilizer

This stabilizer model, shown in Fig 16, is designed to represent a variety of dual-input stabilizers that normally use combinations of power and speed or frequency to derive the stabilizing signal.

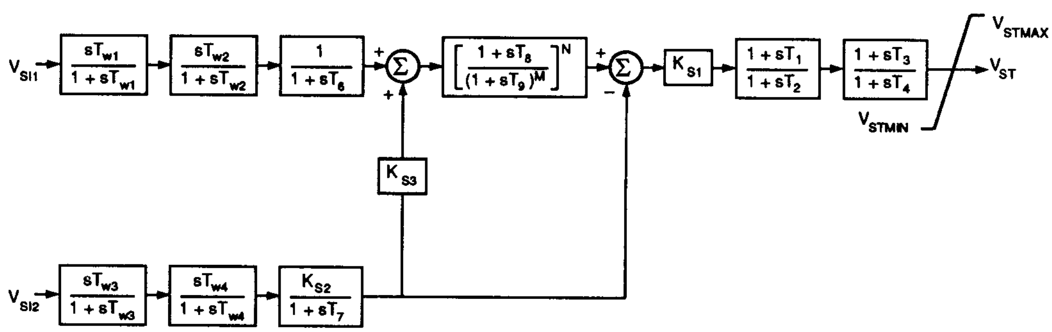

Figure 16—Type PSS2A—Dual Input Power System Stabilizer

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

1) 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.
2) 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 above, 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 constant (T_6, T_7). For the first type of dual-input stabilizer, K_{S3} would normally be 1 and K_2 would be 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, N (an integer up to 4) and M (an integer up to 2), allow a “ramp-tracking” or simpler filter characteristic to be represented. 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 PSS2A model.

9. Supplementary Discontinuous Excitation Control

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 [5], [10], and [13].

9.1 Type DEC1A Discontinuous Excitation Control

The type DEC1A discontinuous excitation control model, shown in Fig 17, 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 in which both local and interarea oscillations are present in the transient, and in which 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 load power, thereby contributing to unit deceleration.

As shown in Fig 17, 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:

1) A drop in terminal voltage in excess of a preset value
2) Regulator output at positive ceiling
3) 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

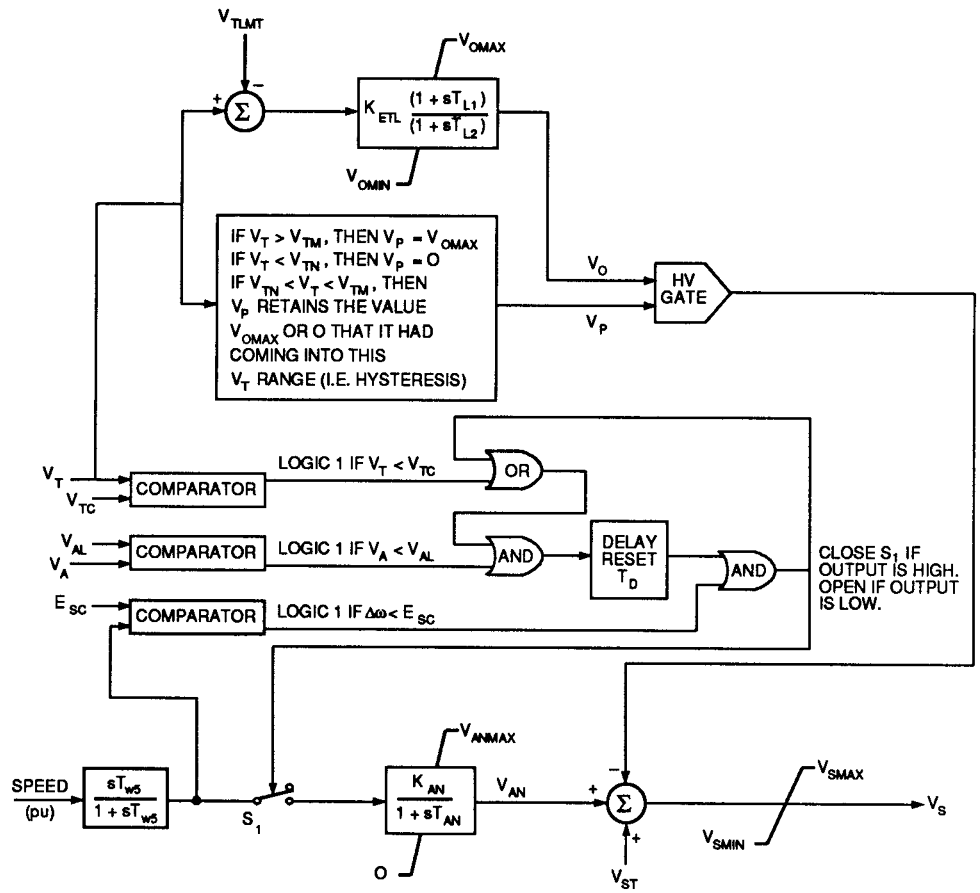

Figure 17—Type DEC1A — Discontinuous Excitation Controller Transient Excitation Boosting With Dual Action Terminal Voltage Limiter

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 DEC 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 power system stabilizer, V_{ST}, the terminal voltage limiter, and the angle signal are combined, and overall limits are applied to the new signal, V_S, that goes to the summing junction of the voltage regulator.

9.2 Type DEC2A Discontinuous Excitation Control

A model for the DEC2A discontinuous excitation control is shown in Fig 18. 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 was implemented at the Grand Coulee third powerhouse, with the control initiated for outage of the Pacific 3100 MW HVDC Intertie, see [13]. For this disturbance, the interarea mode swing center was about 1300 km from the power plant and normal voltage regulator field boosting was minimal.

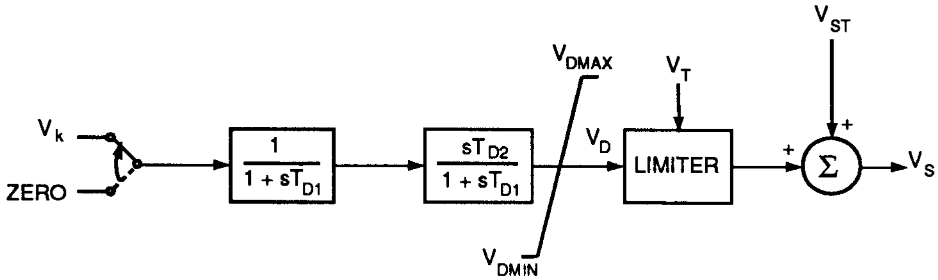

Figure 18—Type DEC2A — Discontinuous Excitation Controller Open Loop Transient Excitation Boosting

9.3 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 Fig 19).

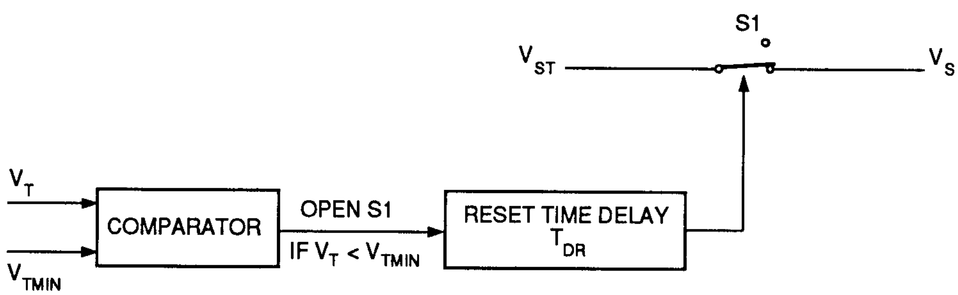

Figure 19—Type DEC3A — Discontinuous Excitation Controller Temporary Interruption of Stabilizing Signal

10. Bibliography

[B1] ANSI C34.2-1968 (Withdrawn), American National Standard Practices and Requirements for Semi-Conductor Power Rectifiers.

[B2] IEEE Std 421.2-1990, IEEE Guide for Identification, Testing, and Evaluation of the Dynamic Performance of Excitation Control Systems (ANSI).

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[B4] Witzke, R. L., Kresser, J. V., and Dillard, J. K. "Influence of AC Reactance on Voltage Regulation of Six-Phase Rectifiers," *AIEE Transactions,* vol. 72, pp. 244–253. July 1953.

Annex A Nomenclature (Informative)

(These appendixes are not a part of IEEE Std 421.5-1992, IEEE Recommended Practice for Excitation System Models for Power System Stability Studies.)

Maximum and minimum limits of parameters are not shown explicitly in the nomenclature, but are presented 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,A_2. PSS signal conditioning frequency filter constants.

E_{FD}. Exciter output voltage.

E_{FDN}. Value of E_{FD} at which feedback gain changes (type AC3A).

E_{FD1}, E_{FD2}. Exciter voltages at which exciter saturation is defined (dc commutator exciters and type AC5A models only).

E_{SC}. Speed change reference (type DEC1A).

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.

I_{FD}. Synchronous machine field current.

I_{LR}. Exciter output current limit reference.

I_N. Normalized exciter load current.

$_T$. Synchronous machine terminal current.

K_A. Voltage regulator gain.

K_{AN}. Discontinuous controller gain (type DEC1A).

K_B. Second stage regulator gain.

K_C. Rectifier loading factor proportional to commutating reactance.

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_N. Excitation control system stabilizer gains.

K_G. Feedback gain constant of the inner loop field regulator (type ST3A).

K_H. Exciter field current feedback gain (type AC2A), exciter field current limiter gain (type AC6A)

K_I. Potential circuit gain coefficient.

K_{LR}. Exciter output current limiter gain.

K_{M}. Forward gain constant of the inner loop field regulator (type ST3A).

$_{\mathrm{P}}$. Potential circuit gain coefficient.

K_{R}. Constant associated with regulator and alternator field power supply (type AC3A).

K_{S}. Power system stabilizer gain (type PSS1A).

K_{S1}, K_{S2}, K_{S3}. Power system stabilizer gains (type PSS2A).

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).

R_{C}. Resistive component of load compensation.

$S_{\mathrm{E}}[E_{\mathrm{FD1}}$ or $E_{\mathrm{FD2}}]$. Exciter saturation function value at the corresponding exciter voltage, E_{FD}.

$S_{\mathrm{E}}[V_{\mathrm{E1}}$ or $V_{\mathrm{E2}}]$. Exciter saturation function value at the corresponding exciter voltage, V_{E}, back of commutating reactance.

S_{E}. Exciter saturation function.

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).

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_{H}, T_{J}. Exciter field current limiter time constants.

T_{K}. Regulator lead time constant (type AC6A).

T_{M}. Forward time constant of inner loop field regulator (type ST3A).

T_{R}. Regulator input filter time constant.

T_{RH}. Rheostat travel time (type DC3A).

T_{W1}, T_{W2}, T_{W3}, T_{W4}, T_{W5}. PSS and DEC washout time constants.

T_1, T_3. PSS lead compensating time constants.

T_2, T_4. 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.

V_A. Regulator internal voltage.

V_{AL}. Regulator voltage reference (type DEC1A).

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_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_{ERR}. Voltage error signal type DC3A model.

V_F. Excitation system stabilizer output.

V_{FE}. Signal proportional to exciter field current.

V_{FELIM}. Exciter field current limit reference.

V_G. Inner loop voltage feedback.

V_H. Exciter field current feedback signal.

V_I. Internal signal within voltage regulator.

V_K. Discontinuous controller input reference (type DEC2A).

V_M. Output factor of converter bridge corresponding to firing angle command to thyristors (type ST3A).

V_N. Rate feedback input variable.

V_O, V_P. Limiter signals (type DEC1A).

V_{OEL}. Overexcitation limiter output (type AC1A, AC2A, ST1A).

V_R. Voltage regulator output.

V_{RH}. Voltage determined by rheostat by rheostat setting (type DC3A)

V_{REF}. Voltage regulator reference voltage (determined to satisfy initial conditions).

V_S. Combined power system stabilizer and possibly discontinuous control output after any limits or switching, as assumed with terminal voltage and reference signals (in per unit equivalent of terminal voltage.

V_{SI}, V_{SI1}, V_{SI2}. Power system stabilizer inputs (speed, power, or frequency deviation).

V_{ST}. Power system stabilizer output (in per unit equivalent of terminal voltage).

V_{T}, $_{T}$. Synchronous machine terminal voltage.

V_{TM}, T_{TN}. Voltage limits (type DEC1A).

V_{TMIN}. Terminal undervoltage comparison level (type DEC3A).

V_{TC}. Terminal voltage level reference (type DEC1A).

V_{UEL}. Underexcitation limiter output.

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 (in degrees).

Annex B Per Unit System (Informative)

Synchronous machine currents and voltages in system studies are represented by per unit variables. In the per unit system used here, one per unit synchronous machine terminal voltage is defined to be rated voltage, one per unit stator current is rated current, one per unit generator field current is that current required to produce rated synchronous machine terminal voltage on the air gap line, and one per unit field voltage is the corresponding field voltage, see [4].

Excitation system models must interface with synchronous machine models at both the stator and field terminals. Signals that are summed with the per unit 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 per unit on the field current base of the synchronous machine, and exciter output voltage must be in per unit 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 per unit system depends directly on the field resistance base. A reference temperature of the field winding was defined with respect to insulation class in ANSI C50.10-1977 [1]. In IEEE Std 421.1-1986 [4], 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 Standard 115-1983 [3], 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 [6].

Annex C Exciter Saturation and Loading Effects (Informative)

The exciter saturation function, $S_E[E_{FD}]$, is defined as a multiplier of per unit exciter output voltage to represent the increase in exciter excitation requirements due to saturation. Fig 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:

$$S_E[E_{FD}] = \frac{A - B}{B}$$

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 Appendix A of [7].

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

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

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 (Appendix 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 is considered to be a part of the particular computer program used.

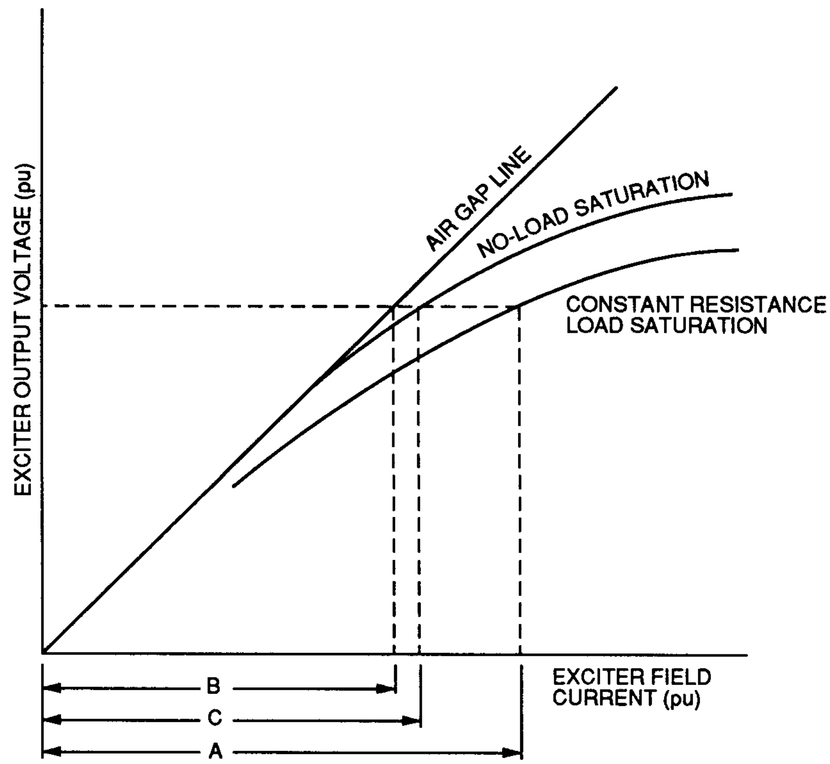


Figure C-1—Exciter Saturation Characteristic

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 voltages, 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 upon K_E. In such cases, $S_E[E_{FD1}]$ corresponds to a specified value of exciter voltage near its expected maximum value.

Annex D Rectifier Regulation (Informative)

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 equations characterizing these three modes are determined by the rectifier load current. Fig D-1 shows the rectifier regulation characteristics determined by the equations shown in Fig 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 Fig 12.

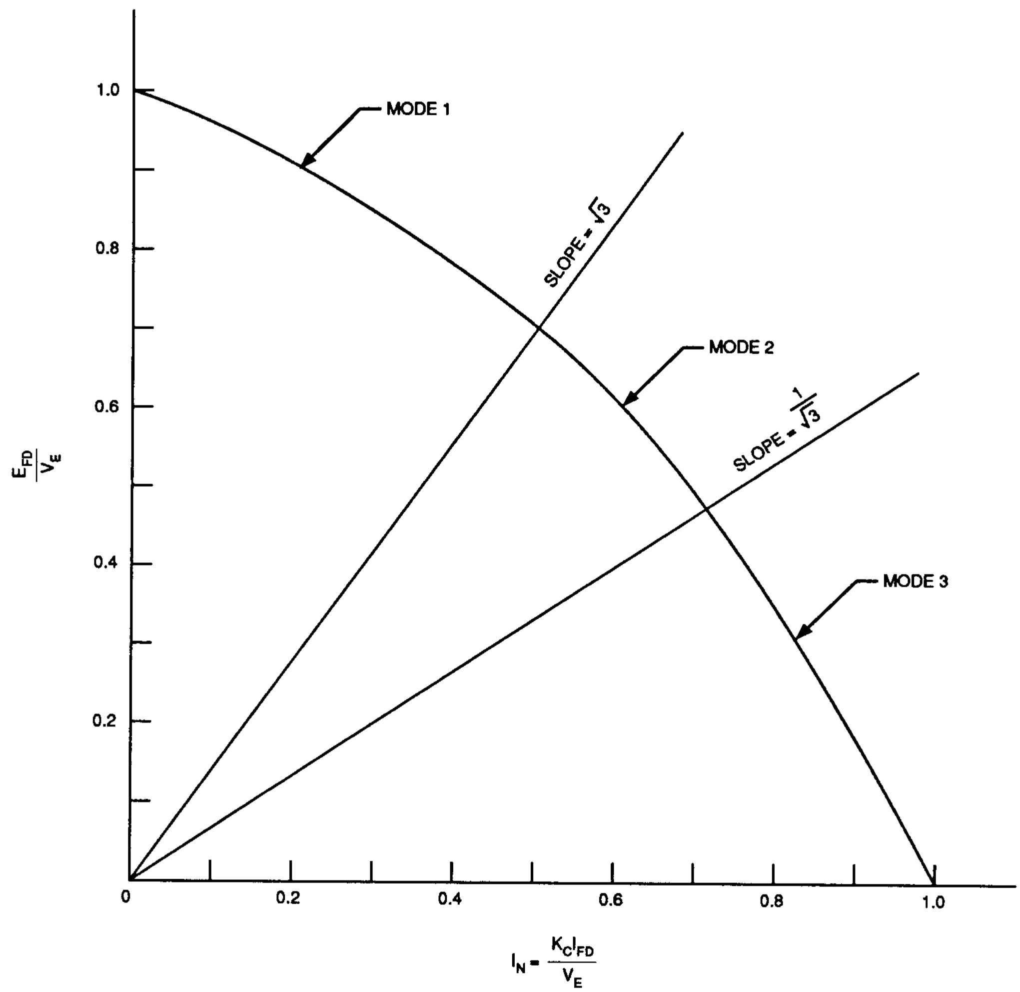


Figure D-1—Rectifier Regulation Characteristic

The quantities E_{FD}, I_{FD}, V_E, and K_C are all in per unit on the synchronous machine field base. For computer simulation purposes, the curve of Fig D-1 is defined by three segments as shown by the equations in Fig D-2.

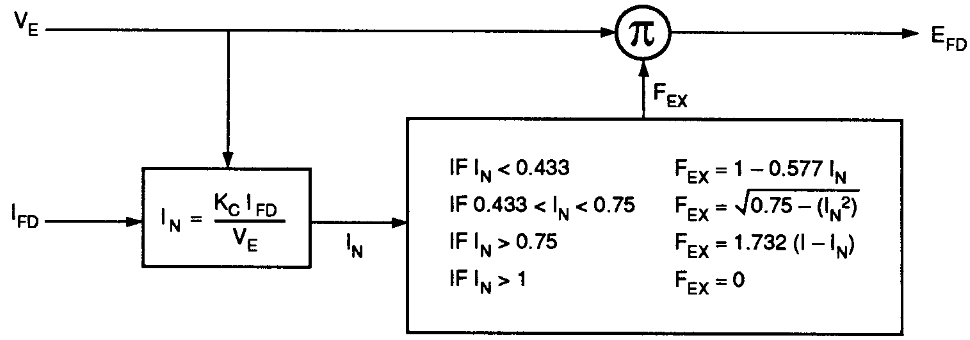


Figure D-2—Rectifier Regulation Equations

Note that I_N should not be greater than 1. However, if I_N is greater that 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 Appendix H would then apply.

D1. Bibliography

[D1] ANSI C34.2-1968 (Withdrawn), American National Standard Practices and Requirements for Semiconductor Power Rectifiers.

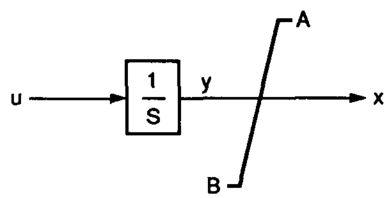
[D1] Witzke, R. L., Kressner, J. V., and Dillard, J. K. "Influence of AC Reactance on Voltage Regulation of Six-Phase Rectifiers," *AIEE Transactions,* vol. 72, pp. 244–253, July 1953.

Annex E Representation of Limits (Informative)

Two distinct types of limiters, windup and nonwindup, are represented in the models. Implementation of the two types of limiters for three types of model blocks is described below.

E1. Simple Integrator

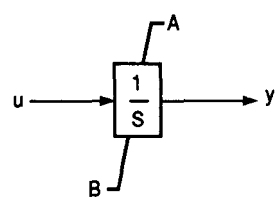
The functions of these two types of limits, as applied to simple integrator blocks, are illustrated in Figs E-1 and E-2. Note the difference in block diagram notation of the two types of limiters. With the nonwindup limiter (see Fig E-2), starting from a limited condition with $y = A$ or $y = B$, the 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 Fig E-1) in which 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 ≥ y ≥ B, THEN x = y
IF y > A, THEN x = A
IF y < B, THEN x = B

Figure E-1—Integrator With Windup Limiter

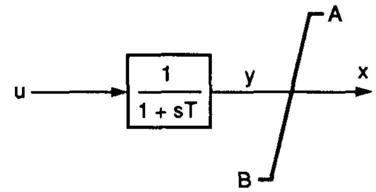


IF A ≥ y ≥ B, THEN dy/dt = u
IF y > A, THEN dy/dt IS SET TO 0
IF y < B, THEN dy/dt IS SET TO 0

Figure E-2—Integrator With Nonwindup Limiter

E2. Simple Time Constant

Figs E-3 and E-4 show the designation of windup and nonwindup limits on single time constant blocks. The equations and Fig E-4(b) 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, the output variable, x, when it hits a limit, cannot come off the limit until y comes within the limits.



dy/dt = (u – y)/T

IF B ≤ y ≤ A, THEN x = y
IF y > A, THEN x = A
IF y < B, THEN x = B

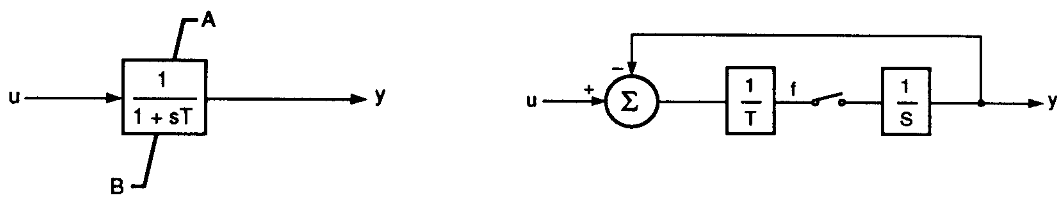
Figure E-3—Simple Time Constant — Windup Limiter

In the case of the nonwindup limit, the variable, *y*, is limited. To be at a limit of $y = A$ or $y = B$ implies an input of $u > A$ 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 $B \le u \le A$.

E3. Lag-Lead Block

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

Fig E-6 shows the block diagram representation for a nonwindup limiter applied to a lag-lead block, along with equations and a diagram showing how it is realized. Other models of nonwindup 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.



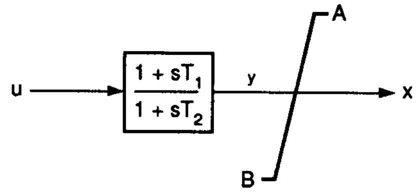
(a)
Block Diagram

(b)
Implementation

f = (u – y)/T

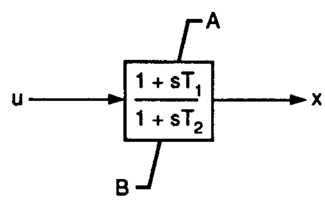
IF y = A, AND f > 0, THEN dy/dt IS SET TO 0
IF y = B, AND f < 0, THEN dy/dt IS SET TO 0
OTHERWISE, B < y < A, AND dy/dt = f

Figure E-4—Simple Time Constant — Nonwindup Limiter

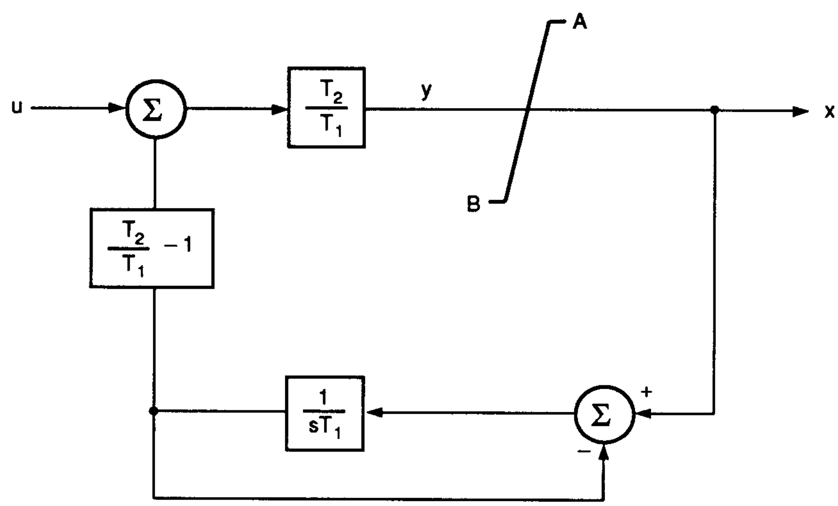


IF $T_1 = T_2$, THEN $y = u$
IF $B \leq y \leq A$, THEN $x = y$
IF $y > A$, THEN $x = A$
IF $y < B$, THEN $x = B$

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 $A \geq y \geq B$, THEN $x = y$

Figure E-6—Lag-Lead With Nonwindup Limiter

Annex F Avoiding Computational Problems by Eliminating Fast Feedback Loops (Informative)

The models represented in the body of this report are reduced order models that 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 appendix 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.

F1. Maximum Field Current Limiter Loop for the AC2A System

The recommended model for the type AC2A system is shown in Fig 7. 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 Fig 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.

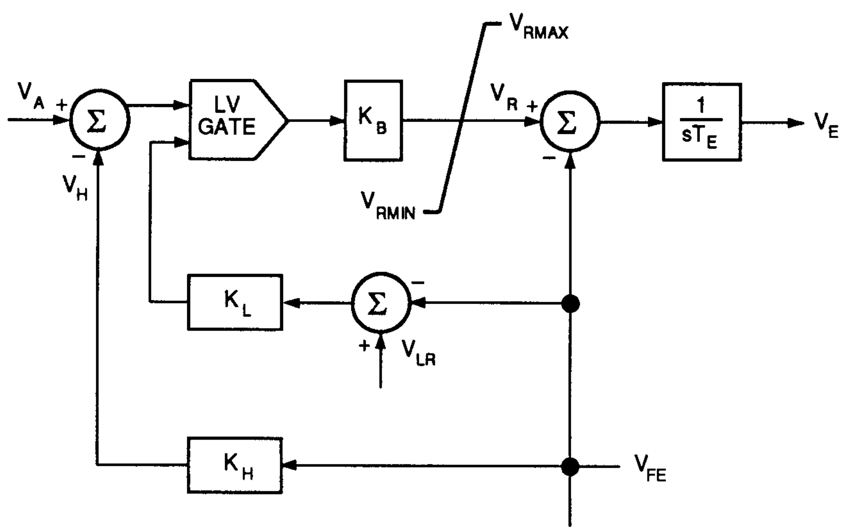


Figure F-1—Maximum Field Current Limiter Loop for the Type AC2A High Initial Response Alternator-Rectifier Excitation System With Noncontrolled Rectifiers and Feedback From Exciter Field Current.

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 Fig 7 simulates the loop as an upper limit on the exciter voltage.

F2. Derivation of Maximum Exciter Voltage for the AC2A System

The equations representing the steady-state position of the exciter voltage can be obtained from Figs 7 and F-1 as follows:

$$V_{FE} = V_R = (V_{LR} - V_{FE})(K_L K_B) \tag{1}$$

$$V_{FE} = (K_E + S_E)V_E + K_D I_{FD} \tag{2}$$

Solving Eq 1 for V_{FE}, then substituting V_{FEMAX} for V_{FE},

$$V_{FEMAX} = \frac{V_{LR} K_L K_B}{1 + K_L K_B} \cong V_{LR} \tag{3}$$

Solving Eq 2 for V_E, then substituting V_{FEMAX} and V_{EMAX} for V_{FE} and V_E, respectively,

$$V_{EMAX} = \frac{V_{FEMAX} - K_D I_{FD}}{K_E + S_E} \tag{4}$$

F3. Minimum Field Voltage Limiter Loop for the AC3A System

The recommended model for the type AC3A system is shown in Fig 8. 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 Fig F-2.

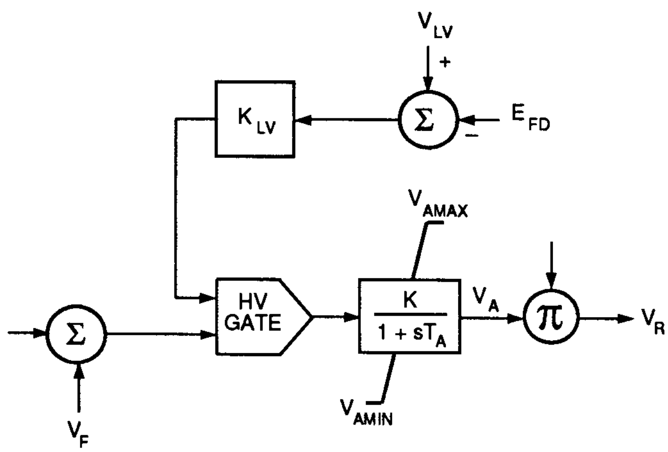


Figure F-2—Minimum Field Voltage Limiter Loop for the Type AC3A Alternator-Rectifier Exciter

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 4.0 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 Fig 8 simulates the loop as a lower limiter on the exciter voltage.

F4. Derivation of Minimum Exciter Voltage for the AC3A System

The equations representing the steady-state position of the exciter voltage can be obtained from Figs 8 and F-2 as follows:

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

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

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

Solving Eq 5 through Eq 7 for E_{FD}, then substituting E_{FDMIN} for E_{FD},

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

where

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

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

Since G_1 is very large (70–1000), E_{FDMIN} can be approximated as

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

The minimum steady-state limit for the exciter voltage can be obtained by substituting Eq 11 into Eq 7.

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

F5. Maximum Field Current Limiter Loop for the AC3A System

The recommended model for the AC3A system is shown in Fig 8. 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 Fig 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.

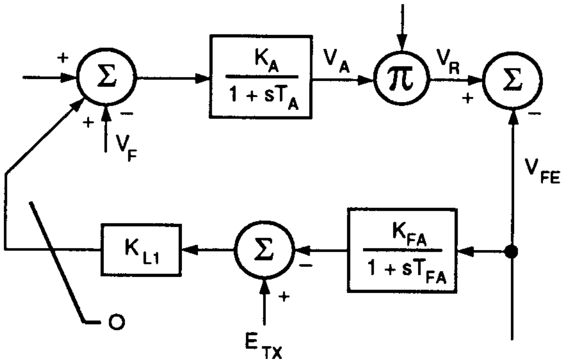


Figure F-3—Maximum Field Current Limiter Loop for the Type AC3A Alternator-Rectifier Exciter With Alternator Field Current Limiter

The field current limiter loop is a fast loop with a natural frequency of oscillation greater than 4.0 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 Fig 8 simulates the loop as an upper limiter on the exciter voltage.

F6. Derivation of Maximum Exciter Voltage for the AC3A System

The equations representing the steady-state position of the exciter voltage can be obtained from Figs 8 and F-3 as follows:

$$V_L = K_{L1}(E_{TX} - K_{FA}V_{FE}) \tag{12}$$

$$V_{FE} = V_R = (K_A K_R E_{FD})(V_L + V_S + V_{ERR} - V) \tag{13}$$

$$V_{FE} = (K_E + S_E)V_E + K_D I_{FD} \tag{14}$$

$$E_{FD} = F_{EX}V_E \tag{15}$$

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 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},

$$V_{FEMAX} = (K_{L1}E_{TX} + V_S + V_{ERR})\frac{G_1}{1 + G_1 K_{FA} K_{L1}} \tag{16}$$

where

$$G_1 = K_A K_R F_{EX} V_{EMAX} \tag{17}$$

The typical values of the parameters when the field voltage is near ceiling are given below:

$K_{LI}E_{TX}$	= 0.93
V_S	= 0.0 to 0.10
V_{ERR}	= 0.0 to 1.0
G_1	= 1000
$G_1K_{FA}K_{LI}$	= 56

Assuming the above typical values, Eq 16 can be simplified.

$$V_{FEMAX} = \frac{K_{L1}E_{TX} + V_S + V_{ERR}}{K_{FA}K_{L1}} \tag{18}$$

Solving Eq 14 for V_E, then substituting V_{EMAX} for V_E,

$$V_{EMAX} = \frac{V_{FEMAX} - K_D I_{FD}}{S_E + K_E} \tag{19}$$

Annex G Paths for Flow of Induced Synchronous Machine Negative Field Current (Informative)

G1. General

For AC and ST type exciters, the current delivered by the exciter cannot be negative. Under some conditions, a negative current may be induced in the field of the synchronous machine. 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, thereby bypassing the exciter itself. These take the form of either "crowbar" circuits (field shorting) or nonlinear resistors (varistors), as shown in Fig G-1.

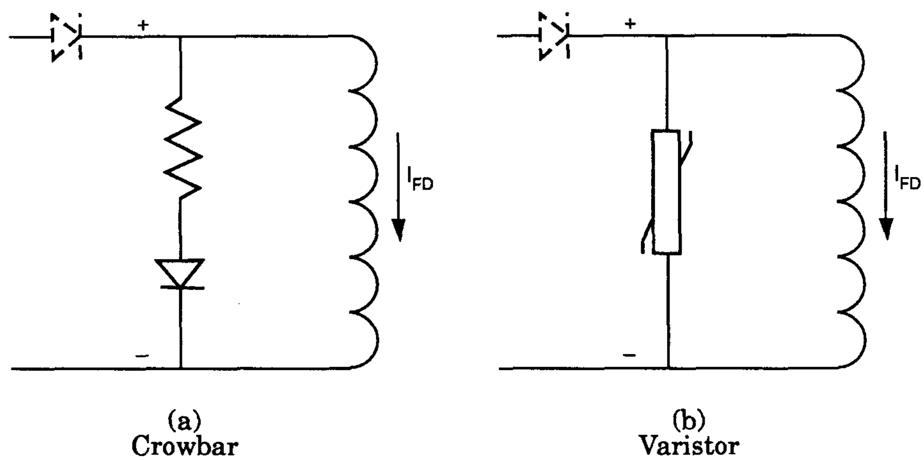


Figure G-1—Bypass Circuits for Induced Negative Field Current

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.

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. 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 subsections.

G1.1 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.

G1.1 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:

$V = KI^{a}$

If there are n varistors in parallel, the varistor characteristic may be expressed in terms of the field current as follows:

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

The effective resistance introduced by the varistor is then given in terms of the magnitude of I_{fd} by:

$$R_{V} = \frac{V}{I_{fd}} = \frac{K}{n^{a}}(I_{fd})^{a-1}$$

G1.2 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 can 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 in which 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.

G2. Bibliography

[G1] de Mello, F. P., Leuzinger, L. M., and Mills, R. J. “Load Rejection Overvoltages as Affected by Excition System Control,” *IEEE Transactions on Power Apparatus and Systems,* vol. PAS-94, no. 2, pp. 280–287, Mar./Apr. 1975.

[G1] Kundur, P. and Dandeno, P. L. “Implementation of Synchronous Machine Models into Power System Stability Programs,” *IEEE Transactions on Power Apparatus and Systems,* vol. PAS-102, pp. 2047–2054, July 1983.

Annex H Excitation Limiters (Informative)

H1. Underexcitation Limiter

The underexcitation limiter (UEL) is an auxiliary control supplied with some excitation systems to limit the extent to which the voltage regulator is allowed to demand underexcited reactive current (or reactive power) from the synchronous machine. This control is frequently referred to by other names, such as minimum excitation limiter and underexcited reactive limiter.

The underexcitation limiter was originally implemented as a steady-state (slow) control, having little effect on first-swing transients. Over time, it has been applied in faster control loops.

The UEL normally uses synchronous machine voltage and current inputs to determine the limit start point and provide the necessary feedback. The limiter output signal, V_{UEL}, generally enters the regulator through a high value gate or a summing junction as indicated in the block diagrams of the various excitation systems. Various articles (see Section H3) discuss implementation of some of the early varieties of UELs.

Models for underexcitation limiters and sample data for them are *not* provided in this document. The complexity and diversity of models and the way in which this control is (or is not) implemented had proved too difficult to resolve satisfactorily at the time this document went to press.

H2. Overexcitation Limiter

Terminal voltage and terminal V/Hz limiters are not normally modeled. Although models for such limiters are not provided (except as noted below), the gated input to the excitation model of the limiter output, VOEL, is shown for the type AC1A, AC2A, and ST1A models. A detailed terminal voltage limiter model is provided as part of the DEC1A controller.

H3. Bibliography

[H1] Rubenstein, A. S. and Temoshok, M. “Underexcited Reactive Ampere Limit for Modern Amplidyne Voltage Regulator,” *AIEE Transactions (Power Apparatus and Systems),* vol. 73, pp. 1433–1438, Dec. 1954.

[H1] Carleton, J. T., Bobo, P. O., and Burt, D. A. “Minimum Excitation Limit for Magnetic Amplifier Regulating System,” *AIEE Transactions (Power Apparatus and Systems),* vol. 73, pp. 869–874, Aug. 1954.

[H1] Nagy, I. “Analysis of Minimum Excitation Limits of Synchronous Machines,“ *IEEE Transactions on Power Apparatus and Systems,* vol. PAS-89, no 6, pp. 1001–1008, July/Aug. 1970.

Annex I Sample Data
(Informative)

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 appendix, consistent sets of data are provided that 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 per unit.

I1. Data for a Type DC1A Excitation System

Exciter	**1/2 ASA Response Exciter With Stabilizer**	
	K_A	46
	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	10
	V_{SMAX}	0.09
	V_{SMIN}	–0.09

I2. Data for a Type DC2A Excitation System

I2.1 Separately Excited Main Exciter

The generator connected to this excitation system has been uprated 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
	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_{SMAX}	0.05
	V_{SMIN}	-0.05

I3. 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

I4. Data for a Type AC1A Excitation System

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

I5. Data for a Type AC2A Excitation System

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

I6. Data for a Type AC3A Excitation System

$T_R = 0$	$V_{LV} = 0.790$	$K_R = 3.77$
$T_C = 0$	$V_{EMAX} = 6.24$	$K_{LV} = 0.194$
$T_B = 0$	$= V_{E1}$	$K_C = 0.104$
$T_A = 0.013$	$S_E[\mathrm{V}_{E1}] = 1.143$	$K_D = 0.499$
$T_E = 1.17$	$V_{E2} = 0.75 \cdot V_{EMAX}$	$K_E = 1.0$
$T_F = 1.0$	$S_E[V_{E2}] = 0.100$	$K_F = 0.143$
$V_{AMAX} = 1.0$	$E_{FDN} = 2.36$	$K_N = 0.05$
$V_{AMIN} = -0.95$	$K_A = 45.62$	$V_{FEMAX} = 16$

I7. Data for a Type AC4A Excitation System

$T_R = 0$	$V_{IMAX} = 10$	$K_A = 200$
$T_C = 1.0$	$V_{IMIN} = -10$	$K_C = 0$
$T_B = 10$	$V_{RMAX} = 5.64$	
$T_A = 0.015$	$V_{RMIN} = -4.53$	

I8. Data for a Type AC5A Excitation System

Sensing, $T_R = 0$, $R_C = 0$, $X_C = 0$

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

I9. Data for a Type AC6A Excitation System

Sensing, $T_R = 0.02$, $R_C = 0$, $X_C = 0$

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

I10. Stabilizer Parameters

Type PSS2A With Speed and Electrical Power Inputs
$K_{S1} = 20$
$K_{S2} = 2.26 = K_{S1}/2H$
$K_{S3} = 1$
$K_1 = K_3 = 0.16$
$K_2 = K_4 = 0.02$
H = Synchronous machine inertia constant
$T_{W1} = T_{W2} = T_{W3} = T_{W4} = 10$
$L = 2.0$
$M = 2$
$N = 4$
$V_{STMAX} = 0.20$
$V_{STMIN} = 0.066$

I11. Data for a Type ST1A Excitation System

I11.1 Data Set 1

A bus-fed thyristor excitation system, with no transient gain reduction, dual-input stabilizer and discontinuous excitation control:

Sensing, TR = 0.02, RC = 0, XC = 0

$K_A = 210.0$	$T_{B1} = 0$	$K_F = 0$
$T_A = 0$	$V_{RMAX} = 6.43$	$T_F = 0$ (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	

I11.1.1 Stabilizer Data (Dual Input With Speed Deviation and Electrical Power as Inputs) (See Fig 16)

V_{SI1} = Speed input in pu

V_{SI2} = Electrical power input in pu

$K_{S1} = 20$

$K_{S2} = 2.26 = K_{S1}/2H$

$K_{S3} = 1$

$T_1 = T_3 = 0.16$

$T_2 = T_4 = 0.02$

H = Synchronous machine inertia constant

$T_{W1} = T_{W2} = T_{W3} = T_{W4} = 10$

$M = 2$

$N = 4$

$V_{STMAX} = 0.20$

$V_{STMIN} = 0.066$

$T_6 = 0$

$T_7 = 0$

$T_8 = 0.3$

$T_9 = 0.15$

I11.1.2 Discontinuous Excitation Control Data (DEC1A, Fig 17)

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

NOTE — If the above stabilizer data is used without the discontinuous control, then the system is most accurately represented by leaving the slower-acting terminal voltge 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.)

I11.1.3 Data Set 2

A Bus-fed thyristor excitation system with transient gain reduction and speed input stabilizer:

Sensing, $T_R = 0.04$, $R_C = 0$, $X_C = 0$

$K_A = 190$	$T_{B1} = 0$	$V_{IMIN} = -999$ (i.e., 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)

I11.2.1 Stabilizer Data, PSS1A (With Speed Deviation as Input) (See Fig 15)

$K_S = 16.7$	$T_3 = 0.15$	$T_6 = 0$
$T_1 = 0.15$	$T_4 = 0.03$	$V_{SMAX} = 0.10$
$T_2 = 0.03$	$T_5 = 1.65$	$V_{SMIN} = -0.066$

I12. Data for a Type ST2A Excitation System

$T_R = 0$	$V_{RMAX} = 1.0$	$K_F = 0.05$
$T_E = 0.5$	$V_{RMIN} = 0$	$K_P = 4.88$
$T_A = 0.15$	$K_E = 1.0$	$K_I = 8.0$
$T_F = 1.0$	$K_A = 120$	$K_C = 1.82$

$E_{FDMAX} = 2.75$ times direct axis synchronous reactance of the synchronous machine in pu

I13. Data for Type ST3A Excitation Systems

I13.1 Data Set 1 — Potential Source

$T_A = 0$	$V_{IMIN} = -0.2$	$K_G = 1.0$
$T_R = 0$	$V_{MMAX} = 1.0$	$K_M = 7.93$
$T_M = 0.4^*$	$V_{MMIN} = 0$	$K_A = 200$
$T_B = 10.0$	$V_{RMAX} = 10.0$	$K_P = 6.15$
$T_C = 1.0$	$V_{RMIN} = -10.0$	$\Theta_P = 0°$
$X_L = 0.081$	$V_{GMAX} = 5.8$	$K_I = 0$
$V_{IMAX} = 0.2$	$E_{FDMAX} = 6.9$	$K_C = 0.20$

*T_M may be increased to 1.0 s for most studies to permit using longer computing time increments, up to 0.02 s.

I13.1.1 PSS Data

Type of Input Signal: Speed or Frequency		
$A_1 = 0.061$	$T_3 = 0.3$	$V_{SMAX} = 0.05$
$A_2 = 0.0017$	$T_4 = 0.03$	$V_{SMIN} = -0.05$
$T_1 = 0.3$	$T_5 = 10$	
$T_2 = 0.03$	$K_S = 5$	

I13.2 Data Set 2 — Compound Power Source

$T_A = 0$	$V_{IMIN} = -0.2$	$K_G = 1.0$
$T_R = 0$	$V_{MMAX} = 1.0$	$K_M = 7.04$
$T_M = 0.4^*$	$V_{MMIN} = 0$	$K_A = 200$
$T_B = 6.67$	$V_{RMAX} = 10.0$	$K_P = 4.37$
$T_C = 1.0$	$V_{RMIN} = -10.0$	$\Theta_P = 20°$
$X_L = 0.09$	$V_{GMAX} = 6.53$	$K_I = 4.83$
$V_{IMAX} = 0.2$	$E_{FDMAX} = 8.63$	$K_C = 1.10$

*TM may be increased to 1.0 s for most studies to permit using longer computing time increments, up to 0.02 s.

I13.2.1 PSS Data

Type of Input Signal: Speed or Frequency

$A_1 = 0.061$	$T_3 = 0.3$	$V_{SMAX} = 0.05$
$A_2 = 0.0017$	$T_4 = 0.03$	$V_{SMIN} = -0.05$
$T_1 = 0.3$	$T_5 = 10$	
$T_2 = 0.03$	$K_S = 5$	