PHASE TO PHASE

Synchronous Machine Excitation System
Vision Dynamical Analysis

Manual

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CONTENTS

1 INTRODUCTION

The basic function of an excitation system is to provide a variable DC current to the synchronous generator field winding. By varying the DC voltage, and thereby the field current, the generator terminal voltage and reactive power output can be regulated. Excitation control is used to maintain the desired operating condition and to enhance power system stability.

The 20 synchronous machine excitation system models implemented in the Vision Network Analysis software are presented in this document. The implemented models are suitable for use in large-scale system stability studies and are standardized by the IEEE (Std. 421.5-2005). The models are valid for frequency deviations of ±5 Hz from the rated frequency and oscillation frequencies up to 3 Hz [1]. The parameters provided as default must be considered as <u>sample data only</u>, the default parameters are neither typical nor representative.

The outline of this report is as follows: first, a general description of excitation systems is provided in Chapter 3. The terminal voltage transducer and load compensator is treated in Chapter 4, whereafter in Chapter 5 the power factor controller and the reactive power controller are described. The saturation function applicable to both the DC and the AC machines is treated in Chapter 6. In Chapters 7, 8, and 9 the twenty IEEE Std. 421.5-2005 excitation system models are presented together with their default parameters and parameter restrictions. Different excitation system types and manufacturers and their corresponding IEEE models are listed in Chapter 10. Finally, an example of a dynamic study for a small industrial network is provided.

This manual is applicable to the Vision Network Analysis version 8.7 or higher.

2 ABBREVIATIONS

AC	Alternating Current
DC	Direct Current
ECS	Excitation Control System
EMF	ElectroMotive Force
ESS	Excitation System Stabilizer
OEL	Over Excitation Limiter
PF	Power Factor
pu	Per unit
SMES	Synchronous Machine Excitation System
ST	Static
UEL	Under Excitation Limiter

3 SYNCHRONOUS MACHINE EXCITATION SYSTEM

3.1 Synchronous machine characteristics

The synchronous machine consists of two major elements: the field and the armature. Since passing the large armature power (e.g. for a 600 MW machine at 20 kV the current equals 17 kA) across moving contacts (slip-rings) is constructively challenging, large synchronous generators are stator-wound armature machines. The field winding is excited by a direct current inducing, when driven by the prime mover, alternating voltages in the three-phase armature windings. The frequency of the induced voltages depends on the speed of the rotor, the electrical frequency is thus synchronised with the mechanical speed of the rotor.

There are two main external variables available to control the synchronous generator behaviour: the mechanical rotational torque and the excitation field voltage. Those two means of synchronous generator control are referred to as: load-frequency control (governor) and excitation control, respectively. The influence of both types of synchronous generator control is illustrated by the following example.

Example of synchronous generator control

Consider the synchronous generator shown in Figure 3.1 (A), operating with a lagging power factor *cosφ*, terminal voltage V_T, stator current I_T, and internal ElectroMotive Force (EMF) E_q. For this example the bus voltage, and thus synchronous generator terminal voltage, is considered to be held constant by the external network. Similarly, it is assumed that input power P_m is held constant by the governor.

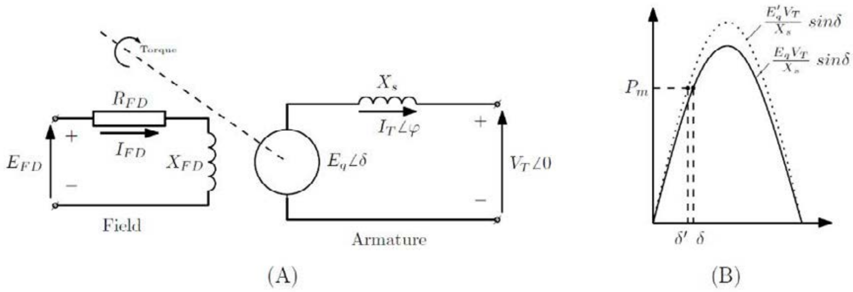

Figure 3.1 Synchronous generator equivalent circuit (A) and power-angle curve (B)

The effect of increasing the excitation voltage, and thus the induced EMF E_q, is shown by sketching the synchronous generator phasor diagram. The phasor diagram of the initial operating condition is depicted in Figure 3.2 (A). For an introduction to the phasor notation see [5] Section 7.3 and [3] Section 1.7. The active power delivered by the generator, can be expressed in terms of generator terminal conditions by equation (2.1) and in terms of power angle by equation (2.2).

$$P = V_T I_T cos\varphi \tag{2.1}$$

$$P = \frac{E_q V_T}{X_s} sin\delta \tag{2.2}$$

Using both above equations and the assumption of a constant terminal voltage and active power, two control constraints can be determined: $I_T\ cos\varphi = k_1$ and $E_q\ sin\delta = k_2$. Both control constraints are shown graphically in phasor diagram Figure 3.2 (B).

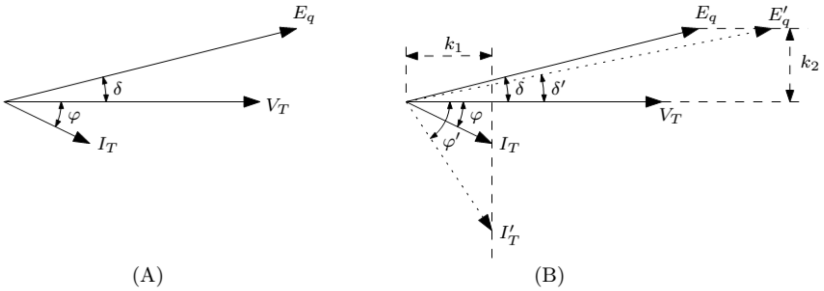

Figure 3.2 Phasor diagram initial condition (A) and final condition (B)

When the excitation is increased, vector *Eq* is forced to follow the dashed line (k2) parallel to the x-axis, the stator current *IT* is similarly constrained to the vertical dashed line (k1). The new equilibrium operating condition is denoted by the apostrophe, whose phasors are dotted in Figure 3.2 (B). Three general observations can been made: by increasing the excitation voltage the torque angle is decreased (see Figure 3.1 (B)), the current is increased, and the power factor *cosφ* is more lagging. It can be concluded that the effect of increasing (decreasing) excitation voltage results in a increasing (decreasing) delivery of reactive power. By similar reasoning the result of governor (load-frequency) control can be evaluated.

In the above example only the effect of going from one steady-state operating point to another is studied. The transient period between these two operating points is neglected. The dynamic package in Vision Network Analysis is to study this transient period to provide insight in the dynamic behaviour of synchronous generators.

3.2 Excitation control elements

An Excitation Control System (ECS) is the feedback control system that includes the synchronous machine and its excitation system. The term is used to distinguish the performance of the synchronous machine and excitation system in conjunction with the power system from that of the excitation system alone. A typical functional block diagram of an excitation control system for large synchronous generators is shown in Figure 3.3. Optional signals as those for the power system stabilizer, over and under-excitation limiter, excitation system stabilizer, the feedback of field current, and the stator current for load compensation are represented by the dashed lines.

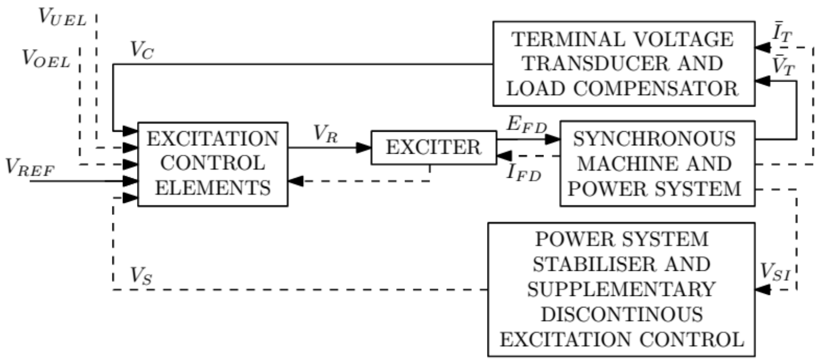

Figure 3.3 General functional block diagram of a synchronous generator excitation control

In the following a brief description of the subsystems shown in Figure 3.3 is given:

Terminal voltage transducer and load compensator: This subsystem represents the sensing and rectifying circuit of terminal voltage; load compensation may be provided to regulate the voltage at a remote point.

Exciter: The actual DC power to the synchronous generator field winding is provided by the exciter. Normal exciter rating varies from 2.0 to 3.5 kW/MVA generator rating, e.g. for a 600 MVA synchronous generator the excitation system should provide 1.2 to 2.1 MW.

Excitation control elements: Controls the output of the exciter such that the generated voltage and reactive power change as desired. The excitation system models described by the IEEE include only linear controllers (P, PI or PID), since they are mostly used in practice.

Power system stabilizer and discontinuous excitation control: Provides an additional input to the controller in order to damp power system oscillations. Discontinuous excitation control may be used to enhance stability following large transient disturbances.

Over- and under-excitation limiters: The Over-Excitation Limiter (OEL) offers protection from overheating due to high field current levels while allowing maximum field forcing capability (power system stability purposes). The Under-Excitation Limiter (UEL) acts to boost excitation in order to avoid under-excited operation.

In the 1981 IEEE report Excitation System Models for Power System Stability Studies [2], three distinct classes of excitation systems are identified based on the excitation power source. Below those different classes are summed:

- Type DC Excitation systems, which utilize a direct current generator with a commutator as the source of excitation system power.
- Type AC Excitation Systems, which use an alternator and either stationary or rotating rectifiers to produce the direct current needed for the generator field.
- Type ST Excitation Systems, in which excitation power is supplied through transformers and rectifiers.

AC and particularly DC type excitation systems contain elements with significant time delays resulting in inherent poor dynamic performance. Those excitation control systems are unstable when the generator is at open circuit (off-line), unless a very low steady-state regulator gain is used. To improve the dynamic performance of the control system, excitation system stabilisation is employed.

3.3 Per Unit System

There are several options for the per unit system of the synchronous machine excitation system. It is chosen to have 1.0 per unit exciter output voltage corresponding to the field voltage required to produce rated synchronous machine armature terminal voltage on the air-gab line; 1.0 p.u. exciter output current equals the synchronous machine field current. Kundur in [6] refers to this per unit system as *non-reciprocal per unit system*. Excitation system models must interface with synchronous machine models at both the stator and field terminals. Since the per unit system, for expressing the terminal input variables, are the same as those used for modelling the synchronous machine, a change of the per unit system is only required for the input-output relations related to the field circuit. In the figure below this per unit conversion is illustrated. Details on this subject are discussed by Kundur in [6] Section 8.6.

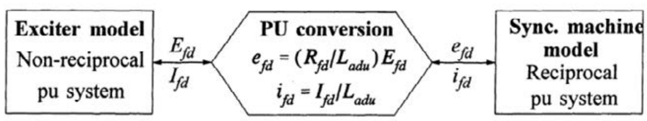

Figure 3.4 Per unit conversion at the interface between excitation system and synchronous machine field circuit [6]

4 TERMINAL VOLTAGE TRANSDUCER AND LOAD COMPENSATOR

Generally, the input to the excitation system model is the terminal voltage of the generator, measured and reduced to a DC-quantity. Sometimes, load compensation is used to control the voltage at some other point than the terminals of the machine. This could either be a point within the generator armature (droop compensation), or a point partway within the step-up transformer or somewhere along in the transmission system (line-drop compensation). Below the IEEE model of the terminal voltage transducer and load compensator is shown. This model is common to all excitation system models described by the IEEE in [1].

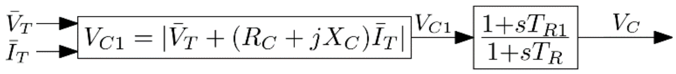

Figure 4.1 Terminal voltage transducer and load compensator

In Vision all elements are modelled in the *DQ0* reference frame to allow the numerical solver to use a larger step size under balanced and steady-state conditions. The inputs of the *Load Compensator* are however in phasor form, the relation between instantaneous *DQ0* reference and phasor symmetrical components as used in Vision is given by the equations below.

$$\overline{V}_T = V_D + jV_Q$$
$$\overline{I}_T = I_D + jI_Q$$

It has to be mentioned that the above relation only holds for sinusoidal steady-state conditions at fundamental frequency. The negative sequence component is present in case of unbalanced conditions in the above signals $\overline{V}_T$ and $\overline{I}_T$. This causes an oscillating component at twice the fundamental frequency in the signal V_{C1}, oscillations of which can be damped by an appropriate choice of filter parameter T_R.

When load compensation is used the parameter values of R_C and X_C are either positive or negative, depending on the kind of compensation required. The time constant T_R represents the rectification and filtering of the terminal voltage. Since for some systems the voltage transducer is represented by a lead-lag element, an extra time constant, T_{R1}, is added in Vision.

4.1 Droop compensation

The specification of reactive power droop is not always by parameters R_C and X_C, sometimes the reactive power droop is specified in percent (*U/Q droop*). Since a dynamic study in Vision is always initialized by performing an automatic loadflow, it is important that the parameters R_C, X_C and U/Q droop are consistent. In Vision parameters R_C and X_C can be user-defined, computed from the specified U/Q droop, or they can be obtained using loadflow. The last two options are discussed in more detail below.

4.1.1 COMPUTATION USING U/Q-DROOP

U/Q-droop, as specified in the general tab of the synchronous generator, is the value for a voltage change in percent for a 1 pu change in reactive power. U/Q-droop can mathematically be expressed as:

$$droop = -\frac{\Delta U}{\Delta Q} \cdot 100\% \tag{4.1}$$

where ΔU and ΔQ are in pu.

When Park's transformation is synchronized with the voltage vector (i.e. $V_Q = 0$) and balanced conditions are assumed, the reactive power output of the synchronous generator can been written as:

$$Q = -V_D \cdot I_Q \tag{4.2}$$

Assuming that V_D equals 1 pu ± 0.05 pu and that $\Delta U = I_Q \cdot X_C$ equation 4.1 can been rewritten:

$$X_C = \frac{droop}{100\ \%} \tag{4.3}$$

where X_C is in pu.

4.1.2 COMPUTATION USING LOADFLOW

Using this method the value of X_C is computed based on the results of loadflow calculation (executed internally during the initialization of a dynamic simulation). R_C is set to 0 in this case. The loadflow results include generator terminal voltage $\bar{V}_T$ and current $\bar{I}_T$. The output of the Load Compensator $\bar{V}_{C1}$ is represented in complex form by the absolute value equal to the generator reference voltage U_{ref} and the angle equal to that of the generator terminal voltage. Then the compensation reactance can be determined as:

$$X_C = \frac{|\bar{V}_{C1} - \bar{V}_T|}{|\bar{I}_T|} \tag{4.4}$$

As can be seen from the formula above, the value of X_C will now differ for each point of generator operation.

4.2 Parameters

Parameter	Unit	Description	Default	Min	Max
Tr	sec	Regulator input filter time constant	0.03	**0.001**	100
Tr 1	sec	Regulator input filter time constant 1	0	0	1000
Rc	Ohm	Load compensation resistance	0	-10	10
Xc	Ohm	Reactance component of load compensation	0	-10	10

5 REACTIVE POWER AND POWER FACTOR CONTROL

Excitation systems are sometimes supplied with automatically adjusting generator reactive power (var) or power factor (PF) output. Those set points are user-specified and can be set in the general tab of the synchronous generator options. The reactive power and power factor controllers are implemented as a slow outer-loop control of the excitation system, where the excitation system reference voltage, V_{REF}, is adjusted based upon the error between the measured and the desired synchronous generator power factor or reactive power output. The load compensation parameters R_C and X_C are internally set to zero when the generator in this control mode.

In industrial applications the synchronous generator is typically tied directly to a plant distribution bus, where the terminal voltage is expected to follow any variation in the unity-fed system voltage. In this case machine terminal voltage regulation may not be desirable, var and PF control is often used in those types of industrial applications.

5.1 Var controller Type II

The var controller is implemented as a PI type controller. The measured reactive power output, Q, is filtered by the lead-lag element and compared with the reactive power set point, Q_{REF}. The produced error signal is the input to the PI controller, the output signal of which is limited by V_{CLMT}. The signal V_{VAR} is summed with the reference voltage ($V_{REFsetpoint}$). This reference voltage is determined using load-flow results. The EXLON flag (EXcitation Limiter ON) is used to disable the integral action when an excitation limiting device is active.

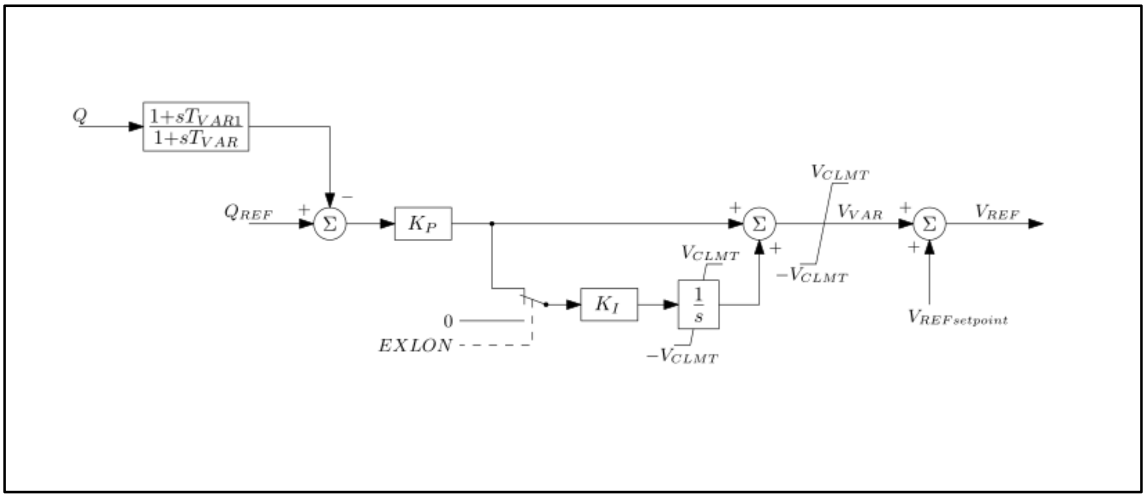

Figure 5.1 Type II var controller

5.1.1 VAR CONTROLLER TYPE II - PARAMETERS

Parameter	Unit	Description	Default	Min	Max
Ki	Pu	Reactive power control integral gain	2	0	50
Kp	Pu	Reactive power control proportional gain	0.02	0.01	100
Tvar	Sec	Input filter time constant	2	0.001	100
Tvar1	Sec	Input filter time constant	0	0	1000
Vcmlt	Pu	Maximum reactive power controller output	0.1	0.01	0.9

5.2 PF controller Type II

The PF controller is implemented as a PI type controller. The measured synchronous generator power factor, expressed as sin(φ), is filtered by the lead-lag element and compared with the set point, $\sin(\varphi)_{REF}$. The produced error signal is the input of the PI controller, the output signal of which is limited by V_{CLMT}. The signal V_{PF} is summed with the reference voltage ($V_{REFsetpoint}$). This reference voltage is determined using loadflow results. The EXLON flag (EXcitation Limiter ON) is used to disable the integral action when an excitation limiting device is active.

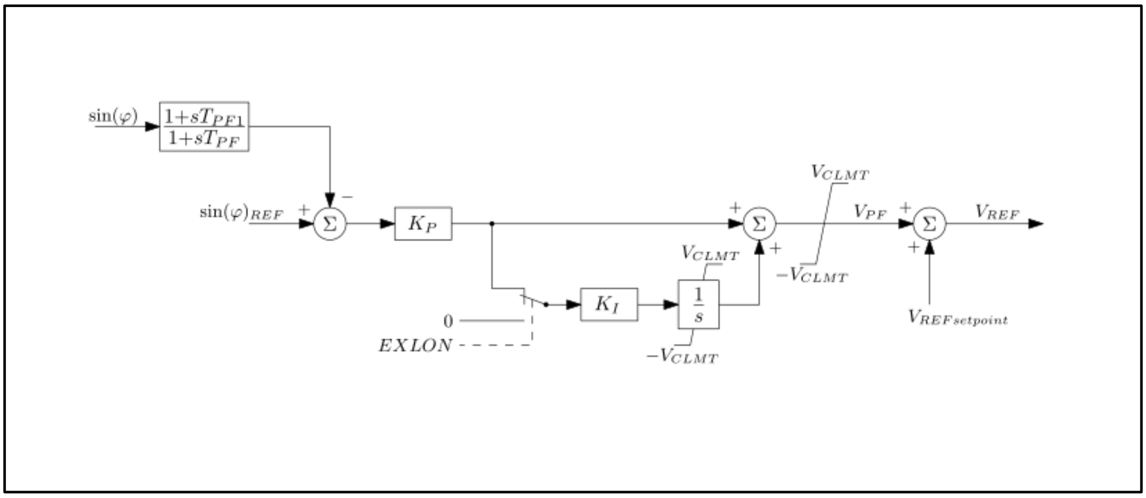

Figure 5.2 Type II PF controller

The PF controller should be able to control the PF of the synchronous machine in the two generating quadrants (leading and lagging PF). As shown in the example of Chapter 3, where the generator was delivering reactive power to the grid, the reactive power output and the power factor is controlled by adjusting the excitation voltage. When the generator delivers reactive power to the grid and the PF is to be increased, the excitation output voltage has to be controlled down. In contrary, when the synchronous machine is absorbing reactive power and the PF is to be increased the excitation output voltage has to be controlled up. As shown below in Figure 5.3 where both sin(φ) (green) as cos(φ) (blue) are plotted against angle φ in degrees, the power factor (cos(φ)) is positive for both the generating quadrants.

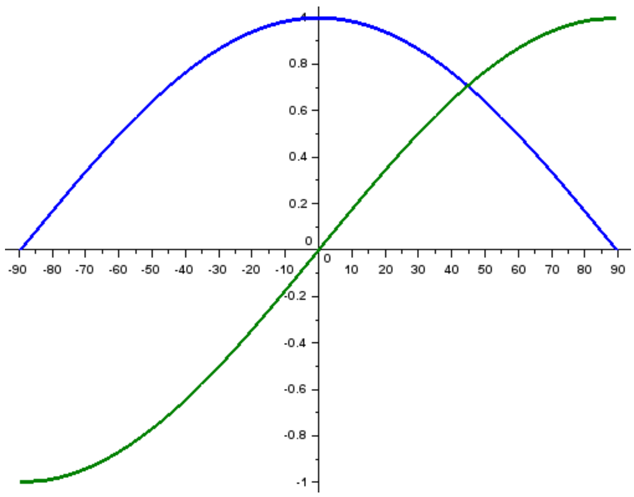

Figure 5.3 cos(φ) and sin(φ) against angle φ in degrees

The operating quadrant, and thus the control strategy, is not to be identified by using cos(φ) as control signal input. In order to control the exciter output in the right direction, sin(φ) is used in Vision as PF controller input since it directly includes the synchronous machine operation quadrant.

5.2.1 PF CONTROLLER TYPE II - PARAMETERS

Parameter	Unit	Description	Default	Min	Max
Ki	pu	Power factor control integral gain	2	0	50
Kp	pu	Power factor control proportional gain	0.02	0.01	100
Tpf	sec	Input filter time constant	2	0.001	100
Tpf1	sec	Input filter time constant	0	0	1000
Vcmlt	pu	Maximum power factor controller output	0.1	0.01	0.9

6 SATURATION FUNCTION IMPLEMENTATION

The saturation curve can be described as the sum of a linear and an exponential update term, S_E. Here, S_E is an approximate function of the exciter output to fit the saturation function. Figure 6.1 (A) illustrates the calculation of the exciter saturation function S_E for a specified value, E_{FD1}, where the value of the saturation function at this point is:

$$S_E(E_{FD1}) = \frac{A_{EFD1} - B_{EFD1}}{B_{EFD1}} \tag{6.1}$$

In general the saturation function is specified by two points. Since saturation effects are more significant at higher voltages, the first point is specified at or near exciter ceiling voltage. The exciter ceiling voltage is the maximum direct voltage that the excitation system is designed to supply from its terminals under defined conditions. The second point is specified at a lower value, commonly at 75% of the exciter ceiling voltage. In Figure 6.1 the exciter load saturation curve and the saturation function are shown.

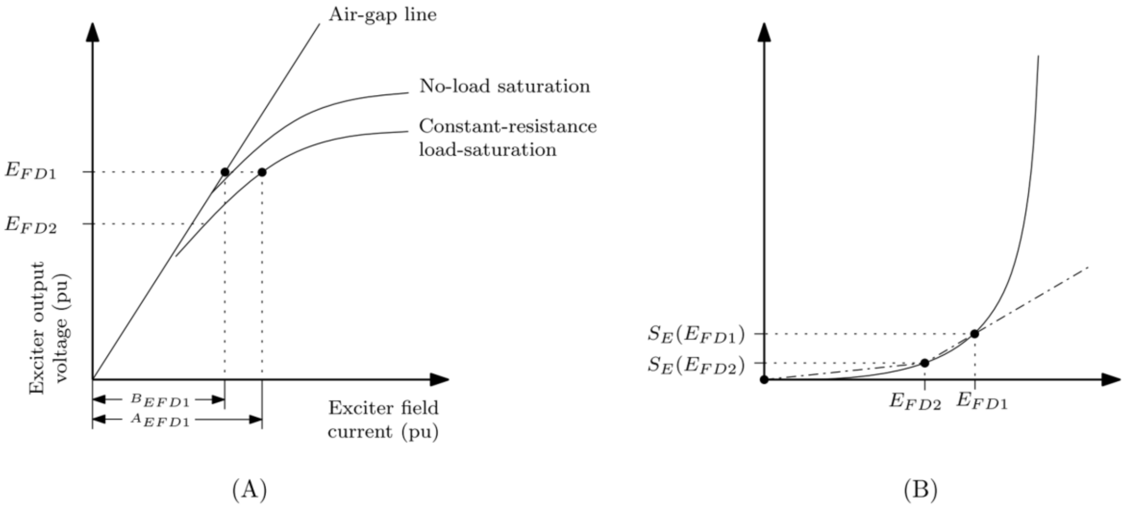

Figure 6.1 Exciter load-saturation curve (A) and saturation function (B)

The load-saturation function $S_E(E_{FD})$ can be represented by several mathematical expressions. The exponential function given below is commonly used to describe saturation update term as shown in Figure 6.1 (B).

$$S_E(E_{FD}) = A\, e^{B\, E_{FD}} \tag{6.2}$$

The unknown parameters A and B in equation (6.2) are computed using the two specified points as follows:

$$A = \frac{S_E^4(E_{FD2})}{S_E^3(E_{FD1})} \tag{6.3}$$

$$B = \frac{4}{E_{FD1}} ln\left(\frac{S_E(E_{FD1})}{S_E(E_{FD2})}\right) \tag{6.4}$$

The complete derivation of the above equations can be found in Appendix D of [4].

7 TYPE DC EXCITATION SYSTEM MODELS

The excitation systems of this category utilize DC generators as source of excitation power, which may be driven either by a motor or the shaft of the synchronous generator. The excitation system output current is provided to the rotor of the synchronous generator through slip rings. DC excitation systems technology represent early systems spanning the years from the 1920s to the 1960s.

The IEEE provides four DC Excitation system models, the DC1A, DC2A, DC3A, and the DC4B respectively. The DC2A model differs from the DC1A model only in the voltage regulator output limits, which is in case of the DC2A model proportional to the terminal voltage. The DC3A excitation system models are used to represent older systems, in particular those with non-continuous acting regulators. The type DC4B excitation system model differs from the DC2A type with an update in control, here a PID regulator is used.

7.1 Type DC1A SMES

The principal input to this model is the output of the terminal voltage transducer and load compensator model, *VC*, which is described in Chapter 4. The terminal voltage transducer output, *VC*, is subtracted at the summing junction from the reference voltage, *VREF*. The stabilizing feedback signal, *VF*, is subtracted and the power system stabilizing signal, *VS*, is added to produce an error voltage. The time constants, *TB* and *TC*, may be used to model equivalent time constants inherent to the voltage regulator, these time constants are generally sufficiently small to be neglected and provision should be made for zero input data (setting *TB* and *TC* to zero). The resulting signal is amplified in the regulator, which for the older excitation systems may be of a magnetic, rotating or electronic type. The major time constant, *TA*, and gain, *KA*, associated with the voltage regulator are shown together with the non-windup limits typical of saturation or amplifier power supply limitations.

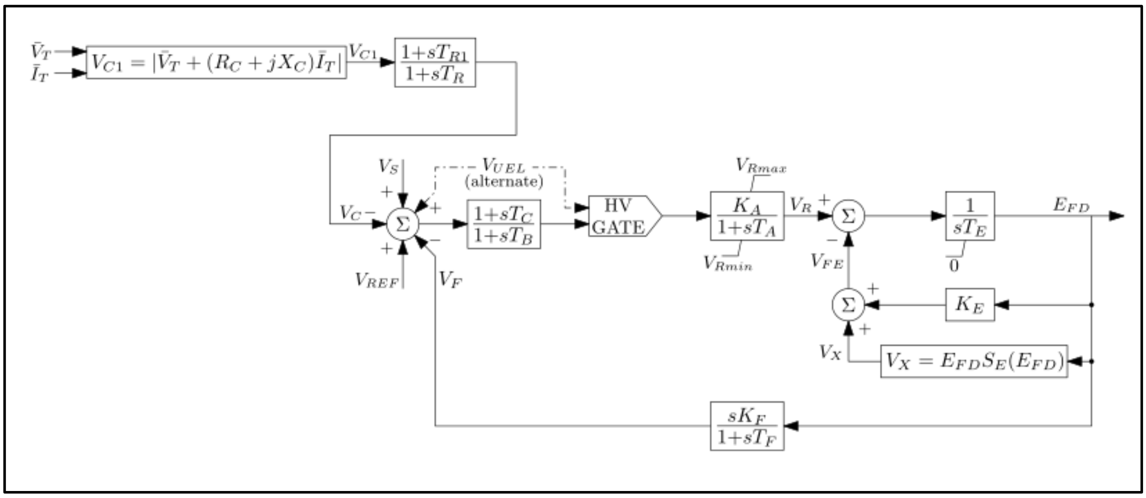

Figure 7.1 Type DC1A - DC commutator exciter

7.1.1 DC1A - PARAMETERS

Parameter	Unit	Description	Default	Min	Max
Ka	pu	Voltage regulator gain	50	**0.1**	1000
Ta	sec	Voltage regulator time constant	0.1	**0.01**	10
VRmin	pu	Minimum voltage regulator output	-10	-10	0
VRmax	pu	Maximum voltage regulator output	10	0.1	10
Tc	sec	Voltage regulator time constant	0.2	0	100

Tb	sec	Voltage regulator time constant	0.1	0	100
Kf	pu	Excitation system stabilizer gain	0.11	0	0.3
Tf	sec	Excitation system stabilizer time constant	1	0	2
Te	sec	Exciter time constant	0.2	**0.01**	2
Ke	pu	Exciter constant related to self-excited field	1	-1	1
Efd1	pu	Exciter voltage at which exciter saturation is defined	3.1	0	100
Efd2	pu	Exciter voltage at which exciter saturation is defined	2.3	0	100
SeEfd1	-	Exciter saturation function value at Efd1	0.33	0	100
SeEfd2	-	Exciter saturation function value at Efd2	0.1	0	100

7.1.2 PARAMETER RESTRICTIONS

There are the following parameter restrictions:

- The Excitation System Stabilizer (ESS) time constant Tf can only be set to zero if the ESS gain Kf equals zero;
- the voltage regulator time constant Tb can only be set to zero if Tc equals zero;
- Efd1 > Efd2 and SeEfd1 > SeEfd2.

7.2 Type DC2A SMES

This model is used to represent field-controlled DC commutator excitation systems with continuously acting voltage regulators having supplies obtained from the generator or auxiliary bus. The model differs from the DC1A model only in the voltage regulator output limits, which are now proportional to the terminal voltage V_T.

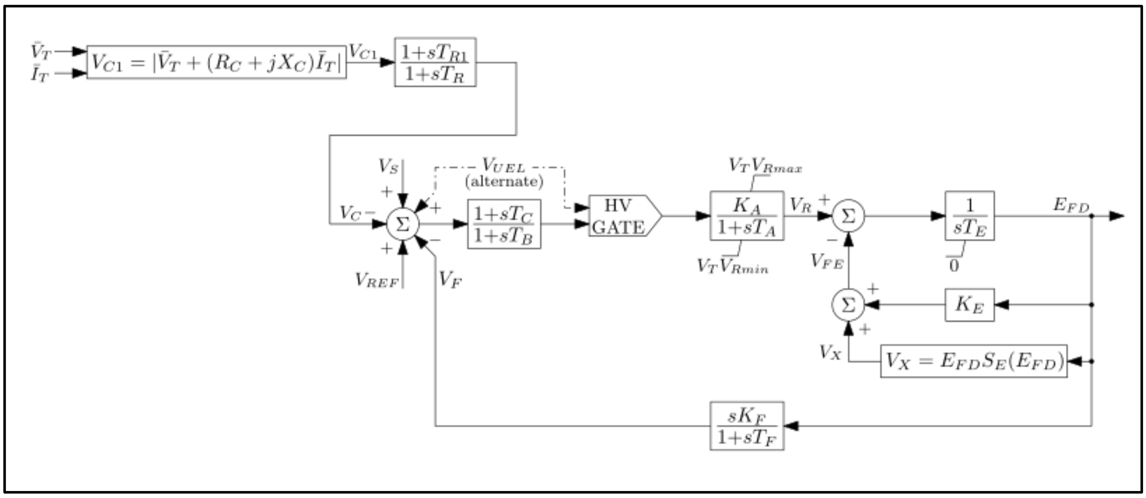

Figure 7.2 Type DC2A - DC commutator exciter with bus-fed regulator

7.2.1 DC2A – PARAMETERS

Parameter	Unit	Description	Default	Min	Max
Ka	pu	Voltage regulator gain	50	**0.1**	1000
Ta	sec	Voltage regulator time constant	0.1	**0.01**	10
VRmin	pu	Minimum voltage regulator output	-10	-10	0
VRmax	pu	Maximum voltage regulator output	10	0.1	10
Tc	sec	Voltage regulator time constant	0.2	0	100
Tb	sec	Voltage regulator time constant	0.1	0	100
Kf	pu	Excitation system stabilizer gain	0.11	0	0.3

Tf	sec	Excitation system stabilizer time constant	1	0	2
Te	sec	Exciter time constant	0.2	**0.01**	2
Ke	pu	Exciter constant related to self-excited field	1	-1	1
Efd1	pu	Exciter voltage at which exciter saturation is defined	3.1	0	100
Efd2	pu	Exciter voltage at which exciter saturation is defined	2.3	0	100
SeEfd1	-	Exciter saturation function value at Efd1	0.33	0	100
SeEfd2	-	Exciter saturation function value at Efd2	0.1	0	100

7.2.2 PARAMETER RESTRICTIONS

There are the following parameter restrictions:

- The Excitation System Stabilizer (ESS) time constant Tf can only be set to zero if the ESS gain Kf equals zero;
- the voltage regulator time constant Tb can only be set to zero if Tc equals zero;
- Efd1 > Efd2 and SeEfd1 > SeEfd2.

7.3 Type DC3A SMES

Before the development of continuously acting regulators non-continuously acting regulators were used, the type DC3A model is used to represent such older systems.

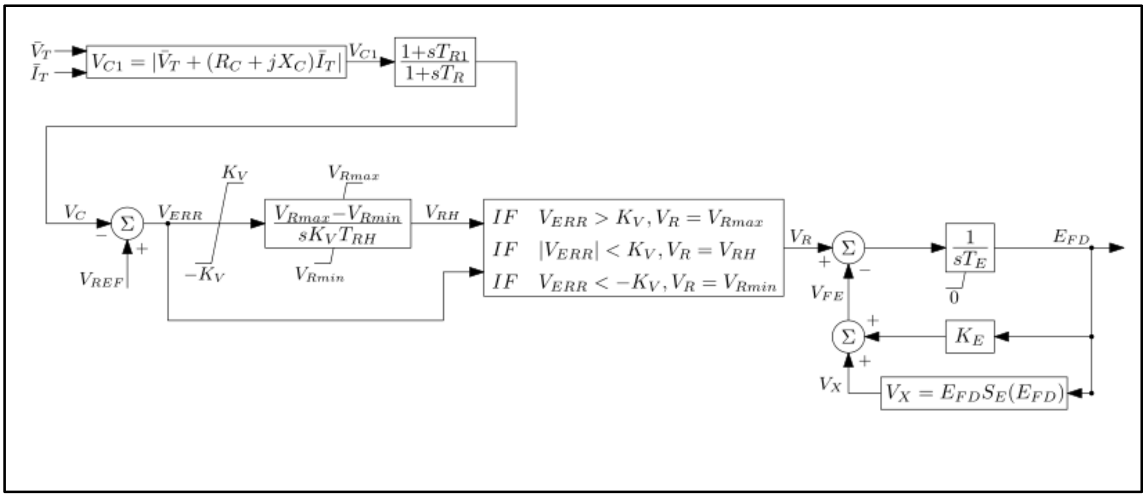

Figure 7.3 Type DC3A - DC commutator exciter with non-continuously acting regulators

7.3.1 DC3A – PARAMETERS

Parameter	Unit	Description	Default	Min	Max
Ke	pu	Exciter constant related to self-excited field	0.05	-1	1
Te	sec	Exciter time constant	0.5	**0.01**	2
VRmin	pu	Minimum voltage regulator output	-10	-10	0
VRmax	pu	Maximum voltage regulator output	10	0.1	10
Kv	pu	Fast raise/lower contact setting	0.05	**0.01**	10
Trh	sec	Rheostat travel time	20	**0.01**	100
Efd1	pu	Exciter voltage at which exciter saturation is defined	3.4	0	100
Efd2	pu	Exciter voltage at which exciter saturation is defined	2.6	0	100
SeEfd1	-	Exciter saturation function value at Efd1	0.3	0	100
SeEfd2	-	Exciter saturation function value at Efd2	0.07	0	100

7.3.2 PARAMETER RESTRICTIONS

There is the following parameter restriction: Efd1 > Efd2 and SeEfd1 > SeEfd2.

7.4 Type DC4B SMES

In this model the voltage regulator is formed by a Proportional, Integral, and Derivative (PID) controller. The rate feedback loop (ESS) is included in the model if the controller's D-action is not used.

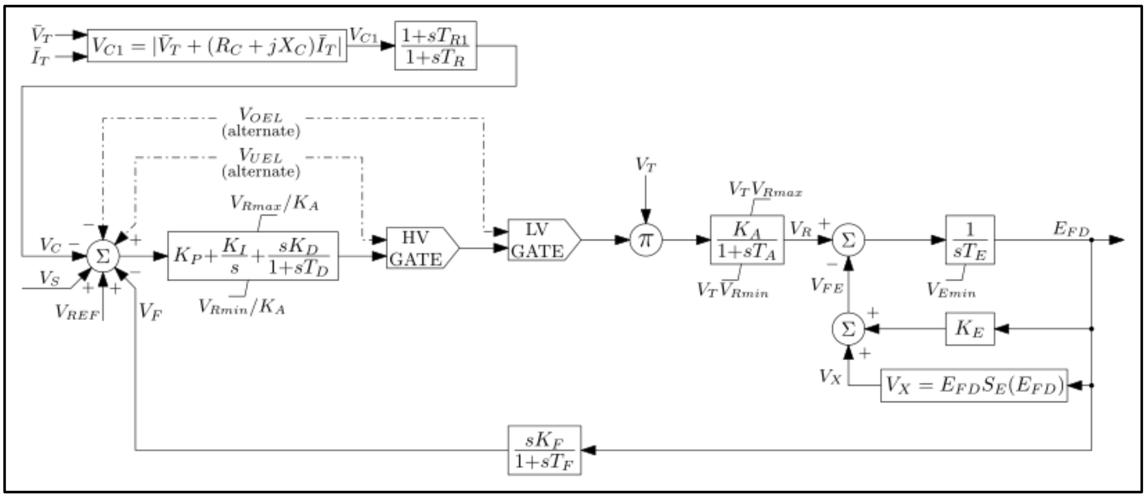

Figure 7.4 **Type DC4B - DC commutator exciter with PID style regulator**

7.4.1 DC4B – PARAMETERS

Parameter	Unit	Description	Default	Min	Max
Ka	pu	Regulator output gain	1	**0.1**	1000
Ta	sec	Regulator output time constant	0.2	**0.01**	10
VRmin	pu	Minimum voltage regulator output	-3	-10	0
VRmax	pu	Maximum voltage regulator output	3	0.1	10
VEmin	pu	Exciter minimum output voltage	0	-10	10
Kp	pu	Regulator proportional gain	80	0	500
Ki	pu	Regulator integral gain	20	0	500
Kd	pu	Regulator derivative gain	20	0	500
Td	sec	Regulator derivative filter time constant	0.01	0	100
Kf	pu	Excitation system stabilizer gain	0	0	0.3
Tf	sec	Excitation system stabilizer time constant	0	0	2
Te	sec	Exciter time constant	0.8	**0.01**	2
Ke	pu	Exciter constant related to self-excited field	1	-1	1
Efd1	pu	Exciter voltage at which exciter saturation is defined	2.33	0	100
Efd2	pu	Exciter voltage at which exciter saturation is defined	1.75	0	100
SeEfd1	-	Exciter saturation function value at Efd1	0.27	0	100
SeEfd2	-	Exciter saturation function value at Efd2	0.1	0	100

7.4.2 PARAMETER RESTRICTIONS

There are the following parameter restrictions:

- The Excitation System Stabilizer (ESS) time constant Tf can only be set to zero if the ESS gain Kf equals zero;
- the derivative-action time constant Td can only be set to zero if Kd equals zero;
- Efd1 > Efd2 and SeEfd1 > SeEfd2.

8 TYPE AC EXCITATION SYSTEM MODELS

AC excitation systems utilize AC machines as source of the main generator excitation power. In order to produce the DC field requirements, either stationary or rotating rectifiers are used, which may be controlled or non-controlled. The IEEE standard [1] provides eight different AC excitation system models.

8.1 Type AC1A SMES

The general structure of the model shows similarities with the DC1A excitation system model previously described. However, the load regulation due to armature reaction is taken into account separately using the negative feedback of the main generator field current, $K_D I_{FD}$. Armature reaction is the reverse effect on the main field flux related to current flowing through the armature coil. Because the output voltage of the rectifier decreases non-linearly as the rectifiers load current increases, the rectifier is modelled by three different models which characterise different modes of rectifier operation.

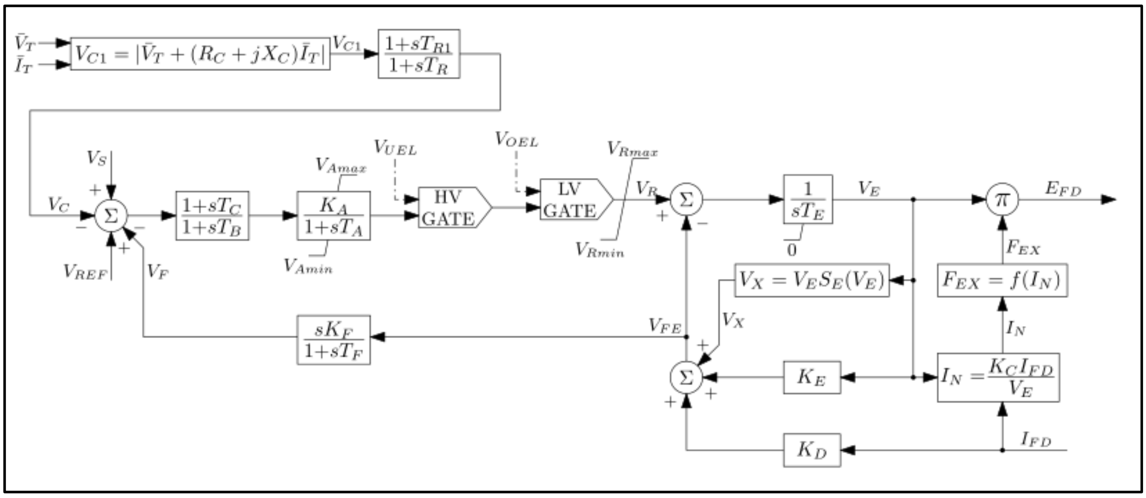

Figure 8.1 Type AC1A - Alternator-rectifier excitation system with non-controlled rectifiers and feedback from exciters field current

8.1.1 AC1A – PARAMETERS

Parameter	Unit	Description	Default	Min	Max
Ka	pu	Voltage regulator gain	80	**0.1**	1000
Ta	sec	Voltage regulator time constant	0.2	**0.01**	10
VRmin	pu	Minimum voltage regulator output	-15	-15	0
VRmax	pu	Maximum voltage regulator output	15	0.1	15
Tc	sec	Voltage regulator time constant	0.2	0	100
Tb	sec	Voltage regulator time constant	0.1	0	100
Kf	pu	Excitation system stabilizer gain	0.03	0	0.3
Tf	sec	Excitation system stabilizer time constant	1.5	0	2
Te	sec	Exciter time constant	0.2	**0.01**	2
Ke	pu	Exciter constant related to self-excited field	1	0	1
Kd	pu	Demagnetisation factor	0.4	0	1
Kc	pu	Rectifier loading factor	1	**0.001**	2
VAmin	pu	Minimum voltage regulator output	-15	-15	0
VAmax	pu	Maximum voltage regulator output	15	0.1	15
Ve1	pu	Exciter voltage at which exciter saturation is defined	5	0	100
Ve2	pu	Exciter voltage at which exciter saturation is defined	4	0	100
SeVe1	-	Exciter saturation function value at Ve1	0.5	0	100

SeVe2	-	Exciter saturation function value at Ve2	0.4	0	100

8.1.2 PARAMETER RESTRICTIONS

There are the following parameter restrictions:

- The Excitation System Stabilizer (ESS) time constant Tf can only be set to zero if the ESS gain Kf equals zero;
- the voltage regulator time constant Tb can only be set to zero if Tc equals zero;
- Ve1 > Ve2 and SeVe1 > SeVe2.

8.2 **Type AC2A SMES**

The type AC2A model represents a high initial response field controlled alternator-rectifier excitation system. The model is similar to the AC1A model except for the inclusion of exciter time constant compensation and exciter field current limiting elements.

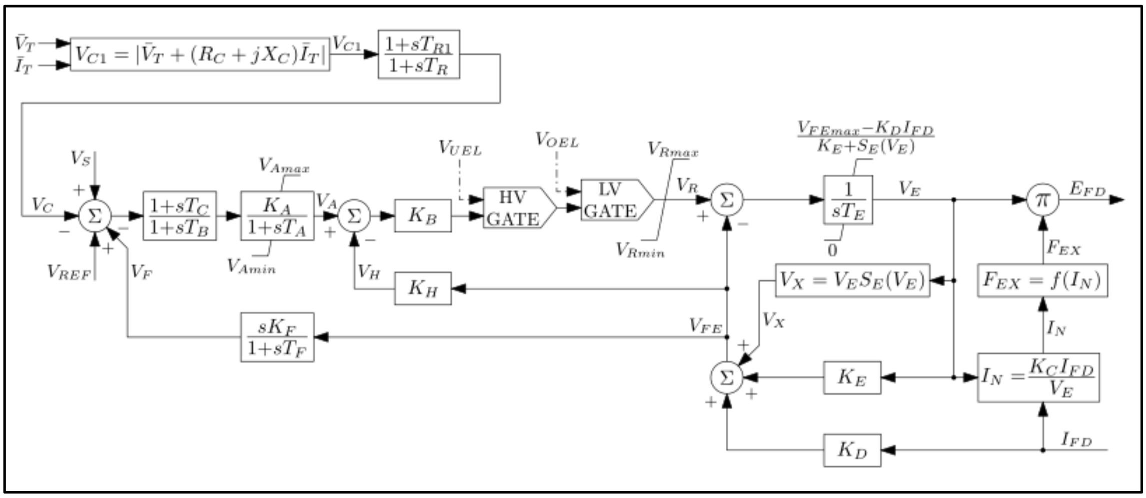

Figure 8.2 Type AC2A - High initial response alternator-rectifier excitation system with non-controlled rectifiers and feedback from exciter field current

8.2.1 AC2A – PARAMETERS

Parameter	Unit	Description	Default	Min	Max
Ka	pu	Voltage regulator gain	400	**0.1**	1000
Ta	sec	Voltage regulator time constant	0.01	**0.01**	10
VRmin	pu	Minimum voltage regulator output	-105	-500	0
VRmax	pu	Maximum voltage regulator output	95	0.1	500
Tc	sec	Voltage regulator time constant	0	0	100
Tb	sec	Voltage regulator time constant	0	0	100
Kf	pu	Excitation system stabilizer gain	0.03	0	0.3
Tf	sec	Excitation system stabilizer time constant	1	0	2
Te	sec	Exciter time constant	0.6	**0.01**	2
Ke	pu	Exciter constant related to self-excited field	1	0	1
Kd	pu	Demagnetisation factor	0.4	0	1
Kc	pu	Rectifier loading factor	0.3	**0.001**	2
Kb	pu	Second stage regulator gain	25	0	500
Kh	pu	Exciter field current feedback gain	1	0	10
VFEmax	pu	Exciter field current limit reference	4.4	-20	20
VAmin	pu	Minimum voltage regulator output	-8	-15	0

VAmax	pu	Maximum voltage regulator output	8	0.1	15
Ve1	pu	Exciter voltage at which exciter saturation is defined	4.5	0	100
Ve2	pu	Exciter voltage at which exciter saturation is defined	3.5	0	100
SeVe1	-	Exciter saturation function value at Ve1	0.04	0	100
SeVe2	-	Exciter saturation function value at Ve2	0.01	0	100

8.2.2 PARAMETER RESTRICTIONS

There are the following parameter restrictions:

- The Excitation System Stabilizer (ESS) time constant Tf can only be set to zero if the ESS gain Kf equals zero;
- the voltage regulator time constant Tb can only be set to zero if Tc equals zero;
- Ve1 > Ve2 and SeVe1 > SeVe2.

8.3 **Type AC3A SMES**

The type AC3A model represents the field-controlled alternator-rectifier (non-controlled) which employs self-excitation. Self-excitation is simulated by the use of a multiplier whose input are the voltage regulator control signal V_A, and the exciter output voltage E_{FD} multiplied with K_R. The ESS has a non-linear characteristic. When the exciter output voltage is less than E_{FDN} the ESS gain equals K_F, the ESS gain is K_N for exciter output voltages which exceeds E_{FDN}.

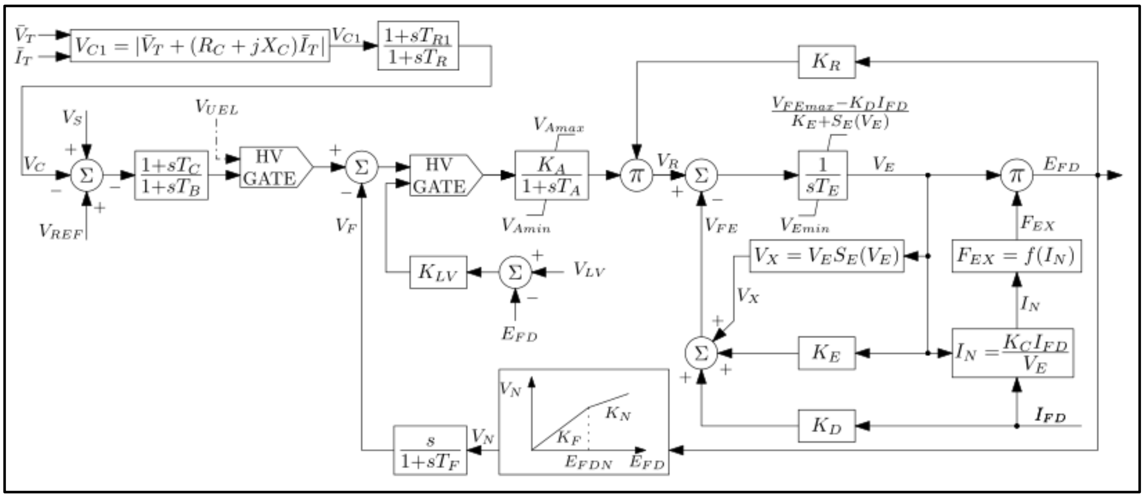

Figure 8.3 Type AC3A – Alternator-rectifier exciter with alternator field current limiter

The physical system contains a fast feedback loop that limits the field voltage. Since this loop has a natural oscillation frequency greater than 4 Hz, this limit is simulated as a lower limit on the exciter voltage (V_{Emin}). For more detailed studies this fast feedback limiting loop can be included (parameters V_{LV} and K_{LV}).

8.3.1 AC3A – PARAMETERS

Parameter	Unit	Description	Default	Min	Max
Ka	pu	Voltage regulator gain	45	**0.1**	1000
Ta	sec	Voltage regulator time constant	0.01	**0.01**	10
Tc	sec	Voltage regulator time constant	0	0	100
Tb	sec	Voltage regulator time constant	0	0	100
Kf	pu	Excitation system stabilizer gain	0.15	0	0.3
Efdn	pu	Value of Efd at which the ESS feedback gain changes	2.4	0	50

Kn	pu	Excitation system stabilizer gain when Efd ≥ Efdn	0.05	0	10
Tf	sec	Excitation system stabilizer time constant	1	0	2
Te	sec	Exciter time constant	1.2	**0.01**	2
Ke	pu	Exciter constant related to self-excited field	1	0	1
Kd	pu	Demagnetisation factor	0.5	0	1
Kc	pu	Rectifier loading factor	0.1	**0.001**	2
Kr	pu	Regulator/alternator field power supply constant	4	**0.01**	100
Vlv	pu	Field voltage limiter reference	0.8	0	10
Klv	pu	Field voltage limiter gain	0.2	0	100
VAmin	pu	Minimum voltage regulator output	-1	-15	0
VAmax	pu	Maximum voltage regulator output	1	0.1	15
VEmin	pu	Minimum exciter voltage output	0.1	-20	20
VFEmax	pu	Exciter field current limit reference	16	-20	20
Ve1	pu	Exciter voltage at which exciter saturation is defined	6.3	0	100
Ve2	pu	Exciter voltage at which exciter saturation is defined	4.7	0	100
SeVe1	-	Exciter saturation function value at Ve1	1.14	0	100
SeVe2	-	Exciter saturation function value at Ve2	0.1	0	100

8.3.2 PARAMETER RESTRICTIONS

There are the following parameter restrictions:

- The Excitation System Stabilizer (ESS) time constant Tf can only be set to zero if the ESS gains Kf and Kn are equal to zero;
- the voltage regulator time constant Tb can only be set to zero if Tc equals zero;
- Ve1 > Ve2 and SeVe1 > SeVe2.

8.4 Type AC4A SMES

The type AC4A alternator-supplied controlled-rectifier excitation system is a high initial response system which utilizes a full thyristor bridge in the output circuit.

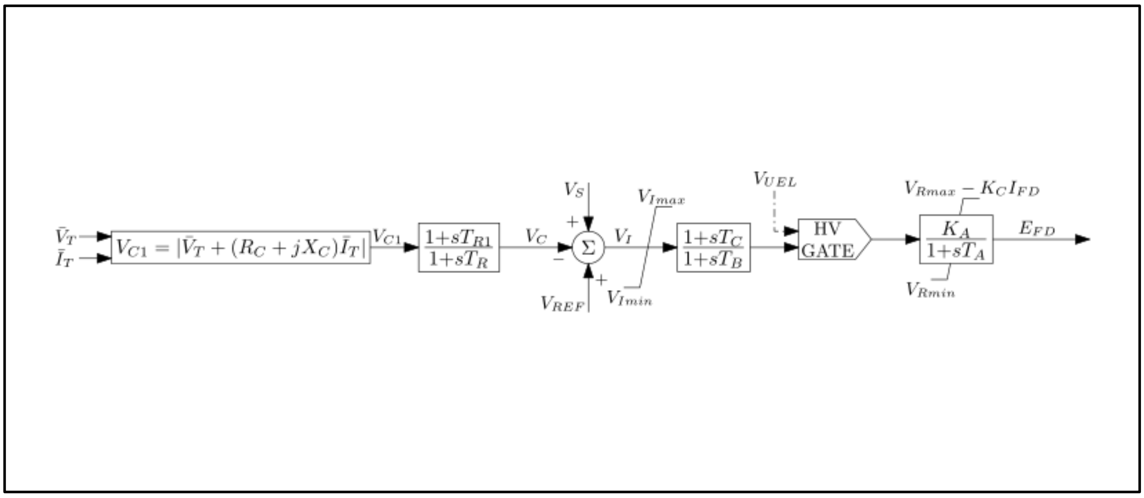

Figure 8.4 Type AC4A - Alternator-supplied controlled-rectifier exciter

8.4.1 AC4A – PARAMETERS

Parameter	Unit	Description	Default	Min	Max
Ka	pu	Voltage regulator gain	200	**0.1**	1000
Ta	sec	Voltage regulator time constant	0.02	**0.01**	10
Tb	sec	Voltage regulator time constant	10	0	100
Tc	sec	Voltage regulator time constant	1	0	100
Kc	pu	Rectifier loading factor	0	0	2
VImin	pu	Minimum voltage regulator input limit	-0.2	-5	0
VImax	pu	Maximum voltage regulator input limit	0.2	0.01	5
VRmin	pu	Minimum voltage regulator output	-4.5	-15	0
VRmax	pu	Maximum voltage regulator output	5.5	0.1	15

8.4.2 PARAMETER RESTRICTIONS

The voltage regulator time constant Tb can only be set to zero if Tc equals zero.

8.5 Type AC5A SMES

This model is a simplified mathematical representation of a brushless excitation system. This model is sometimes used to represent other types of SMESs when either detailed data is not available or a simplified model is required.

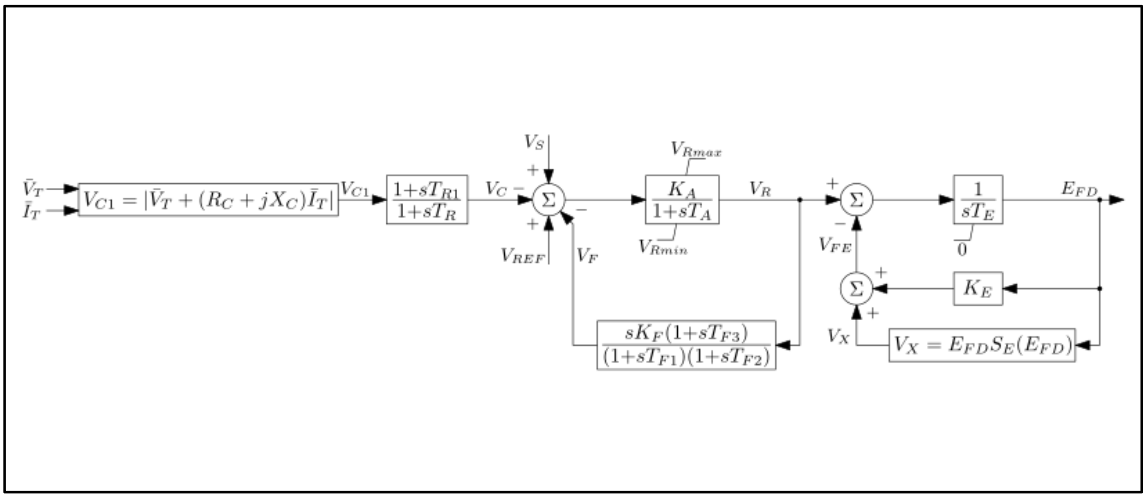

Figure 8.5 Type AC5A - Simplified rotating rectifier excitation system representation

8.5.1 AC5A – PARAMETERS

Parameter	Unit	Description	Default	Min	Max
Ka	pu	Voltage regulator gain	400	**0.1**	1000
Ta	sec	Voltage regulator time constant	0.02	**0.01**	10
Ke	pu	Exciter constant related to self-excited field	1	0	1
Te	sec	Exciter time constant	0.8	**0.01**	2
Kf	pu	Excitation system stabilizer gain	0.03	0	0.3
Tf1	sec	Excitation system stabilizer time constant	1	0	2
Tf2	sec	Excitation system stabilizer time constant	0	0	2
Tf3	sec	Excitation system stabilizer time constant	0	0	2
VRmin	pu	Minimum voltage regulator output	-7.5	-15	0
VRmax	pu	Maximum voltage regulator output	7.5	0.1	15
Efd1	pu	Exciter voltage at which exciter saturation is defined	5.6	0	100
Efd2	pu	Exciter voltage at which exciter saturation is defined	4.2	0	100
SeEfd1	-	Exciter saturation function value at Efd1	0.9	0	100
SeEfd2	-	Exciter saturation function value at Efd2	0.5	0	100

8.5.2 PARAMETER RESTRICTIONS

There are the following parameter restrictions:

- The ESS time constant Tf 1 can only be set to zero if the ESS gain Kf equals zero;
- the time constant Tf2 can only be set to zero if Tf3 equals zero;
- Efd1 > Efd2 and SeEfd1 > SeEfd2.

8.6 Type AC6A SMES

The type AC6A excitation system model is used to represent field-controlled alternator-rectifier systems with system-supplied electronic voltage regulators.

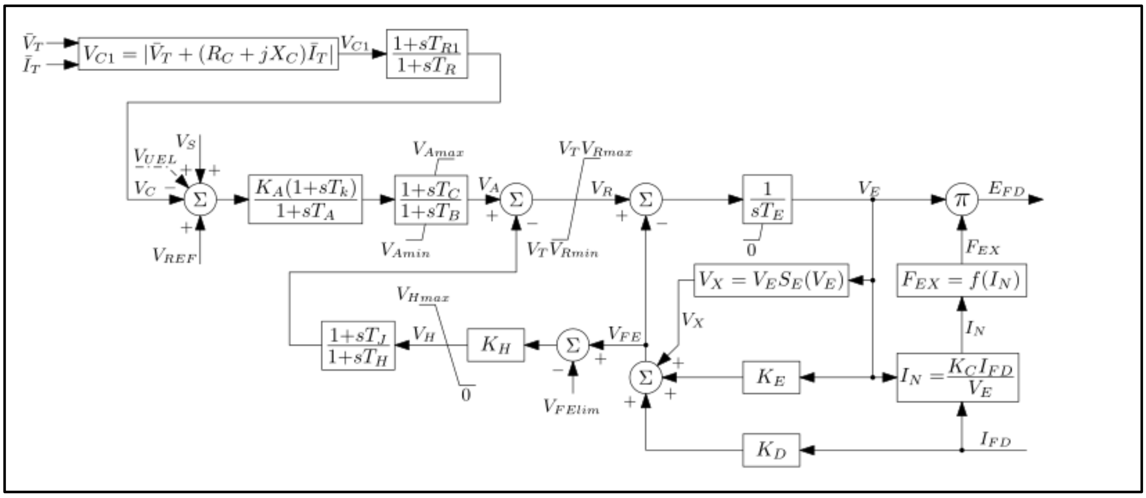

Figure 8.6 Type AC6A - Alternator-rectifier excitation system with non-controlled rectifiers and system-supplied electronic voltage regulator

8.6.1 AC6A – PARAMETERS

Parameter	Unit	Description	Default	Min	Max
Ka	pu	Voltage regulator gain	540	**0.1**	1000
Ta	sec	Voltage regulator time constant	0.09	**0.01**	10
Tk	sec	Voltage regulator lead time constant	0.2	0	10
Tb	sec	Voltage regulator time constant	9	0	100
Tc	sec	Voltage regulator time constant	3	0	100
Kh	pu	Exciter field current limiter gain	90	0	100
Th	sec	Exciter field current limiter time constant	0.08	0	2
Tj	sec	Exciter field current limiter time constant	0.02	0	2
Kc	pu	Rectifier loading factor	0.2	**0.001**	1
Kd	pu	Demagnetisation factor	2	0	5
Ke	pu	Exciter constant related to self-excited field	1.6	0	5
Te	sec	Exciter time constant	1	**0.01**	2
VAmin	pu	Minimum voltage regulator output	-75	-150	0
VAmax	pu	Maximum voltage regulator output	75	0.1	150
VRmin	pu	Minimum voltage regulator output	-36	-150	0
VRmax	pu	Maximum voltage regulator output	44	0.1	150
VHmax	pu	Maximum exciter field current feedback signal	75	0	100
VFElim	pu	Exciter field current limit reference	19	0	100
Ve1	pu	Exciter voltage at which exciter saturation is defined	7.5	0	100
Ve2	pu	Exciter voltage at which exciter saturation is defined	5.5	0	100
SeVe1	-	Exciter saturation function value at Ve1	0.2	0	100
SeVe2	-	Exciter saturation function value at Ve2	0.04	0	100

8.6.2 PARAMETER RESTRICTIONS

There are the following parameter restrictions:

- The voltage regulator time constant Tb can only be set to zero if Tc equals zero;
- the exciter field current limiter time constant Th can only be set to zero if Tj equals zero;
- Ve1 > Ve2 and SeVe1 > SeVe2.

8.7 Type AC7B SMES

This alternator-rectifier excitation system type include a high bandwidth inner loop regulating field voltage or exciter current (Kf1, Kf2), a fast exciter current limit (*VFEmax*), and a PID voltage regulator.

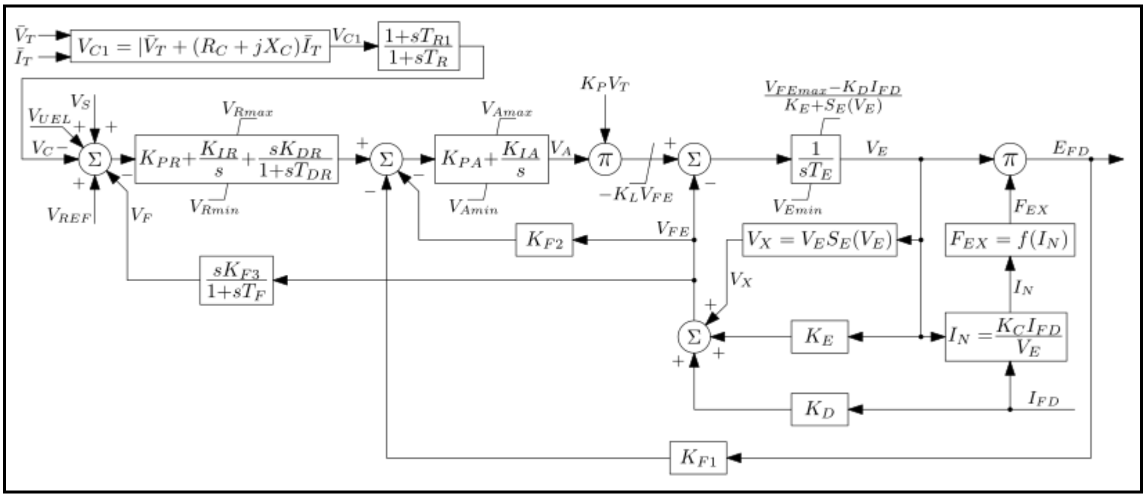

Figure 8.7 Type AC7B - Alternator-rectifier excitation system

8.7.1 AC7B – PARAMETERS

Parameter	Unit	Description	Default	Min	Max
Kpr	pu	Voltage regulator proportional gain	4.3	0	500
Kir	pu	Voltage regulator integral gain	4.3	0	500
Kdr	pu	Voltage regulator derivative gain	0	0	500
Tdr	sec	Voltage regulator derivative filter time constant	0	0	100
Kpa	pu	Voltage regulator proportional gain	65	0	500
Kia	pu	Voltage regulator integral gain	60	0	500
Kc	pu	Rectifier loading factor	0.2	**0.001**	2
Kd	pu	Demagnetisation factor	0.02	0	1
Ke	pu	Exciter constant related to self-excited field	1	0	1
Te	sec	Exciter time constant	1.1	**0.01**	2
Kf1	pu	Inner loop regulating field voltage gain	0.2	0	100
Kf2	pu	Inner loop regulating field current gain	0	0	100
Kf3	pu	Excitation system stabilizer gain	0	0	100
Tf	sec	Excitation system stabilizer time constant	1	0	2
Kl	pu	Lower limit coefficient of regulator output	10	0	100
Kp	pu	Potential circuit gain coefficient	5	0	100
VAmin	pu	Minimum voltage regulator output	-1	-15	0
VAmax	pu	Maximum voltage regulator output	1	0	15
VRmin	pu	Minimum voltage regulator output	-5.8	-15	0
VRmax	pu	Maximum voltage regulator output	5.8	0	15

VFEmax	pu	Exciter field current limit reference	7	0	100
VEmin	pu	Minimum exciter voltage output	0.5	-20	20
Ve1	pu	Exciter voltage at which exciter saturation is defined	6.5	0	100
Ve2	pu	Exciter voltage at which exciter saturation is defined	4	0	100
SeVe1	-	Exciter saturation function value at Ve1	0.45	0	100
SeVe2	-	Exciter saturation function value at Ve2	0.08	0	100

8.7.2 PARAMETER RESTRICTIONS

There are the following parameter restrictions:

- The Excitation System Stabilizer (ESS) time constant Tf can only be set to zero if the ESS gain Kf3 equals zero;
- the derivative-action time constant Tdr can only be set to zero if Kdr equals zero;
- Ve1 > Ve2 and SeVe1 > SeVe2

8.8 Type AC8B SMES

The AC8B alternator-rectifier excitation system type can be used to represent static voltage regulators applied to brushless excitation systems. By setting parameters Kc and Kd to zero the model can be used to represent digitally based voltage regulators feeding dc rotating main exciters. For thyristor power stages fed from the generator terminals the voltage regulator output limits should be dynamic by including terminal voltage: $V_T\,V_{Rmax}$ and $V_T\,V_{Rmin}$.

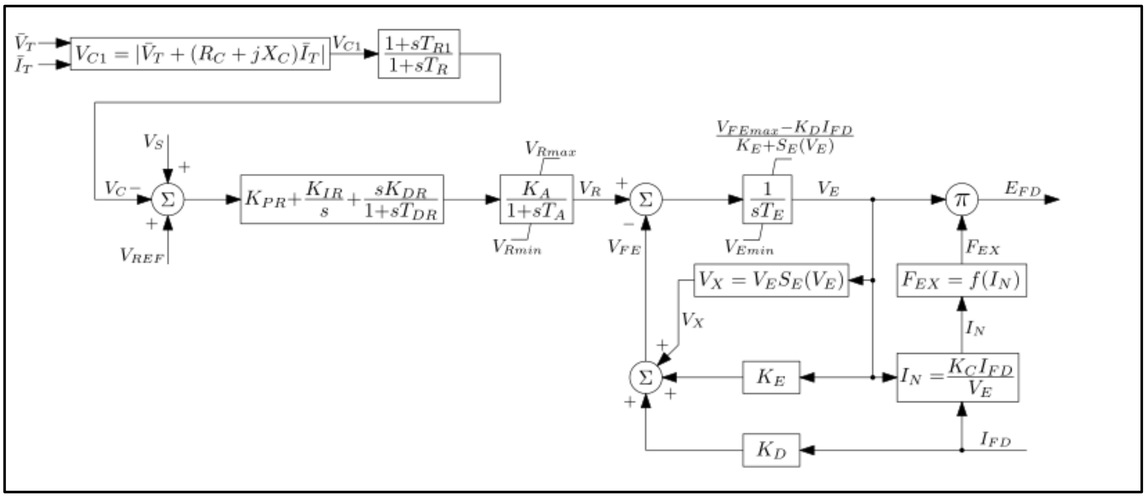

Figure 8.8 Type AC8B - Alternator-rectifier excitation system

8.8.1 AC8B – PARAMETERS

Parameter	Unit	Description	Default	Min	Max
Ka	pu	Voltage regulator gain	1	**0.1**	1000
Ta	sec	Voltage regulator time constant	0.1	**0.01**	10
Kpr	pu	Voltage regulator proportional gain	80	0	500
Kir	pu	Voltage regulator integral gain	5	0	500
Kdr	pu	Voltage regulator derivative gain	10	0	500
Tdr	sec	Voltage regulator derivative filter time constant	0.1	0	100
Kc	pu	Rectifier loading factor	0.55	0	2
Kd	pu	Demagnetisation factor	1.1	0	1
Ke	pu	Exciter constant related to self-excited field	1	0	1
Te	sec	Exciter time constant	1.2	**0.01**	2

VRmin	pu	Minimum voltage regulator output	0	-100	0
VRmax	pu	Maximum voltage regulator output	35	0.1	100
VFEmax	pu	Exciter field current limit reference	15	0	100
VEmin	pu	Minimum exciter voltage output	0.5	-20	20
Ve1	pu	Exciter voltage at which exciter saturation is defined	9	0	100
Ve2	pu	Exciter voltage at which exciter saturation is defined	6.5	0	100
SeVe1	-	Exciter saturation function value at Ve1	3	0	100
SeVe2	-	Exciter saturation function value at Ve2	0.3	0	100

8.8.2 PARAMETER RESTRICTIONS

There are the following parameter restrictions:

- The derivative-action time constant Tdr can only be set to zero if Kdr equals zero;
- Ve1 > Ve2 and SeVe1 > SeVe2

9 TYPE ST EXCITATION SYSTEM MODELS

Unlike the excitation types described before, all components in ST excitation systems are static or stationary (i.e. not rotating). The excitation power is supplied through transformers or auxiliary generator windings and rectifiers. Voltage (and current in compounded systems) is transformed to an appropriate level and rectifiers, either controlled or uncontrolled, provide the necessary direct current for the generator rotor field.

9.1 Type ST1A SMES

With this type of system the excitation power is supplied through a transformer from the generator terminals (or the unit's auxiliary bus) and is rectified and regulated by a controlled rectifier. The maximum exciter voltage available from such systems is directly related to the main generator terminal voltage. Hence, during system-fault conditions causing depressed generator terminal voltage, the exciter ceiling voltage is reduced. The ST1A model provides flexibility to represent series lead-lag or rate feedback stabilisation. The exciter ceiling voltage is proportional to the main generators terminal voltage, and the effect of rectifier regulation is represented by K_C. 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}. This limiter is described in this model to maintain consistency with the original ST1A model. However, it is possible to disable this limiter by setting K_{LR} to zero.

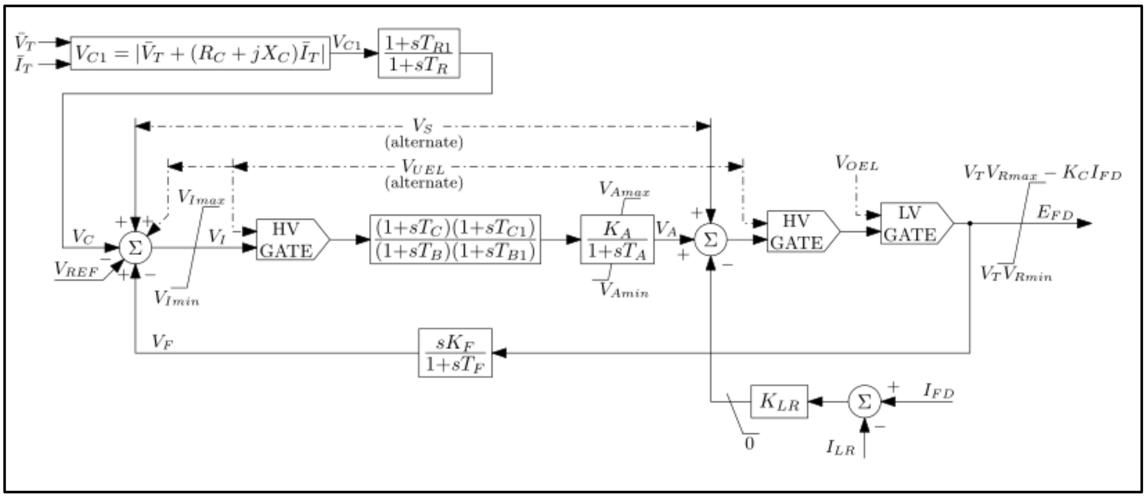

Figure 9.1 **Type ST1A - Potential-source, controlled-rectifier exciter**

9.1.1 ST1A – PARAMETERS

Parameter	Unit	Description	Default	Min	Max
Ka	pu	Voltage regulator gain	210	**0.1**	1000
Ta	sec	Voltage regulator time constant	0.01	**0.01**	10
Tc	sec	Voltage regulator time constant	1	0	100
Tb	sec	Voltage regulator time constant	1	0	100
Tc1	sec	Voltage regulator time constant	0	0	100
Tb1	sec	Voltage regulator time constant	0	0	100
Kc	pu	Rectifier loading factor	0.04	0	2
Kf	pu	Excitation system stabilizer gain	0	0	0.3
Tf	sec	Excitation system stabilizer time constant	0	0	2
Klr	pu	Exciter output current limiter gain	4.5	0	100
Ilr	pu	Exciter output current limiter reference	4.5	0	100

VAmin	pu	Minimum voltage regulator output	-1	-15	0
VAmax	pu	Maximum voltage regulator output	1	0	15
VRmin	pu	Minimum voltage regulator output	-6	-15	0
VRmax	pu	Maximum voltage regulator output	6.5	0.1	15
VImin	pu	Minimum voltage regulator input limit	-0.2	-5	0
VImax	pu	Maximum voltage regulator input limit	0.2	0.01	5

9.1.2 PARAMETER RESTRICTIONS

There are the following parameter restrictions:

- The Excitation System Stabilizer (ESS) time constant Tf can only be set to zero if the ESS gain Kf equals zero;
- the voltage regulator time constant Tb can only be set to zero if Tc equals zero;
- the voltage regulator time constant Tb1 can only be set to zero if Tc1 equals zero;

9.2 Type ST2A - 2005 SMES

Excitation power with this type of excitation system is formed by utilizing both the current and the voltage of the main generator. The excitation system output voltage is controlled through controlled saturation of the current transformer. When the generator is operating at no-load the potential source supplies the entire excitation power. Under loaded conditions, part of the excitation power is derived from the generator current. During a system-fault condition the current input enables the exciter to provide high field-forcing capability.

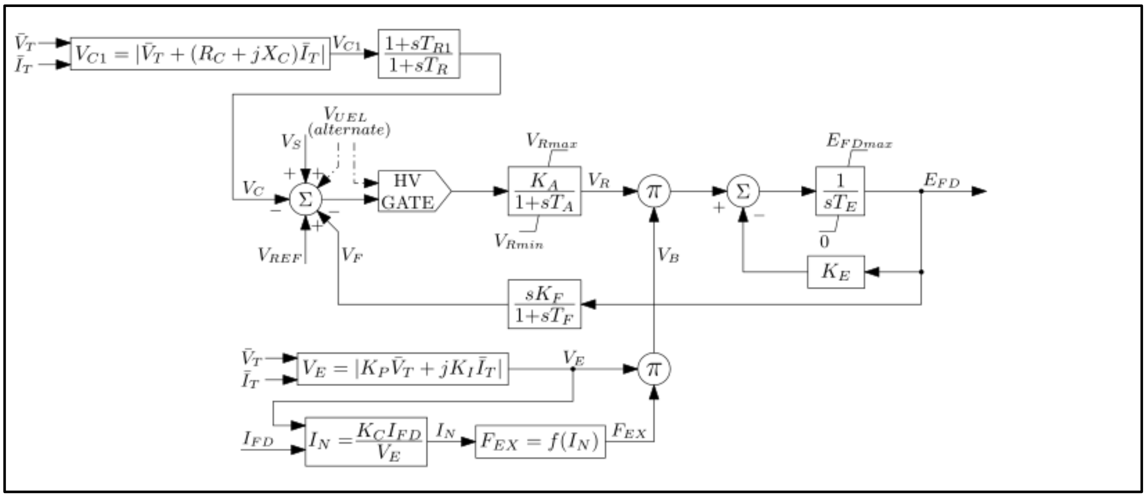

Figure 9.2 Type ST2A 2005 - Compound-source rectifier exciter

9.2.1 ST2A 2005 – PARAMETERS

Parameter	Unit	Description	Default	Min	Max
Ka	pu	Voltage regulator gain	120	**0.1**	1000
Ta	sec	Voltage regulator time constant	0.15	**0.01**	10
Kc	pu	Rectifier loading factor	1.82	**0.001**	2
Ke	pu	Exciter constant related to self-excited field	1	0	1
Te	sec	Exciter time constant	0.5	**0.01**	2
Kf	pu	Excitation system stabilizer gain	0.05	0	1
Tf	sec	Excitation system stabilizer time constant	1	0	2
Ki	pu	Potential circuit gain coefficient	8	0	10

Kp	pu	Potential circuit gain coefficient	5	0	10
VRmin	pu	Minimum voltage regulator output	0	-15	0
VRmax	pu	Maximum voltage regulator output	1	0.1	15
EFDmax	pu	Exciter field current limit	4	0	10

9.2.2 PARAMETER RESTRICTIONS

There are the following parameter restrictions:

- The Excitation System Stabilizer (ESS) time constant Tf can only be set to zero if the ESS gain Kf equals zero;

9.3 Type ST2A - 1981 SMES

In older IEEE excitation system reports (1968 and 1981) the ST2A excitation system model is referred to as Type 3 and ST2, respectively. In these older models the regulator output signal, V_R, is summed with V_B, whereas those signals are multiplied in the new 2005 standard.

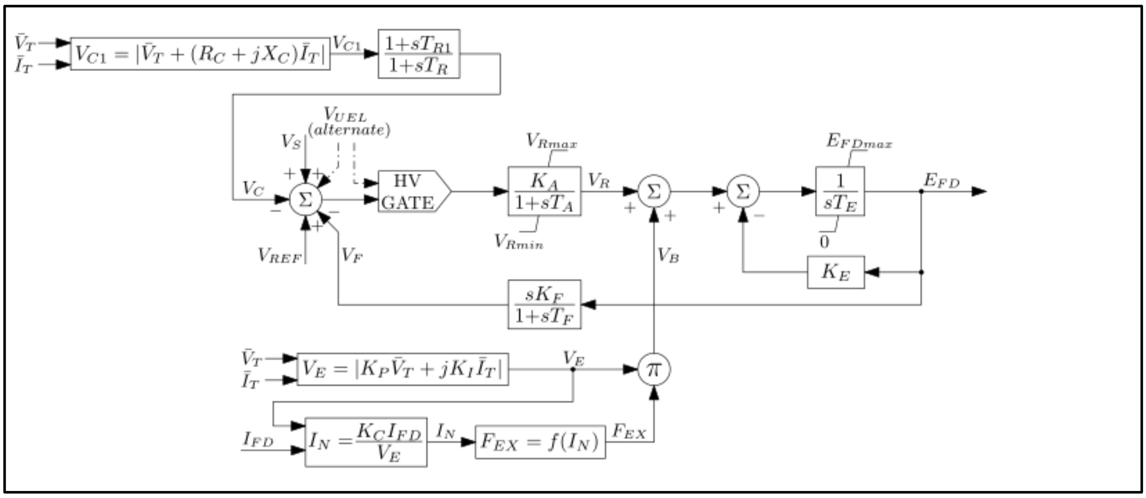

Figure 9.3 Type ST2A 1981 - Compound-source rectifier exciter

9.3.1 ST2A 1981 – PARAMETERS

Parameter	Unit	Description	Default	Min	Max
Ka	pu	Voltage regulator gain	120	**0.1**	1000
Ta	sec	Voltage regulator time constant	0.15	**0.01**	10
Kc	pu	Rectifier loading factor	1.82	**0.001**	2
Ke	pu	Exciter constant related to self-excited field	1	0	1
Te	sec	Exciter time constant	0.5	**0.01**	2
Kf	pu	Excitation system stabilizer gain	0.05	0	0.3
Tf	sec	Excitation system stabilizer time constant	1	0	2
Ki	pu	Potential circuit gain coefficient	8	0	10
Kp	pu	Potential circuit gain coefficient	5	0	10
VRmin	pu	Minimum voltage regulator output	-15	-150	0
VRmax	pu	Maximum voltage regulator output	15	0.1	150
EFDmax	pu	Exciter field current limit	4	0	10

9.3.2 PARAMETER RESTRICTIONS

There are the following parameter restrictions:

- The Excitation System Stabilizer (ESS) time constant Tf can only be set to zero if the ESS gain Kf equals zero;

9.4 **Type ST3A SMES**

The ST3A excitation system model is used to represent static systems with a field control loop to linearize exciter control characteristics.

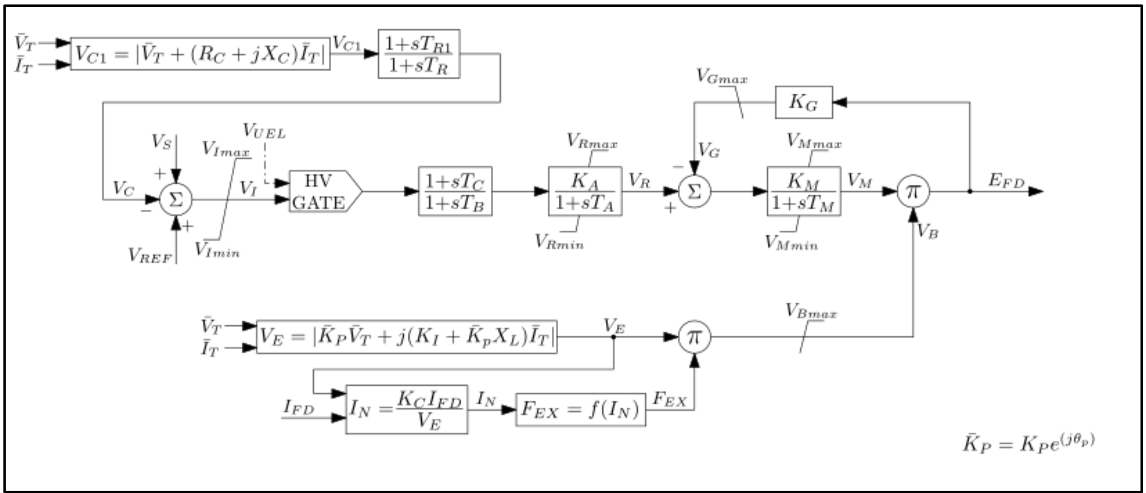

Figure 9.4 Type ST3A - Potential- or compound-source controlled-rectifier exciter with field voltage control loop

9.4.1 ST3A – PARAMETERS

Parameter	Unit	Description	Default	Min	Max
Ka	pu	Voltage regulator gain	200	**0.1**	1000
Ta	sec	Voltage regulator time constant	0.01	**0.01**	10
Tb	sec	Voltage regulator time constant	10	0	100
Tc	sec	Voltage regulator time constant	1	0	100
Kc	pu	Rectifier loading factor	0.2	**0.001**	2
Kg	pu	Feedback gain inner loop field regulator	1	0	2
Km	pu	Forward gain inner loop field regulator	8	0	1000
Tm	sec	Forward time constant inner loop field regulator	0.4	0	10
Ki	pu	Potential circuit gain coefficient	0	0	500
Kp	sec	Potential circuit gain coefficient	6	0	500
θp	deg	Potential circuit phase angle	0	-180	180
Xl	pu	Reactance associated with potential source	0.08	0	10
VBmax	pu	Maximum available exciter voltage	10	0	100
VGmax	pu	Maximum feedback inner loop voltage	6	0	100
VImin	pu	Minimum voltage regulator input limit	-0.2	-5	0
VImax	pu	Maximum voltage regulator input limit	0.2	0.1	5
VMmin	pu	Minimum converter bridge output	0	-150	0
VMmax	pu	Maximum converter bridge output	1	0.1	150
VRmin	pu	Minimum voltage regulator output	-10	-15	0
VRmax	pu	Maximum voltage regulator output	10	0.1	15

9.4.2 PARAMETER RESTRICTIONS

The voltage regulator time constant Tb can only be set to zero if Tc equals zero.

9.5 Type ST4B SMES

The ST4B excitation system model is the PI (proportional plus integral) controlled ST3A equivalent.

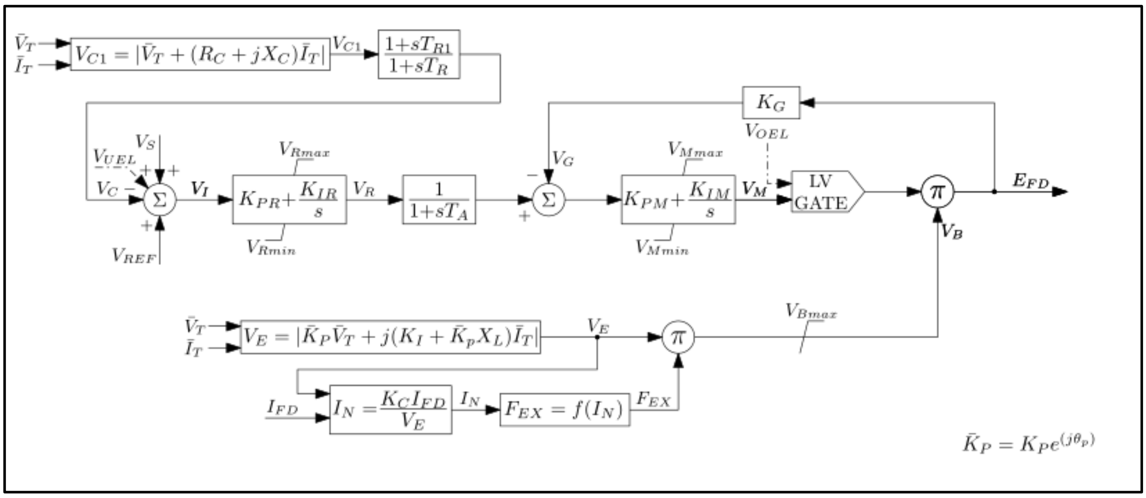

Figure 9.5 Type ST4B - Potential- or compound-source controlled-rectifier exciter

9.5.1 ST4B – PARAMETERS

Parameter	Unit	Description	Default	Min	Max
Kpr	pu	Voltage regulator proportional gain	11	0	500
Kir	pu	Voltage regulator integral gain	11	0	500
Kpm	pu	Voltage regulator proportional gain	1	0	500
Kim	pu	Voltage regulator integral gain	0	0	500
Ki	pu	Potential circuit gain coefficient	0	0	500
Kp	sec	Potential circuit gain coefficient	9.3	0	500
Ta	sec	Voltage regulator time constant	0.02	**0.01**	10
Kc	pu	Rectifier loading factor	0.1	**0.001**	2
Kg	pu	Feedback gain inner loop field regulator	0	0	2
θp	deg	Potential circuit phase angle	0	-180	180
Xl	pu	Reactance associated with potential source	0.1	0	10
VBmax	pu	Maximum available exciter voltage	12	0	100
VMmin	pu	Minimum converter bridge output	-99	-150	0
VMmax	pu	Maximum converter bridge output	99	0.1	150
VRmin	pu	Minimum voltage regulator output	-0.9	-15	0
VRmax	pu	Maximum voltage regulator output	15	0.1	15

9.6 Type ST5B SMES

The ST5B excitation system model is a variation of the type ST1A model.

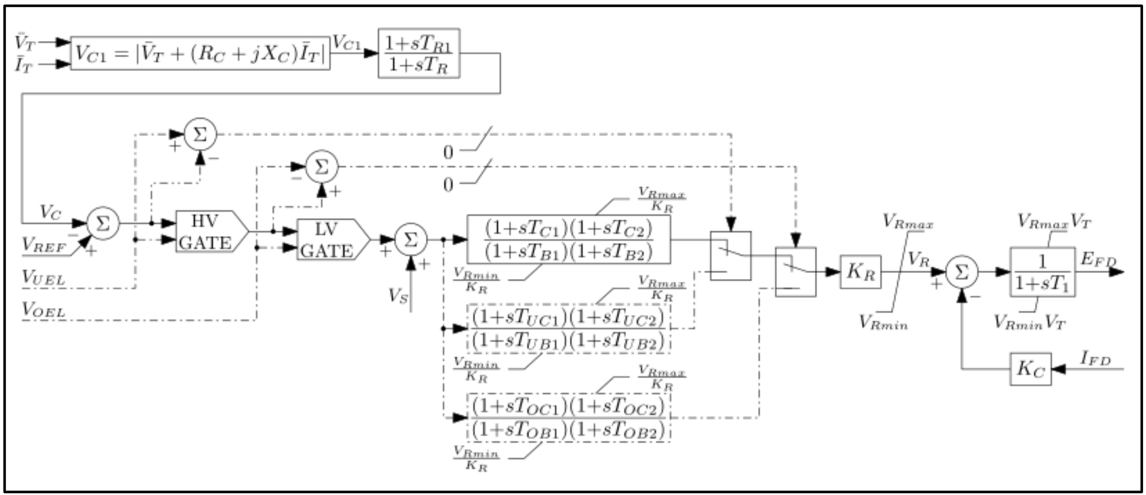

Figure 9.6 Type ST5B - Static potential-source excitation system

9.6.1 ST5B – PARAMETERS

Parameter	Unit	Description	Default	Min	Max
Tb1	sec	Voltage regulator time constant	6	0	100
Tc1	sec	Voltage regulator time constant	0.8	0	100
Tb2	sec	Voltage regulator time constant	0.08	0	100
Tc2	sec	Voltage regulator time constant	0.01	0	100
Tub1	sec	UEL time constant	10	0	100
Tuc1	sec	UEL time constant	2	0	100
Tub2	sec	UEL time constant	0.1	0	100
Tuc2	sec	UEL time constant	0.05	0	100
Tob1	sec	OEL time constant	2	0	100
Toc1	sec	OEL time constant	0.1	0	100
Tob2	sec	OEL time constant	0.08	0	100
Toc2	sec	OEL time constant	0.08	0	100
Kc	pu	Rectifier loading factor	0.004	0	2
Kr	pu	Voltage regulator gain	100	**0.1**	1000
T1	pu	Voltage regulator time constant	0.004	**0.01**	10
VRmin	pu	Minimum voltage regulator output	-4	-150	0
VRmax	pu	Maximum voltage regulator output	25	0.1	150

9.6.2 PARAMETER RESTRICTIONS

There are the following parameter restrictions:

- the voltage regulator time constant Tb1 can only be set to zero if Tc1 equals zero;
- the voltage regulator time constant Tb2 can only be set to zero if Tc2 equals zero;
- the UEL time constant Tub1 can only be set to zero if Tuc1 equals zero;
- the UEL time constant Tub2 can only be set to zero if Tuc2 equals zero;
- the OEL time constant Tob1 can only be set to zero if Toc1 equals zero;
- the OEL time constant Tob2 can only be set to zero if Toc2 equals zero.
- Tb1 ≥ Tc1 > 0, Tb2 ≥ Tc2 > 0, Tub1 ≥ Tuc1 > 0, Tub2 ≥ Tuc2 > 0, Tob1 ≥ Toc1 > 0, Tob2 ≥ Toc2 > 0

9.7 Type ST6B SMES

The type ST6B excitation system is a PI controlled system with an inner loop field voltage regulator and pre-control. If the excitation system is self-excited, the terminal voltage of the synchronous machine V_T is used as V_B input. If excitation comes from a separate source, then V_B has to be explicitly specified.

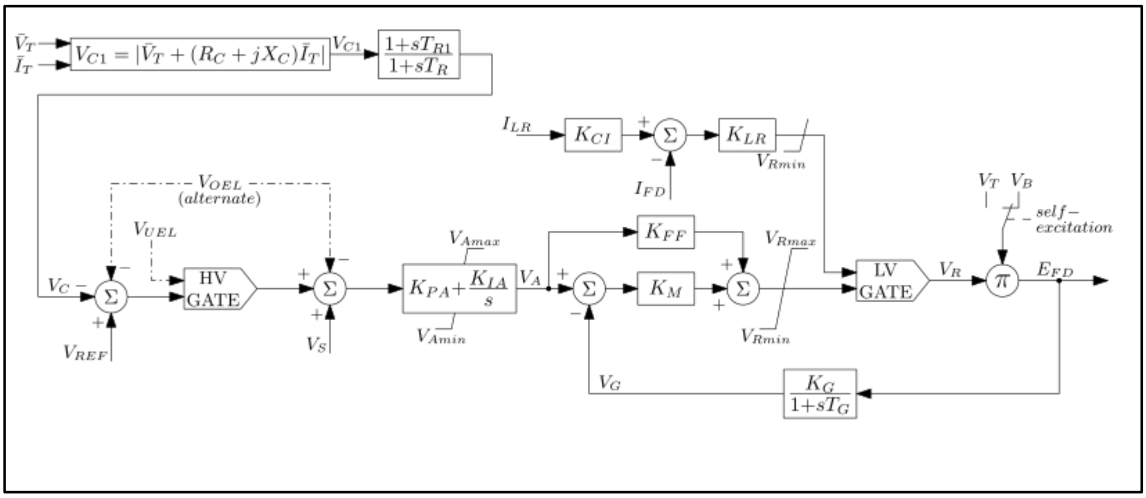

Figure 9.7 Type ST6B - Static potential-source excitation system with field current limiter

9.7.1 ST6B – PARAMETERS

Kpa	pu	Voltage regulator proportional gain	18	0	500
Kia	pu	Voltage regulator integral gain	45	0	500
Kg	pu	Feedback gain inner loop field regulator	1	0	500
Tg	pu	Feedback time constant inner loop field regulator	0	0	100
Kff	pu	Pre-control gain inner loop field regulator	1	0	100
Km	pu	Forward gain inner loop field regulator	1	0	100
Klr	pu	Exciter output current limiter gain	17	0	100
Ilr	pu	Exciter output current limiter reference	4	0	100
Kci	pu	Exciter output current limit adjustment	1	0	100
Vb	pu	Available exciter voltage	1	0	10
VAmin	pu	Minimum voltage regulator output	-4	-15	0
VAmax	pu	Maximum voltage regulator output	5	0.1	15
VRmin	pu	Minimum voltage regulator output	-4	-150	0
VRmax	pu	Maximum voltage regulator output	5	0	150

9.7.2 PARAMETER RESTRICTIONS

The pre-control gain inner loop field regulator plus the forward gain inner loop field regulator (Km+Kff) cannot be equal to zero.

9.8 Type ST7B SMES

The type ST7B excitation system is a PI controlled system where the lead-lag element can be used to introduce a derivative function (D-action).

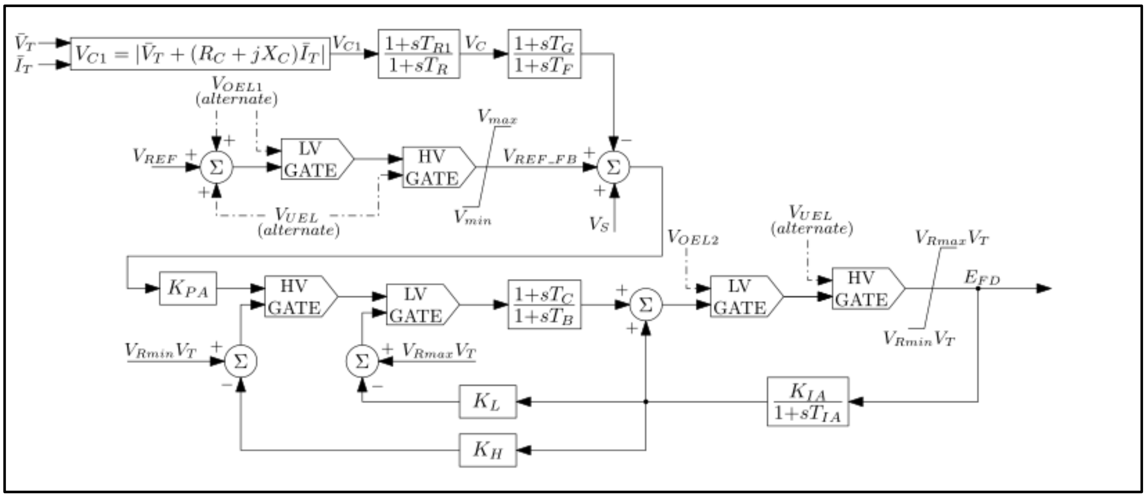

Figure 9.8 Type ST7B - Potential- or compound-source controlled-rectifier exciter

9.8.1 ST7B – PARAMETERS

Parameter	Unit	Description	Default	Min	Max
Kpa	pu	Voltage regulator proportional gain	40	0	500
Kia	pu	Voltage regulator integral gain	1	0	500
Tia	sec	Voltage regulator integral time constant	3	0	100
Tb	sec	Voltage regulator time constant	1	0	100
Tc	sec	Voltage regulator time constant	1	0	100
Tf	sec	Lead-lad element time constant	1	0	100
Tg	sec	Lead-lad element time constant	1	0	100
Kl	pu	Lower voltage regulator limiter gain	1	0	100
Kh	pu	Higher voltage regulator limiter gain	1	0	100
Vmin	pu	Minimum reference voltage	0.9	0	2
Vmax	pu	Maximum reference voltage	1.1	0	2
VRmin	pu	Minimum voltage regulator output	-4.5	0	0
VRmax	pu	Maximum voltage regulator output	5	0	15

9.8.2 PARAMETER RESTRICTIONS

There are the following parameter restrictions:

- the voltage regulator time constant Tb can only be set to zero if Tc equals zero;
- the time constant Tf can only be set to zero if Tg equals zero;
- Vmax > Vmin.

10 EXCITATION SYSTEM MODEL MANUFACTURER CROSS REFERENCE

In the tables below the IEEE models are listed together with corresponding systems of different manufactures. This list is made available by the IEEE and documented in Std. 421.5-2005 [1].

Type DC	Examples
DC1A	Regulex is a trademark of Allis Chalmers Corp. Amplidyne and GDA are trademarks of General Electric Co. Westinghouse Mag-A-Stat, Rototrol, Silverstat, and TRA. AB and KC are trademarks of Asea Brown Boveri Inc. The type KC may be modeled with some approximations.
DC2A	Westinghouse PRX-400. General Electric SVR. Eaton Cutler Hammer/Westinghouse type WDR retrofit.
DC3A	GFA 4 is a trademark of General Electric Co. Westinghouse BJ30.
DC4B	Basler DECS or Eaton/Cutler Hammer ECS2100 applied to a dc commutator exciter.

Type AC	Examples
AC1A	Westinghouse Brushless Excitation System; Cutler Hammer Westinghouse WDR brushless exciter retrofit.
AC2A	Westinghouse High Initial Response Brushless excitation system.
AC3A	ALTERREX is a trademark of General Electric Co.
AC4A	ALTHYREX is a trademark of General Electric Co.; General Electric Rotating Thyristor Excitation system.
AC5A	This model can be used to represent small excitation systems such as those produced by Basler and Electric Machinery.
AC6A	Stationary diode systems such as those produced by C.A. Parsons.
AC7B	Basler DECS and EATON ECS2100 applied to ac/dc rotating exciters; Brush PRISMIC A50-B, GE EX2000/2100, SIEMENS RG3, and THYRISIEM brushless excitation. Voltage regulator replacements for GE Alterrex (Type AC3A model) or dc exciters. DECS is a trademark of Basler Electric Co. Brush and PRISMIC are trademarks of FKI plc. RG3 and THYRISIEM are registered trademarks of Siemens AG.
AC8B	Basler DECS and Brush PRISMIC A30 and A10.

Type ST	Examples
ST1A	Silcomatic (a trademark of Canadian General Electric Co.). Westinghouse Canada Solid State Thyristor Excitation System; Westinghouse Type PS Static Excitation System with Type WTA, WTA-300, and WHS voltage regulators. Static excitation systems by ALSTOM, ASEA, Brown Boveri, GEC-Eliott, Hitachi, Mitsubishi, Rayrolle-Parsons, and Toshiba. General Electric Potential Source Static Excitation System. Basler Model SSE. UNITROL (a registered trademark of Asea Brown Boveri, Inc.); THYRIPOL (a registered trademark of Siemens AG.); Westinghouse WDR and MGR.
ST2A	General Electric static excitation systems, frequently referred to as the SCT-PPT or SCPT.
ST3A	General Electric Compound Power Source and Potential Power Source GENERREX excitation systems. GENERREX is a trademark of General Electric Co.
ST4B	Basler DECS applied to static excitation, Brush PRISMIC A50-S and A50-A, General Electric EX2000/2100 bus-fed potential source and static compound source and Generrex-PPS or -CPS; Canadian General Electric SILCOmatic 5 or EATON ECS2100 static excitation system.
ST5B	UNITROL D, P, F, and 5000 (trademarks of Asea Brown Boveri); Brush DCP.
ST6B	THYRIPOL (a trademark of Siemens AG) and EATON ECS2100 static excitation systems.
ST7B	ALSTOM excitation systems-Eurorec, Microrec K4.1, ALSPA P320 (ALSPA P320 is a trademark of ALSTOM).

11 EXAMPLE

Below an example of a dynamic study is provided where two different dynamic study cases are treated. Further in this text a 'dynamic study case' is referred simply as a 'case'. The first case consists of two events: a positive reference step at the terminals of the synchronous generator from 1 p.u. to 1.05 p.u. at 1 sec, and a negative reference step back to 1 p.u. at 15 sec. The second case is a direct start of the 1,4 MVA asynchronous motor AM1.

11.1 Description of the system

The single-line diagram shown below represents a simple industrial network. The Vision Network File (vnf) of this example is made available on our website, you can download this example using the following link: http://www.phasetophase.nl/vnf/DemoVisionManualSMES.vnf

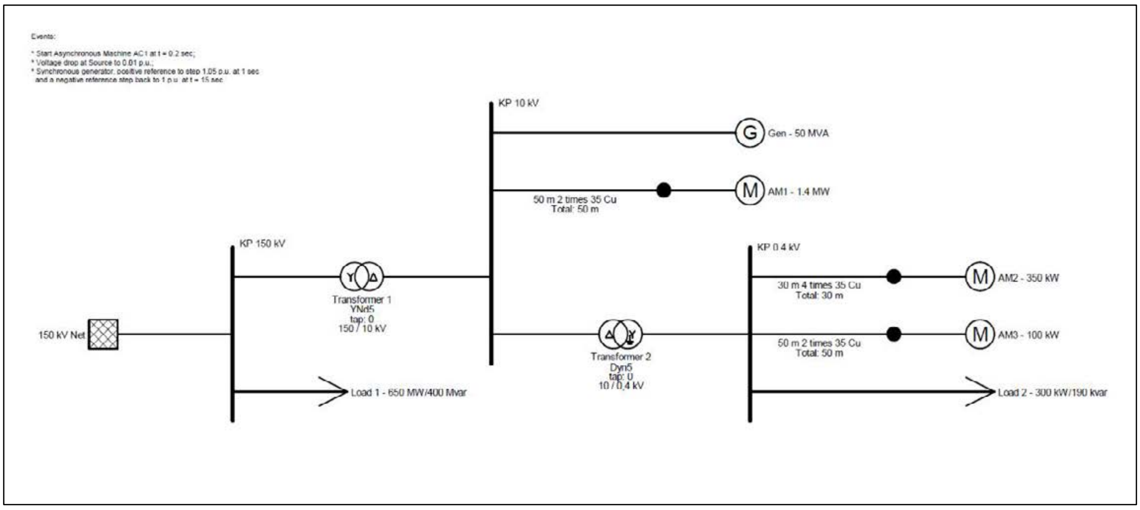

Figure 11.1 Single-line diagram demo network

The external network has, deviating from the parameters installed by default, a short-circuit power, S''_{Knom}, of 7,800 MVA, and a R/X ratio of 0.1. The load at the 150 kV node (Load 1) is of a constant impedance type with an active power of 650 MW and a reactive power of 400 Mvar. Node KP 10 kV is fed by a 60 MVA, 150/10 kV YNd5 transformer (Transformer 1) and a 50 MVA synchronous generator. The generator field is excited by a PID controlled alternator-rectifier excitation system represented by the IEEE type AC8B ESM. The asynchronous motor AM1 is connected to the 10 kV node via two parallel 50 meter 35 mm^2 Cu cables. At the low voltage side of the 2 MVA, 10/0,4 kV Dyn5 transformer (Transformer 2) two asynchronous machines and a 300 kW, 190 kvar load are coupled. The asynchronous machines AM2 and AM3 are 350 kW and 100 kW, respectively.

Below the input forms of the 50 MVA synchronous generator, the tab sheets of interest are **General** and **Dynamic**. When the field of the synchronous generator is controlled by an excitation system the generator could either be in **voltage control** or in **PF- or reactive power control**.

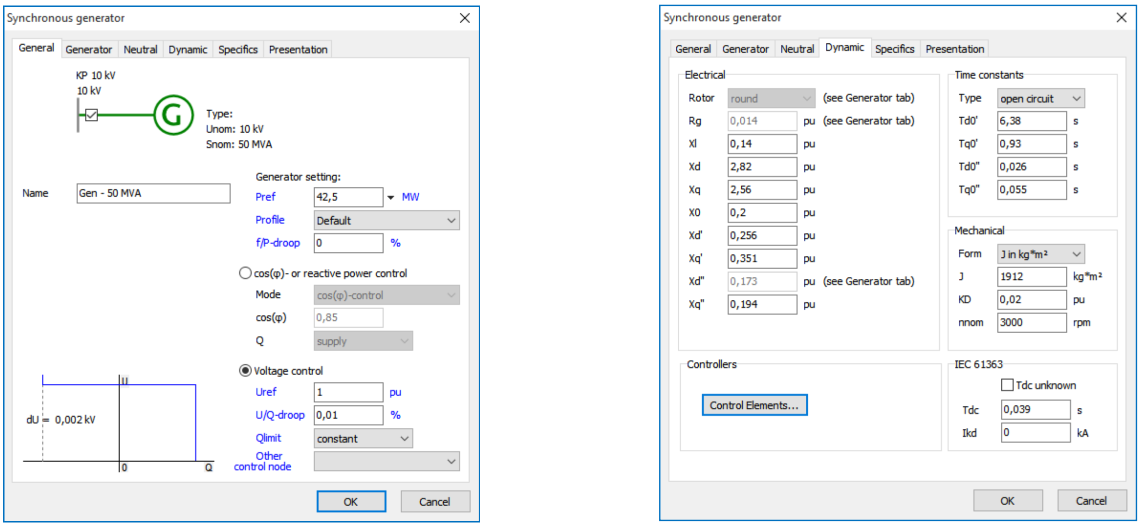

Figure 11.2 **Input forms General and Dynamic of the synchronous generator Gen – 50 MVA**

In this example the type AC8B excitation system model is used to represent the PID controlled alternator-rectifier excitation system. The PID controller is tuned for this specific case to meet the desired specifications. The form below provides an overview of the control elements of the synchronous generator. The control elements can be enabled/disabled there, and the model and its parameters can be specified.

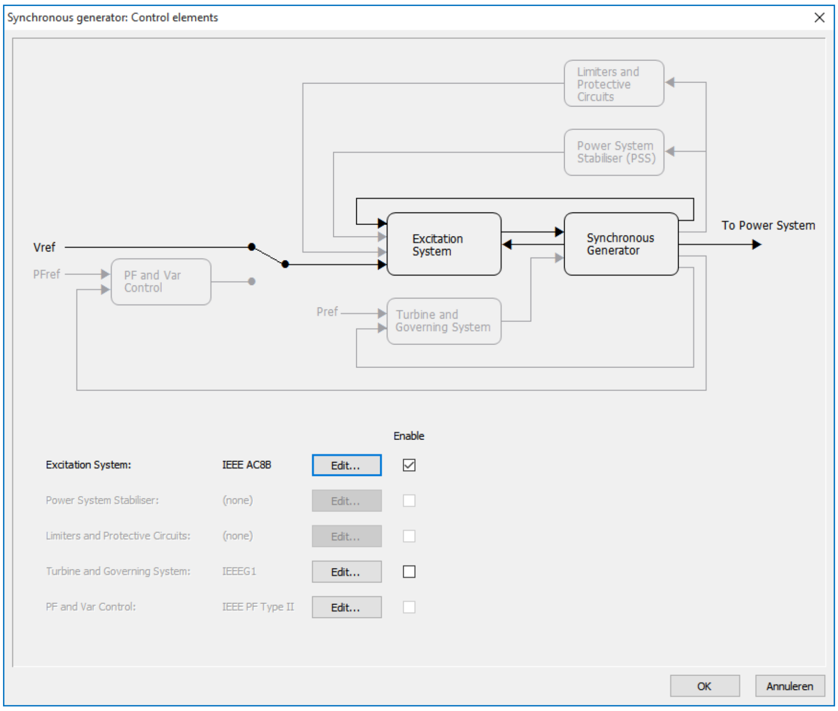

Figure 11.3 **Excitation system selection and parameter input form**

The excitation system selection and parameter input form (see the figure below) can be accessed via parameters of a synchronous generator using tabs **Dynamic | Control Elements | Edit**.

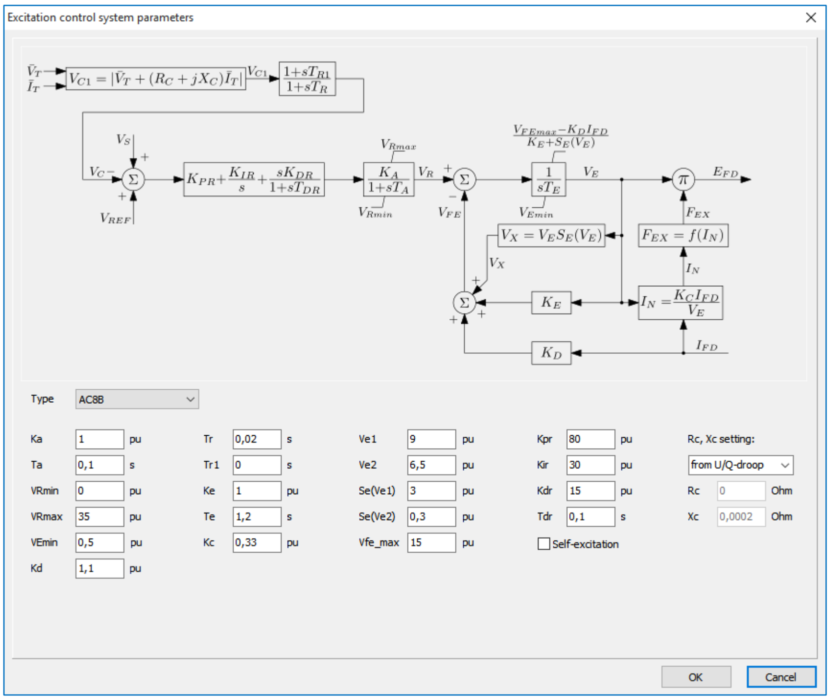

Figure 11.4 Excitation system selection and parameter input form

11.2 Dynamic Case 1: Reference step

The voltage at the terminals of the synchronous machine can be controlled by an excitation system as shown in the example of Chapter 3. The event ***Adjust voltage reference*** can therefore only be selected for networks with field controlled synchronous generators. Below the input form which can be accessed via **Insert | Dynamic case.** The dynamic case consists of two events, one positive reference step from 1 p.u. to 1.05 p.u. and one negative reference step from 1.05 p.u. back to 1 p.u.

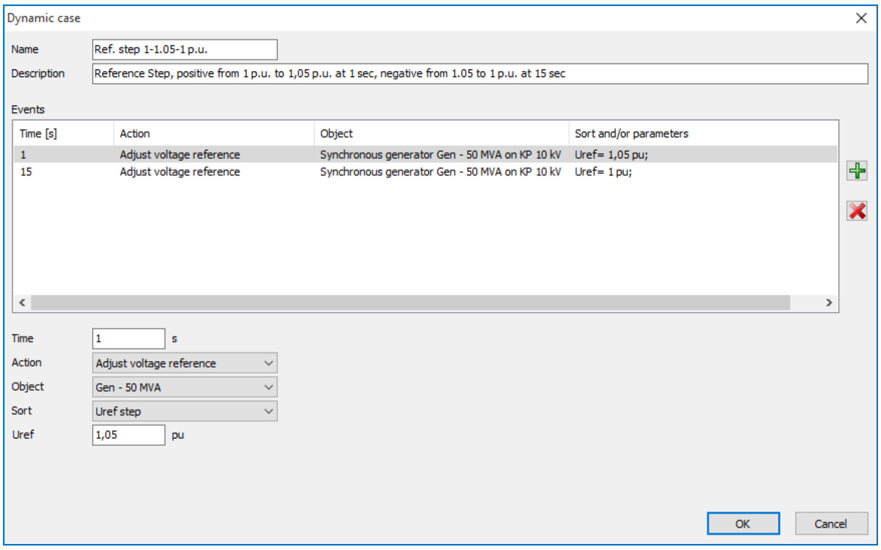

Figure 11.5 Dynamic case 1: synchronous generator reference step

After defining the dynamic case the simulation can be started using **Calculate | Dynamic analysis**. For this example only the end time of the simulation need to be specified together with the dynamic case to be simulated. Below the window with calculation parameters is shown.

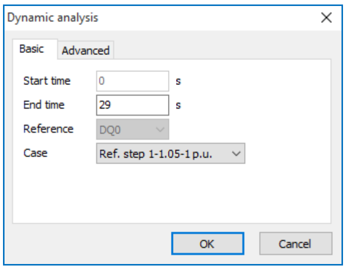

Figure 11.6 Dynamic calculation settings

Results of a dynamic calculation are shown in the form of graphical plot. By clicking on an object with the right mouse button after performing a dynamic calculation, the following form with the options of the plot will appear.

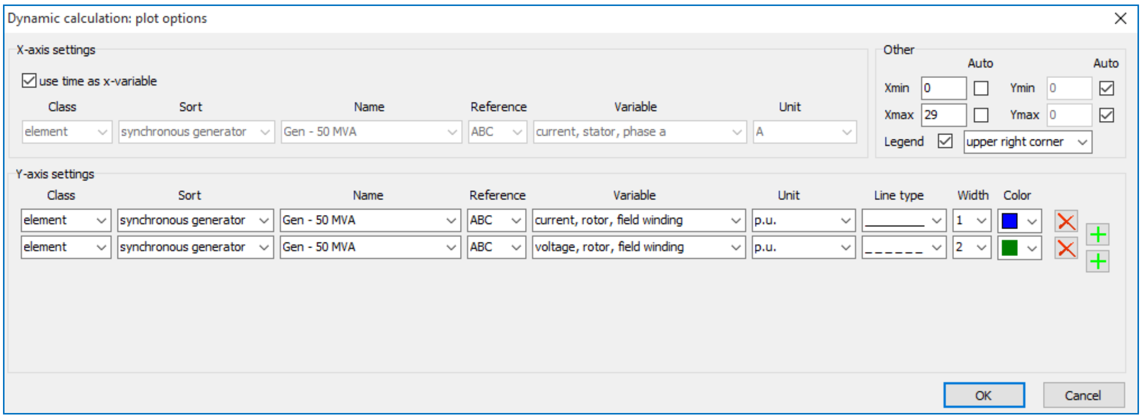

Figure 11.7 Plot options

For this plot the element of interest is the 50 MVA synchronous generator, where the variable ***current, rotor, field winding*** (I_{FD}) is plotted against time together with the variable ***voltage, rotor, field winding*** (E_{FD}). The variable *voltage, rotor, field winding* will be plotted in green with a dashed line of width 2. The legend will be shown by default in the upper right corner of the graph.

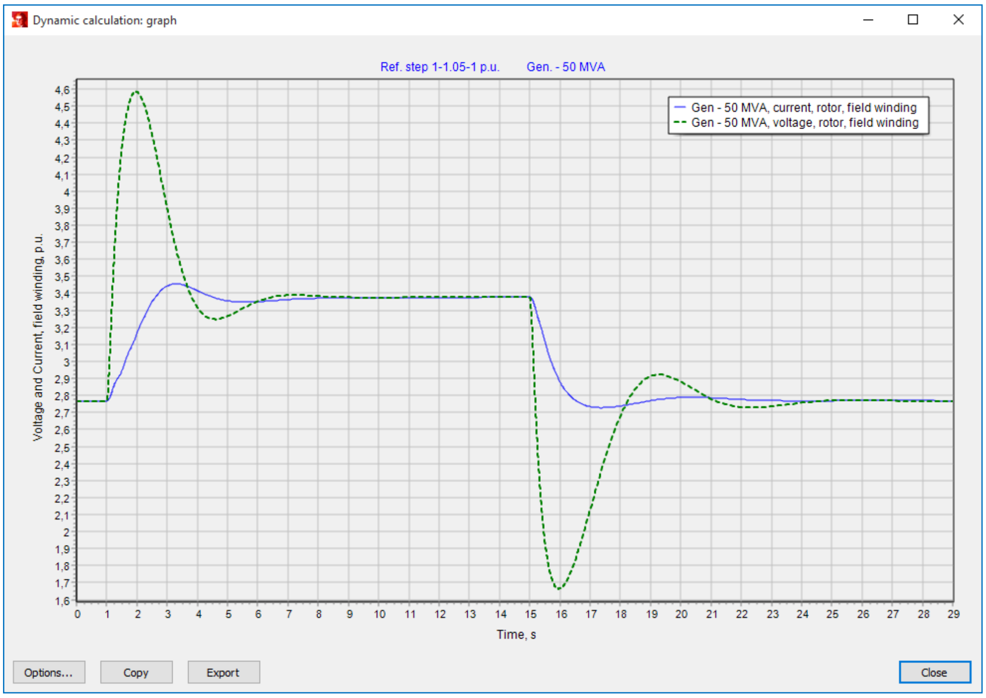

Figure 11.8 The synchronous generator field voltage and current as function of time

The control signal *voltage, rotor, field winding* (shown in the above plot) results in a change of terminal voltage as plotted in Figure 9.8. In this figure the terminal voltage magnitude is plotted, this is by selecting the variable ***excitation, x_tr***. This is a temporary variable which represents the state of the terminal voltage transducer, this variable has the same numerical value as the signal V_{c1}.

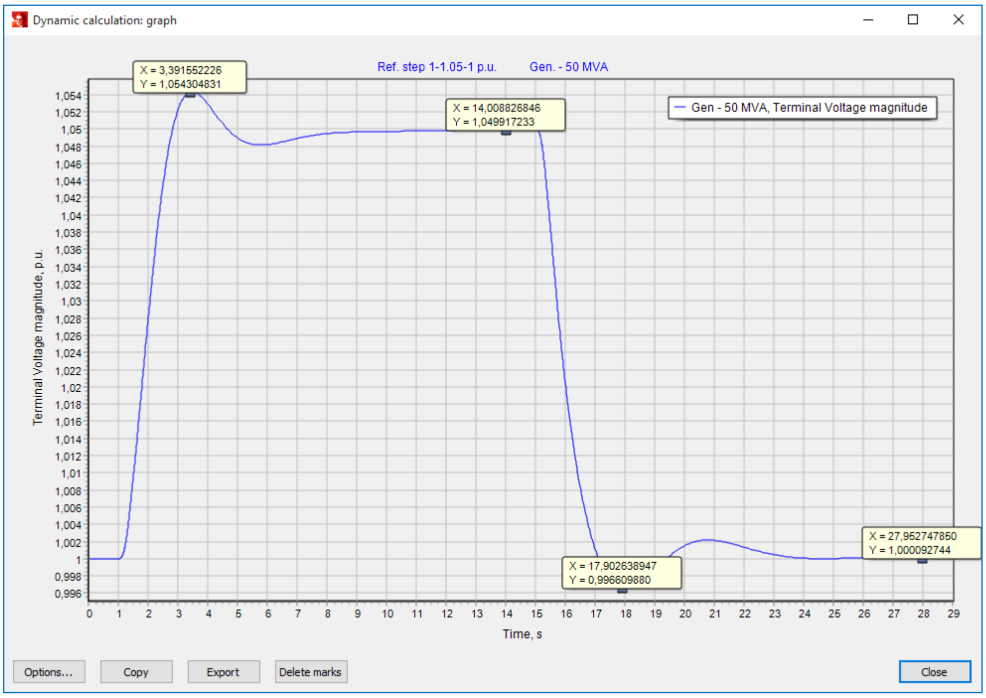

Figure 11.9 The synchronous generator terminal voltage magnitude as function of time

By clicking on the legend, plot title, and the x- and y-axis the text can be customised. By clicking on the plotted line the exact computed value is shown (the computed value nearest to the chosen point is shown), the marks can be deleted by **Delete marks**.

11.3 Dynamic Case 2: Motor start

After adding the dynamic reference step case, an extra tab ***Dynamics*** appears in the main menu, where dynamic cases can be added, modified, and erased. All cases are saved in the network file. This case consists of only one event, namely the direct start of the 1.4 MW asynchronous machine, AM1. Below the input window of this dynamic case is shown.

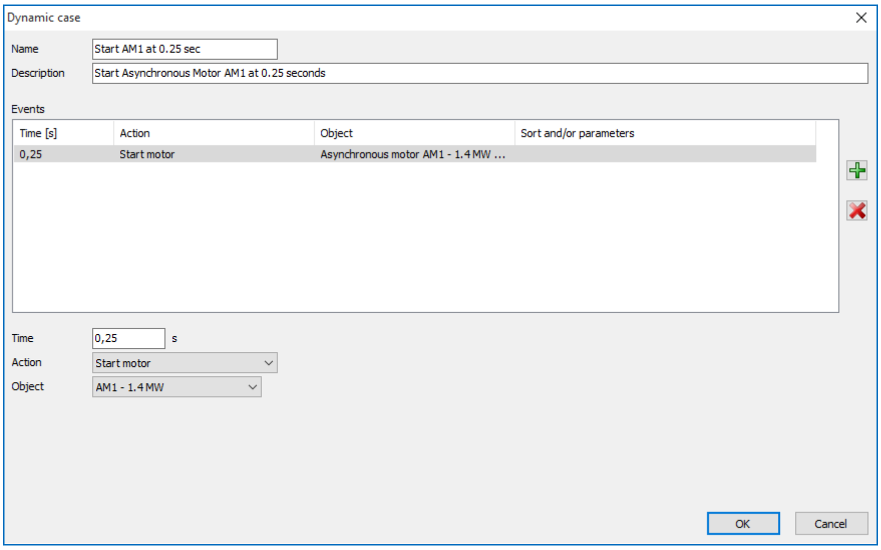

Figure 11.10 Dynamic case 2; direct start of asynchronous motor AM1

The end time of the dynamic simulation is 7 seconds, again only the basic parameters have to be specified.

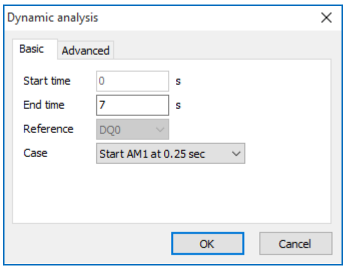

Figure 11.11 Dynamic calculation settings

To study the mechanical characteristics of the asynchronous machine the electrical and the mechanical torques are plotted against the speed of the machine (in contrary to the previous plots where the time was used as x-axis variable).

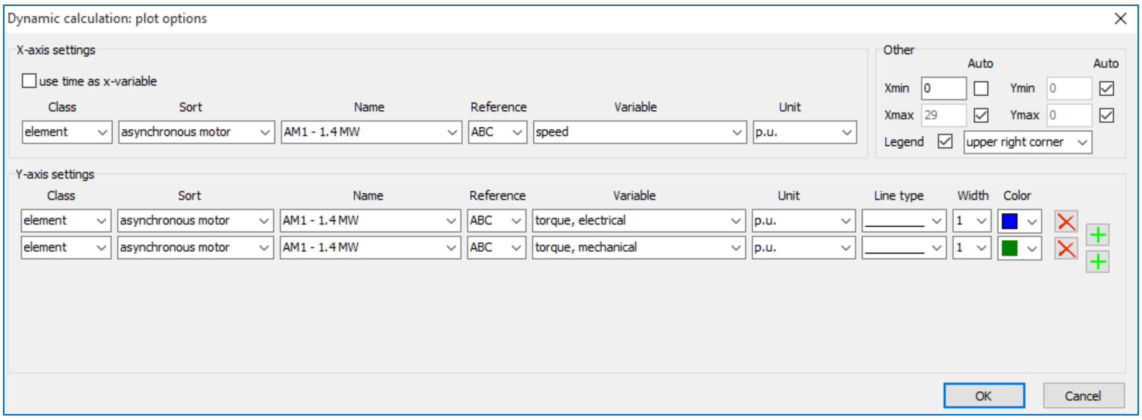

Figure 11.12 Plot options

The result is plotted below, where the mechanical and electrical torque meet in the working point.

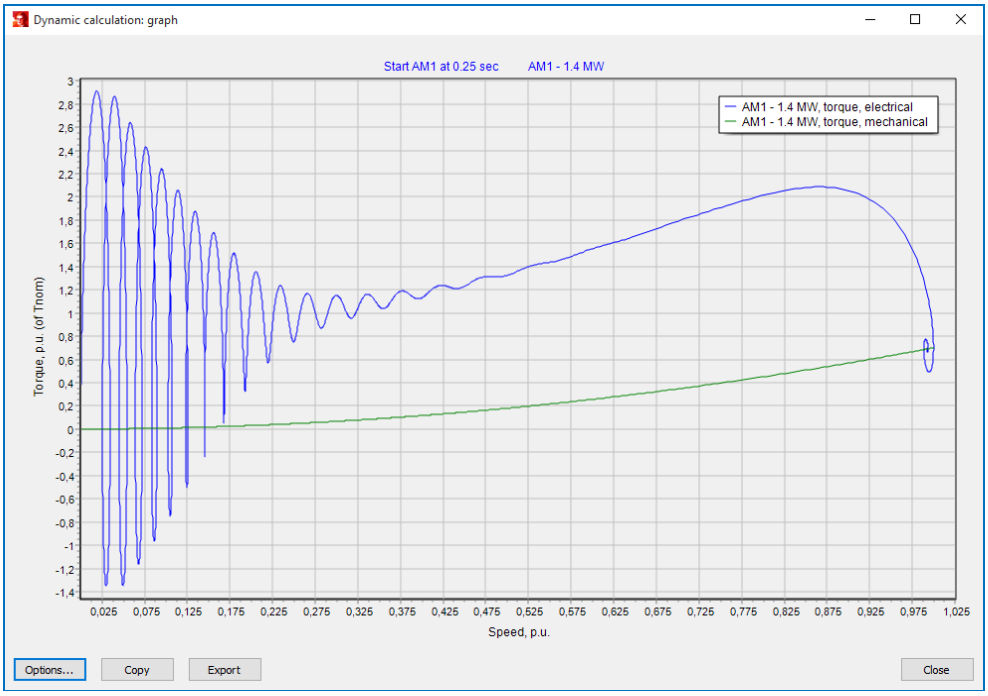

Figure 11.13 Electrical- and mechanical torque plotted against speed

The output of the excitation system (*EFD*) is plotted together with the synchronous machine field current (*IFD*), the oscillations which can be observed during acceleration of AM1 can also be observed in the field current (*IFD*).

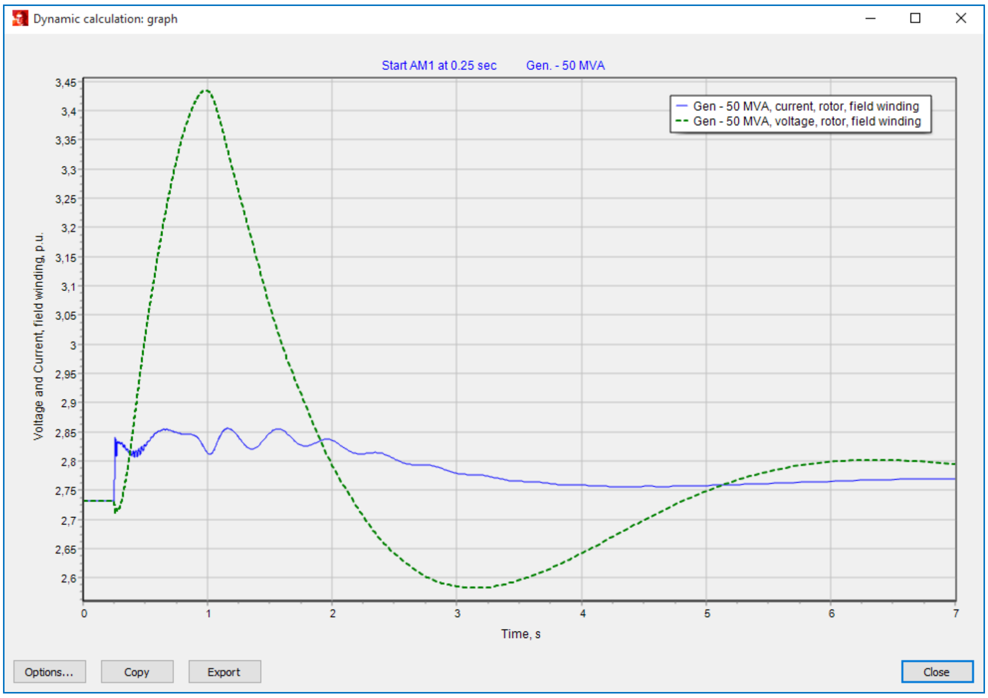

Figure 11.14 The synchronous generator field voltage and current as function of time

The above excitation system response is a result of the voltage drop at the 10 kV bushbar, this drop in voltage is plotted in the next Figure.

Using **Copy** the graph is copied to the clipboard to be pasted in a report as shown below for the synchronous machine terminal voltage magnitude.

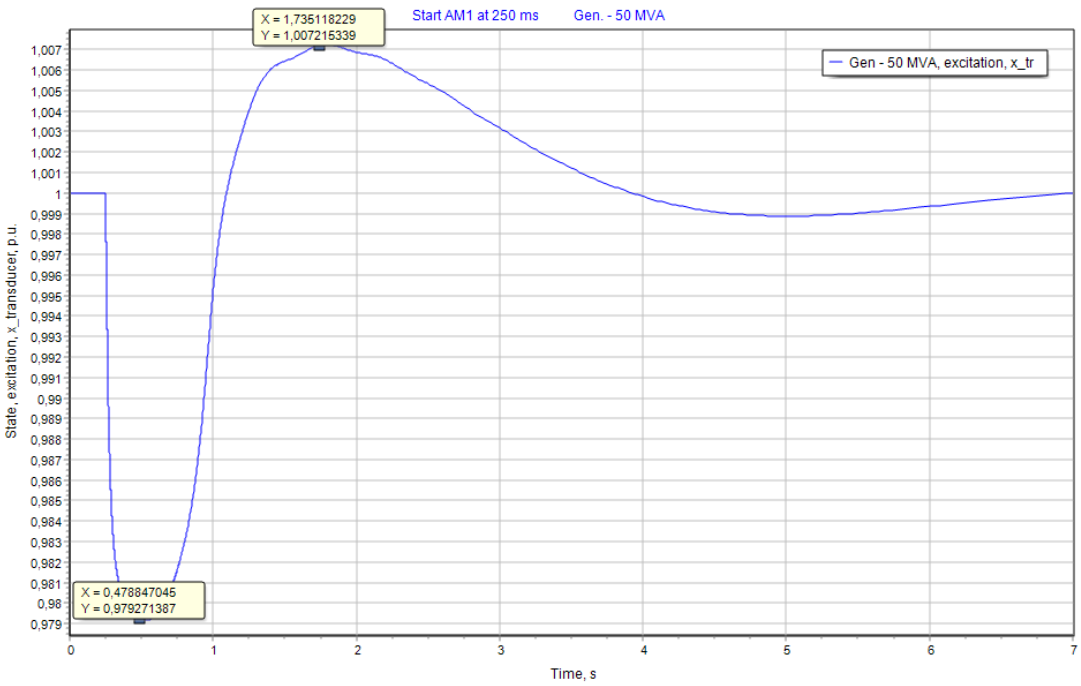

Figure 11.15 The synchronous generator terminal voltage magnitude as function of time

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