PERFORMANCE OF A SOLID STATE EXCITER FOR POWER SYSTEM STABILITY

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صفحة ٣٤

لقد صمم مستشير طلب سريع الاستجابة ومنظم للجهد الكهربائي وأنشئا بإستخدام مقوم التيار المتحكم فيه والمصنوع من مادة السلكون .
فبالاضافة الى التغذية المرتدة للجهد الطرفي العادي عملت زيادة للتحكم في جهد الاستشارة بواسطة تغذية مرتدة من السرعة .
لقد وصل كهربائي تزامني صغير في العمل مع موصل كهربائي عمومي من خلال نموذج لخط توصيل اكهربائي طويل حيث كان مجاله مستمدا من المستشير المصمم .
* ولتقويم أداء المستشير فقد سجلت إستجابة الجهاز بأنواع مختلفة من التشويش جداول لسرعة عمود الدوران وللجهد الطرقي. وقد تبين تحسن ثبات النظام عندما غذيت أشارة كهربائية أضافية تؤخذ من سرعة العضو الدوار إلى نظام المستشير الصلب .

ABSTRACT

A fast response solid state exciter and voltage regulator has been designed and constructed using silicon controlled rectifiers. In addition to normal terminal voltage feedback, provision was made to control the excitation voltage through velocity feedback. A laboratory synchronous generator was paralleled to a power system bus through a simulated long transmission line and its field was supplied from the exciter constructed. To evaluate the performance of the exciter, the response was recorded for various types of disturbances. Records of shaft velocity and terminal voltage show a definite improvement in system stability when an additional signal derived from rotor speed was fed to the solid state excitation system.

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INTRODUCTION

A power system is said to remain in stable equilibrium when the steady state electrical power output including losses equals the shaft input power. The power balance could significantly be altered when major system switchings, faults, and other large disturbances appear on the system, leading the generator rotor angles to such a value where normal power flow could be seriously impaired. Under such conditions, some or all of the machines in the system could fall out of step with each other. One of the effective methods to control this power unbalance is to drive the exciter of the synchronous machines beyond the normal operating range which transiently controls the power output of the machines. This could be easily seen from the following well known swing equation of a synchronous generator infinite bus system:

$$\frac{T_m}{\omega_0}\frac{d^2\delta}{dt^2}+D\frac{d\delta}{dt}=P_i-\frac{E_{fd}V}{X}\text{ Sin }\delta \qquad (1)$$

E_{fd} and V are the excitation voltage of the generator and busbar voltages respectively; P_i is the net power input. The reactance X in the expression for power output includes those of the machine, transformer, and transmission line.

In order to be able to control the output and hence accelerating/decelerating power, the excitation voltage E_{fd} should be varied over a large range with fast acting high gain exciters with a large ceiling voltage. Use of fast response exciters, in turn, introduces instability in the system even in the absence of disturbances [1, 2]. The possibility of improving the response with the help of various signals like velocity, acceleration and their combinations have been reported [3, 4]. A closed loop state feedback excitation strategy which is time optimal has been investigated by the authors, [5, 6]. Simplified control strategies with various feedback signals like rotor velocity deviation, acceleration, rotor angle, field and armature current etc. were attempted with digital simulation of the single machine infinite bus system considered [7]. It was observed that rotor velocity feedback was essential for improvement of the transient performance in all the cases, though combination of some other signals with it improved the response further.

This study reports the performance of a laboratory synchronous generator infinite bus system, the excitation voltage of the generator being supplied from a solid state exciter. In addition to normal terminal voltage feedback circuits, the exciter has an auxiliary rotor shaft speed deviation sensing network. The gains and time constants of the different blocks can be easily adjusted. The fact that additional shaft speed deviation signal is useful in controlling transients has been demonstrated with the help of a simple and inexpensive excitation system.

THE POWER SYSTEM CONFIGURATION

A small synchronous generator driven by a d.c. shunt motor on an AEG laboratory test set was considered for this study. The test set comprises four machines on the same shaft with provisions for measurement of voltage, power, frequency etc. The synchronous machine is rated at 1.5 kW, 400 V, the rated excitation being 200 V. The generator is connected to the power system bus through a simulated transmission line. The d.c. voltage for the generator field is provided from the main exciter. The excitation system, in addition to the normal automatic voltage regulator circuit, has an auxiliary velocity feedback loop. The block diagram of the power system is given in Figure 1.

THE EXCITATION SYSTEM

The different components of the excitation system are shown in the block diagram of Figure 2, the circuit details being provided in Figure 3. The exciter comprised of sawtooth generator, adder, comparator and inverter circuits, and a set of rectifiers. A small analog computer provided the operational amplifiers, the fixed voltages in the comparator circuit, and the precision resistances.

A set of three controlled and three uncontrolled rectifiers rectify the three-phase a.c. voltages obtained from the bus and feed the field of the generator. By chainging the firing angles of the controlled rectifiers, the excitation voltage may be varied from nearly zero to maximum value. Variation of d.c. output voltages with change in firing angle α, however, is not linear as shown in Figure 4.

The heart of the firing control circuit consists of a set of three comparators, one for each phase. The

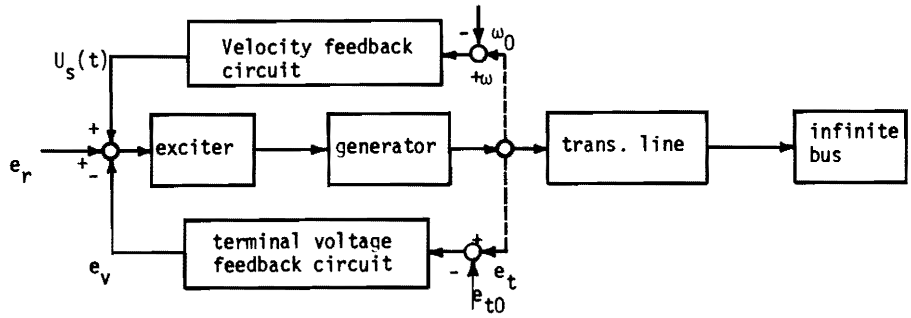


Figure 1. Power System Configuration

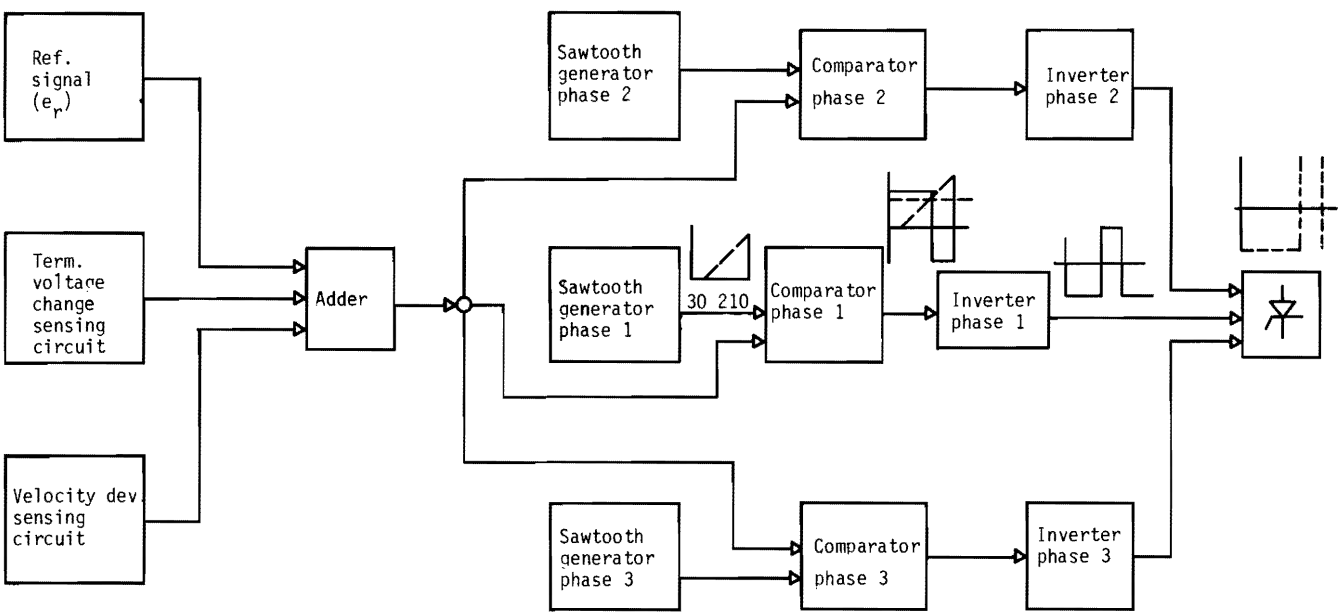


Figure 2. Block Diagram of Excitation System

comparator compares two signals, (a) a voltage time base signal (sawtooth) corresponding to the positive half-cycle, and (b) a d.c. signal which is the algebraic sum of the reference signal and the terminal voltage and velocity feedback signal. The output of the comparator is normally positive but switches its mode when the two inputs are exactly equal and opposite (Figure 2). Since the comparator switches from positive to negative voltage, this signal is inverted before being used to fire the SCR's. The comparator and inverter outputs from the experimental setup are shown in Figure 5.

Two circuits for sensing and recording the change in terminal voltage and deviation in velocity were constructed. The circuit which senses the deviation in velocity consists of a d.c. tachogenerator which produces a constant voltage when the alternator is running at synchronous speed. The output of the tachogenerator is compared with a reference voltage to produce zero output at steady state. Similarly, in the circuit for sensing the terminal voltage of the generator, the d.c. signal proportional to terminal voltage is compared with a reference signal. For any change in terminal voltage a signal appears at the input of the comparator. The adder adds the output of terminal voltage and velocity feedback sensing circuits and the reference signal to produce a controlling d.c. signal for the comparator. This circuit also serves the purpose of gain control for individual feedback signals. Control of nominal excitation voltage was obtained by changing the reference signal. The details of the design for the

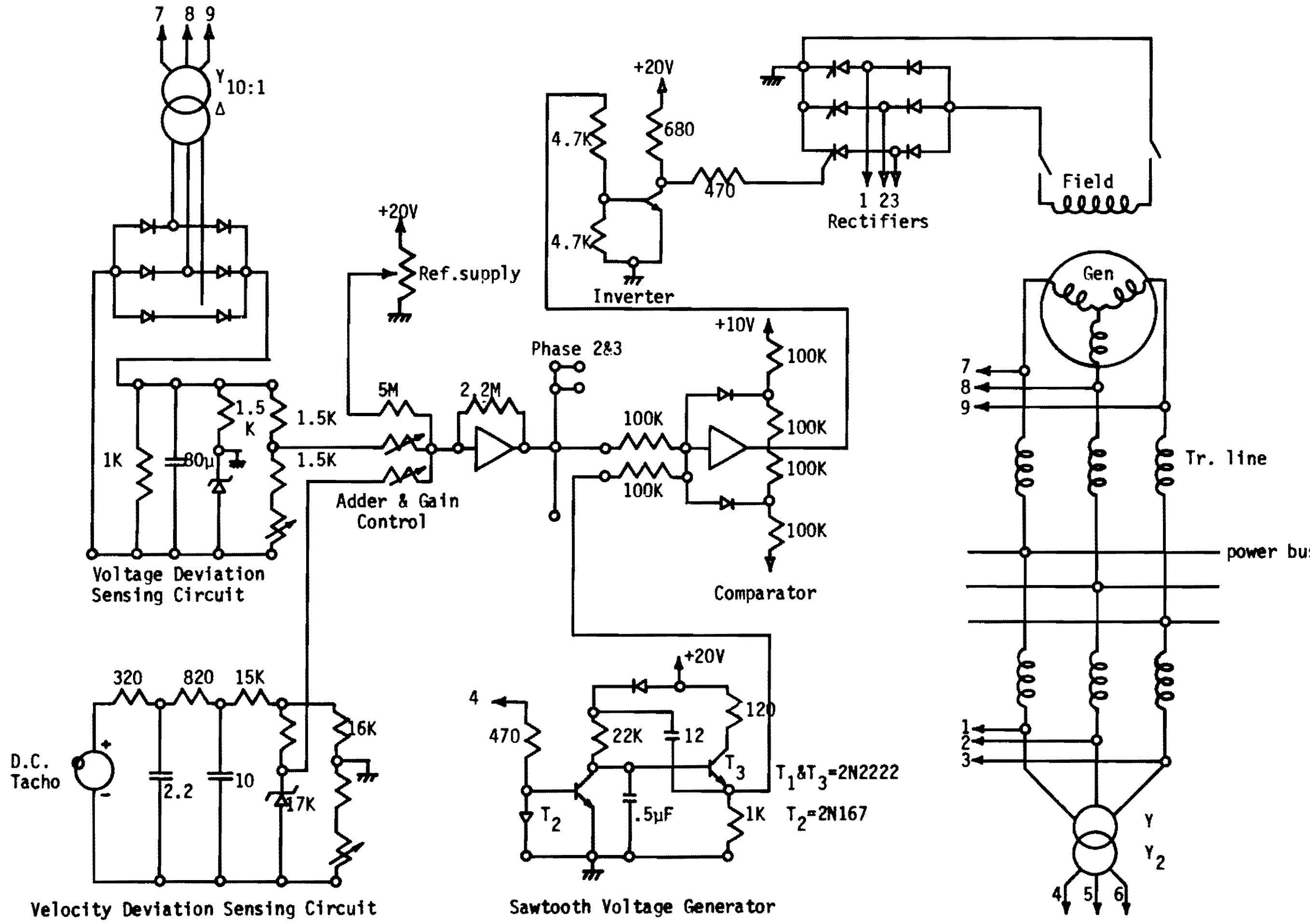


Figure 3. Circuit Diagram of Exciter (One-phase only)

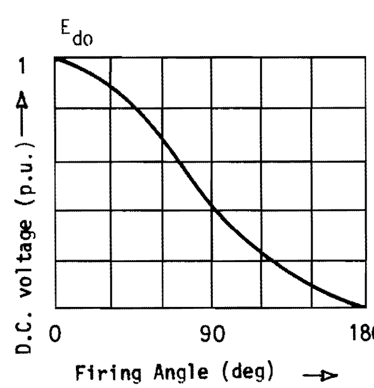
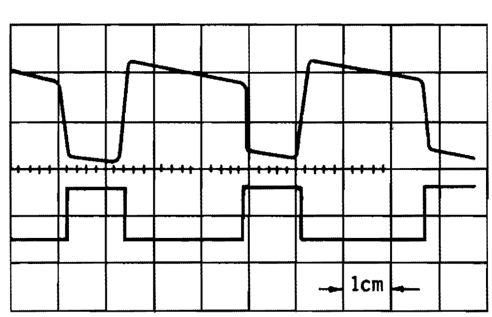


Figure 4. Phase Control Curve for the Rectifier Circuit at No Load



Time (5 msec/cm)

Figure 5. Output of the Inverter (Bottom) and Comparator (Top)

different components of the excitation system are available in [8–10].

MATHEMATICAL MODEL OF THE SYNCHRONOUS GENERATOR EXCITER SYSTEM

Park's equations relating flux, voltage, and current can also be applied to the salient pole laboratory synchronous machine in the following normalized form [6, 11].

$$\psi_{fd} = x_{ffd} i_{fd} - x_{afd} i_d \tag{2a}$$

$$\psi_d = x_{afd} i_{fd} - x_d i_d \tag{2b}$$

$$\psi_d = -x_q i_q \tag{2c}$$

$$E_{fd} = x_{afd} i_{fd} + \frac{x_{afd}}{\omega_0 r_{fd}} p\psi_{fd} \tag{3}$$

$$e_d = -r_a i_d - \frac{\omega}{\omega_0}\psi_q + \frac{1}{\omega_0} p\psi_d \tag{4a}$$

$$e_q = -r_a i_q + \frac{\omega}{\omega_0}\psi_d + \frac{1}{\omega_0} p\psi_q \tag{4b}$$

where ψ, i, e are the flux linkage, current, and voltages respectively of the different circuits. The r's and x's are the resistances and reactances, and E_{fd} is the excitation voltage. Subscripts f, d, and q refer to the field, direct, and quadrature axes armature circuits. The machine did not have an amortisseur circiut.

The equations relating the voltages and currents of the synchronous machine feeding the power system bus of voltage V through a simulated transmission line of resistance and reactance r_e and x_e respectively can be reduced to

$$e_d = r_e i_d - \frac{\omega}{\omega_0} x_e i_q + \frac{x_e}{\omega_0} p i_d + V \sin\delta \tag{5a}$$

$$e_q = r_e i_q + \frac{\omega}{\omega_0} x_e i_d + \frac{x_e}{\omega_0} p i_q + V \cos\delta \tag{5b}$$

The basic swing equation describing the electromechanical relations of the synchronous generator can be expressed as

$$\frac{T_m}{\omega_0} p^2\delta + Dp\delta = T_i - T_e \tag{6}$$

where

$$T_e = \psi_d i_g - \psi_q i_d \tag{7}$$

The various parameters of the machine are given in the appendix.

Substituting the flux linkage relations (2) into (3) and (4) and equating the expressions for direct and quadrature axes voltages in (4) and (5), a set of 3 first order differential equations in terms of field, direct, and quadrature axes armature currents can be obtained. Further, the swing equation can be broken up into the following two first-order differential equations

$$p\delta = \omega_0 n \tag{8}$$

$$pn = \frac{T_i}{T_m} - \frac{x_{afd}}{T_m} i_{fd} i_q + \frac{(x_q - x_d)}{T_m} i_d i_q - D\omega_0 n$$

where $n = \dfrac{\omega - \omega_0}{\omega_0}$.

The input torque T_i, supplied by the d.c. shunt motor, can be considered constant. Combining the differential equations in terms of currents with (8), the simplified dynamic equations of the synchronous generator are expressed as

$$\dot{\mathbf{X}} = f[\mathbf{X}, E_{fd}] \tag{9}$$

where $\mathbf{X}$ is a vector of i_{fd}, i_d, i_q, δ, and n.

The mathematical model of the solid state excitation system can be combined with the synchronous generator infinite bus equation (9) to give a complete system model. The gains and time constants of the different blocks can be varied by adjusting values of resistance and capacitance. The values mentioned in the following analysis are for those shown in Figure 3. For Zener voltage of 9.1 volts, the output voltage of the terminal voltage sensing network (Figure 3) can be expressed as

$$e_v = \frac{0.907}{1 + 0.0077\,s}\Delta e_t \tag{10}$$

where $\Delta e_t = e_t - e_{t0}$

Similarly, the output of the speed deviation sensing network can be expressed as

$$e_n = \frac{-7.16}{1 + 0.0086\,s} n \tag{11}$$

The output of the adder circuit can then be expressed as

$$\Delta e_e = K_v e_v + K_n e_n \tag{12}$$

where K_v and K_n are the adjustable gains of the respective circuits. The quantity e_n has been referred to as $U_s(t)$ or the stabilizing signal in Figure 1. The reference supply in the adder block supplies nominal excitation. The d.c. output voltage of the SCR exciter (Figure 4) can be expressed in terms of the firing angle α by the following nonlinear relations

$$E_{fd}=1.865(1+\cos\alpha),\ \alpha<60^\circ$$
$$E_{fd}=3.904(1+\cos\alpha)/(\pi-\alpha),\ \alpha>60 \quad (13)$$

For a very small variation of the firing angle α, the above can be approximated by the linear expression as

$$\Delta E_{fd}=-1.1664\ \Delta\alpha \quad (14)$$

In general, the sawtooth generator, comparator, inverter circuits, and the SCR can be combined in one block and the input/outputs are related by

$$\Delta E_{fd}=\frac{K_r}{1+T_r s}\Delta e_e \quad (15)$$

where the value of T_r obtained was 0.02 s approximately. The excitation system shown in Figure 1 may be represented by the simplified block diagram shown in Figure 6.

The time constants in the velocity and voltage feedback loops are small in comparison to T_r and hence may sometimes be neglected. This assumption gives a very simple input/output relation for the exciter system as follows

$$pE_{fd}=\frac{-K_r}{T_r}e_t-\frac{1}{T_r}E_{fd}+(E_{fd0}+K_r e_r)/T_r+\frac{K_r}{T_r}U_s(t) \quad (16)$$

Equation (16) and matrix differential relationship (9) give the complete synchronous generator exciter model.

RESULTS

The performance of the excitation system in stabilizing a single machine infinite bus power system has been studied considering different disturbances. For each disturbance, speed and terminal voltage variations of the machine were recorded for three different modes of operation of the exciter: (a) exciter on open loop; (b) with terminal voltage feedback only (normal a.v.r. action); and (c) with both terminal voltage and velocity feedback. Results for only two types of disturbances involving extreme power unbalance viz a momentary three-phase short circuit while the machine was delibering rated power, and sudden loading of the generator (100% and 40%) are reported here.

The terminal voltage and velocity deviation characteristics of the generator for sudden application of full

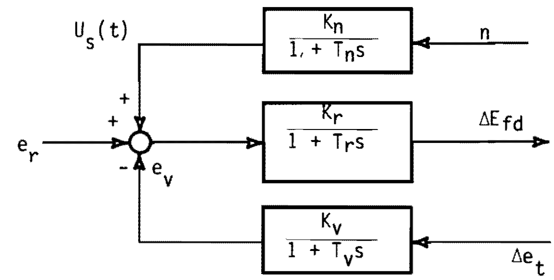


Figure 6. Block Diagram of Excitation System

load while it was floating on the power system bus, are shown in Figure 7. The plot of rotor velocity shows that without feedback, the transients die down very slowly. While voltage feedback alone improves the situation, additional velocity feedback reduces the magnitude and duration of the transients, significantly. With a large gain in the voltage feedback circuit, the first swing is large but settling time is less. The value of gain used for the case in Figure 7 is 4. The variation of terminal voltage and rotor velocity following a momentary three-phase short circuit on the generator terminals is shown in Figure 8. Examination of Figure 8b (top) and c (bottom) shows that transients are sufficiently damped when additional velocity feedback signal is used. Without any feedback (open loop exciter), terminal voltage fluctuations are completely unacceptable and hence are not recorded.

The response of the system depends very much on the gains and time constants of the different blocks of the exciter. It was observed that significant increase of the time lags, indicated in the previous section, worsened the response. With the experimental setup, an extensive study of the various types of faults could not be done because of some physical limitations. For the two types of faults studied, the gain settings for best transient response were found to be different. In another study [7], the synchronous generator was simulated on a digital computer. Though basically a similar exciter representation like the one in this study was used, the gains and time constants were varied over a wide range. Also the time lag in the velocity feedback circuit was considered zero. From study of a large number of cases, it was observed that the optimum gain in the velocity feedback circuit was about 20. For this particular synchronous generator (data given in the appendix), the overall regulator gain (K_r) of about 20 was found to be satisfactory both in terms of peak overshoot and settling time. Table 1 shows the gain settings of the different blocks of the exciter for the laboratory setup.

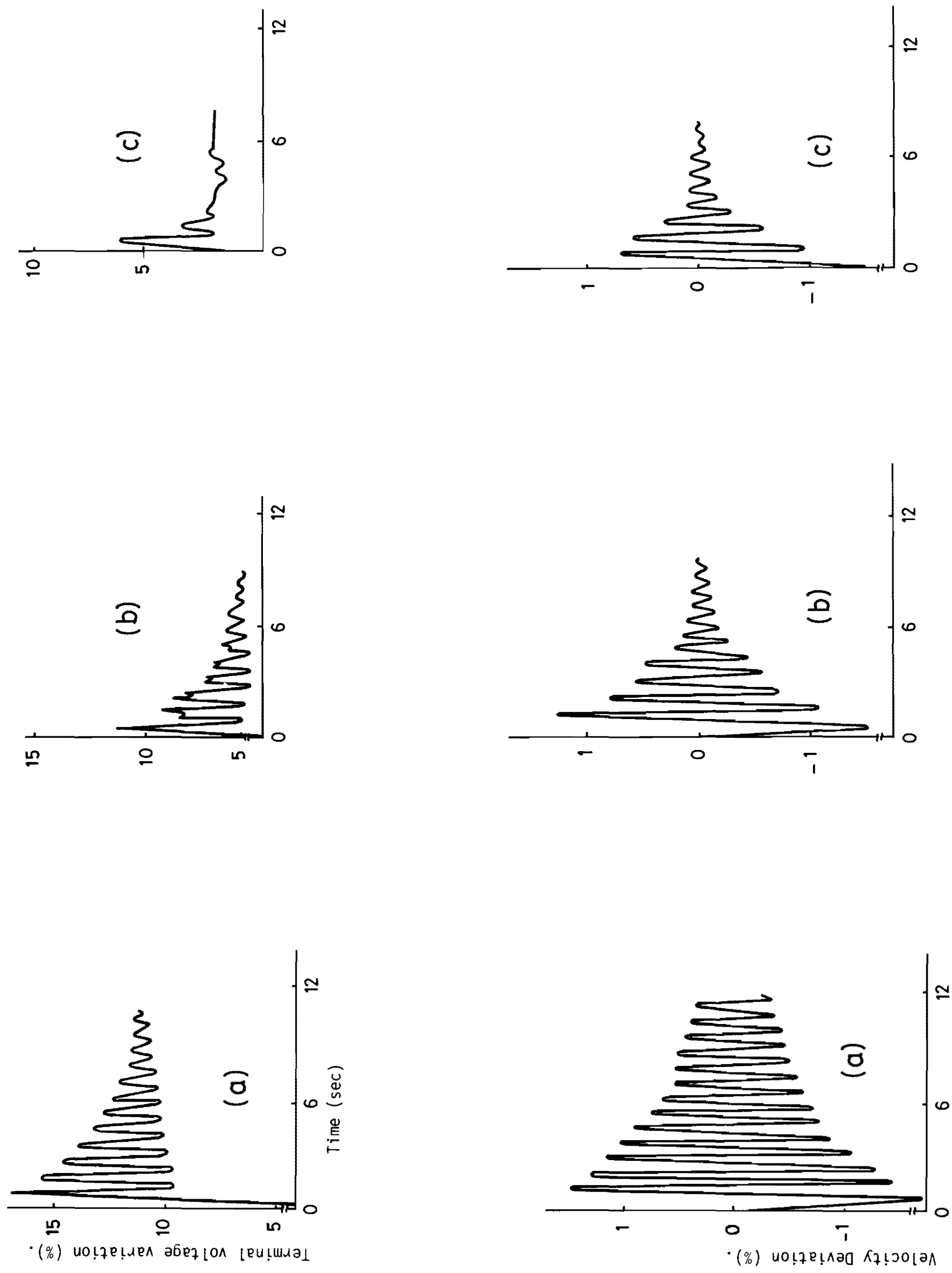


Figure 7. *Terminal Voltage and Velocity Deviation vs. Time Characteristics for a 100% Torque Step When the Generator is Floating (a) Without or Velocity Feedback, (b) With a.v.r. Only, (c) With a.v.r. and Velocity Feedback*

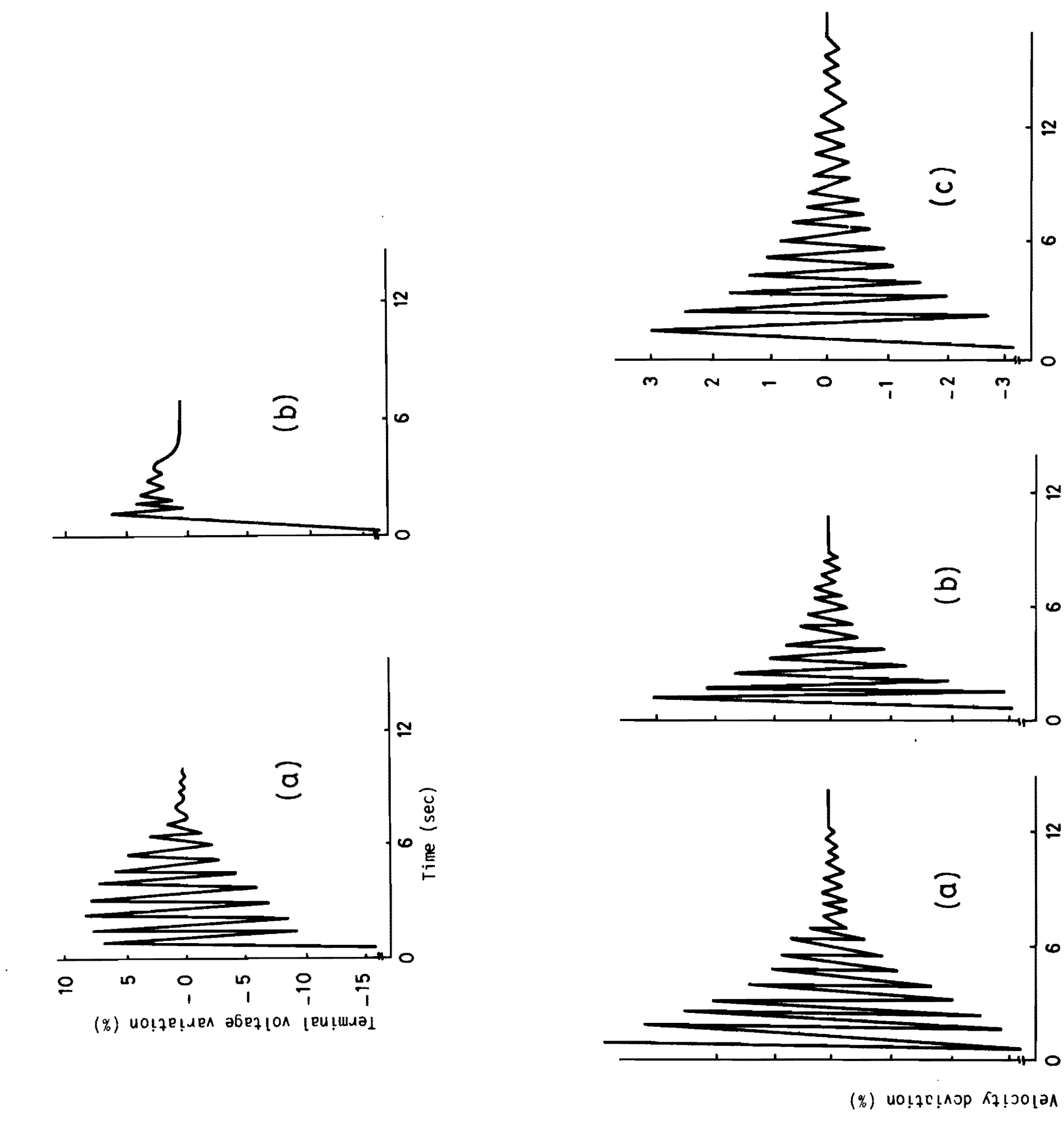


Figure 8. Top: Terminal Voltage–Time Characteristics Following a Momentary Three-phase Short Circuit at the Generator Terminals (b) With a.v.r. Only, (b) with Voltage regulator and Velocity Feedback. Bottom:Corresponding Velocity–Time Characteristic (a) With a.v.r. Only, (b) With a.v.r. and Velocity Feedback, (c) Without a.v.r.

Table 1. Results for Different Gains of the Exciter Blocks

Nature of Disturbance	Gains of: Voltage Sensing Circuit	Gains of: Velocity Sensing Circuit	Maximum Deviation (%): Velocity	Maximum Deviation (%): Term. Voltage.	Setting Time (s): Velocity, 0.1% of S.S. Value	Setting Time (s): Voltage, 1% of S.S. Value	S.S. Voltage Error
100% Torque Step.	0	0	1.7	17	18	8	11.5
	4	0	1.6	7	7	6	1
	4	6	1.5	—	5	—	—
	2	10	—	6.5	—	3	2.5
40% Torque Step.	0	0	0.5	6	4	4	3
	4	0	0.7	5	8	6	1
	4	6	0.4	3	3.5	3	1
Momentary Short Circuit on Gen. Terminal	0	0	3.25	—	12	8	—
	4	0	4.5	10	11	8	0
	4	10	3	6	8	5	0

CONCLUSION

A very simple, inexpensive, and efficient excitation system for a laboratory test machine has been designed and constructed using silicon controlled rectifiers. The time constants of the exciter circuits could be made very small. While for the range of gains studied, the a.v.r. action above is superior to that without a.v.r., additional velocity deviation feedback improves damping and the transients are controlled effectively. Particularly, terminal voltage characteristics show a marked improvement.

The use of supplementary stabilizing signal particularly velocity feedback for stabilizing synchronous generators with fast response excitation system is not new. This work was intended for construction of a reasonably efficient device with a minimum of components for a laboratory test machine, with the intention of extending the design for larger machines. Of course, modification and expansion of the circuitry will be necessary to suit particular requirements. A digital study similar to the one reported by the first author and discussed earlier, may be a good starting point in selecting the various parameters.

APPENDIX

Synchronous generator infinite bus system parameters in per unit on machine base:

$x_{afd} = 1.0$	$x_{ffd} = 1.195$	$x_d = 1.05$
$x_q = 0.558$	$r_a = 0.11$	$r_{fd} = 0.01542$
$r_e = 0.0425$	$x_e = 1.56$	$T_m = 4.8$ s
$\omega_0 = 314$ rad/s		

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