DESIGN OF A PI CONTROLLER FOR A SUPERCONDUCTING GENERATOR

G.A. Morsy , H.Khattab and A.M. Kinawy

Electrical Engineering Department, Faculty of Engineering,
Menoufiya University, Shebin El-Kom, EGYPT.

ABSTRACT

This paper proposes proportional integral (PI) controller to modulate the performance of a superconducting generator (SCG) according to its speed variation. The control design procedure is simple and the proposed controller is also relatively simple for practical implementation. Eigenvalue analysis of the controlled system reveals that the PI controller is quite effective. Digital simulation studies using detailed nonlinear system model are also performed in order to show the effectiveness of the proposed controller over a wide range of operating conditions.

1. INTRODUCTION

The flexability and effectiveness of the control methods in generating plants are of great importance. The availability of electro-hydraulic governors with fast valving and modern thyristor exciters has made it possible to obtain rapid control schemes for turbo-generators. Considerable attention has been directed to the application of integrated control to improve the performance of generating units [1-4].

Manuscript received from Dr. G.A. Morsy on : 16/11/1999
Accepted on : 31/11/1999
Engineering Research Bulletin, Vol 23,No 1, 2000 Minufiya University, Faculty of Engineering , Shebien El-Kom , Egypt, ISSN 1110-1130

Superconducting generators are expected to replace conventional machines in modern turbogenerators, this is because of their capability to supply greater base load, smaller size and weight, high efficiency and possible generation at bus votlages. However, these machines have low per-unit reactance, low inherent damping and high hunting frequency which affects the system stability [5,6]. Furthermore, the SCG has almost zero resistance of field winding consequently an extremly long field circuit time constant (750 Sec.) which made it necessary to consider only the governor control loop to enhance the machine performance. Several arrangements have been previously proposed to improve the performance and to provide extra damping for the SCGs [7-11].

The purpose of this paper is to design a PI controller in the governor feedback loop using the speed error signal. The proposed PI controller is relatively simple for practical implementation and can effectively enhance the system performance, particularly to minimize post fault oscillations. Eigenvalue analysis and time domain nonlinear simulation are performed in order to demonstrate the effectiveness of the proposed controller.

2. SYSTEM DESCRIPTION

The system considered is a superconducting generator unit connected to a large power system via a transformer and a double circuit transmission line. The generator is driven by a three-stage reheat steam turbine with fast acting electrohydraulic governor and interceptor valves [1-3]. A schematic diagram of this system is shown in Fig. (1).

3. NON-LINEAR MATHEMATICAL MODEL

3-1 Superconducting Generator

The following non-linear equations based on Park's d-q axes, together with the mechanical equations of motion, are used to represent the SCG [12]. For simplicity, each of the rotor screens are represented by one fixed coil in each axis,

$$P\Psi_f = \omega_o (v_f - R_f i_f) \tag{1}$$

$$P\Psi_d = \omega_o (v_d - R_a i_d + \Psi_q) + \omega\Psi_q \tag{2}$$

$$P\Psi_q = \omega_o (v_q - R_a i_q - \Psi_d) - \omega\Psi_d \tag{3}$$

$$P\Psi_{KD1} = \omega_o R_{KD1} i_{KD1} \tag{4}$$

$$P\Psi_{KQ1} = \omega_o R_{KQ1} i_{KQ1} \tag{5}$$

$$P\Psi_{KD2} = \omega_o R_{KD2} i_{KD2} \tag{6}$$

$$P\Psi_{KQ2} = \omega_o R_{KQ2} i_{KQ2} \tag{7}$$

$$P\delta = \omega \tag{8}$$

$$P\omega = (\omega_o / 2H) [T_m - T_e] \tag{9}$$

where,

$$T_e = \Psi_d i_q - \Psi_q i_d \tag{10}$$

3.2 Transformer and Transmission Line

$$V_d = V_b \sin \delta + R_e I_d - X_e I_q \tag{11}$$

$$V_q = V_b \cos \delta + R_e I_d + X_e I_q \tag{12}$$

where, $X_e = X_T + X_L$

$R_e = R_T + R_L$

3.3 Turbine and Governor System

The turbine and governor are represented by six-order model with appropriate limits on valve position and velocity.

$$PY_{HP} = (G_M P_o - Y_{HP}) / T_{HP} \tag{13}$$

$$PY_{RH} = (Y_{HP} - Y_{RH}) / T_{RH} \tag{14}$$

$$PY_{IP} = (G_I\, Y_{RH} - Y_{IP}) / T_{IP} \qquad (15)$$

$$PY_{LP} = (Y_{IP} - Y_{LP}) / T_{LP} \qquad (16)$$

$$T_m = F_{HP}\, Y_{HP} + F_{IP}\, Y_{IP} + F_{LP}\, Y_{LP} \qquad (17)$$

The electro-hydraulic governor and interceptor valve mechanisms equations are:

$$PG_M = (u_{GM} - G_M) / T_{GM} \qquad (18)$$

$$PG_I = (u_{GI} - G_I) / T_{GI} \qquad (19)$$

where, the position and rate limits are,

$$0 \leq G_M, G_I \leq 1 \quad \text{and} \quad -6.7 \leq PG_M, PG_I \leq 6.7$$

Y_{HP} is the output of the high pressure stage in per-unit, and F_{HP} Y_{HP} is the contribution of the high pressure stage to the total shaft torque, etc. All the SCG, transmission system, turbine and governor parameters are given in Appendix (A). Fig. (2) shows the representation of turbine and governor system.

4. CONTROLLER DESIGN

4.1 Linearized Model

The non-linear model presented in the previous section is essential to investigate the transient performance of the SCG. However, to design controllers for the machine a linear model is required. So, the non-linear equations (1-19) are perturbed about a steady state operating point. This provides a linearized model of the system.

The eigenvalues of the system without controller and with speed governor at different operating conditions are listed in Tables (1) and (2). The results shown in the tables illustrate that the dominant eigenvalues of the system are those corresponding to the rotor and field modes, and which affect directly the system stability. Any control system may concentrate to move these roots towards the left hand side of the S-plane.

TABLE (1) Eigenvalues of the open loops system (P = 0.8 p.u.)

System	$\alpha + j\omega$		
Modes	0.8 lead p.f.	unity p.f.	0.8 lag. p.f.
Stator	-6.576 ± j 313.91	-6.578 ± j 313.91	-6.58 ± j 313.91
Rotor	-0.388 ± j 6.47	-0.3 ± j 9.05	-0.276 ± j 10.58
Field	-0.000505	-0.000642	-0.000658
Screens	-30.431 -30.773 -2.838 -1.0362	-30.379 -30.841 -3.007 -1.004	-30.373 -30.858 -3.0341 -1.0293
Turbine and Governor	-3.333 -3.333 -0.100 -10.00 -10.00 -10.00	-3.333 -3.333 -0.100 -10.00 -10.00 -10.00	-3.33 -3.333 -0.100 -10.00 -10.00 -10.00

TABLE (2) Eigenvalues of system with speed governor (SG).

Domainant Modes	0.8 Lead p.f.		unity p.f.		0.8 Lag. p.f.	
	Open loop	with SG	Open Loop	With SG	Open Loop	With SG
Rotor	- 0.388 ± j 6.47	- 0.34 ± j 7.25	- 0.31 ± j 9.05	- 0.174 ± j 9.59	- 0.276 ± j 10.58	- 0.11 ± j 11
Field	-0.0005	-0.0005	-0.00064	-0.00064	-0.00066	-0.00066

4.2 Design Procedure

PI controller is introduced to enhance the system performance and to add positive damping. In order to determine the parameters of this controller, the state equations of the linearized system are written as,

$$[\dot{X}] = [A]\,[X] + [B]\,[u] \quad (20)$$
$$[Y] = [C]\,[X] \quad (21)$$

where, [X] is a 15th order state vector.

$$[X]^t = (\delta, \omega, \Psi_f, \Psi_d, \Psi_q, \Psi_{KD1}, \Psi_{KQ1}, \Psi_{KD2}, \Psi_{KQ2}, Y_{HP}, Y_{RH}, Y_{IP}, Y_{LP}, G_M, G_I)$$

and,

[u] = the control signal (PI output)

[Y] = $\Delta\omega$ is the output signal (PI input).

A schematic diagram of the control system is shown in Fig. (3).

Taking the Laplace transform of eqns. (20) and (21), we have the state equations in frequency domain.

$$SX(S) = A\,X(S) + B\,U(S) \quad (22)$$

$$Y(S) = C\,X(S) \quad (23)$$

Equation (22) can written as,

$$X(S) = (SI - A)^{-1}\,B\,U(S) \quad (24)$$

The control signal can be expressed as,

$$U(S) = H(S)\,Y(S)$$

$$= [S/(1+ST_W)]\,(K_P + K_I/S)\,Y(S) \quad (25)$$

Where the washout time constant T_w and the gains K_p and K_I are the controller parameters to be determined. Combining eqns. (23), (24) and (25) we get,

$$X(S) = (SI - A)^{-1}\,B\,H(S)\,C\,X(S) \quad (26)$$

The characteristic equation of the system is then given by:

$$I - C\,(SI - A)^{-1}\,B\,H(S) = 0 \quad (27)$$

Substituting by the desired values of the dominant eigenvalues λ_i, i=1,2,3 into equation (27) we have,

$$H(\lambda_i) = I / C(\lambda_i I-A)^{-1} B$$
$$= (\lambda_i / 1+\lambda_i T_w)) (K_p + K_I / \lambda_i) \quad (28)$$

Thus, we have a set of algebriac equations with three unknowns T_w, K_p and K_I. Solving the above set of equations the controller parameters can be obtained as:

$T_w = 0.412$ Sec. , $K_p = 0.0744$ and $K_I = 2.667$

The eigenvalues for the system with PI controller are listed in Table (3). It is illustrated that the dominant modes has been shifted to the left to the new desired position.

Domainant Modes	$\alpha \pm j\omega$					
	0.8 Lead p.f.		unity p.f.		0.8 Lag. p.f.	
	Open loop	with PI	Open Loop	With PI	Open Loop	With PI
Rotor	- 0.388 ± j 6.47	- 5.3 ± j 10.5	- 0.31 ± j 9.05	- 3.8 ± j 12.0	- 0.276 ± j 10.58	- 2.95 ± j 13.6
Field	-0.0005	-0.0005	-0.00064	-0.00064	-0.00066	-0.00066

Table (3) Eigenvalues with PI controller.

5. TIME DOMAIN SIMULATION

To illustrate the effectiveness of the previously designed PI controller, digital computer simulation using the non-linear model is performed for the system subject to symmetrical three phase short circuit of 120 ms duration at the high voltage busbars of the generator transformer. In the digital simulation the system non-linear equations were solved using the Runge-Kutta integration technique. The system response with and without controllers are plotted in Figs.(4) and (5), at a lagging and leading power factors respectively. The results clearly shows a significant improvement in the system performance via a well designed PI controller, since the speed deviation, the rotor angle and the terminal voltage oscillations die away more quickly with the prevention of steam valve excessive movements. Also, figures (6) and (7) illustrates the effectiveness of the designed PI controller compared with the previously designed phase advance circuit [11] which has a transfer function of the form $G_{ph.a}(s) = K\ (1+S\ T_1)\ /\ (1+S\ T_2)$, with $T_1 = 0.5$ Sec., $T_2 = 0.01$ Sec., and $K = 0.1$.

6. CONCLUSIONS

PI controller have been designed and implemented for a SCG connected to an infinit power system. The controller parameters are determined by shifting the system dominant eigenvalues to desirable locations. The eigenvalue analysis indicate that the designed PI controller yield a satisfactory damping for the system under various operating conditions.

Time domain simulation using the system non-linear model is also performed to show the validity of the designed controller. The results illustrate a well damped response which substantiates the proposed controller.

Appendix - A

* SCG parameters

2000 MVA, 1700 MW, 3000 rpm

$X_d = X_q = 0.0453$ p.u. , $X_f = 0.541$ p.u.

$X_{KD1} = X_{KQ1} = 0.2567$ p.u. , $X_{FKD2} = 0.3398$ p.u.

$X_{af} = X_{fKD1} = X_{ad1} = X_{ad2} = X_{KD1\ KD2} = 0.237$ p.u.

$X_{aq1} = X_{aq2} = X_{KQ1\ KQ2} = 0.237$ p.u.

$R_{KD1} = R_{KQ1} = 0.01008$ p.u.

$R_a = 0.003$, RKD2 = RKQ2 = 0.00134 ,

H = 3 KWS/KVA

* Transmission System Parameters

$X_T = 0.15$ p.u. , $R_T = 0.003$ p.u.

$X_L = 0.05$ p.u. , $R_L = 0.005$ p.u.

* Parameters of Governor and Turbine

$T_{HP} = 0.1$ sec. , $F_{HP} = 0.26$, $T_{IP} = 0.3$ Sec.,

$F_{IP} = 0.42$

$T_{LP} = 0.3$ sec. , $F_{LP} = 0.32$, $T_{RH} = 10$ sec.

$T_{GM} = T_{GI} = 0.1$ sec. , $P_o = 1.2$ p.u.

Nomenclature

H inertia constant (kWs/kVA)
I current (p.u.)
P differential operator
R resistance (p.u.)
T torque
V voltage (p.u.)
X reactance (p.u.)

Greek letters

δ rotor angle
ψ flux linkage (p.u.)
ω angular speed (rad/s)

Subscripts

a armature
d,q d and q components of stator winding
e,m electrical, mechanical
f field
o steady state
fKD_1,fKQ_1 d and q mutual components between outer screen and field winding SCG
fKD_2,fKQ_2 d and q mutual components between inner screen and field winding SCG
KD_1,KQ_1 d and q components of outer screen
KD_2,KQ_2 d and q components of inner screen

REFERENCES

[1] S.I. Ahson, B.W. Hogg and R.T. Pullman, "Integrated control system for turbogenerator designed by inverse Nyquist array method", IEEE. Trans., PAS-98, (2), pp. 543-553 (1979).

[2] R.T. Pullman and B.W. Hogg, "Integrated control system for a turbogenerator", Int. J. Control, 29, (3), pp. 505-521 (1979).

[3] S.I. Ahson and B.W. Hogg, "Application of multivariable frequency response methods to control turbogenerators", Int. J. control, 30(4), pp. 533-548 (1979).

[4] S.M. Osheba and B.W. Hogg, "Mutlivariable controller for a turbogenerator", IEEE, Winter Power Meeting, New-York, paper A 80, 106-5, Feb., 1980.

[5] P.J. Lawrenson, T.J.E. Miller, J.M. Stephenson and A.H. M.S. ULa, "Damping and screening in synchronous superconducting generator", Proc. IEE, Vol. 123, No.8, pp. 787-794 (1976).

[6] D.L. Prior, M.A.A.S., Alyan and C.A. Anyaeji, "Equivalent circuit representation of a superconducting alternator", Proc. IEE, vol. 129, pt C., No.6, pp. 266-277 (1982).

[7] R.M. Mather, P.K. Dash and A.E. Hammad, "Transient and small signal stability of a superconducting turbo-generator operating with thyristor controlled static compensator", IEEE Trans., PAS-98, No.6, pp. 1937-1945 (1979).

[8] S.Y. Hahn, A. Mailfert and A. Rezzoug., "Transient performance of superconducting alternator with damper winding", IEEE. PES Winter Meeting, New York, Paper A79 010-0 (1979).

[9] Jr.J.L. Kirtley, "Armature motion damping of superconducting generators", IEEE, PES. Winter Meeting, New-York, Paper A79 012-6 (1979).

[10] M.A.A.S. Alyan, Y.H. Rahim, "A Discreet state space controller for superconducting turbogenerators", IEEE. Trans. on Energy Conv. Vol. 3, No.2, pp. 300-304, June 1988.

[11] G.A. Morsy, A. Kinawy and S.M. Osheba, "Frequency domain analysis of a superconducting generator", Elect. Power System Research 30, pp. 107-113 (1994).

[12] S.M. Osheba et al., "Comparison of transient performance of superconducting and conventional generators in a multi-machine system", Proc. IEE., Vol.135, Pt. C, No.5, pp. 289-295, Sept. 1988.

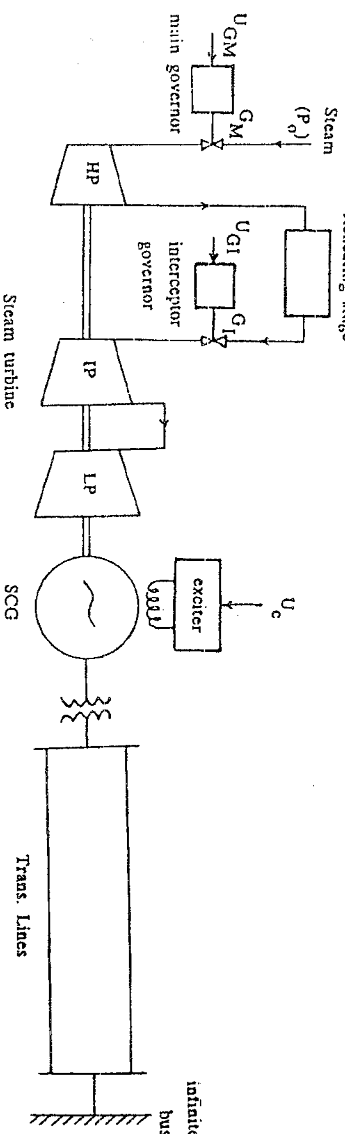


Fig.(1) Schematic diagram of a superconducting turbogenerator system.

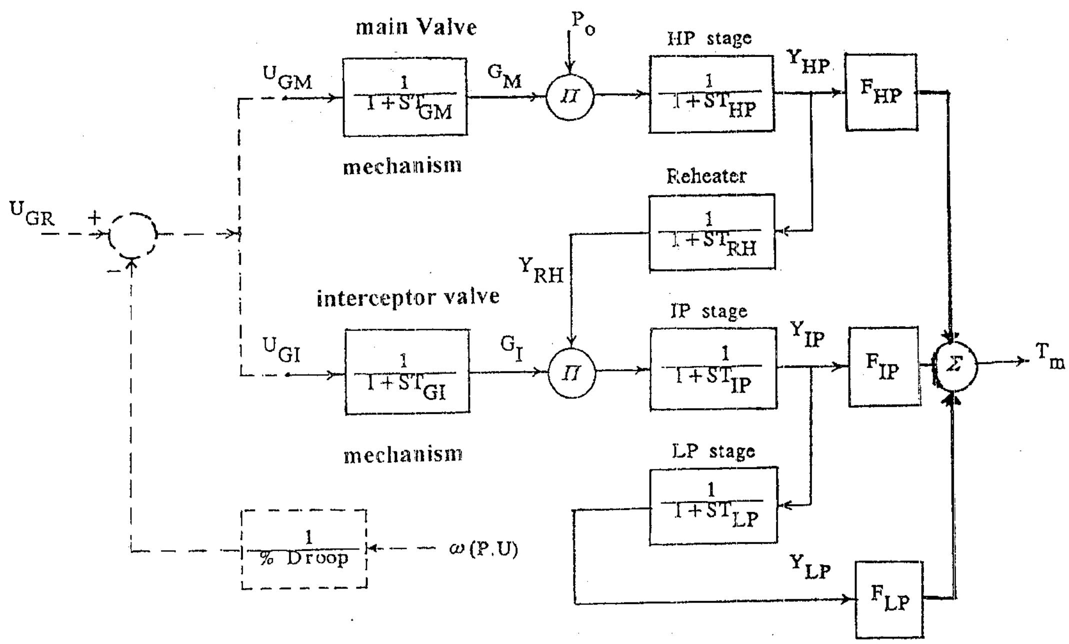


Fig.(2) Representation of turbine and governor system.

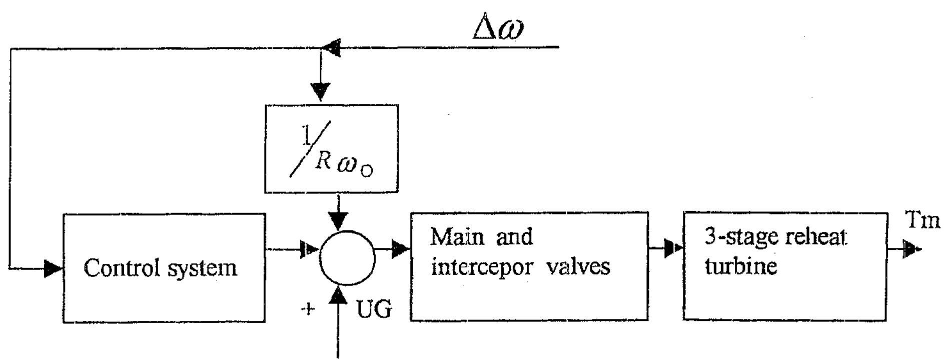


Fig. (3) Schematic diagram of the control system.

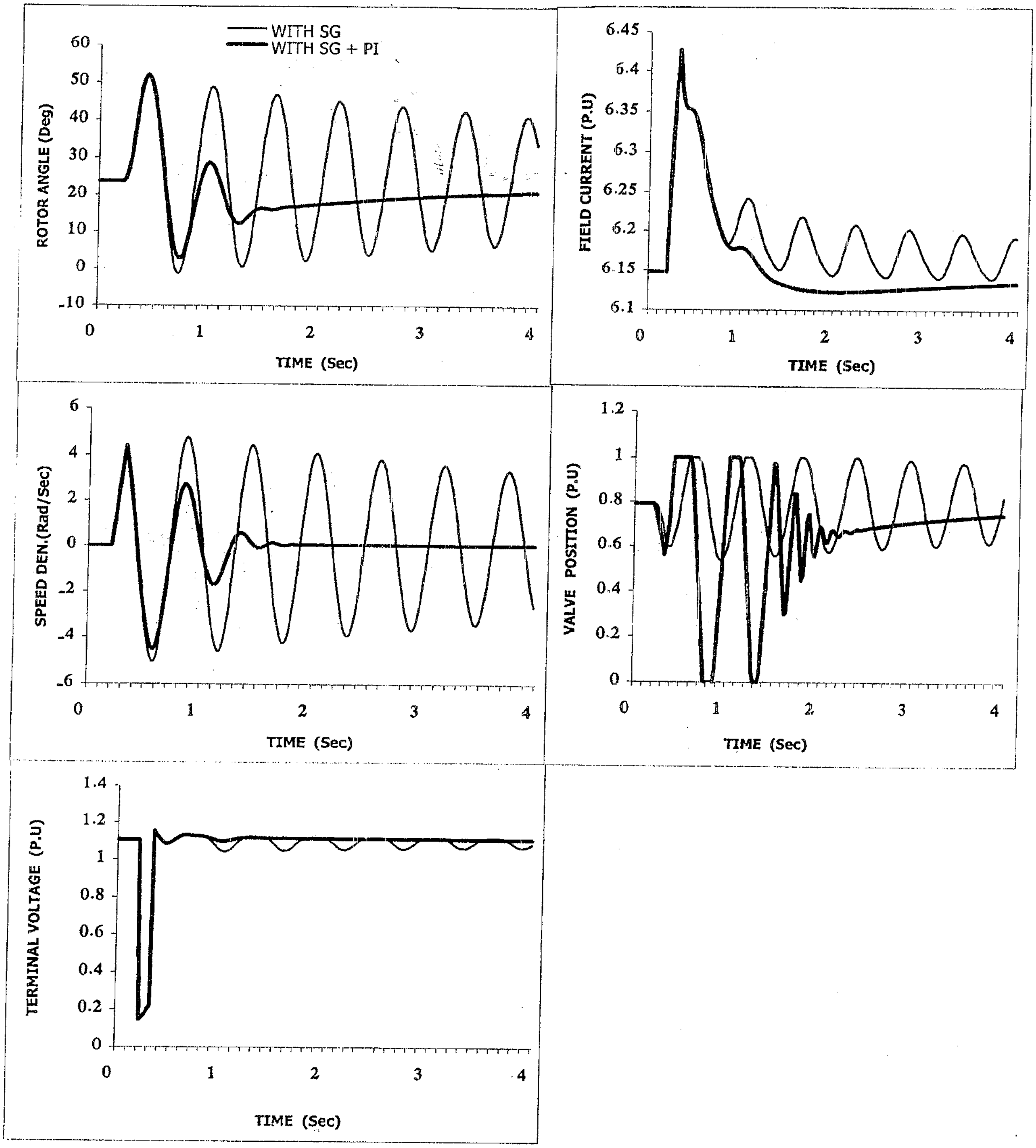


Fig.(4) Response to a 3-phase short circuit for 120 ms
Pt = 0.8 , 0.8 Lag P.F

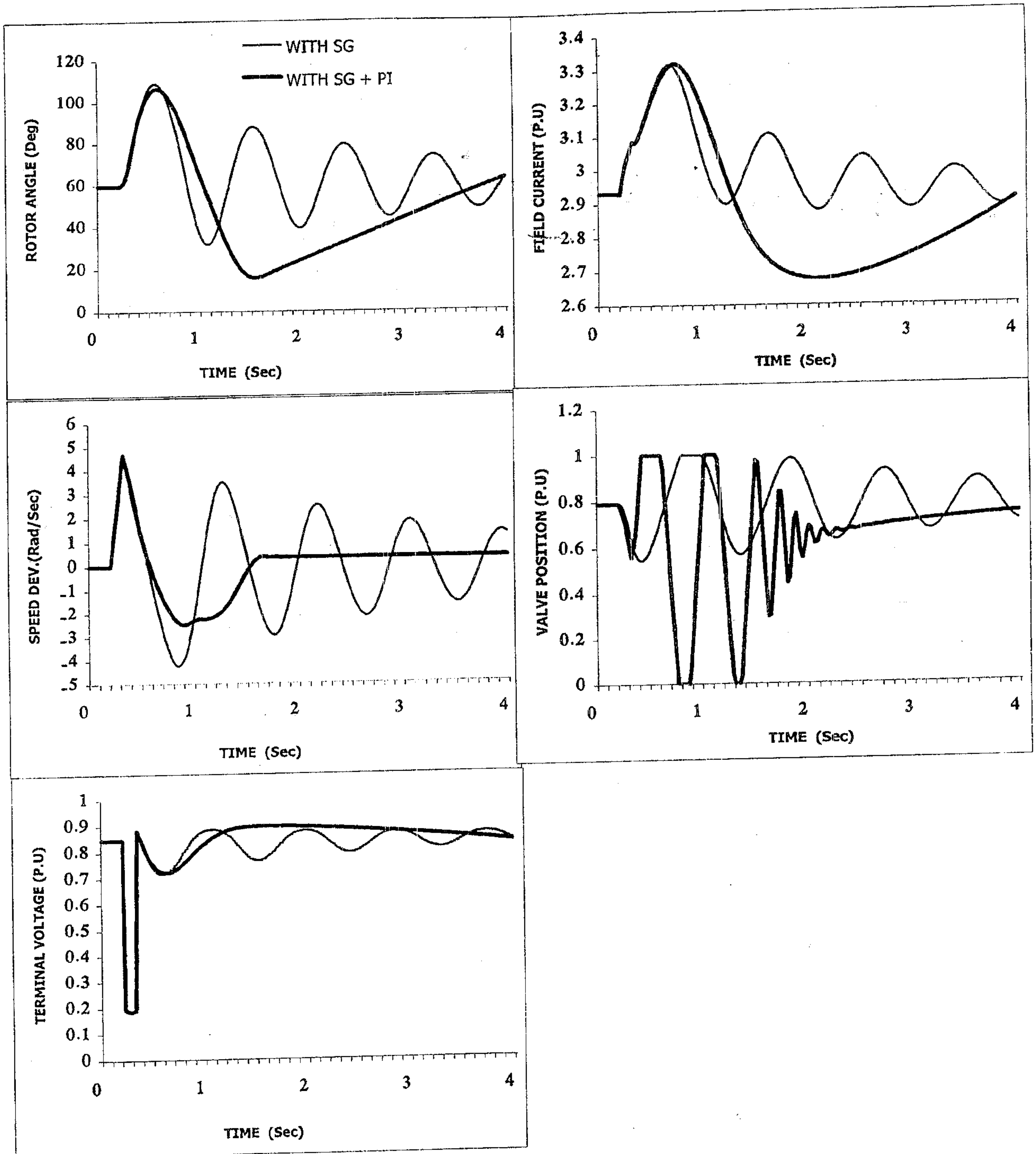
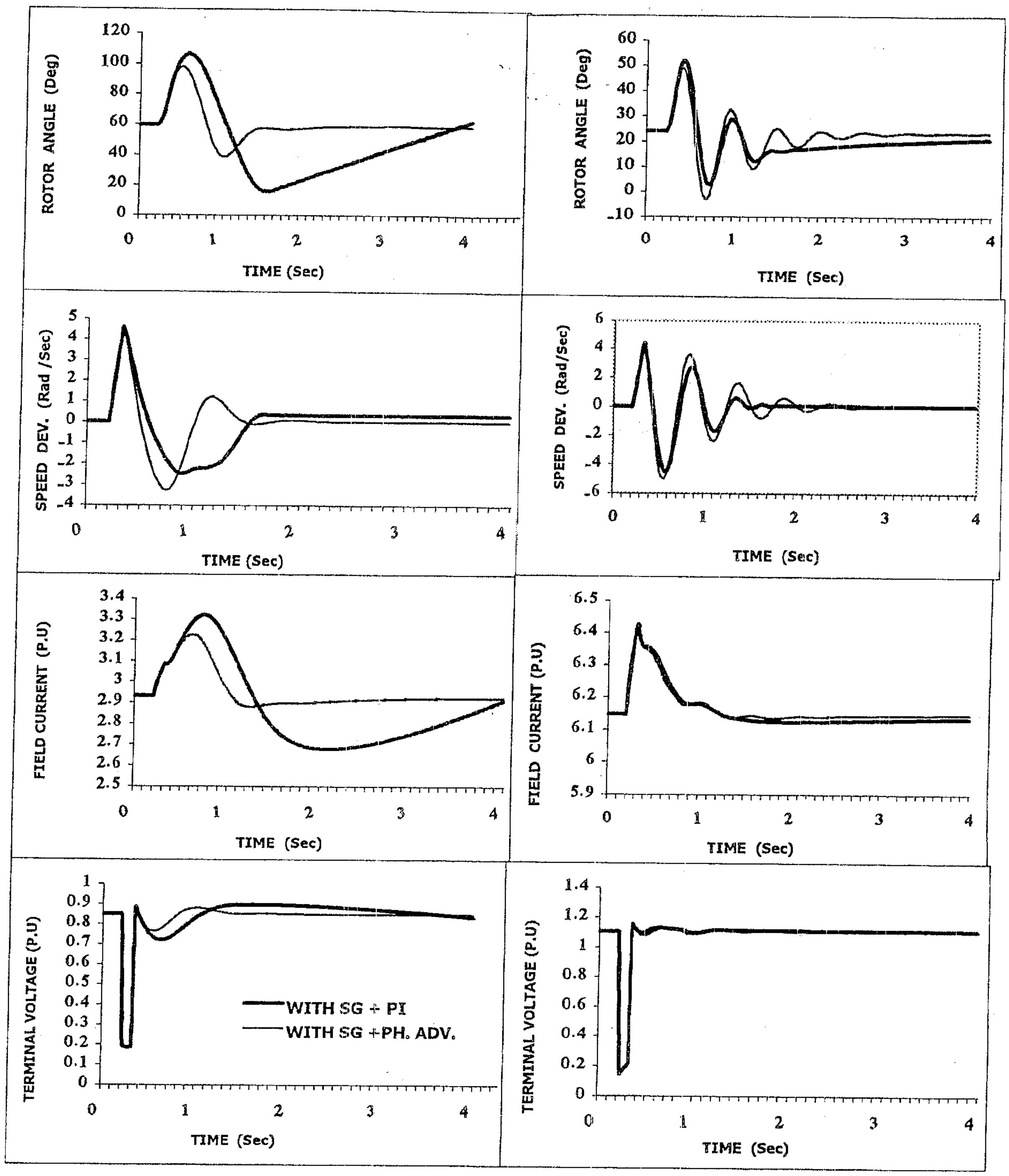


Fig.(5) Response to a 3-phase short circuit for 120 ms
Pt = 0.8 , 0.8 Lead P.F



(a) (b)

Fig.(6) Response to a 3-phase short circuit for 120 ms

(a) Pt = 0.8 , P.F = 0.8 Lead **(b) Pt = 0.8 , P.F = 0.8 Lag**

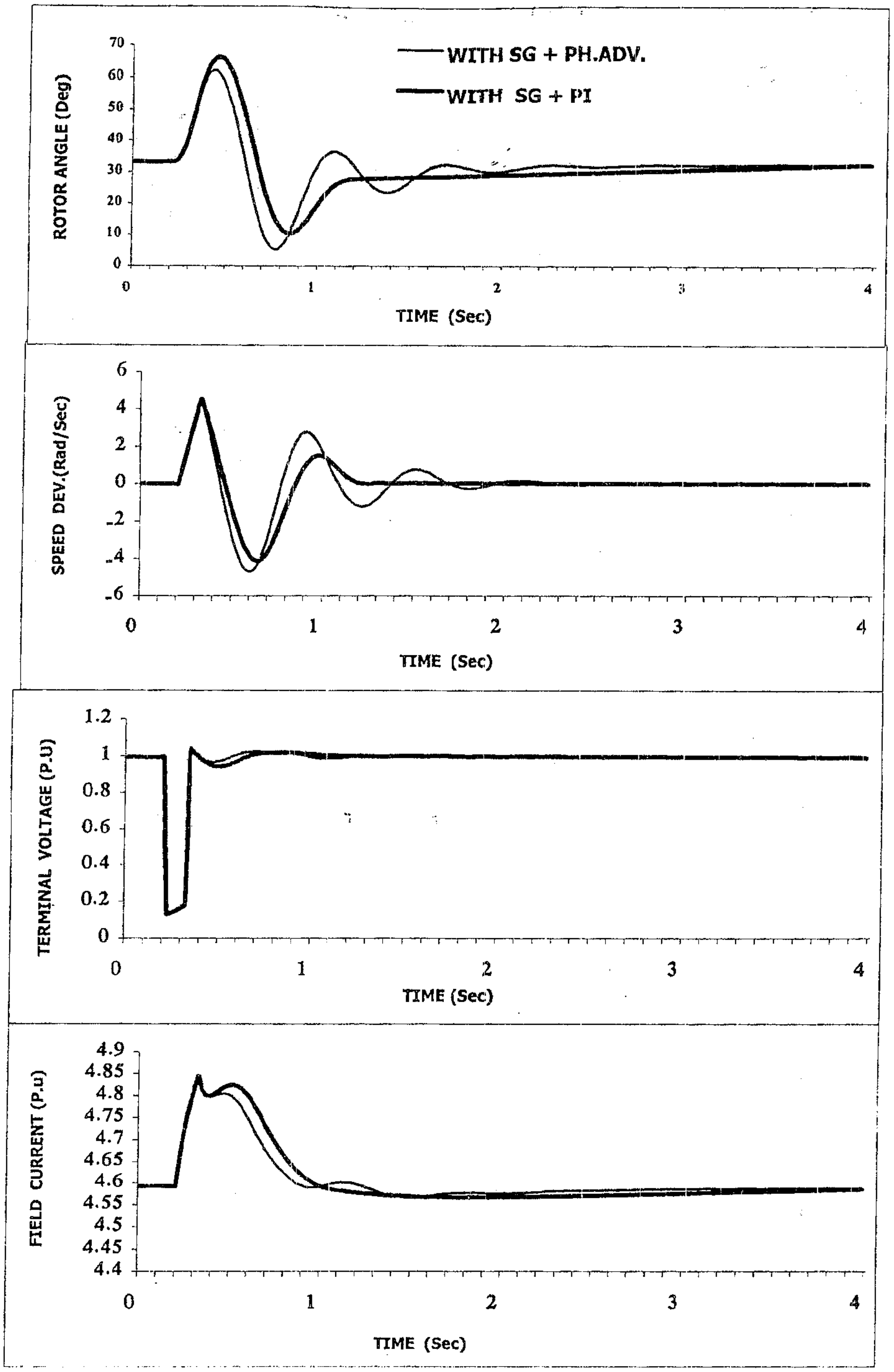


Fig.(7) Response to a 3-phase short circuit for 120 ms unity p.f

تصميم حاكم تناسبى تكاملى لآلة فائقة التوصيل

د/ جمال عبدالوهاب مرسى م/ هبه عبدالحميد خطاب أ٠د/ عبدالمحسن محمد قناوى

- هذا البحث يقترح طريقة لتصميم حاكم للآلة فائقة التوصيل سهل التطبيق عمليا وهو من النوع التناسبى التكاملى .
- يستخدم النموذج الخطى للنظام فى تصميم الحاكم وذلك باختيار الأوضاع المرغوبة للقيم المميزة ذات الوضع الحرج والتى تؤثر على اتزان النظام (الخاصة بالعضو الدائر وبملفات المجال) ومنها وبالطريقة المقترحة يتم حساب ثوابت الحاكم المطلوب .
- تم تطبيق الحاكم المصمم مع النموذج غير الخطى التفصيلى للنظام وبدراسة الأداء فى ظروف التشغيل المختلفة تبين أن الحاكم الجديد يضيف خمد موجب للنظام وأن أداء النظام فى وجود الحاكم الجديد أفضل منه فى وجود منظم البخار التقليدى وحده أو حتى فى وجود منظم البخار ومعه جهاز التحكم الذى يعطى زاوية وجه متقدمة (phase advance)