VALIDATION OF A FLEXIBLE CONTROLLER FOR A SUPERCONDUCTING GENERATOR

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ABSTRACT

This paper describes an improved version of the H ∞ control schemes to enhance the performance and stability of the superconducting generator (SCG). A Flexible control structure is proposed, designed and implemented to overcome the problems that resulting from the low inherent damping nature of the superconducting generator. The controller is implemented using a detailed nonlinear simulation. The time-invariant state space model is also obtained and the system oscillatory modes are given. The simulation results are represented in comparison with other results which obtained using conventional control systems. The linear time response simulation and the non-linear time response with the transient stability analysis confirms the superiority of the proposed controller and illustrate its effectiveness in system stabilization.

1- INTRODUCTION

Power systems face instability problems or poorly damped electromechanical modes in the range of .02 Hz to 2.5 Hz [1,2]. As oscillations of small magnitude and low frequency often persisted for long periods of time and in some cases presented limitations on power transfer capability. Power system control techniques have been implemented to improve system performance and to extend power transfer stability limits. This accomplished via the positive damping that such techniques and methodology add to the system modes of oscillation. Many studies have been done in order to improve the dynamic and transient stability of power systems. These include the design of conventional PSSs, static Vars compensators, series condensers and multi-variable controllers etc [3,4]. More

recent, the H∞ and the fuzzy rule based controllers are winning substantial credits [5-7]. Some authers, however, thought that the range of the instability mode should be treated very carefully via different control channels [9]. Therefore, the heuristic design approach proposed in [1] achieves the conflicting goals of providing damping torques at both high and low frequencies. An improved version of that control structure, called " flexible controller " or the H∞ controller. The flexible controller can be seen as an increased order robust controller [8], since it is a sum of differential lead-lag filters each of them aimed at damping a specific frequency band [9]. Although many tuning procedures have been developed for PSS and other conventional control schemes, most of them not to be suitable for the design of the flexible controller. The SCGs are expected to be the optimum choice among ac generation systems in the future, because of their reduced size, weight , high efficiency, higher generator terminal voltage and its contribution to stability of power systems. However, SCGs have a complex structure and require materials different from those normally used in conventional machines. At the same time these machines are characterized by their low inertia and low inherent damping owing to the interactions between their two electrothermal and damper shields. So, the SCGs requires special attention and consideration. Moreover, the very long field winding time constant make the achievement of acceptable dynamic performance very difficult using excitation control. Therefore, it is necessary to consider only the governor control loop. Various types of controllers were developed to enhance the performance of that complex structure machine, such as phase advance networks, self tuning controller, proportional plus integral controller and neural networks [10,11].

This paper presents the design and implementation procedures of a flexible control scheme to improve the performance of the SCG. After the problem formulation, the modal performance measure were presented taking into consideration the damping ratios of the oscillation modes. This criteria is applied to design a flexible controller. The linear and non-linear simulation results illustrates the robustness of the controller structure to enhance the system performance and stability.

2-SYSTEM MODEL

The power system model considered in this study is shown in Fig.(1). It consists of a superconducting generator connected to an infinite bus bar. The generator is driven by a three-stage steam turbine with reheat and fast acting electro-hydraulic governor. A selection switch has been used to consider the control action. The dynamic behavior of this system is governed by fifteen (15) differential equations, seven of which belong to the SCG itself (including two damper windings in each axes), two describe the mechanical torque and the remaining six describe the turbine stages and the electro-hydraulic governor. The system state equations and parameters are given in the appendix.
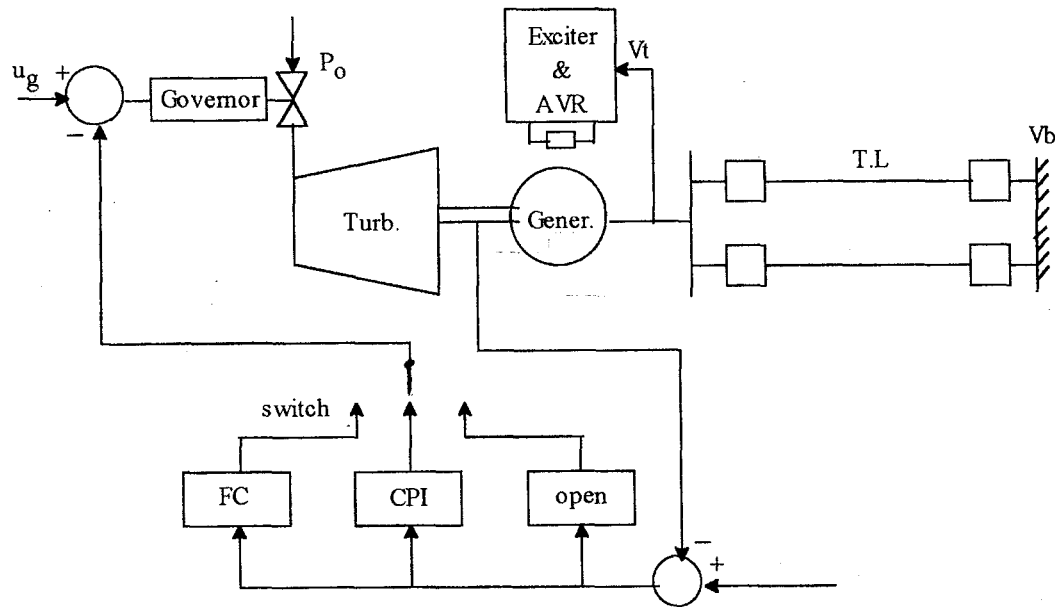
Fig.(1) Schematic diagram of a power system under study
with different control scheme

3- CONTROL STRUCTURE AND PROBLEM FORMULATION

The control objective for SCGs is to generate a stabilizing signal, which is added to the governor loop, in order to enhance the damping of the rotor oscillations after disturbances and consequently improve both the transient and dynamic performance of the system. The flexible controller is a high order controller, whose time constants are chosen in order to damp out specific ranges of modes. It consists of three frequency bands each of them contain two multi-stage control channels. Considering the general definition given in [9] and the system shown in Fig. (2), the controller can be defined as follows [12] :

$$H (s) = K \{ K_{lf} \ H_{lf} (s) + K_{if} \ H_{if}(s) + K_{hf} \ H_{hf} (s) \} \qquad (1)$$

Where, K is the controller overall gain . Subscripts lf, if, hf stand for low-, intermediate- and high-frequency respectively. Each compensator contributing to H (s) is tuned to damp a specific frequency band. For each frequency band:

$$H_{jf} (s) = H_{jf1} (s) - H_{jf2} (s) \qquad , j = l, i , h \qquad (2)$$

Previous extensive investigation revealed that for the SCG the time constants ratio is 50 for each control channel. Also, only one stage for each frequency band channel was found enough. Therefore, each controller stage takes the form :

$$H_{jfi} (s) = 1 + s \ T_{jf1} / 1 + s \ T_{jf2} \qquad (3)$$

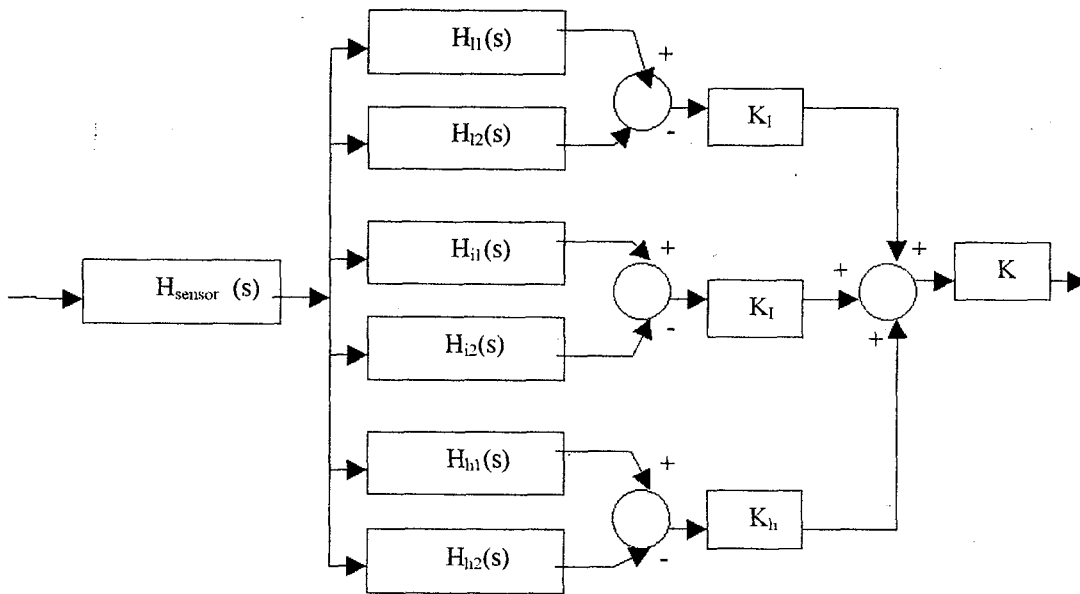where,   i   is 1 and 2 for each frequency band.

J = l, i and f

Fig. (2) Schematic diagram of the flexible controller

The state-space model of the controller is then :

$$\dot{Z} = P Z + Q \omega \qquad (4)$$

$$U = K R Z \qquad (5)$$

where : P, Q, R depend on the time constants
     ω is the controller input
     U   is the controller output

$$K = [\ K_{lf} \qquad K_{if} \qquad K_{hf} \ ]$$

The non-linear model of the power system are perturbed about a steady state operating point. This provides the open –loop linearized system model as :

$$\dot{X} = A X + B U \qquad (6)$$

$$\omega = C X \qquad (7)$$

where,   X   is a state vector
    U   is an input vector $= [\ U_c \qquad U_{ref} \ ]^T$
    U_c is the input from the controller
    U_{ref} is the reference voltage input
    ω is the speed output

The control problem is to determine a matrix K so that the output oscillations of the closed loop system will be damped out when a perturbation occurs. Then the closed loop system state space model is :

$$\dot{X}_c = A_c X_c + B_c U \qquad (8)$$

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$$\omega \ = \ C_c \ \dot{X_c} \qquad\qquad\qquad (9)$$

$$A_c = \begin{bmatrix} A & BKR \\ QC & P \end{bmatrix} \quad , \quad B_c = \begin{bmatrix} B \\ 0 \end{bmatrix} \qquad \& \quad C_c = [\ C \quad 0\ ] \qquad (10)$$

The modal performance measure J, for the closed loop system equations (8), (9) and (10) is defind as [12]:

$$J = \sum_{i=1}^{N} \ \{ (X_o^T \ V_i^T) \ U_i^T \ M_i \ U_i^* \ (V_i^* \ X_o) \ \Psi(\ \sigma_i \ , \ \omega_i\ )\ \} \qquad (11)$$

where: N is the order of the closed loop state matrix A_c,

U_i, V_i are right and left eigen vectors corresponding to the $i\,th$ mode

$(\ )^T, (\ )^*$ are the matrix transpose and complex conjugate,

X_o is the initial state of the closed loop system,

$\Psi(\ \sigma_i\ , \ \omega_i\ )$ is a function of the I th mode $\lambda_i = \sigma_i \pm \omega_i$,

$\zeta_i \qquad = - \sigma_i\ /\ \sqrt{\ \sigma_i^2 \ + \ \omega_i^2}$ is the damping ratio of the i th mode.

The optimization algorithm used in [12] is implemented , with a linear convergence rate, then the values of the controller gains are obtained .
The controller gains and time constants are given in the appendix.

4-EIGEN VALUES ANALYSIS:

Using the time invariant state space model , a conventional PI controller is designed as well as the flexible controller. The eigenvalues are obtained for the system as shown in Table 1. These results show that the damping ratios of the oscillation modes are greatly improved with the use of the flexible controller.

Critical oscillation mode									
Operating point	Open loop			SG + Conventional PI			SG + Flexible Controller		
At	$\sigma_i \pm \omega_i$	F hz	ζ_i	$\sigma_i \pm \omega_i$	F hz	ζ_i	$\sigma_I \pm \omega_i$	F hz.	ζ_I
Lead pf	-0.338± j6.47	1.03	0.06	-5.3 ± j10.57	1.68	0.479	-5.95±j11.2	1.78	0.51
Unit pf	-0.31 ± j9.05	1.44	.033	-3.8 ±j12.05	1.91	0.303	-4.41 ±j12.9	2.05	0.33
Lag pf	-0.276±j10.6	1.68	.025	-2.95 ±j13.69	2.18	0.21	-3.51±j14.0	2.23	0.24

Table 1

5- SIMULATION RESULTS AND DISCUSSIONS

To indicate the effectiveness of the proposed flexible controller, results simulation for the system are obtained under different operating conditions and the modal performance measure was evaluated in response to a 120 ms duration short circuit at the transformer high voltage side. The system detailed non-linear equations including all control loops are solved by using the Rung-Kutta technique. Figures (3) to (5) depicts the system performance in case of three-phase short circuit fault with the proposed controller for different operating conditions. The simulation results illustrate that the proposed controller achieve a significant improvement in the system behavior , a considerable reduction in the valve movements and a high damping to the rotor oscillations. The results thus demonstrate clearly the effectiveness of the proposed scheme in damping the system oscillations and improving its performance.

6- CONCLUSIONS

The paper described a new proposed flexible controller to enhance the performance and extend the stability limits of SCGs.. The proposed scheme is validated and verified via eigenvalues analysis and simulated non-linear time response of the new controller in comparison with other control systems. It is clear that the new strategy is significant in damping the system oscillations and enhancing its dynamic performance for a wide range of operating conditions. The system behavior with the proposed control scheme is compared with the behavior when it's equipped with speed governor accompanied with proportional plus integral controller. The paper demonstrated that the proposed controller can provide significant performance improvements to power system oscillations and can be a useful substitute to other conventional schemes, in damping the system low frequency oscillations.

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APPENDIX

A- THE STATE EQUATIONS REPRESENTED THE POWER SYSTEM ARE

$$p\psi_f = \omega_o \left(V_f - i_f R_f\right) \tag{1}$$

$$p\psi_d = \omega_o \left(V_d + i_d \left(R_a + R_e\right) + \psi_q\right) + \omega\psi_q \tag{2}$$

$$p\psi_q = \omega_o \left(V_q + i_q \left(R_a + R_e\right) - \psi_d\right) - \omega\psi_d \tag{3}$$

$$p\psi_{D1} = - \omega_o i_{D1} R_{D1} \tag{4}$$

$$p\psi_{Q1} = - \omega_o i_{Q1} R_{Q1} \tag{5}$$

$$p\psi_{D2} = - \omega_o i_{D2} R_{D2} \tag{6}$$

$$p\psi_{Q2} = - \omega_o i_{Q2} R_{Q2} \tag{7}$$

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

$$p\omega = \frac{\omega_o}{2H} \left(T_m - T_e\right) \tag{9}$$

$$T_e = \psi_d i_q - \psi_q i_d \tag{10}$$

The transmission system is includeed in the model, replacing R_a by $(R_a + R_e)$ and X_d and X_q by $(X_d + X_e)$ and $(X_q + X_e)$ respectively.

The model of the three-stage steam turbine with reheat and the electro-hydraulic governor considered in this study follows the IEEE standard representation and the special IEEE recommendations for the turbine of the SCG. Their state equations may be written as:

$$pY_{HP} = (G_M P_o - Y_{HP})/T_{HP} \tag{11}$$

$$pY_{RP} = (Y_{HP} - Y_{RH})/T_{RH} \tag{12}$$

$$pY_{IP} = (G_1 Y_{RH} - Y_{IP})/T_{IP} \tag{13}$$

$$pY_{LP} = (G_{IP} - Y_{LP})/T_{LP} \tag{14}$$

$$T_m = F_{HP}Y_{HP} + F_{IP}Y_{IP} + F_{LP}Y_{LP} \tag{15}$$

The electro-hydraulic governor equations are :

$$pG_M = (U_{GM} - G_M)/T_{GM} \tag{16}$$
$$pG_I = (U_{GI} - G_I)/T_{GI} \tag{17}$$

Where the position and rate limits are,
$0 \leq G_M, G_I \leq 1.0$ and $-6.7 \leq pG_M, pG_I \leq 6.7$ p.u/sec

B -THE SYSTM PARAMETERS

• **SCG parameters**
2000 MVA, 1700 MW, 3000 rpm
$X_d = X_q = 0.453$ 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.
$R_a = 0.003$, $R_{KD2} = R_{KQ2} = 0.00134$,
$H = 3$ KWS/KVA

Transmission System Parameters
$X_T = 0.15$ p.u. , $R_T = 0.0003$ 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.,
$F_{LP} = 0.3$ sec	$F_{LP} = 0.32$	$T_{RH} = 10$ sec.
$T_{GM} = T_{G.1} = 0.1$ sec.	$P_o = 1.2$ p.u.	

•
• **Parameters of Flexible Controller**

$T_{l1} = 0.01$ sec.	$T_{l2} = 0.5$ sec	$T_{i1} = 0.008$ sec.,
$T_{i2} = 0.4$ sec	$T_{h1} = 0.004$ sec	$T_{H2} = 0.2$ sec.
$K_{lf} = 0.1$,	$K_{if} = 0.02$	$K_{hf} = 0.05$

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
q	d and q componenets 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,fQ	d and q mutual components between inner screen and field winding SCG
KD_1,KQ_1	d and q componenets of outer screen
KD_2,KQ_2	d and q components of inner screen
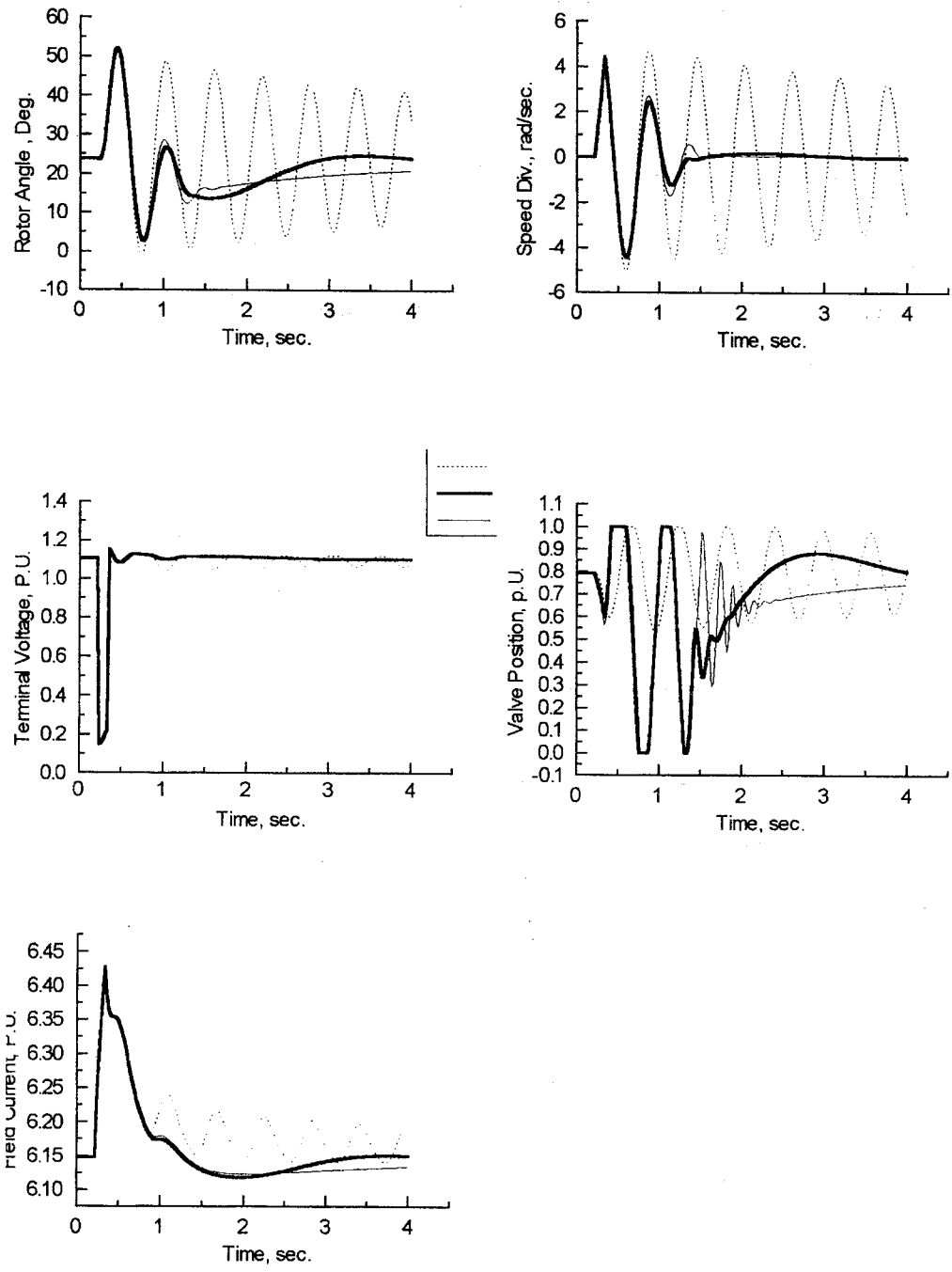
Fig.(3)Transient response of a SCG to a 3-phase s. c.
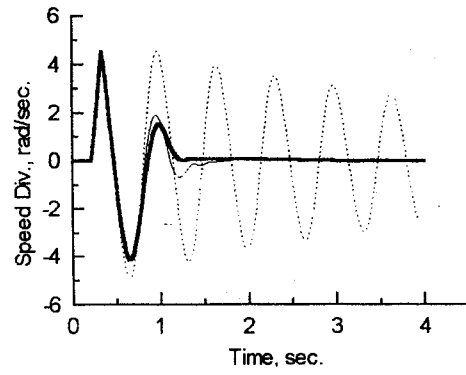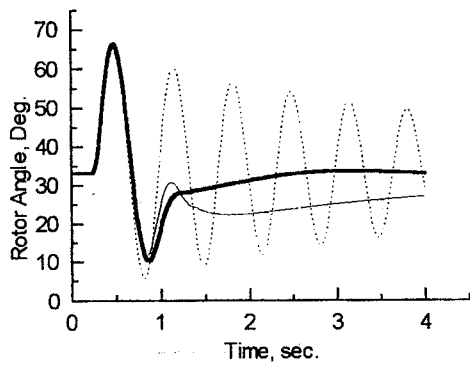(lag power factor)

...... SG only ——— SG + PI —— SG + FC
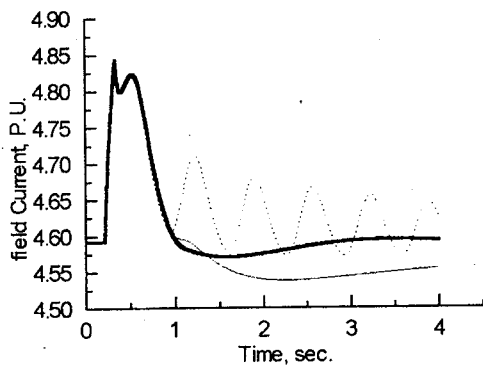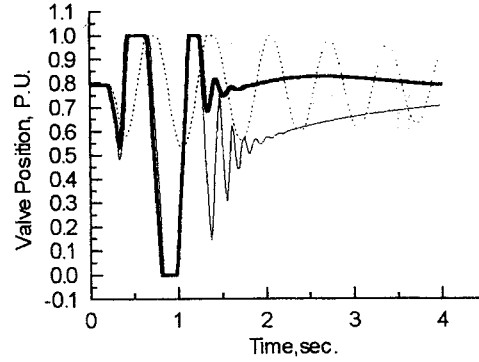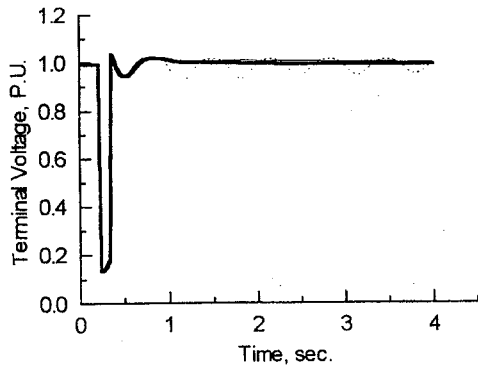
Fig.(4) Transient response of a SCG to a 3-phase s. c.

(unity power factor)

....   SG only   ———————   SG + PI   —————   SG + FC
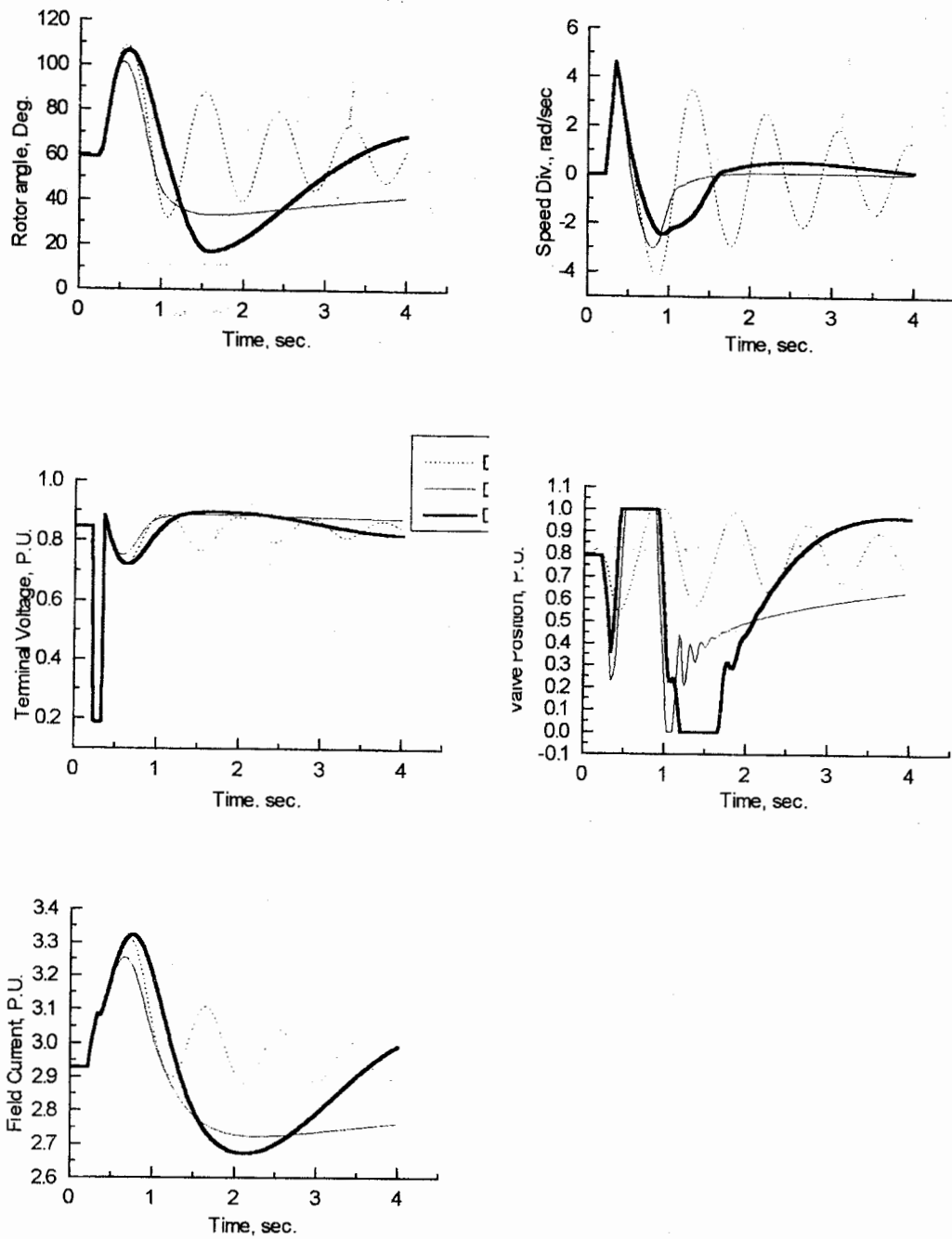
Fig.(5) Transient response of a SCG to a 3-phase s. c.
(lead power factor)

..... SG only ———— SG + PI ———— SG + FC

تصميم وتحقيق استخدام حاكم مرن قوى لآلة فائقة التوصيل

د / جمال عبد الوهاب مرسى

- هذا البحث يقترح حاكم مرن قوى للالة فائقة التوصيل يتكون من عدة أفرع كل فرع مسئول عن خمد الاهتزازات الكهروميكانيكية فى مدى تردد معين بحيث يضمن خمد الاهتزازات فى المدى الذى تعانى منة نظم القوى الكهربية وهو من تردد ٢ , ٠ ذ/ث الى تردد ٢،٥ ذ/ث.

- تم تصميم الحاكم الجديد باختيار افضل البارامترات optimization التى تضمن الوصول الى انسب وافضل مقياس اداء performance measure

- باستخدام نموزج خطى لنظام القوى المتضمن للالة الفائقة تم حساب القيم المميزة للنظام عند ظروف تشغيل مختلفة و هو يعمل فى وجود منظم البخار فقط ثم وهو يعمل فى وجود منظم البخار مع حاكم تناسبى تكاملى وكذلك عند استخدام الحاكم المرن المقترح وتبين ان الحاكم الجديد يضيف افضل خمد موجب للأوضاع الحرجة مما يوضح تميزة عن الأنواع السابقة.

- تم تطبيق الحاكم الجديد مع النموزج غير الخطى التفصيلى للنظام وبدراسة اداء النظام عند ظروف تشغيل مختلفة عند تعرض النظام لقصر ثلاثى عند اطراف الجهد العالى للمحول ومقارنة اداء النظام فى وجود الحاكم الجديد مع ادائة فى وجود الحاكمات السابقة تبين مدى التحسن فى الأداء و قلة حركة صمامات البخار بشكل ملحوظ.