OPTIMAL CONTROLLER DESIGN FOR THE EXCITATION OF A GAS TURBINE GENERATING UNIT

E.S. Abdin
Electrical Engineering Department,
Faculty of Engineering, Menoufiya University,
Shebin El-Kom, Menoufiya, Egypt.

ABSTRACT

This paper describes the dynamic model of a gas turbine generator, which supplies a radial distribution system. An optimal controller for the excitation system is designed based on the linear model. The response of the closed loop system with optimal and conventional controllers are compared under different type of electrical disturbances such as a 3-phase short circuit at different loads and switching some of loads off or on.

KEYWORDS: Gas turbine generator, power system dynamics, and optimal control.

1- INTRODUCTION

During the last twenty years, the industrial gas turbines have been developed to produce more power with the same sizes by raising both firing temperature and compressor air flow. Recent work concerning the approach for modeling gas turbines has been done by Rowen [1]. His model consists of two parts, namely the single shaft gas turbine and its control. Hannett and Khan [2] have made a comparison between different type of governor models for the gas turbines. The dynamic performance of gas turbine generator was studied as a stand-alone unit with both static and dynamic loads [3]. In this reference, the effect of starting of induction motor was studied for two different rates of gas turbine generators.

In this paper, the modeling of a synchronous generator driven by a gas turbine with its governor control system is presented. The conventional controller for the excitation system is replaced by an optimal design one. The dynamic performances of the closed loop with conventional and optimal controllers are compared under different type of electrical disturbances such as 3-phase short circuit and loads switching off or on.

2- SYSTEM CONFIGURATION

The system consists of a synchronous generator driven by a gas turbine with a single shaft and connected to the utility network through a distribution feeder with two loads as shown in Fig.1

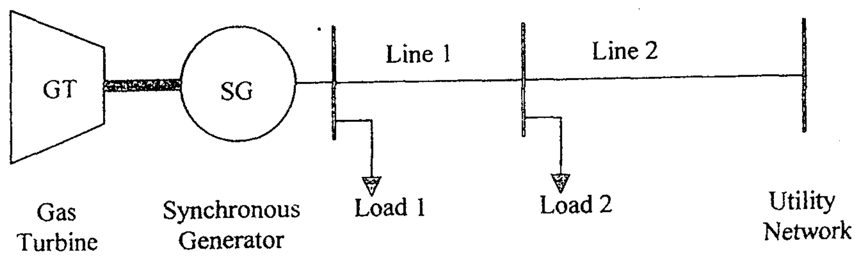

Fig. 1 Gas turbine generating unit.

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3- SYSTEM MODELING

3-1 Synchronous Generator Model

The transient model of the synchronous generator can be represented by a 3[rd] order model on its rotor reference frame as follows [4]:

$$pe_q^{'} = [E_F - e_q^{'} - (x_d - x_d^{'})i_{ds}] / \tau_{do}^{'} \tag{1}$$

$$p\delta = \omega_r - \omega_o \tag{2}$$

$$p\dot{\delta} = \frac{\omega_o}{2H}(T_m - T_e - D\dot{\delta}) \tag{3}$$

where D is a damping factor to compensate the effect of neglecting of damper windings. The electrical torque can be calculated from the following equation:

$$T_e = e_q^{'} i_{qs} + (x_q - x_d^{'}) i_{ds} i_{qs} \tag{4}$$

The stator voltage components in d- and q-axis rotor reference frame can be written as:

$$v_{ds} = -r_a i_{ds} + x_q i_{qs} \tag{5}$$

$$v_{qs} = e_q^{'} - r_a i_{qs} - x_d^{'} i_{ds} \tag{6}$$

and the stator terminal power will be

$$P_s = v_{ds} i_{ds} + v_{qs} i_{qs} \tag{7}$$

3-2 Single Shaft Gas Turbine Model

It is often sufficient to consider a simplified model for the single shaft gas turbine [1-2], where the temperature control is eliminated. The gas turbine has a PID speed governor. The schematic diagram of this model is shown in Fig. 2 and may be represented by the following equations:

$$\omega_{ref} - N = 1 - \frac{\omega_r}{\omega_o} = -\frac{\dot{\delta}}{\omega_o} \tag{8}$$

$$px_1 = -K_1 \frac{\dot{\delta}}{\omega_o} \tag{9}$$

$$V_{ce} = x_1 - K_P \frac{\dot{\delta}}{\omega_o} - K_D \frac{p\dot{\delta}}{\omega_o} \tag{10}$$

$$px_2 = [F + (1 - F)(1 + \frac{\dot{\delta}}{\omega_o})V_{ce} - x_2] / \tau_P \tag{11}$$

$$p\omega_F = (x_2 - \omega_o) / \tau_{FC} \tag{12}$$

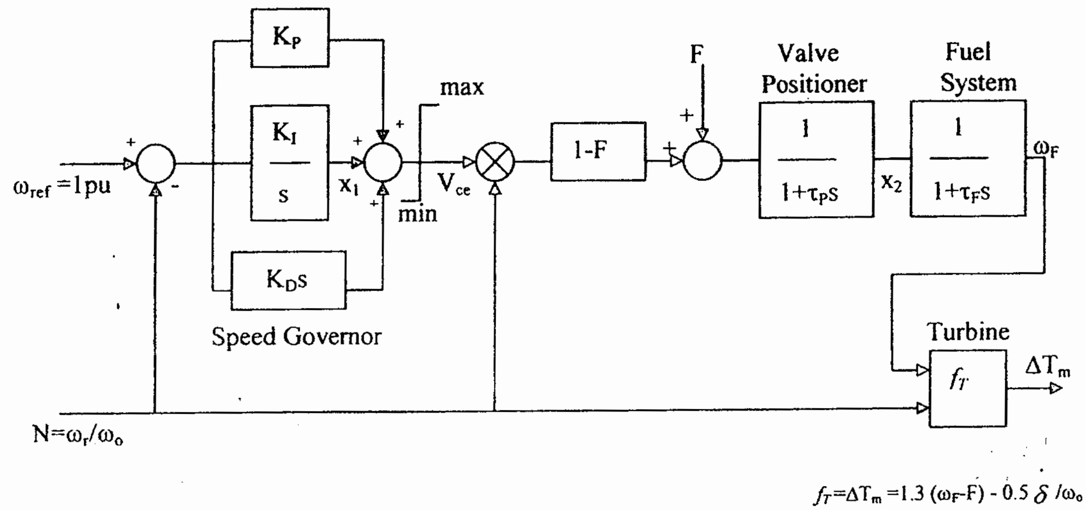

Fig. 2 Schematic diagram of a simplified single shaft gas turbine.

3-3 Conventional Excitation Control

In this paper, IEEE type 1 excitation system model [4-5] is used. The block diagram of the excitation system is shown in Fig. 3 and can be represented by the following equations:

$$pU_E = [K_A(V_{ref} - V_s - V_{ss}) - U_E]/\tau_A \tag{13}$$

$$p\Delta E_F = [U_E - (1 + S_E)\Delta E_F]/\tau_E \tag{14}$$

$$pV_{ss} = \left\{\frac{K_F}{\tau_E}[U_E(1 + S_E)\Delta E_F] - V_{ss}\right\}/\tau_F \tag{15}$$

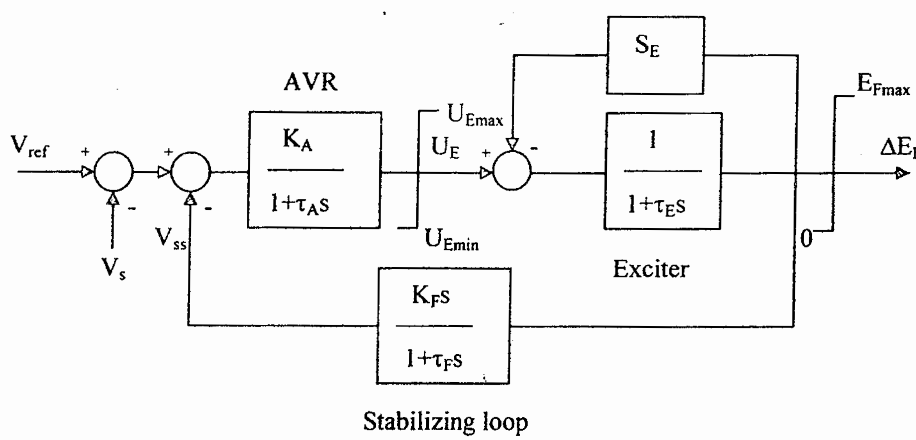

Fig. 3 IEEE type 1 Excitation system

4- LINEARISED MODEL

The nonlinear differential equations are linearised around an operating point to obtain the state space linear model. For the optimal controller design for the excitation system, the change in the mechanical torque can be treated as an input disturbance. So, the linear model can be represented by a 4th order model. It takes the following form:

$$px = Ax + Bu \tag{16}$$

where

$$x = [\Delta e_q', \Delta\dot{\delta}, \Delta\delta, \Delta E_F]^t$$
$$u = U_E$$

This linear model is taken as a base for the optimal controller design for the excitation system. The block diagram representation of the linear model is shown in Fig. 4 where the constants from K_1 to K_5 can be derived from the constant matrices A and B.

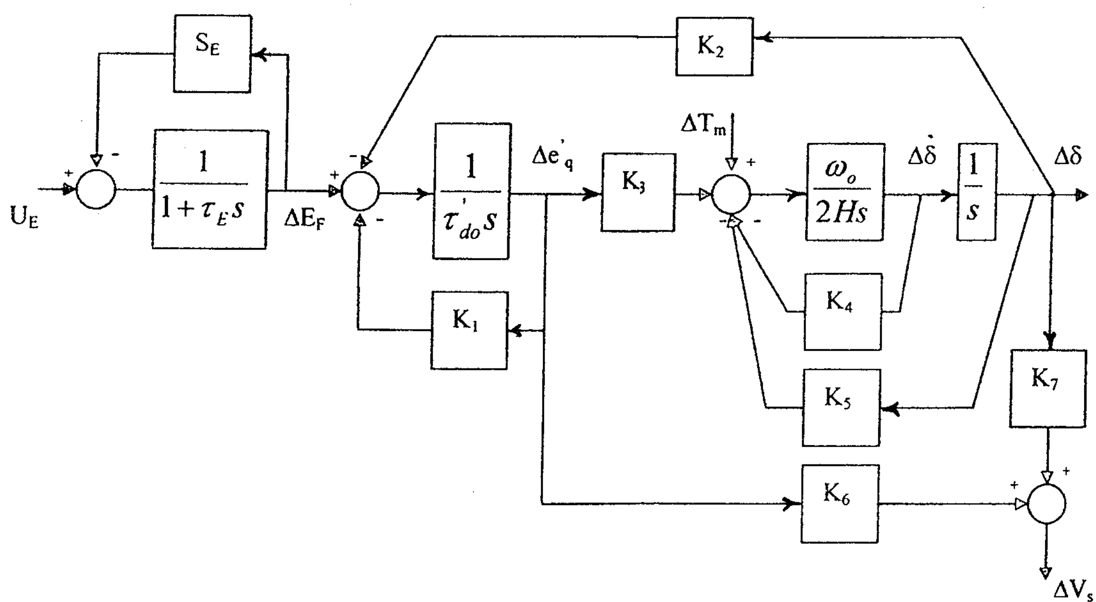

Fig. 4 Block diagram representation of a linear model

5- OPTIMAL CONTROLLER DESIGN FOR THE EXCITATION SYSTEM

Based on the linear model, the optimal controller can be designed as follows:

i) In the state vector x, replace $\Delta e_q'$ by the measurable voltage signal ΔV_s to obtain a new state vector y with all accessible components. The relation between y and x is:

$$y = Cx \tag{17}$$

where

$$y = [\Delta V_S, \Delta\dot{\delta}, \Delta\delta, \Delta E_F]^t$$

$$C = \begin{bmatrix} K_6 & 0 & K_7 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

ii) Multiply equation (16) by the matrix, C to obtain the following model:

$$py = \alpha y + \Gamma u \tag{18}$$

where

$$\alpha = CAC^{-1}, \qquad \Gamma = CB$$

iii) Define the control law by

$$u = -K_O y \tag{19}$$

iv) The optimal feedback gain matrix K_O can be obtained by minimizing the following performance index [5]:

$$J = \int_0^{t_f} (y^t Q y + u^t R u) dt \tag{20}$$

The minimization of J leads to the following algebraic Riccati equation:

$$Q - S\beta R^{-1}\beta^t S + \alpha^t S + S\alpha = 0 \tag{21}$$

v) By solving the Riccati equation to obtain the matrix S using the Matlab software, the optimal gain matrix K_O can be calculated as follows:

$$K_O = R^{-1}\beta^t S \tag{22}$$

6- SIMULATION RESULTS

For the optimal controller design, the weighting matrices Q and R are selected after many trail as follows:

$$Q = diag[20000, 0, 5000, 0], \qquad R = 0.5$$

The corresponding optimal feedback gain matrix is

$$K_O = [439.724 \quad -14.090 \quad 8.441 \quad 2.406]$$

The eigenvalues of the open loop and closed loop with optimal feedback controller are given in table 1.

Table 1

Eigenvalues of open loop	Eigenvalues of closed loop with optimal feedback
-0.2860 ± j5.3622 -0.3369 -5.3798	-2.2136 ± j6.2860 -5.6853 ± j3.4426

Fig. 5 shows a comparison between the dynamic responses of the open loop and closed loop with both optimal and conventional exciter control for a 3-phase short circuit at load 1 and is cleared at 120 msec. It is noted that at the instant of short circuit the rotor speed is decreased instead of increased. This is because at the instant of short circuit the electrical power loss in the stator copper is greater than the mechanical power (back swing phenomena). The system with optimal excitation control has a good damping performance compared to the conventional excitation control. Fig. 6 shows a comparison between the responses of the optimal and conventional excitation control for a 3-phase short circuit at load 1 and after 120 msec. the load 1 is switched off. With optimal excitation control, the rotor angle δ reaches to a new steady state value with less oscillations and minimum overshoot compared to the conventional excitation control. Fig. 7 shows a comparison between the responses of the optimal and conventional excitation control for a 3-phase short circuit at load 2 and after 120 msec. the load 2 is switched off. The back swing phenomena does not appear because the value of electrical power loss in the stator copper for short circuit at load 2 is less than that at load 1 as shown in Figures 6 and 7. Fig. 8 shows the response of the closed loop system with optimal excitation control for switching the load 1 off and after 6 second the load 1 is switched on. As shown in Fig. 8, the closed loop system reaches to the new steady state values in a very short time with a minimum overshoot.

7-CONCLUSIONS

The dynamic model for a gas turbine generator connected to a radial distribution system has been presented. An optimal controller was designed for the excitation system based on the linearised model. A comparison between the responses of the closed loop system with optimal and conventional excitation control has been made under different type of electrical disturbances. The system with optimal controller for the excitation system had a good damping performance and a minimum overshoot as well as it is easy to implement it in the practical work.

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Appendix

Synchronous generator parameters

x_d = 1.640 pu.,	x_q = 1.575 pu.,	x'_d = 0.159 pu.
r_a = 0.034 pu.,	D = 3.0 pu.,	τ'_{do} = 7.5 sec.
U_{Emax} = 7.3 pu.,	U_{Emin} = -7.3 pu.	

Excitation system parameters

K_A = 400.0,	τ_A = 0.02 sec.,	τ_E = 0.253 sec.
K_F = 0.03 ,	τ_F = 1.0 sec.	

Line parameters

x_{TL1} = 0.05 pu.,	r_{TL1} = 0.005 pu.,	V_B = 1.04 pu.
x_{TL2} = 0.10 pu.,	r_{TL2} = 0.010 pu.	

System loads

P_{L1} = 0.4 pu.,	Q_{L1} = 0.194 pu.
P_{L2} = 0.2 pu.,	Q_{L2} = 0.150 pu.

Gas turbine parameters

F = 0.23 pu.,	τ_P = 0.05 sec.,	τ_{FC} = 0.4 sec.
K_P = 12.0 ,	K_I = 5.0,	K_D = 14.0
V_{cemax} = 1.5 ,	V_{cemin} = -0.1 ,	$H_{(Turbine+Generator)}$ = 11.4 sec.

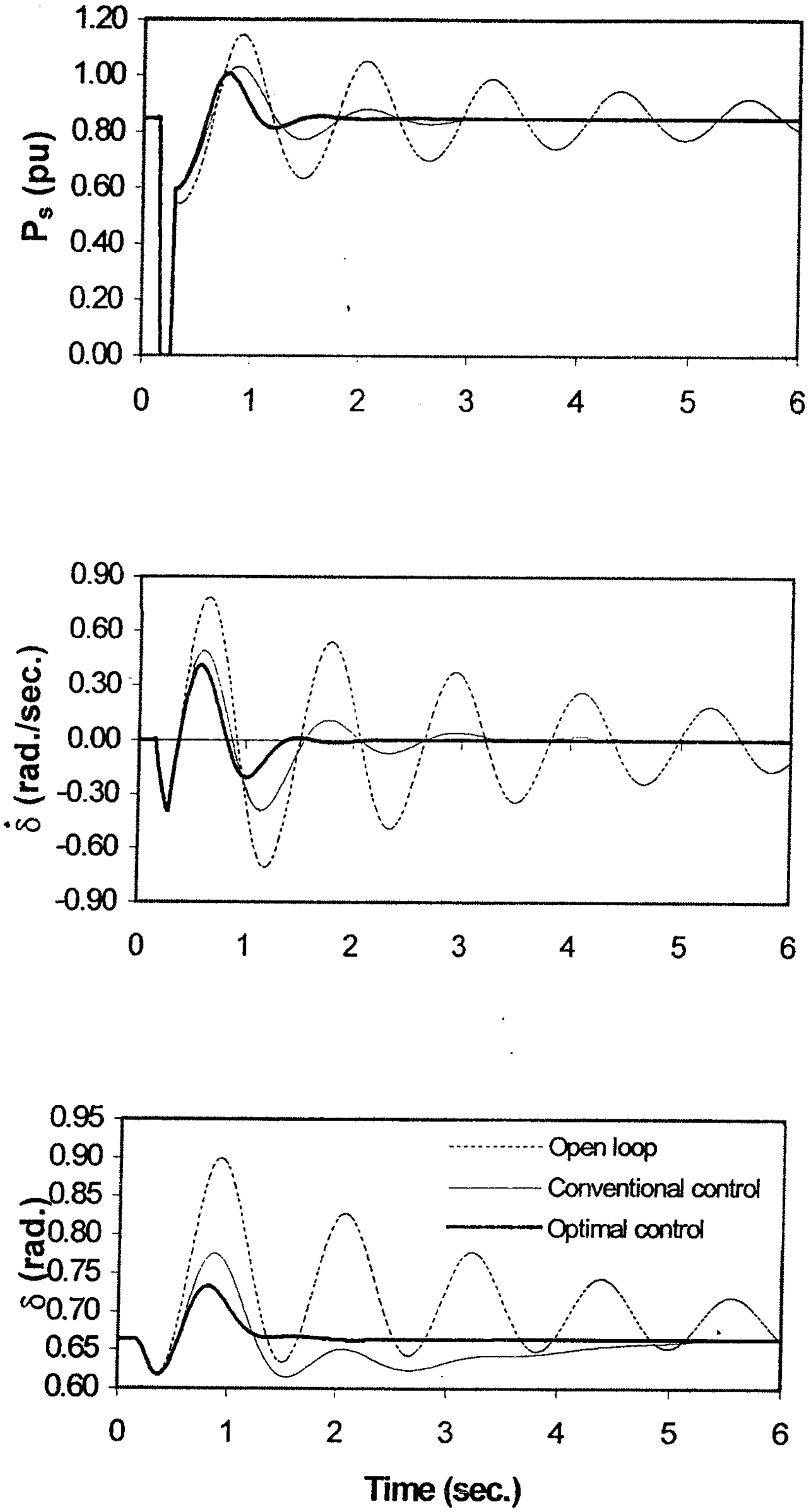

Fig. 5 Response of the GTG system for a 3-phase short circuit at load 1 (T_f = 120 msec.)

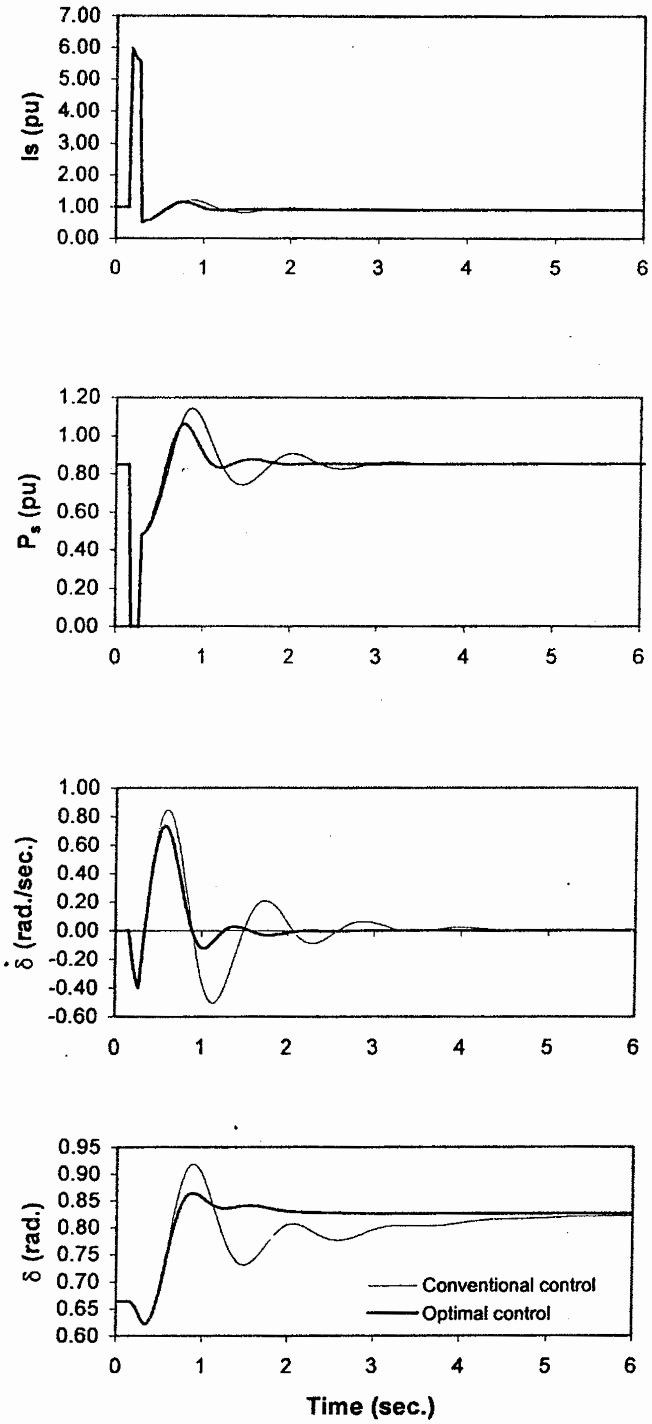

Fig. 6 Response of the closed loop system for 3-phase short circuit at load 1 following by switching the load 1 off (T_f=120 msec.).

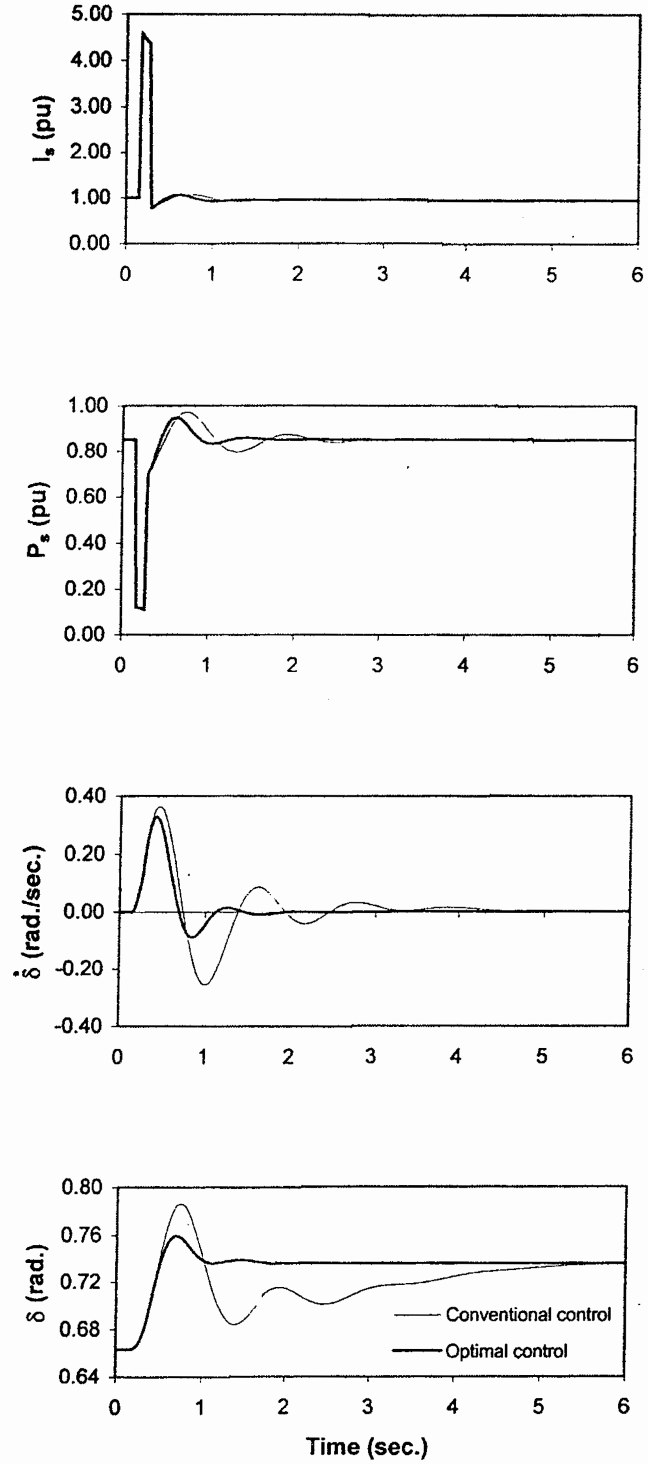

Fig. 7 Response of the closed loop system for 3-phase short circuit at load 2 following by switching the load 2 off (T_f=120 msec.).

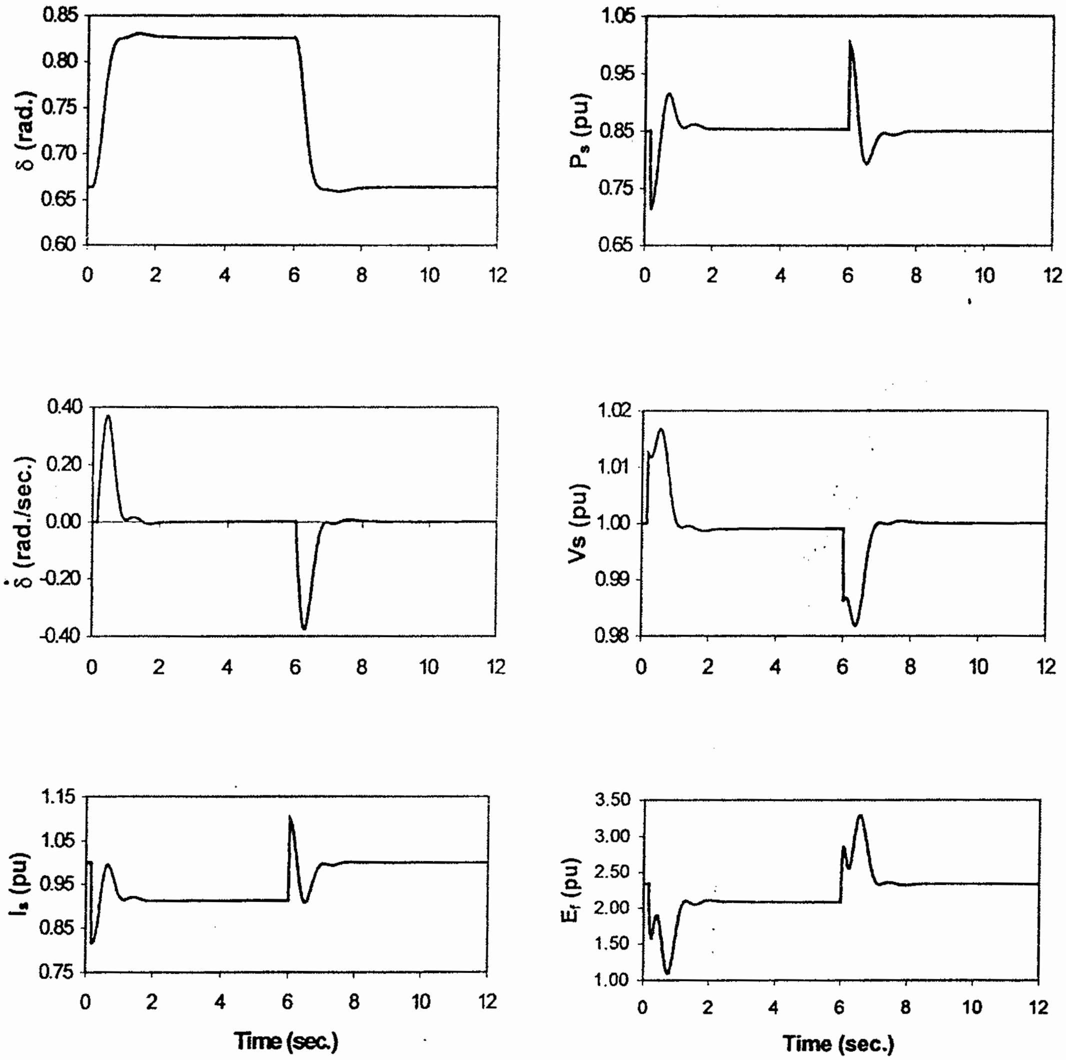

Fig. 8 Response of the closed loop system with optimal output excitation control for switching load 1 off and on.

تصميم حاكم مثالى للإثارة لوحدة توليد ذو توربينـــة غازيـــة

د/عزالدين شـــعبان عبد العزيز عابدين
قسم الهندسة الكهربائية
كليـــة الهندسة، جامعة المنوفيـــة

يقدم هذا البحث نموذج ديناميي لمنظومة وحدة توليد ذو توربينـــة غازيـــة تغذى نظام توزيـــع خطـــى. تتكون وحدة التوليد من توربينـــة غازيـــة، مولد تزامنى، خطى نقل، ثلاث قضبـــان توزيـــع، حملـــين كهربائيين. تم تصميم حاكم مثالى لنظام الإثارة مستند على النموذج الخطي المســـتنتج مـــن النمـــوذج الدينامي. تم إختبار آداء المنظومة المغلقة باســـتخدام الحاكم المثالى مع مقارنتها بالحواكم التقليدية وذلك عند تعرضها للإضطرابات الكهربائية المختلفة مثل حدوث قصر ثلاثى الأطـــوار عنـــد الأحمـــال المختلفة أو فصل أو توصيل بعض من الأحمال . أثبتت النتائج أن آداء المنظومة المغلقة باســـتخدام الحاكم المثالى المصمم لنظام الإثارة يملك خواص تخميديـــة جيده مع تحقيق الحـــد الأدنى لأقصـــى قيمـــة للمتغيرات. الحاكم المثالى المصمم سهل تطبيقه معمليا لأنه يعتمد على متغيرات يمكن قياسها فى المعمل.