THE OPTIMAL CONTROL OF ITU TRIGA MARK-II REACTOR

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ABSTRACT

In this study, optimal control of ITU TRIGA Mark-II Reactor is discussed. A new controller has been designed for ITU TRIGA Mark-II Reactor. The controller consists of a main and an auxiliary controllers. The forme is based on Pontragyn's Maximum Principle and the latter is based on PID approach. For the desired power program, a cubic function is chosen. Integral Performance Index includes the mean square of error function and the effect of selected period on the power variatio. YAVCAN2 Neutronic - Thermal -Hydraulic code is used to solve the equations, 11 equations, dealing with neutronic -thermal - hydraulic behavior of the reactor. For the controller design, a new code, KONTCAN, is written. In the application of the code, it is seen that the controller controls the reactor power to follow the desired power program. The overshoot value alters between 100 W and 500 W depending on the selected period. There is no undershoot. The controller rapidly increases reactivity, then decreases, after that increases it until the effect of temperature feedback is companseted. Error function varies between 0-1KW.

1- INTRODUCTION

ITU TRIGA Mark-II Reactor can be operated in automatic mode by means of Requlating Control Rod. As a Controller, an electromecanic chopper has been used [1].

In the control of reactor, different control methods which are based on reactor power, period and reactivity information have been used [2,3].

In the literature, there have been two research dealing with the control of ITU TRIGA Mark-II Reactor [4,5]. In both reseacrh, a real control problem is not examined. However several pre-conditions dealing with reactor control are offered. It is shown that the reactor can be controlled depending on these conditions.

In this study, in order to control the reactor, a new controller is designed and is defined.

2 - PHYSICAL MODEL

The equation System representing neutronic - thermal - hydraulic behavior of reactor core can be written in matrix notation as follows [6]:

$$\frac{dX}{dt} = AX + BU \qquad (1)$$

Where,

$$X^T = [n, C_1, \ldots. C_6, T_f, T_m, \vartheta] \;, \; U^T = [U, 0,0 \ldots 0,1,1] \qquad (2)$$

$$A = \begin{bmatrix} w & \lambda_1 & \lambda_2 & 0 & 0 & \lambda_6 & 0 & 0 & 0 & 0 \\ w_1 & -\lambda_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ w_2 & 0 & -\lambda_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ w_6 & 0 & 0 & 0 & 0 & 0 & -\lambda_6 & 0 & 0 & 0 \\ a_1 & 0 & 0 & 0 & 0 & 0 & 0 & -a_2 & a_2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & b_1 & -b_2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\vartheta_1 \end{bmatrix} \qquad B = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & b_3 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \vartheta_2 \end{bmatrix} \qquad (3)$$

$$a_1 = \frac{Cev}{N.C_F} \;, a_2 = \frac{\mu}{C_F} \;, \; b_1 = \frac{\mu N}{M\, C_m} \;, \; b_2 = \frac{\mu N + 2m\, Cm}{M\, C_m} \qquad (4)$$

$$b_3 = \frac{2m\, Cm}{M\, C_m} T_{min} \;, \; \vartheta_1 = \zeta\vartheta \;, \; \vartheta_2 = \frac{\rho_{in} - \rho_m}{\rho_m} g \qquad (5)$$

$$w = \frac{\rho_f - \beta}{\ell} \;, w_i = \frac{\beta_i}{\ell} \;, \zeta = \frac{1}{2}\frac{f}{D_H} + \frac{1}{2}(K_{in} + K_c)\frac{1}{H_c}$$

$$U = \frac{\rho_{ex} \cdot n}{\ell} \qquad (6)$$

In this model, we assumed that mass flow rate and inlet temperature of the coolant are time independent. However the thermal conductivity and specific heat of the fuel and thermal conductivity of the clad and the physical properties of the coolant are temperature - dependent. More information about the formulation can be obtained from Ref.6:

3 - CONTROLLER

The controller explained here is composed of two parts as a main controller and auxiliary controller, Figure-1.

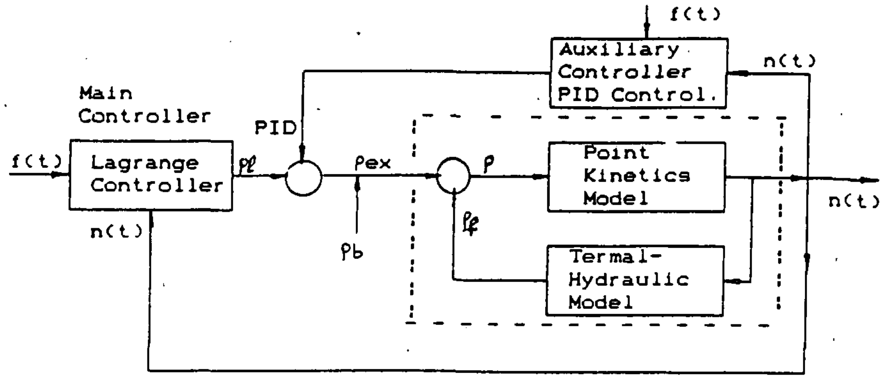

Figure-1: Controller

The main controller is based on Pontragyn´s Maximum Principle and is defined by Langrange multiplier. The auxiliary controller is a PID (Proportional-Integral-Derivative)controller.

The Controller produces a control function which causes the system output to follow a desired power program (trajectory). The control function, U, is chosen as follows:

$$U = U_{\ell} + U_{PID} \qquad = \rho_{ex}\frac{n}{\ell} \tag{7}$$

$$U_{\ell} = \rho_{\ell}\frac{n}{\ell}\ ,\quad U_{PID} = \rho_{PID}\frac{n}{\ell}\ ,\quad \rho_{ex} = \rho_{\ell} + \rho_{PID} \tag{8}$$

Ul and UPID control functions are produced by the main and the auxiliary controller, respectively.

3.1 The Main Controller; Langrange Controller

The main controller produces a control function Uℓ causing the system Output to follow the desired trajectory as optimal. In this design, Pontragyn´s Maximum principle is used.

For the optimal control method, a suitable performance index (cost function) must be chosen. Here, the integral performance index is taken into consideration as follows:

$$S(t) = \int_0^t \left\{\alpha^2[n(\sigma) - f(\sigma)]^2 + [\tau\,\dot{n}(\sigma) - n(\sigma)]^2\right\} d\sigma \tag{9}$$

The first term of integral in Equation 9 is mean square value of error function, the deviation of the reactor power output from its desired power program (trajectory). α is a weighting function which shows the importance of the mean square of error function. The second term in Equation 9 is used to force the system output to change in a certain period. τ is the reactor period and limits the rate of change of the reactor power.

The Hamiltonian is defined as follows:

$$H = \sum_{i=1}^{10} p_i \dot{X}_i - \dot{S} \tag{10}$$

$$\frac{dp_i}{dt} = -\frac{\partial H}{\partial X_i}\ ,\quad i = 1,\dots\ 10 \tag{11}$$

Where, Pi is lagrange multiplier.

By the use of the maximum principle, the control function Ul which minimizes Eq.9 necessarily maximizes Eq.10.In this situation, the optimal value of control function is obtained by taking $\dot{H}u$=0 ;

$$U_{\ell} = \frac{1}{2\tau^2}\,p_1 - \sum_{i=1}^{6}\lambda_i C_i - \left(w' - \frac{1}{\tau}\right) n \tag{12}$$

The control function Ul in the Eq.12 depends on P1,n and Ci. n,Ci can be calculated from Eq.1.and P1 can be found from Eq.11.

When derivative ∂H/∂Xi is taken from Eq.11 and organized in a new form, a new equation system for Pi´s is obtained as follows:

$$\frac{dY}{dt} = AL \cdot Y + BL \tag{13}$$

$$Y = [p_1, p_2 \dots p_{10}]^T$$

$$AL = \begin{bmatrix} -\frac{1}{\tau} & -w_1 & -w_2 & 0 & 0 & 0 & -w_6 & -a_1 & 0 & 0 \\ 0 & \lambda_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \lambda_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \lambda_6 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & a_2 & -b_1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -a_3 & b_2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{\tau} \end{bmatrix} \qquad BL = \begin{bmatrix} 2\alpha^2(n - f) \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{14}$$

3-2 The Auxiliary Controller, PID Controller

PID controller has been selected as the auxiliary controller. Its equation is written as follows:

$$U_{PID}(t) = P.\,e(t) + I\int_0^t e(t)\,dt + D\frac{de(t)}{dt} \quad (15)$$

$$e(t) = [n(t) - f(t)]\frac{1}{\ell}\,, \quad (16)$$

Where P, I,D, respectively, are proportional, integral, derivative control coefficients. e(t) is the error function, which represents deviation between calculated reactor output power and desired output power program.

If Equation 15 is written by considering finite difference approach, UPID in the j.time interval is obtained as follows:

$$H_{PID_j} = \left(P + \frac{D}{h}\right)e_j - \frac{D}{h}e_{j-1} + I.\,h\sum_{i=0}^{j} e_i \quad (17)$$

3-3 Trajectory: Desired Power Programme

In order to calculate equation 14 and 16, f(t) has to be known. f(t) is a desired power program which is predicted by user. It is desired that the reactor output power must follows the f(t) function.

In this study, the trajectory, Py, is considered as a Cubic function, Figure-2:

$$P_y = f_3 t^3 + f_2 t^2 + f_1 t + f_0 \qquad t \le t_{max} \quad (18)$$

$$Py = P_{max} \qquad t > t_{max} \quad (19)$$

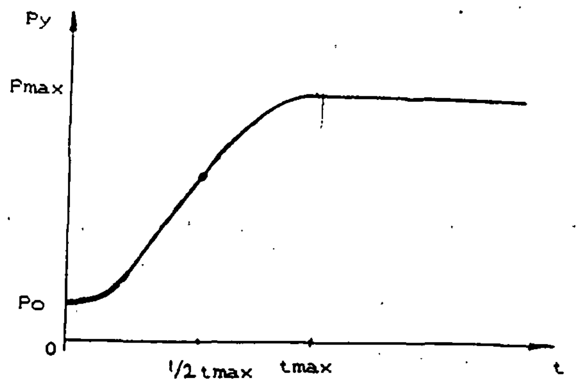

Figure-2: Trajectory.Desired Power Program

f3 - fo coefficients in the equation 18 can be calculated by considering the initial and final conditions:

$$P_y = P_0\,,\ t = 0 \qquad \text{Initial condition} \quad (20)$$
$$\dot{P}_y = 0$$

$$Py = P_{max}\,,\ \dot{P}_y = 0\,,\ t = t_{max}\,, \ \text{Final condition} \quad (21)$$

$$\frac{P_y}{\dot{P}_y} = \tau, \qquad t = 0.5\ t_{max}\,, \ \text{Period condition} \quad (22)$$

Eq.7 includes reactor period . The rate of the reactor power change has been limited by inserting reactor period into the performance index. Also, Same restriction must be done for the trajectory So, Equation 22 is predicted.

f3 - fo coefficients can be found easily from Eq.18 - 22.

$$f_3 = 2\frac{P_0 - P_{max}}{t_{max}^3}\,,\ f_2 = -3\frac{Po - P_{max}}{t_{max}^2}\,,\ f_1 = 0\,,\ f_0 = P_0 \quad (23)$$

$$t_{max} = 3\tau\,\frac{P_{max} - P_0}{P_{max} + P_0} \quad (24)$$

If Pmax $\gg$ Po in the Eq.24, tmax $\simeq 3\tau$. This means that the rise time to maximum power level is, approximately, three times of the chosen period.

4 - SOLUTION METHOD

Eq.1 and Eq.13 are solved by using the Modify Hansen Method. The detail information dealing with the solution can be obtained from Ref.6. Both equations system are solved seperately, But the solution method is the same. So, new symbols can be used to represent both equations:

$$\frac{dZ_i}{dt} = E_i\,Z_i + F_i\,, \quad i = 1,2$$

$$Z_i = X,\ E_i = A\,,\ F_i = B\,, \quad i = 1 \quad (25)$$

$$Z_i = Y\,,\ E_i = AL\,,\ F_i = BL\,, \quad i = 2$$

When the Modify Hansen Method is applied to Eq.25, the solution can be expressed as follows (6):

$$Z_{ij+1} = H_i + Z_{ij} + R_i\,.\,F_i\,, \quad (26)$$

$$H_i = e^{D_i.h} + (wo_i I - D_i)^{-1}\left[e^{wo_i.h.I} - e^{D_i.h}\right]\left[L_i + U_i\right] \quad (27)$$

$$R_i = D_i^{-1}\left[e^{D_i.h} - 1\right] \quad (28)$$

Where, Di, Li and Ui, respectively, represent, diagonal, Lower triangle and upper triangle matrix of coefficients matrix Hi. Woi is the biggest positive eigenvalue of Hi

To calculate Woi the different methods can be used[6].W´in Eq.3 is strongly dependent to the fuel temperature. There fore Wo1 must be calculated for each time interval. The elements of AL are not very much dependent to the fuel temperature as comparing with w´. The first element of AL matrix is independent from the temperature variations and it is unnecessary to calculate wo2 for each time interval.

To calculate the neutronic - thermal - hydraulic behavior of the reactor, YAVCAN2 code is used. By inserting the solution of Eq.13, Eq 17 and 18 to this code, a new control code, KONTCAN, is realized.

5 - CONCLUSION

KONTCAN Code is operated for different start-up conditions. At the beginning it is assumed the reactor is critical at 100W. While the reactor is operating at this power level, it is asked the reactor power level to be once 100KW and once 250 kW by following the trajectory defined before. For both situation, the reactor period is assumed as 10 sec. The results are shown in Figure-3 and Figure-4. In both situation, it is observed that error function varies from o to 200W. The error decreases While approaching to maximum power level and it goes zero after 100W of Overshoot value. Figure-5 and Figure-6. In both computer experiments, any undershoot was not seen.

Also, In both situation, the external reactivitiy is rapidly increased at the beginning, then it is reduced, after that it is increased to compensate the effect of the fuel temperature feedback as shown in Figure-3 and Figure-4.

KONTCAN Code is reoperated by selecting 5 sec of period and 250 kw of set point. The result is shown in Figure 7-9. It is observed that the Overshoot value increases and the settling time extends. By comparing Figure-4 and Figure-7, When the period is selected smaller, maximum power level is reached faster, but the overshoot and settling time increase.

The external reactivity is essentialy altered by the main controller. PID controller slightly affects on the reactivity variation, Figure-10 and Figure-11.

The regulating control rod in reactor can not be withdrawn faster than 16c/sec of speed. This restriction is inserted into the KONTCAN code.

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In this study a new controller has been realized to control the research Triga type reactors. The controller consist of

the main, Langrange, and the auxiliary, PID controllers. Maximum principle approach is used in design of the main controller.

The external reactivity is essentialy altered by the main controller. The error function is very small. The controller forces the reactor output power to follow the trajectory very well. These results have not been tested by doing experiments in the reactor,yet, It is not known whether both results fit each other or not.

NOMENCLATURE

Acc : The cross - sectional area of a coolant channel
c : Specific heat
C_F : Heat capacity of a fuel
$C_i(t)$: The 1´th precursor concentration
D_h : Equivalent hydraulic diameter.
f(t) : Desired output program
g : Gravity
H : Hamiltonian
Hc Active core height
l : Mean neutron life time
M : Mass
m : The total mass flow rate of coolant
N : The number of the fuel elements
n(t) : Nevtron density
p(t) : Power
Pi : The i.. Langrange multiplier
P : Proportional controller coefficient

T(t) : Temperature
Tmin : The inlet temperature of a coolant
U(t) : Control function
V : Volume
v : Coolant velocity
α : Weighting function
β : Total delayed neutron fraction
β_i : The fraction of all fission neutrons

λ_i : The decay constant of the 1´th precursor
μ : The over-all heat transfer coefficient of a fuel element.
ρ_m : Density of coolant
ρ_{in} : Density of Inlet coolant
$\rho(t)$: Net reactivity
$\rho_{ex}(t)$: External reactivity
ρ_f : Feedback reactivity
ρ_l : Langrange reactivity
ρ_{PID} : PID reactivity
τ : Period

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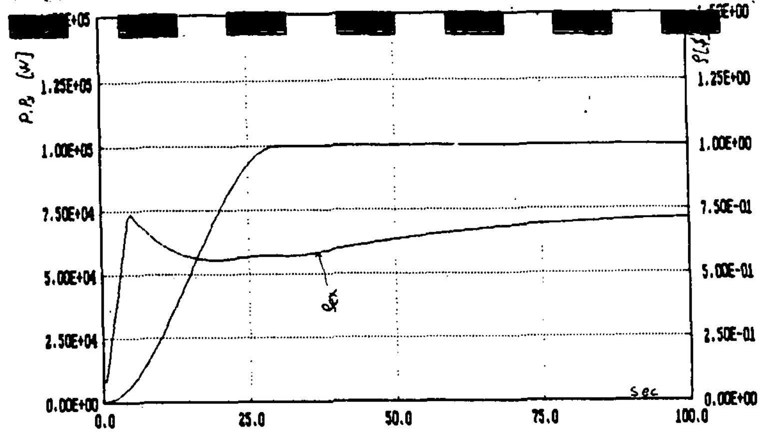

Figure-3 : Time response of power and Reactivity the controlled Reactor, τ= 10 sec Pmax= 100 kw

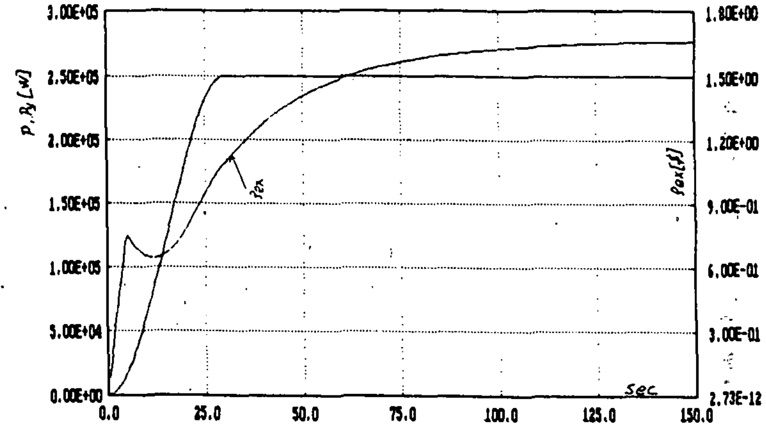

Figure-4 : Time response of power and Reactivity in the controlled Reactor, τ= 10 sec, Pmax= 250kw

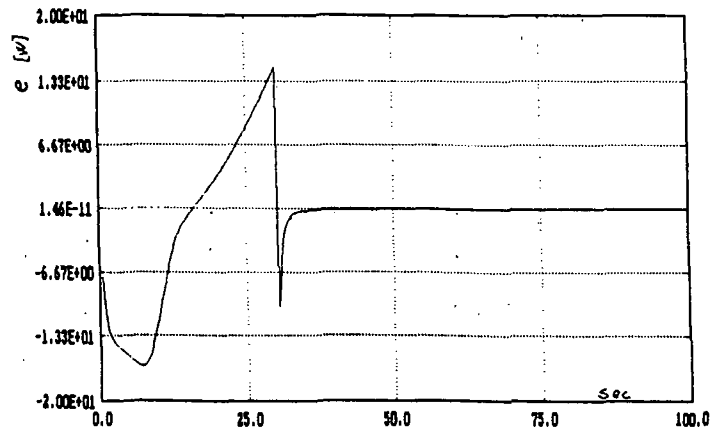

Figure-5 : Error function, τ= 10 sec, Pmax=100kw

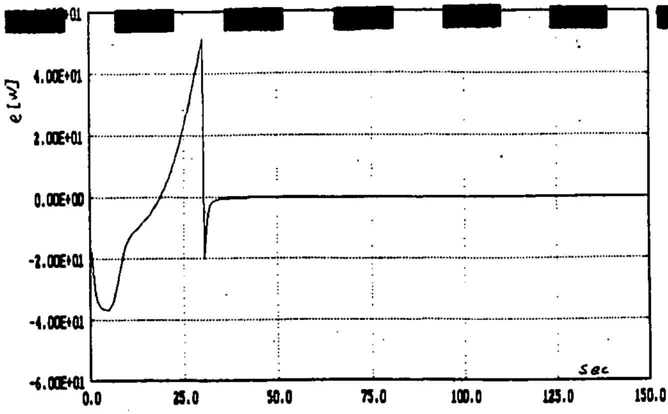

Figure-6 : Error function, τ= 10 sec, Pmax= 250kw

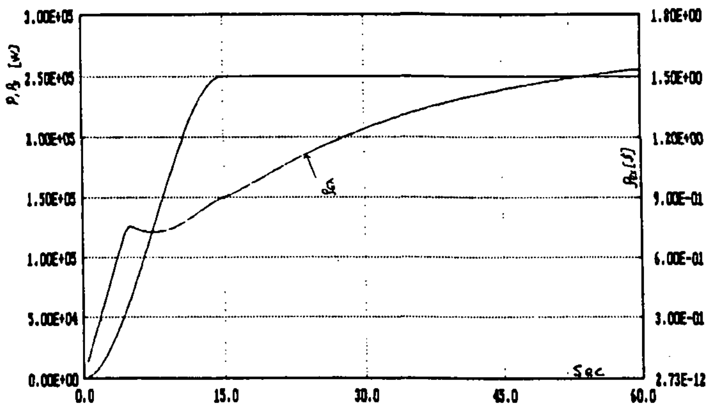

Figure-7 : Time response of power and Reactivity in the controlled Reactor, τ= 5 sec, Pmax= 250 kw

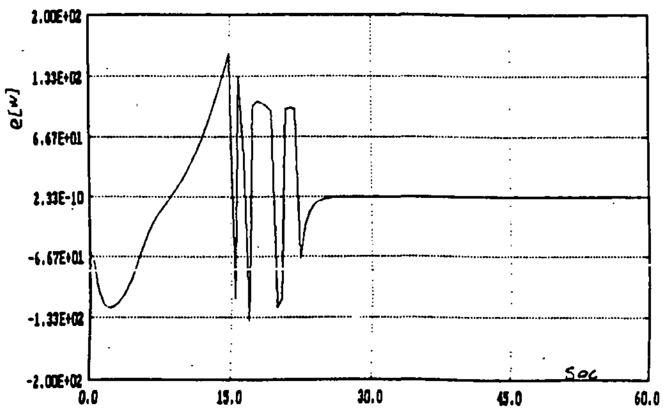

Figure-8 : Error function, τ= 5 sec, Pmax= 250kw

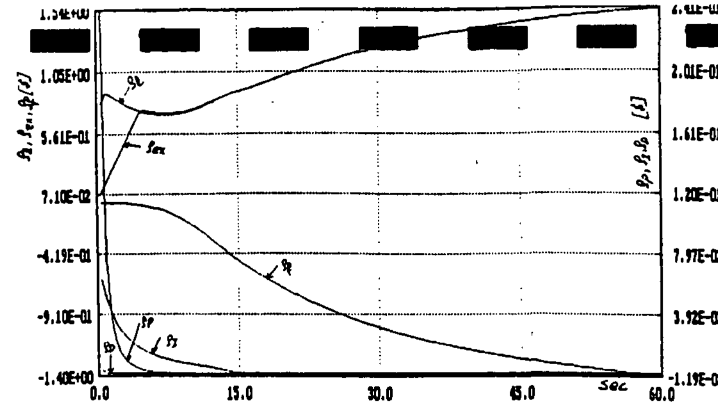

Figure-9 : The effect of lagrange and PID controller on the reactivity, τ= 5 sec, Pmax= 250 kw

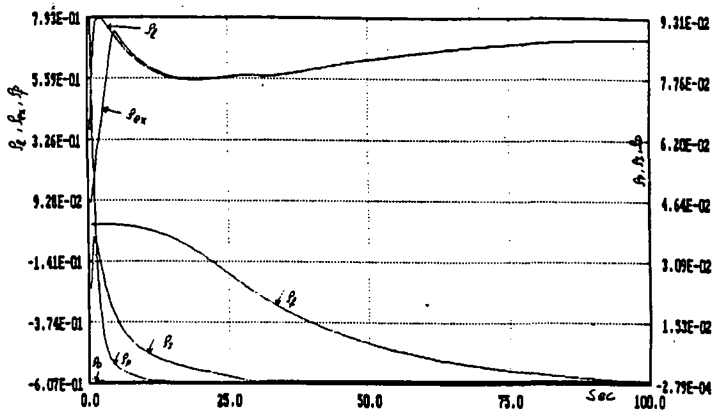

Figure-10: The effect of langrange and PID controller on the reactivity, τ= 10 sec, Pmax= 100 kw

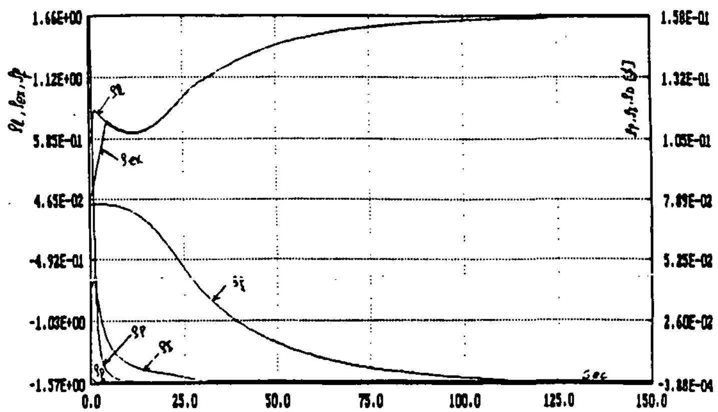

Figure-11: The effect of langrange and PID controller on the reactivity, τ= 10 sec, Pmax= 250 kw