Vectorized quadrant model simulation and spatial control of Advanced Heavy Water Reactor (AHWR)

SWETHA R KUMAR
Department of Instrumentation and Control Engineering
PSG College of Technology,
Peelamedu, Coimbatore, Tamilnadu 641004
INDIA
swetha19.raj@gmail.com

Abstract: This paper describes a method to develop a vectorized nonlinear quadrant model and controller design to achieve spatial stability of AHWR core. The AHWR is a 920MWth, heavy water moderated, boiling light water cooled natural circulation reactor. Reactor core of AHWR is fictitiously divided into 17 non-overlapping nodes to ensure spatial stability. The non-linear coupled core neutronics - thermal hydraulics model of AHWR core is represented by 90 first order differential equations. The total reactor power and 17 nodal powers are controlled by manipulating four voltage signals to the Regulating Rods (RRs). It is necessary to design an effective controller to maintain the total power of the reactor while the xenon induced oscillations are being controlled. Thus it is essential to control nodal powers along with total power. Genetic algorithm is incorporated in controller design for optimal control of reactor power.

Key-words: Coupled neutronics, Thermal hydraulics, Relay feedback approach, Vectorized model, Nuclear Power Program, Mathematical modeling, Genetic algorithm.

1 Introduction

Energy is one of the most significant resources of global economy, and is necessary to increase the opportunities of economic and social development. 80% of world's energy consumption is produced from fossil fuels, whose combustion generates carbon dioxide and other greenhouse gases which accounts for 12 billion tons of oil equivalent.

Therefore, we must face several challenges such as meeting significant electricity needs while facing the reduction of fossil fuels and enacting measures to tackle climate change. The most suitable solution would be a balanced generation mix that includes fossil fuels, renewables and nuclear power. Indeed, nuclear ensures the stability of electricity generation while allowing the reduction of carbon dioxide emissions.

Uranium fuelled nuclear reactors are popular throughout the world. Considering the large reserves of Thorium in India, an innovative thorium fuelled nuclear reactor is designed. The advanced heavy-water reactor AHWR is the latest Indian design for a next-generation nuclear reactor that burns thorium in its fuel core. Nuclear reactor power control plays a major role in the safety of the nuclear power plant. Hence, there is a need for control of nuclear reactor power control.

The availability of uranium is limited in India. However, 1/3rd of the world's Thorium resources are in India. Hence Thorium utilization is an important part of the program. The conversion of fertile material to fissile material, to harness nuclear energy from the later forms an integral part of the programme.

The Nuclear Power Program (NPP) is classified into three stages as seen below.

Stage – I: Use of pressurized heavy water reactor fuelled by natural uranium

Stage – II: Fast breeder reactors that utilize Plutonium-based fuel

Stage – III: Advanced nuclear power systems for Thorium utilization

Fig. 1 shows the schematic diagram of a Advanced heavy water reactor. The reactor core is housed in a low-pressure reactor vessel called calandria. The calandria contains heavy water, which act as moderator as well as reflector. The light water coolant picks up nuclear heat in boiling mode from fuel assemblies. The coolant circulation is driven by natural convection through tail pipes to steam drums, where steam is separated and is supplied to the turbine.

Four steam drums each catering to one-fourth of the core, receive feed water at 403K to provide

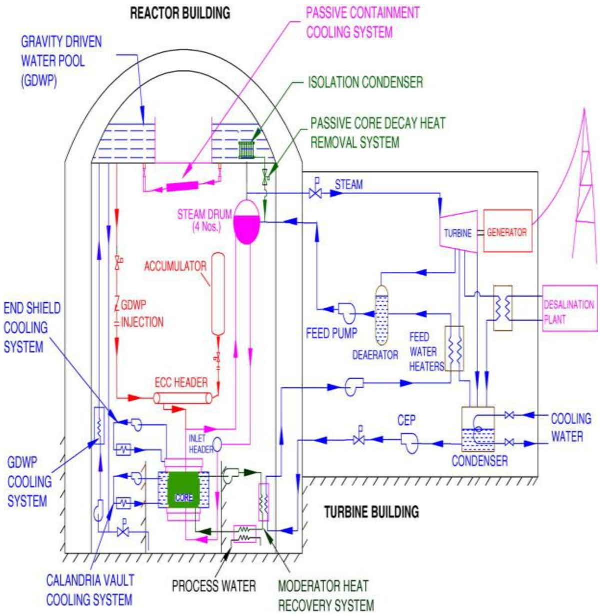

Fig.1 Schematic diagram of AHWR plant

optimum sub-cooling at the reactor inlet.. Four down-comers, from each steam drum, are connected to a circular inlet header. The inlet header distributes the flow to each of the 452 coolant channels through individual feeders.

The core dimension of AHWR is several times larger as compared to the neutron migration length, due to which one part of the core may undergo xenon oscillation opposite in phase to the other parts of the core. It is necessary to design an effective controller to maintain the total power of the reactor while the xenon induced oscillations are being controlled. Thus, AHWR core is fictitiously divided into 17 nodes as depicted in Fig. 2

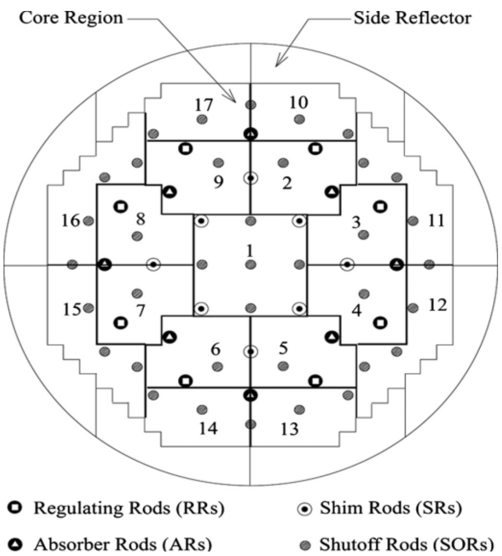

Fig.2 Division of core into seventeen nodes

2 Spatial instability

Fission reactions taking place in nuclear reactors give rise to the formation of several nuclear species. However, the isotope ^{135}Xe requires attention in operation and control of thermal reactors. A small fraction of this isotope is formed directly in fission but the major portion results from the radioactive decay of ^{135}I. The ^{135}Xe has very large thermal neutron absorption cross section and undergoes radioactive decay at a relatively slower rate than ^{135}I does. Hence, the immediate effect of an increase in neutron flux in the reactor is to cause a decrease in the concentration of ^{135}Xe, which in turn results into an increase in neutron flux.

This continues for few hours after which the reverse takes place, where the increased neutron flux results into formation of more xenon which in turn reduces the neutron flux. In this manner, oscillations of the neutron flux are introduced by ^{135}Xe (Duderstadt and Hamilton, 1983). Such oscillations induced by xenon can be broadly classified in two categories as fundamental mode or total power oscillation, and higher mode or spatial oscillations.

In fundamental mode, the total power of the reactor undergoes oscillations which can be readily noticed and suppressed by a control system whereas in spatial oscillations, power in different regions of the core oscillates asymmetrically such that the total power remains more or less constant. If the spatial oscillations in a reactor are not controlled, a serious situation known as ''flux tilting'' may arise, i.e., one portion of the reactor may tend to produce more energy than the other portion does, and this can cause fuel in that region to exceed its thermal design limits.

Such spatial oscillations are more prominent in ''large'' nuclear reactors having physical dimensions several times the neutron migration length. Hence during the design stages of any large nuclear reactor, analysis to identify the existence of spatial instabilities and design of a suitable control strategy for regulating the spatial power distribution becomes essential.

3 Mathematical Modeling

A simple nodal model of AHWR is derived based on finite difference approximation of the two group neutron diffusion equations and the associated equations for delayed neutron precursor's concentrations

3.1 Core neutronics model

$$\frac{dW_i}{dt} = -\alpha_{ii}\frac{W_i}{l} + \sum_{j=1}^{17}\alpha_{ji}\frac{W_j}{l} + (\rho_i - \beta)\frac{W_i}{l} + \lambda C_i \quad (1)$$

$$\frac{dC_i}{dt} = \frac{\beta}{l}W_i - \lambda C_i \quad (2)$$

where α_{ji} and α_{ii} denote the coupling coefficients between *j*th and *i*th nodes and self coupling coefficients of *i*th node respectively, β and λ are respectively effective one group delayed neutron yield and decay constant, l is the neutron lifetime and W_i and C_i are the nodal power level and the effective one group delayed neutron precursor concentration of ith node respectively

The most important fission product poison is xenon because of its exceptionally large capture cross section for thermal neutrons with half-life of 9.2 h. To formulate xenon reactivity feedback, iodine and xenon dynamics in each node are represented as

$$\frac{dI_i}{dt} = \gamma_i \in_{fi} W_i - \lambda_i I_i \quad (3)$$

$$\frac{dX_i}{dt} = \gamma_X \in_{fi} W_i + \lambda_i I_i - (\lambda_X + \overline{\sigma}_{Xi} W_i)X_i \quad (4)$$

where γ_i and γ_X are fission yields of iodine and xenon respectively, λ_i and λ_X are respectively decay constants of iodine and xenon.

$$\overline{\sigma}_{Xi} = \frac{\sigma_{Xi}}{E_{eff}\in_{fi}V_i} \quad (5)$$

I_i denotes iodine concentration and X_i the xenon concentration of ith node. Also, E_{eff} is energy liberated in each fission, V_i is the node volume and $\in_{fi}$ is thermal neutron fission cross-section of *i*th node. The speed of RR is directly proportional to the voltage applied to the drive motor, and it is given by

$$\frac{dH_i}{dt} = k\gamma_k \quad (6)$$

where *i*, *j* = 1, 2 ...17 and k = 2,4,6,8

3.2 Thermal hydraulics model

Thermal hydraulics model of MHT system of AHWR has been developed by evolving separate models for reactor core thermal hydraulics and for the steam drums, and afterwards clubbing them together.

3.2.1 Core thermal hydraulics

A thermal hydraulics model of the reactor core is obtained assuming an equivalent coolant channel for each node. Applying mass and energy balance to the boiling section and solving them together, the core thermal hydraulics model is written as

$$e_{vp_i}\frac{dP}{dt} + e_{vx_i}\frac{dx_i}{dt} = W_i - q_{di}(h_w - h_d) - x_i h_c q_{di} \quad (7)$$

where P is drum pressure, h_w, h_d and h_c are water, downcomer and condensation enthalpies respectively, x_i is the average exit quality,q_{di} is flow rate of the coolant entering the ith node through downcomer and e_{vp_i} and e_{vx_i} are constants of ith node.

3.2.2 Steam drums

A mixture of saturated water and steam enters the steam drum and subcooled water leaves steam drum into the reactor core; Average values of density and enthalpy of the water in the steam drum have been considered. Mass and energy balance equations of the steam drums are respectively represented by

$$e_{pv}\frac{dV_w}{dt} + e_{pp}\frac{dP}{dt} = -\sum_{i=1}^{17}\left(q_{d_i} - q_{r_i}\right) + q_f - q_s \quad (8)$$

$$e_{x_v}\frac{dV_w}{dt} + e_{x_p}\frac{dP}{dt} = q_f h_f + x q_r h_s + (1-x)q_r h_w - q_d h_d - q_s h_s \quad (9)$$

where q_f, q_s, q_r and q_d are average values of feed water, steam, saturated steam and subcooled water flow rates respectively and V_w is the volume of water in the steam drum.

Finally applying energy balance equation to water volume in steam drum yields

$$e_{p_i}\frac{dP}{dt} + e_{v_i}\frac{dV_w}{dt} + e_{x_i}\frac{dh_d}{dt} = q_f h_f + (1-x)q_r h_w - q_d h_d \quad (10)$$

Complete thermal hydraulics model is given by above four equations. Assuming drum water volume and pressure are being regulated at respective set points by plant control system, the thermal hydraulics model is given by

$$e_{vxi}\frac{dx_i}{dt} = W_i - q_{di}(h_w - h_d) - x_i h_c q_{di} \quad (11)$$

$$e_{xi}\frac{dh_d}{dt} = q_f\left(\hat{k}_2 h_f - \hat{k}_1\right) - q_d\left(\hat{k}_2 h_d - \hat{k}_1\right) \quad (12)$$

where $\hat{k}_2=\frac{h_s}{h_d}$, $\hat{k}_1=h_w\hat{k}_2$

The coolant flow rate through the channels is the function of normalized nodal powers, given as

$$q_{di} = \{k_1\left[\frac{W_i}{W_{i0}}\right]^3 + k_2\left[\frac{W_i}{W_{i0}}\right]^2 + k_3\left[\frac{W_i}{W_{i0}}\right]^1 + k_4\}$$

where k_1 = 0.2156, k_2 = -0.5989, k_3 = 0.48538 and k_4 = 0.8988. W_{i0} denotes the power produced by ith node under full power operation and q_{di0} is the corresponding coolant flow rate.

3.2.3 Reactivity feedbacks

The reactivity term ρ_i is expressed as,

$$\rho_i = \rho_{iu} + \rho_{iX} + \rho_{i\alpha} \tag{14}$$

where ρ_{iu} is the reactivity introduced by the control rods, ρ_{iX} is the reactivity feedback due to xenon and $\rho_{i\alpha}$ is the reactivity feedback due to coolant void fraction.

The reactivity contributed by the movement of the RRs is expressed as

$$\rho_{iu}\begin{cases}(-10.234H_I + 676.203)10^{-6} & \text{if} i = 2,4,6,8 \\ 0 & \text{elsewhere}\end{cases} \tag{15}$$

The xenon reactivity feedback in node i can be expressed as

$$\rho_{iX} = \frac{\overline{\sigma_{XI}X_i}}{\epsilon_{ai}} \tag{16}$$

The reactivity contribution by the coolant void fraction is

$$\rho_{i\alpha} - (5*10^{-3})*\begin{pmatrix}9.2832{x_i}^5 - 27.7192{x_i}^4 + 31.7643{x_i}^3 \\ -17.7389{x_i}^2 + 5.2308{x_i}^1 + 0.0792\end{pmatrix} \tag{17}$$

4 Process data for AHWR core under normal operating condition

The neutronics are listed in Table 1. Nodal volumes and cross sections and Constant coefficients of thermal hydraulics model are summarized in Table 2 and Table 3 respectively. The Constant coefficients of thermal hydraulics model and Nodal powers and coolant flow rates under full power operation are given in Table 2 and Table 3 respectively..

Table 1 Neutronic data used in AHWR model

β	2.643×10^{-3}
λ	6.4568×10^{-2} s^{-1}
ℓ	3.6694×10^{-4} s
λ_I	2.878×10^{-5} s^{-1}
λ_X	2.1×10^{-5} s^{-1}
γ_I	5.7×10^{-2}
γ_X	1.1×10^{-2}
σ_X	1.8×10^{-22} cm^{-1}
E_{eff}	3.2×10^{-11} J

Table 2 Nodal volumes and cross sections

Node No.	Volume (m^3)	Σ_f (cm^{-1})	Σ_a (cm^{-1})
1	8.6822	2.6657×10^{-3}	6.9514×10^{-3}
2, 5, 6, 9	5.4042	2.3898×10^{-3}	6.6828×10^{-3}
3, 4, 7, 8	5.1384	2.5325×10^{-3}	6.7898×10^{-3}
10, 13, 14, 17	4.4297	2.5665×10^{-3}	6.8991×10^{-3}
11, 12, 15, 16	5.5814	2.5665×10^{-3}	6.8991×10^{-3}

Table 3 Coupling coefficients for the AHWR model

$\alpha_{1,1} = 3.1567 \times 10^{-2}$
$\alpha_{2,2} = \alpha_{5,5} = \alpha_{6,6} = \alpha_{9,9} = 5.4918 \times 10^{-2}$
$\alpha_{3,3} = \alpha_{4,4} = \alpha_{7,7} = \alpha_{8,8} = 6.2052 \times 10^{-2}$
$\alpha_{10,10} = \alpha_{13,13} = \alpha_{14,14} = \alpha_{17,17} = 3.8351 \times 10^{-2}$
$\alpha_{11,11} = \alpha_{12,12} = \alpha_{15,15} = \alpha_{16,16} = 4.3567 \times 10^{-2}$
$\alpha_{1,2} = \alpha_{1,5} = \alpha_{1,6} = \alpha_{1,9} = 6.5746 \times 10^{-3}$
$\alpha_{1,3} = \alpha_{1,4} = \alpha_{1,7} = \alpha_{1,8} = 6.5204 \times 10^{-3}$
$\alpha_{2,1} = \alpha_{5,1} = \alpha_{6,1} = \alpha_{9,1} = 4.5833 \times 10^{-3}$
$\alpha_{3,1} = \alpha_{4,1} = \alpha_{7,1} = \alpha_{8,1} = 4.3309 \times 10^{-3}$
$\alpha_{2,3} = \alpha_{5,4} = \alpha_{6,7} = \alpha_{9,8} = 1.3044 \times 10^{-2}$
$\alpha_{3,2} = \alpha_{4,5} = \alpha_{7,6} = \alpha_{8,9} = 1.2428 \times 10^{-2}$
$\alpha_{3,4} = \alpha_{4,3} = \alpha_{7,8} = \alpha_{8,7} = 1.6097 \times 10^{-2}$
$\alpha_{2,9} = \alpha_{5,6} = \alpha_{6,5} = \alpha_{9,2} = 1.0445 \times 10^{-2}$
$\alpha_{2,10} = \alpha_{5,13} = \alpha_{6,14} = \alpha_{9,17} = 2.3481 \times 10^{-2}$
$\alpha_{3,11} = \alpha_{4,12} = \alpha_{7,15} = \alpha_{8,16} = 2.7555 \times 10^{-2}$
$\alpha_{10,2} = \alpha_{13,5} = \alpha_{14,6} = \alpha_{17,9} = 1.9198 \times 10^{-2}$
$\alpha_{11,3} = \alpha_{12,4} = \alpha_{15,7} = \alpha_{16,8} = 2.9941 \times 10^{-2}$
$\alpha_{10,17} = \alpha_{17,10} = \alpha_{11,12} = \alpha_{12,11} = \alpha_{13,14} = \alpha_{14,13} = \alpha_{15,16} = \alpha_{16,15} = 9.9912 \times 10^{-3}$
Rest all $\alpha_{ij} = 0$

Table 4 Constant coefficients of thermal hydraulics model

Node No., i	e_{vx_i}
1	2.4406
2, 5, 6, 9	1.0909
3, 4, 7, 8	1.2160
10, 13, 14, 17	1.9861
11, 12, 15, 16	1.1677
$e_{xh} = 0.5114$	

Table 5 Nodal powers and coolant flow rates under full power operation

Node No.	Steady state values of Power (MW thermal)	Steady state values of Coolant flow rate (kg/s)
1	91.8743	187.32
2, 5, 6, 9	54.9991	130.20
3, 4, 7, 8	55.7410	125.38
10, 13, 14, 17	42.6967	97.06
11, 12, 15, 16	53.7146	125.78
Total	920.480	2101.0

Table 6 Notations and Subscripts

C	delayed neutron precursor concentration
E_{eff}	Average thermal energy liberated per fission
E_n	Identity matrix of dimension n
H	% in position of regulating rods
I	Iodine concentration
P	Steam drum pressure
W	Fission power
V	Volume
X	Xenon concentration
h	Enthalpy
q	Mass flow rate
v	Control signal to regulating rod drive
x	Exit mass quality
α	Coupling coefficient
β	Delayed neutron fraction
γ	Fractional fission yield
l	Neutron life time
ρ	Reactivity
σ_a	Microscopic absorption cross-section
$\in_a$	Macroscopic absorption cross-section
$\in_f$	Fission cross-section

5 Vectorization of the AHWR

The dynamics equations representing the mathematical model of AHWR can be written in vector/ matrix form to implement in MatLab/Simulink environment.

For that, rearrange Eq. (1) of nodal powers as

$$\frac{dWi}{dt} = \frac{1}{l}[-\alpha_{ii}W_i + \sum_{j=1}^{17} \alpha_{ji}W_j + (\rho_i - \beta)W_i + \lambda l C_i]$$

In the above equation α, β are constants, W_i, α_{ii}, $C_i$and ρ_i are column vectors of order 1x17 and α_{ji} is a matrix of order 17x17. However, each term in this equation becomes a column vector of same dimensions.

If scalar multiplication is denoted by ‘ · ’, element- wise multiplication is denoted by ‘°’ and array multiplication is denoted by ‘∗’ then the above equation can be rewritten as

$$\frac{dWi}{dt} = \frac{1}{l} \cdot [-\alpha_{ii}{}^{\circ}\, W_i + \sum_{j=1}^{17} \alpha_{ji}W_j + \rho_i{}^{\circ}W_i - \beta \cdot W_i + (\lambda l) \cdot C_i]$$

Similarly all the equations of AHWR model are expressed in its vectorized form and implemented.

6 Division of core into four zones

The core of AHWR is fictitously divided into four quadrants as shown in fig 3

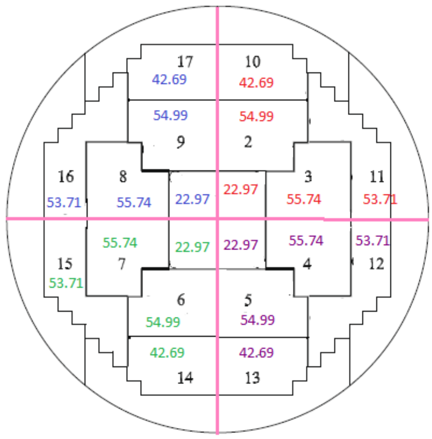

Fig.3 Division of AHWR core into four zones

By controlling the quadrant powers, spatial control can be achieved i.e., the nodal powers can be controlled.

As it can be noted, core exhibits symmetry in dimensions and power. Thus, partition the core into 4 quadrants along the lines of symmetry. Each quadrant has one Regulating Rod.

The Simulink diagram along with interactions is as shown in fig 4.

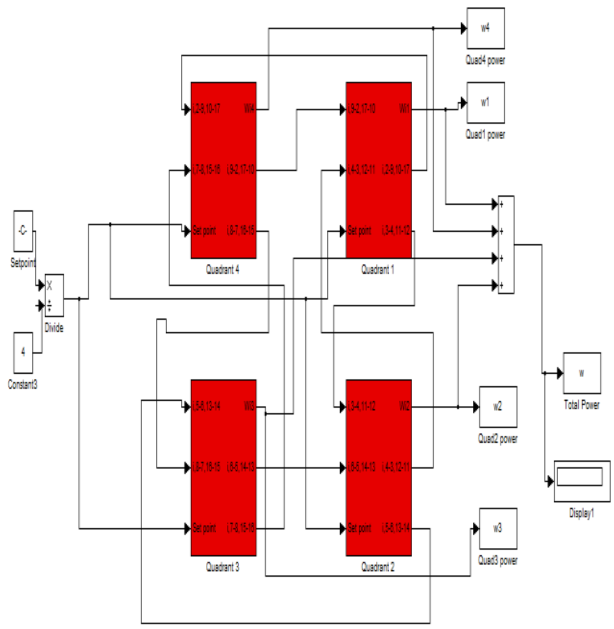

Fig.4 Simulink diagram

7 Controller design

A conventional PID controller is designed using relay feedback approach. Optimization of this controller is carried out using Genetic Algorithm.

7.1 Relay Feedback method of tuning controllers

In this AHWR process, relay input is total power and relay output is position of RRs.

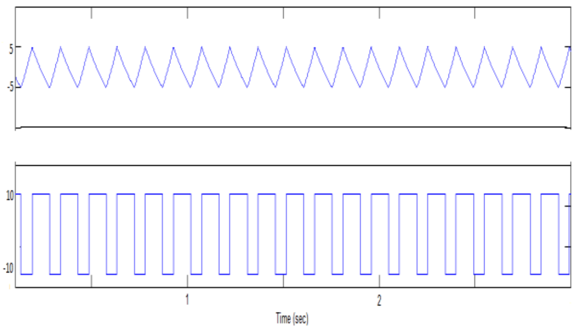

Fig.5 Relay response

By carrying out relay test on the model, the following controller settings are obtained. Table 7 shows the controller settings obtained for quadrant model.

For the vectorized model of AHWR, parameters obtained from auto tuning are

Ultimate period : 9.549 seconds

Ultimate frequency : 3.1415 Hz

Table 7 Controller settings

	K_P	K_I	K_D
PI	4.2975	2.6168	0
PID	5.7294	1.5705	0.3927

7.2 Genetic algorithm

Optimization minimizes error and maximizes yield. Optimal control of AHWR plant is more effective and improves safety. Genetic Algorithms are evolutionary algorithms for finding a global optimal solution for an optimization problem. Here the fitness function used in the proposed methodology is given as

$f(x) = 1/(\text{error}+1)$

where, error = (set point – Total reactor power)

The General representation of GA performance steps is given in Fig 6 and the various Parameters used for GA in this proposed methodology are shown in table 8

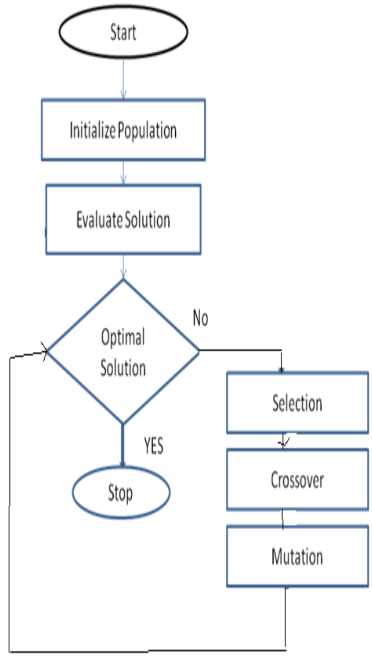

Fig.6 Flow chart for Genetic Algorithm

Table 8 Parameters for GA based tuning

Parameters	Values
Population Size	50
String Length	3
Fitness function	1/(error+1)
Selection	Ranking Selection
Cross Over	Simple Crossover
Mutation	Single Value Mutation
Coding Method	Real Coded
Probability of Crossover	.99
Probability of Mutation	.01

Parameters and controller settings obtained from GA are,

Error : 2.129509e-004

Fitness : 4.67390e+003

Table 9 Optimal controller settings

	K_P	K_I	K_D
PI	6.073603	4.52896	0
PID	7.297506	4.653988(6.1)	0.3895836

8 Results and Discussions

The open loop response for total power and nodal powers are as shown in Fig 7, 8

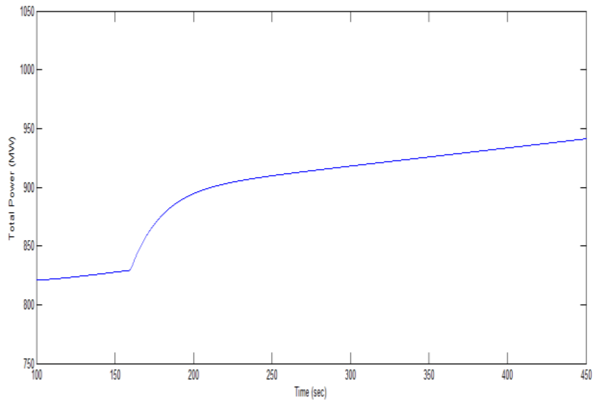

Fig. 7 Open loop response of total power

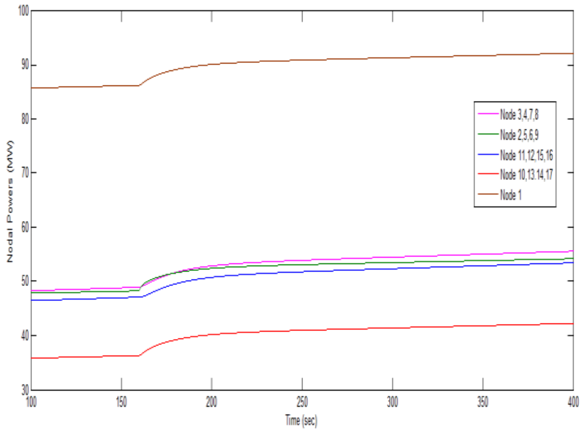

Fig. 8 Variations of nodal power in open loop

A conventional PI and PID controllers are designed using RFB approach. Optimization techniques are also implemented using Genetic algorithm.

8.1 RFB tuned PI and PID controllers

Response of the controller for various changes in set point has been studied. Noted that the PID controller has reduced overshoot and smooth performance than PI controller. Fig.9 shows the set point tracking capability of conventional controllers.

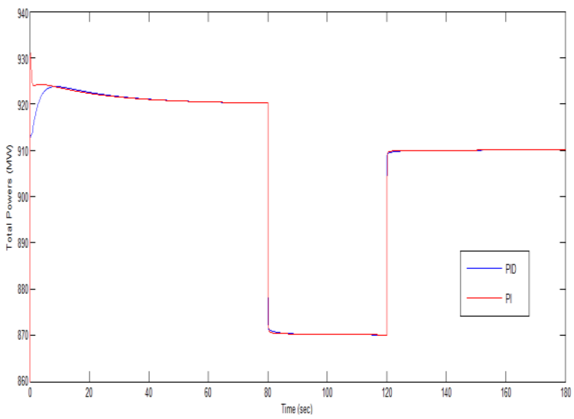

Fig.9 Total power variation as per demand

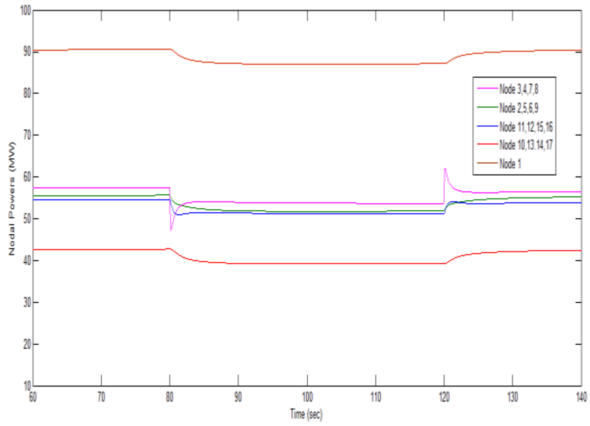

Fig.10 Nodal power variation as per demand

For the above responses, the controller output is shown in Fig.11.

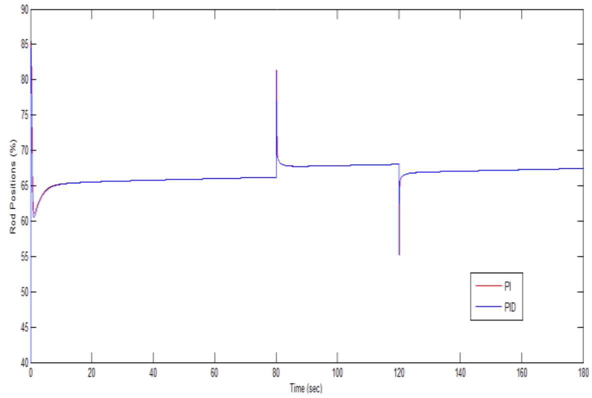

Fig.11 Manipulated rod positions as per demand

For nominal power 920.48MW, value of rod position is 66.1%.

8.2 Optimal PI and PID controllers

The controllers are optimized using Genetic Algorithm. Servo response of the process is shown in Fig.12 and Fig.13. Changes in set point are tracked effectively using optimally tuned PI and PID controllers.

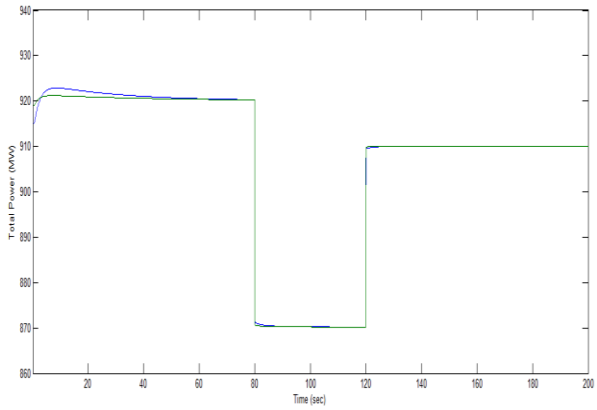

Fig.12 Total power variation

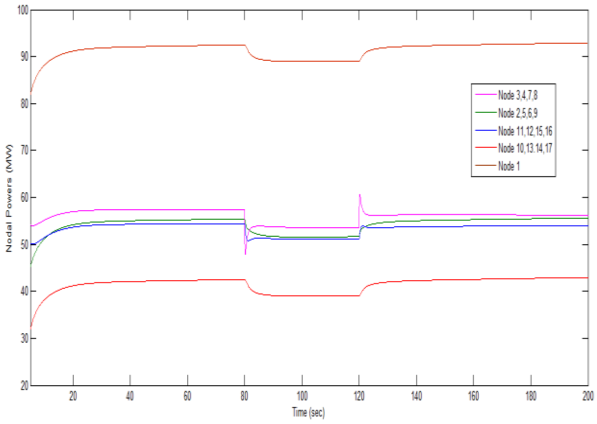

Fig.13 Nodal power variation

For these changes in set point, the controller response is as shown below

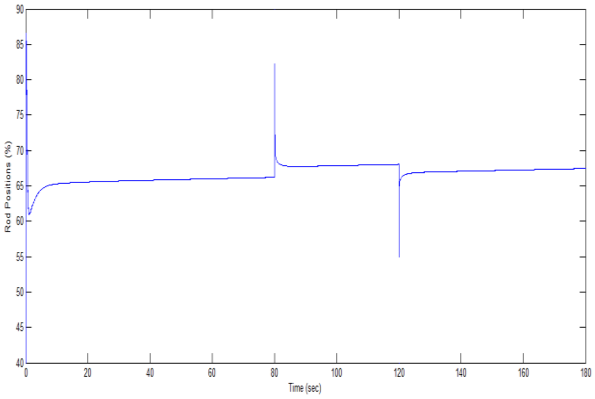

Fig.14 Manipulated rod position

A disturbance is introduced in the process and the regulatory performance of optimally tuned PID controller is noted. Feed water flow rate is increased by 5% and controlled output is plotted as in Fig.15

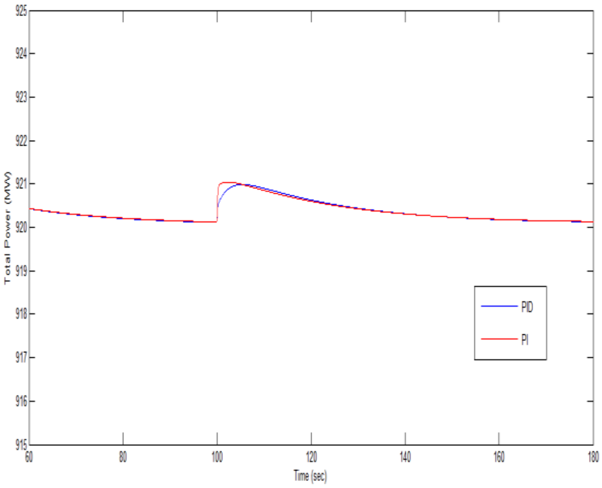

Fig.15 Controlled total power output for change in feed flow

Now, comparison between RFB tuned PID controller and optimally tuned PID controller is carried out by plotting the servo responses of both.

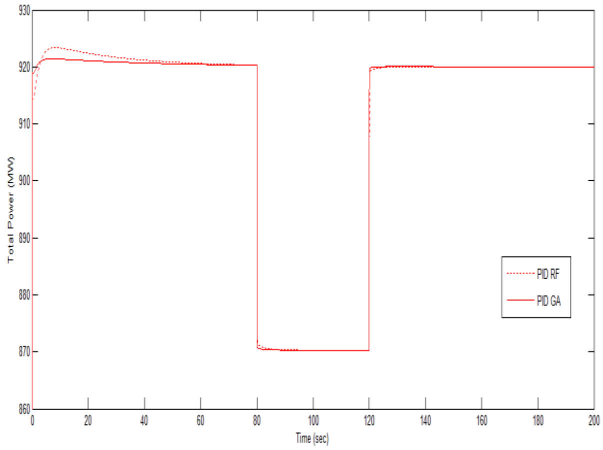

Fig.16 Comparison of total power with RFB and GA based optimal PID

9 Conclusion

A vectorized nonlinear quadrant model of Advanced Heavy Water Reactor has been developed using the core neutronics and Thermal hydraulics equations. It is essential to control total reactor power and 17 nodal powers due to spatial instability of reactor core.

A conventional PID controller and Optimal PID controller are implemented for controlling the nodal powers by manipulating position of four regulating rods. Servo and regulatory performance of the controller has been studied.

References:

[1] R.K.Munje, B.M.Patre, A.P.Tiwari, Non-linear simulation and control of xenon induced oscillations in Advanced Heavy Water Reactor, *Annals of Nuclear Energy*, Vol.64, 2014,pp. 191–200

[2] S.R.Shimjith, A.P.Tiwari, B.Bandyopadhyay and R.K.Patil, Spatial stabilization of Advanced Heavy Water Reactor, *Annals of Nuclear Energy*, Vol.38,2011,pp. 1545–1558

[3] R.K.Munje, B.M.Patre, S.R.Shimjith and A. P.Tiwari, Sliding Mode Control for Spatial Stabilization of Advanced Heavy Water Reactor, *IEEE transactions on nuclear science*, Vol. 60, No. 4, August 2013

[4] P.S.Londhe, B.M.Patre and A.P.Tiwari, Fuzzy-like PD controller for spatial control of advanced heavy water reactor, *Nuclear Engineering and Design*, Vol 274, 2014,pp. 77–89

[5] R.K.Sinha and A.Kakodkar, Design and development of the AHWR—the Indian thorium fuelled innovative nuclear reactor, *Nuclear Engineering and Design*, Vol 236, 2006,pp. 683–700
[6] B.Bandyopadhyay, S.R.Shimjith and A.P.Tiwari, Coupled Neutronics Thermal Hydraulics Model of Advanced Heavy Water Reactor for Control System Studies, *India Conference, 2008.INDICON 2008. Annual IEEE*, Vol.1, 2008, pp.126-131.
[7] P.S.Londhe, B.M.Patre and A.P.Tiwari, Design of Single-Input Fuzzy Logic Controller for Spatial Control of Advanced Heavy Water Reactor, *IEEE transactions on nuclear science*, Vol. 61, no. 2,2014.
[8] Duderstadt.J.J, Hamilton.L.J, *Nuclear Reactor Analysis*. John Wiley & Sons Inc., New York, 1983