CONTROL OF SPATIAL XENON OSCILLATIONS IN LARGE POWER REACTORS

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Abstract

Phenomenon of xenon induced power density oscillations in large thermal reactors has been considered as an important problem of fission product poisoning. Major difficulty associated with this neutronic instability is that poison concentration cannot be measured directly. Existing techniques to handle this instability are approximate. The Indian pressurised heavy water reactor (540 MWe) has fourteen zone independent monitoring system for spatial control. Thus xenon instability, which is a spatial phenomenon, is controlled by local treatment. This requires detailed computer logic and rigorous control effort. In the present work, one spatial parameter, power tilt has been introduced, which is the normalized difference of power level in two halves of the reactor core. This parameter has been chosen as basic control parameter for controlling spatial oscillations. Linear control theory has been adopted and linear models are used for extrapolation of power and power tilt for subsequent time steps. Control law aims to limit power tilt within safe limits. Thus problem of fourteen zones monitoring now has been simplified to monitoring of power tilts in x, y and z direction, only three parameters instead of fourteen. This scheme has been found to be simple and accurate. Two-group diffusion theory has been used for solutions of neutron diffusion equation. Space-time kinetics computations have been done by flux factorization technique.

***KEYWORDS*:** Pressurized heavy water reactor; fission product poisoning; spatial xenon oscillations, spatial control; xenon-induced oscillations.

1. Introduction

Nuclear reactors of the current generation are large in size and this makes them loosely coupled. Loose coupling of the reactor core is further enhanced by flux flattening to maximize the total reactor power. This loose coupling creates power density oscillations in the reactor and fission product Xe^{135} is the source of this neutronic instability. Xenon induced power density oscillation is one of the important problems with spatial control of large thermal reactors and for large pressurised heavy water reactors (PHWR), this problem is very severe. These power density oscillations generally occur at constant reactor power, hence remain unnoticed. The net effect is transfer of the hot spot from one location to another and back to the initial position with a certain period of cycle time. These oscillations are dangerous since they cause thermal cycling of reactor fuel and structural elements. They lower fuel life and hence they should be avoided for efficient fuel use and safe reactor operation. Major difficulty in monitoring and controlling these oscillations is that the source of instability, namely, the xenon concentration, cannot be directly measured. Thus detection of the instability itself is a challenge. Even after detection, suppression of these oscillations with the best possible reactivity devices is again a question. There exists a constant need of practically achievable spatial control strategy, which will ensure safe reactor operation against these oscillations without the loss of optimal fuel use. Control scheme should be simple and it should involve the least possible control effort.

Present work includes the transient simulation of xenon instability for the Indian large pressurized heavy water reactor (540 MWe). Present control practice to suppress power oscillations has been analysed. A new practically possible control scheme has been proposed based on the reactor kinetics feedback. Two-group diffusion theory has been adopted to solve neutron diffusion equations using the space-time kinetics approach. Xenon induced power density oscillation is a problem of slow transients and hence the flux factorization method is ideally suited and adopted. The computational results are first validated for a benchmark problem involving an AECL reactor [1]. The numerical procedure is then applied to the Indian PHWR. Some parametric studies have been made to understand the threshold for xenon instability. Different modes of oscillations have been analysed. Results are compared for two control schemes and it is shown that the proposed control scheme is much simpler and accurate against xenon induced power density oscillations as compared to the existing scheme. The results are obtained for a PHWR but this concept of spatial control can be extended to any large thermal reactor since the control parameter (power tilt) is independent of the reactor type.

2. Mathematical Model

Starting point for describing nuclear reactor kinetics is time dependent, multi-group, multi-dimensional neutron diffusion equation, along with the associated equation for delayed neutron precursors. At any time t and space point r, the time dependent neutron group diffusion equation can be written as,

$$\begin{aligned}\frac{1}{v_g}\frac{\partial \phi_g(r,t)}{\partial t} &= \nabla\cdot D_g \nabla\phi_g(r,t) - \Sigma_g^r \phi_g(r,t) + \chi_g^p (1-\beta)\sum_{g'} \nu\Sigma_{g'}^f \phi_{g'}(r,t) + \sum_{g'\neq g}\Sigma_{g'\to g}\phi_{g'}(r,t) \\ &+ \chi_g^d \sum_i \lambda_i C_i \quad ; \qquad (g=1,2,\ldots,G)\end{aligned} \tag{1}$$

where $\phi_g(r,t)$ is the g^{th} group flux, D_g is the group diffusion coefficient, Σ_g^r is the group removal cross section, $\Sigma_{g'\to g}$ is the group transfer cross section, Σ_g^f is the group fission cross section and other symbols have their usual meanings. The concentration of delayed neutron precursor satisfies the equation,

$$\frac{\partial C_i(r,t)}{\partial t} = \beta_i \sum_g \nu\Sigma_g^f \phi_g(r,t) - \lambda_i C_i(r,t) \quad ; \qquad (i=1,2,\ldots,6) \tag{2}$$

where β_i is the delayed neutron fraction in the i^{th} delayed group, C_i is the i^{th} group delayed neutron precursor and λ_i is the i^{th} delayed group decay constant.

2.1 Xenon and Iodine Equations

Let I be the instantaneous concentration of iodine, λ_I and y_I be the decay constant and fission yield of iodine, respectively. Then the iodine equation can be written as

$$\frac{\partial I(r,t)}{\partial t} = -\lambda_I I + y_I \left[\Sigma_1^f \phi_1(r,t) + \Sigma_2^f \phi_2(r,t)\right] \tag{3}$$

Similarly the xenon concentration X satisfies the equation

$$\frac{\partial X(r,t)}{\partial t} = -\lambda_X X + \lambda_I I + y_X \left[\Sigma_1^f \phi_1(r,t) + \Sigma_2^f \phi_2(r,t)\right] - \left[\sigma_1^X \phi_1(r,t) + \sigma_2^X \phi_2(r,t)\right] X(r,t) \tag{4}$$

where σ^X is the Xe^{135} absorption cross-section. For two-group diffusion theory, the equation (1) is modified to explicitly account for the absorption due to xenon in the thermal group. These four equations form the basic mathematical model. For the solution of these equations, the space-time kinetics is used as the xenon oscillation is a space dependent phenomenon.

2.2 Space-Time Kinetics

A number of techniques could be used to solve the above system of equations, which include the direct method to very simple point kinetics model. However, the point kinetics model can not capture the xenon oscillations and the full finite differencing approach (direct method) is very expensive computationally. The flux factorization approach, an indirect solution technique has been used for the solution. The improved quasistatic (IQS) method, which is highest level of approximation, has been adopted. In this method the neutron group flux $\phi_g(r,t)$ is factorized into a shape function $\psi_g(r,t)$ which is assumed to be a weakly varying function of time and an amplitude factor $n(t)$ which is a rapidly varying function of time.

$$\phi_g(r,t) = n(t)\, \psi_g(r,t); \qquad (g = 1, 2, ..., G) \tag{5}$$

Using this factorization, the above equations are transformed into kinetics equations for $n(t)$ and shape function equations for $\psi_g(r,t)$. The time domain is divided into two levels of time intervals; fairly coarse intervals known as macro-intervals, and fine intervals called micro-intervals. The amplitude factor is obtained by solving the kinetics equations over micro-intervals. The shape function is calculated at the end of every macro-interval. In the IQS method the prompt and delayed neutron sources are treated separately. Also the time derivative of the shape function over macro-interval is approximated by a backward difference scheme. The computational details of the method are presented in an earlier paper [2].

3. Transient Simulations

The space-time kinetics scheme was validated against 3-D AECL benchmark reactor [1]. Subsequently, it was used to model the Indian 540 MWe PHWR. The geometric details of the reactor consisting of 14 power zones are shown in Fig. 1, which shows a cross section of the reactor core.

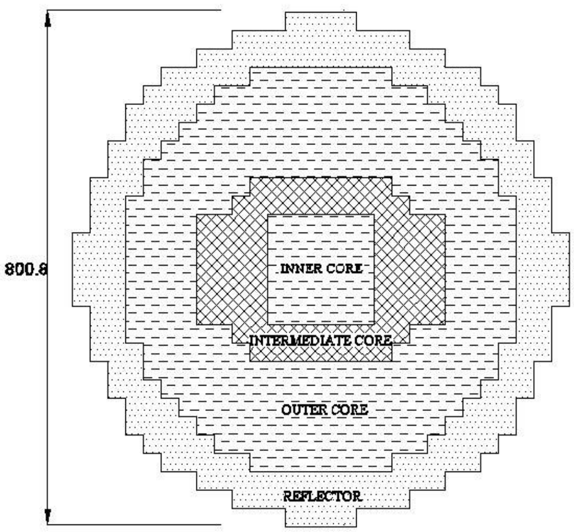


Figure1(a): Region details of PHWR

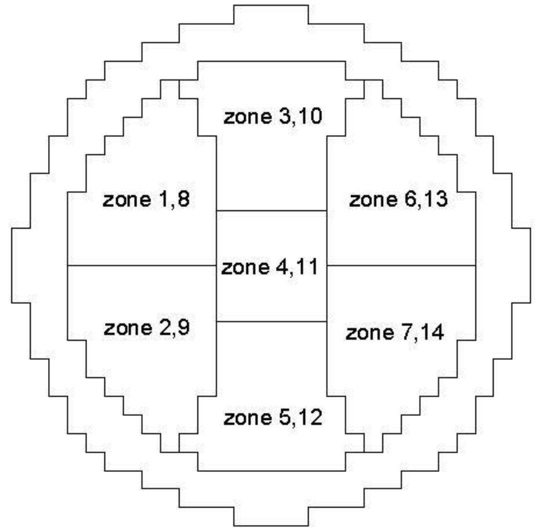
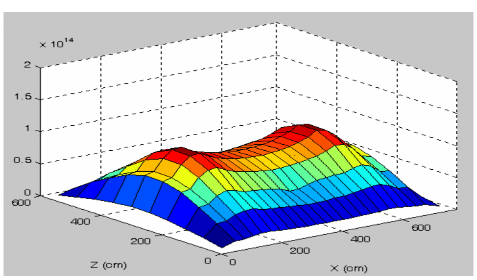


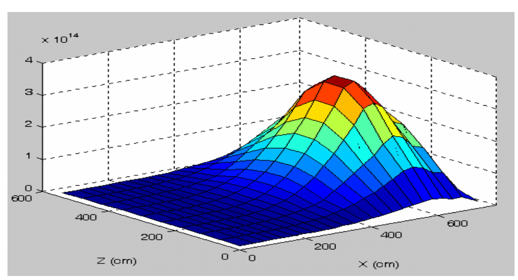
Figure1(b): Details of power zones in PHWR

An initial perturbation which causes a local reactivity change can trigger xenon instability. In the present simulation, the initial perturbation has been induced by a change in the water level in the liquid zonal control units (LZCUs). These units are placed in the reactor core essentially to control the local neutron flux in any power zone. Three basic modes (side to side, top to bottom and front to back) of oscillations have been analysed. To simulate side-to-side oscillation, water level is increased by 25% in left ZCUs (e.g., 1, 2, 8 and 9) and reduced in right ZCUs (6, 7, 13 and 14) by 25% (to ensure constant total reactor power). This is kept for initial few seconds and then the water levels are brought back to the initial equilibrium positions

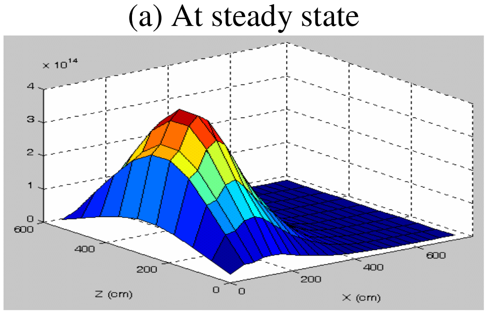
Figure 2: Thermal flux shapes at horizontal central plane



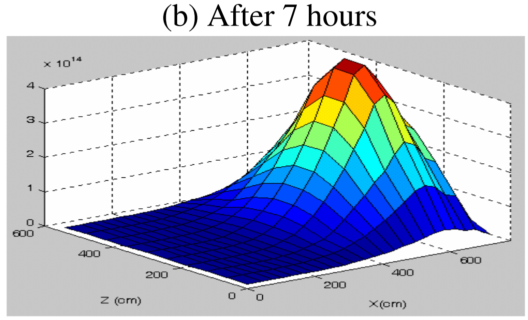
(a) At steady state



(b) After 7 hours



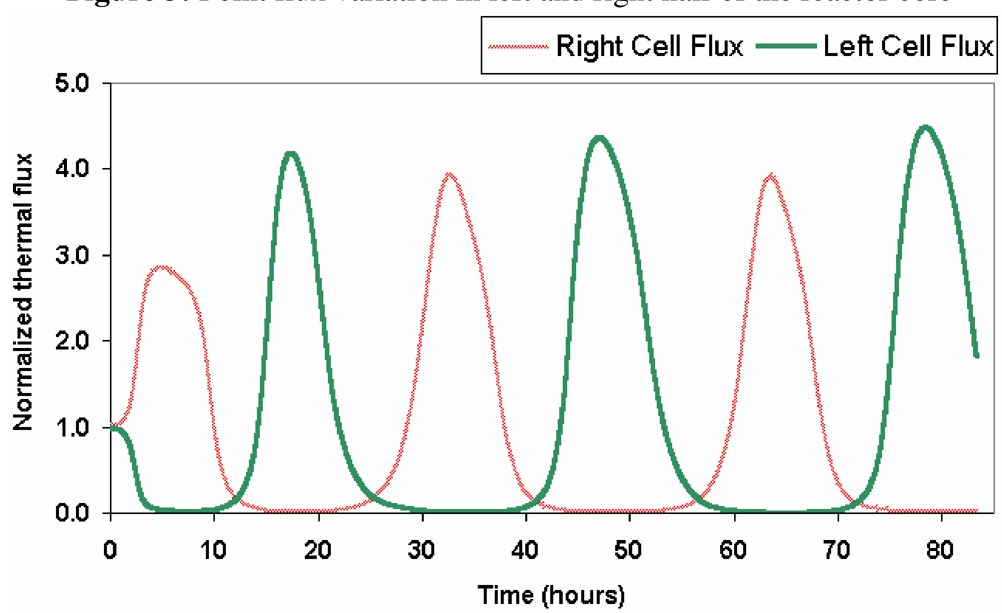
(c) After 20 hours



(d) After 35 hours

Phenomenon has been observed at constant total reactor power for several hours and results are shown in Fig. 2. The thermal neutron flux shapes at horizontal central plane of the reactor at different times are shown, e.g., Fig. 2(a) shows the initial thermal flux at the steady state, Fig. 2(b) after 7 hours, Fig. 2(c) after 20 hours, and Fig 2(d) shows the thermal flux after 35 hours. The thermal flux time history at two centrally located cells, one in the left half and the other in the right half of the reactor core is shown in Fig. 3. It is observed that the flux oscillations maintain nearly constant amplitude, i.e., the decay ratio of nearly unity during the transient. The period of oscillations is found to be between 25 to 28 hours in all cases for the Indian PHWR. In a separate study, it was also observed that the self sustaining xenon oscillations occur only above the reactor power above 75 % of full power implying a threshold power (or flux) for xenon oscillations.

Figure 3: Point flux variation in left and right half of the reactor core



4. Spatial Control System

Spatial control system is necessary for maintaining proper power distribution in reactor core. A detailed review of control techniques was made by Karppinen [3]. However, often the practical solutions adopted in nuclear industry are not the best possible ones. The departure from the most economical operational conditions are often due to difficulties in monitoring xenon induced oscillations and inadequate control actions. General scheme in almost all large reactors is that the entire reactor is divided into small power zones and each zone is monitored and controlled individually. This is single input and single output type of logic. Often, local positive temperature coefficient of reactivity is a problem associated with PHWR, which requires a computer based detailed control logic whereas only simple hard-wired system is adequate for a pressurised water reactor (PWR). Indian PHWR is divided into fourteen power zones and hence it has fourteen input, fourteen output type of control logic. In short, the xenon phenomenon which is a spatial instability is handled by a local treatment. Present work is an effort to simplify this control strategy so that simple hard-wired system can be used in PHWR taking into account the flux (power) shape in the entire core and the tilt between various zones of the core.

4.1 Proposed Control Scheme

Major difficulty associated with xenon instability is that the xenon concentration cannot be measured directly. Thus, it is essential to determine some indirect means of monitoring the instability source. Lin and Lin [4] have used an observer model for poison monitoring.

Observer Model:

Entire reactor is divided into two halves in all three directions x, y and z (top and bottom, left and right, front and back). The dynamic equations for the xenon and iodine for the top and bottom halves of the core are as follows:

$$\frac{\partial I_t}{\partial t} = -\lambda_I I_t + \gamma_I \Sigma_f \phi_t \tag{6}$$

$$\frac{\partial I_b}{\partial t} = -\lambda_I I_b + \gamma_I \Sigma_f \phi_b \tag{7}$$

$$\frac{\partial X_t}{\partial t} = \lambda_I I_t - (\sigma^x \phi_t + \lambda_x) X_t + \gamma_x \Sigma_f \phi_t \tag{8}$$

and

$$\frac{\partial X_b}{\partial t} = \lambda_I I_b - (\sigma^x \phi_b + \lambda_x) X_b + \gamma_x \Sigma_f \phi_b \tag{9}$$

where the symbols have their usual meanings and the subscript t refers to the top half, whereas, the subscript b refers to the bottom half of the core. With linearization, the normalized form of above equations reduces to following state equation [4]

$$\frac{d}{dt} x = A_c x + B_c \frac{\phi_t - \phi_b}{\phi_0} \tag{10}$$

where $x = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$ is the state vector and x_1 and x_2 are iodine and xenon concentration difference in the top and bottom halves of the core, respectively. A_c is a (2 x 2) matrix and B_c is a (2 x 1) vector. Both A_c and B_c are dependent on properties of iodine, xenon and steady state flux level, and can be treated as constants. Assuming the reactor core to be homogeneous, one can write

$$\frac{\phi_i}{\phi_0} = \frac{P_i}{P_0 / 2} \ ; \qquad (i = t, b)$$

where P_0 is the rated power, and ϕ_0 is the rated flux. Hence

$$\frac{\phi_t - \phi_b}{\phi_0} = \frac{2(P_t + P_b)}{P_0} * \left(\frac{P_t - P_b}{P_t + P_b} \right) = \frac{2(P_t + P_b)}{P_0} * (tilt)_y \tag{11}$$

Substituting back this value, the state equation (10) takes the form

$$\frac{d}{dt}x = A_c x + B_c \frac{\phi_t - \phi_b}{\phi_0} = A_c x + B_c \frac{2(P_t + P_b)}{P_0} * (tilt)_y$$

This equation relates iodine and xenon dynamics with total reactor power and tilt. Total power generally remains constant for base load power stations and hence the only dynamic parameter in state equation is tilt, which is the normalized power difference in two halves of the reactor core. Thus monitoring of power tilt implies monitoring of the reactor xenon.

4.1.1 Tilt based Spatial Control

The present spatial control practice includes power level monitoring of 14 individual zones separately and varying water level in respective zonal control compartments (ZCC) for correction. For larger changes in reactivity, other reactivity devices (like adjuster rod, liquid poison, etc.) are incorporated. This complete system forms a complex control logic, which is known as the reactor regulatory system (RRS). It is proposed that the control system, which uses power tilt as the basic control parameter is simpler and more effective than the existing system. Three basic modes of oscillations are described here and accordingly three tilts are defined as follows.

$$(tilt)_y = \frac{(P_{1,8} + P_{3,10} + P_{6,13}) - (P_{2,9} + P_{5,12} + P_{7,14})}{\sum_i P_i} \qquad \text{(top-to-bottom tilt)}$$

$$(tilt)_x = \frac{(P_{1,8} + P_{2,9}) - (P_{6,13} + P_{7,14})}{\sum_i P_i} \qquad \text{(side-to-side tilt)}$$

$$(tilt)_z = \frac{\sum_{i=1}^{7} P_i - \sum_{i=8}^{14} P_i}{\sum_i P_i} \qquad \text{(front-to-back tilt)}$$

where P_i denotes total power of i^{th} zone and $P_{i,j} = P_i + P_j$.

Instead of monitoring individual zone power, it is proposed to monitor just these three power tilts. Two safe temperature limits specified by core designer sets reference limit for power tilts. Concentration difference of xenon between two halves of the reactor is the source of instability and this has been related to power tilt in the state equation. Corrective action is taken by changing water level in ZCUs such that;

1. It regains the power distribution to the desired safe limit for all zones.
2. Criticality of the reactor is maintained
3. Total reactor power is maintained constant.

Assuming linear variation, we can write a simple control equation,

$$(tilt)_{target} - (tilt)_{n+1} = \frac{d(tilt)}{dXe}(Xe_{n+1} - Xe_n) + \sum_{i=1}^{14} \frac{d(tilt)}{dR_i}(R_{i,n+1} - R_{i,n}) \qquad (12)$$

where i is the zone number and n corresponds to the computation time step. First term in the right hand side of the above equation is the instability source (which is the xenon concentration difference) whereas, the second term is the balancing corrective action for all fourteen ZCCs, so that the net effect of these two terms can be made zero to limit the power tilt in any direction to the targeted safe limit. It is required to project the values of power tilt and xenon to generate the control signal from the control equation (12). Power and tilt values have been extrapolated using a simple linear extrapolation technique, whereas, xenon concentration is extrapolated using a quadratic exponential model. These extrapolated values have been found to be accurate to within 7% of the actual calculated values. All derivatives involved in the control equation have been computed by simple backward differencing scheme of first order. Thus, the control scheme can be described as a linear control theory, which uses a spatial parameter (power tilt) to handle spatial xenon instability.

Control equations were introduced in the simulation model. Instability was induced by an external perturbation and computations were carried out. Currently used control scheme, as well as, tilt based control scheme were analysed and compared for the Indian PHWR. The results are shown in the following Figs. 4, 5 and 6.

Figure 4: Existing Control scheme (Power variation in 14th zone)

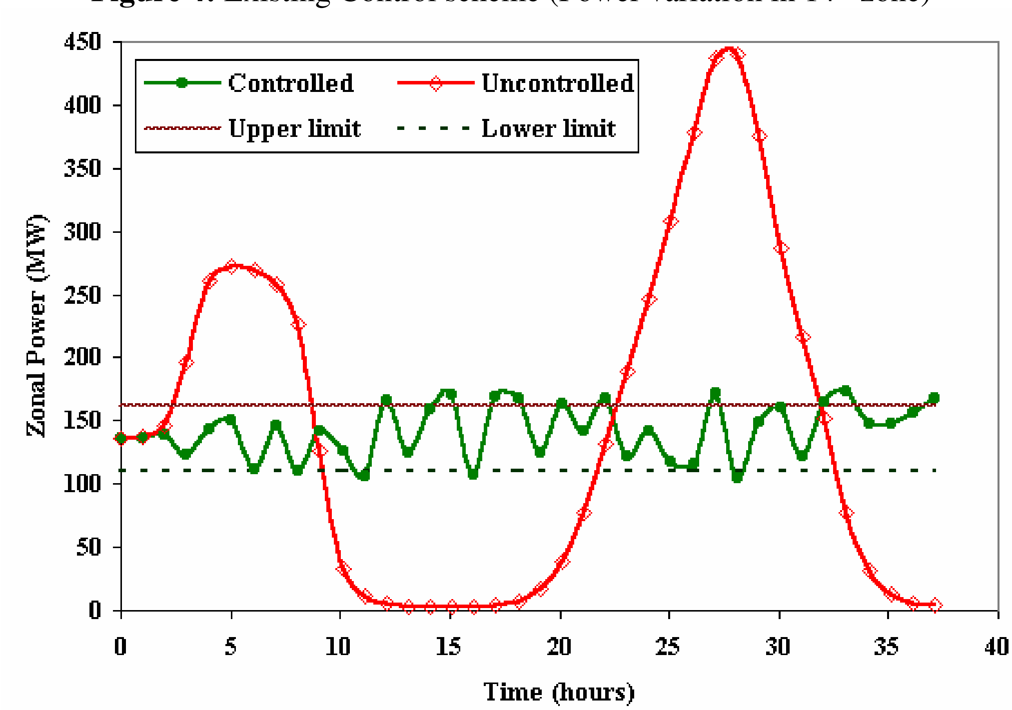


Fig. 4 shows the power variation in the fourteenth zone with and without the control action. This clearly shows that existing control scheme aims to limit the zonal power within two reference limits. This, however, leads to many oscillations in the zonal power between the two limits. Figs. 5 and 6 show the results of tilt based control scheme for two power zones, namely, zones 1 and 14. In this, the global tilt is monitored and corrected instead of zonal power. This scheme tries to suppress a complete mode of oscillation and does not monitor individual zonal power. This is the reason why central zones generally do not show good response since they are not accounted in tilt computation. Control results are superior to existing control scheme for all zones except two central zones, where the effect of xenon oscillations is anyway not severe.

Figure 5: Tilt based Control scheme (Power variation in 14th zone)

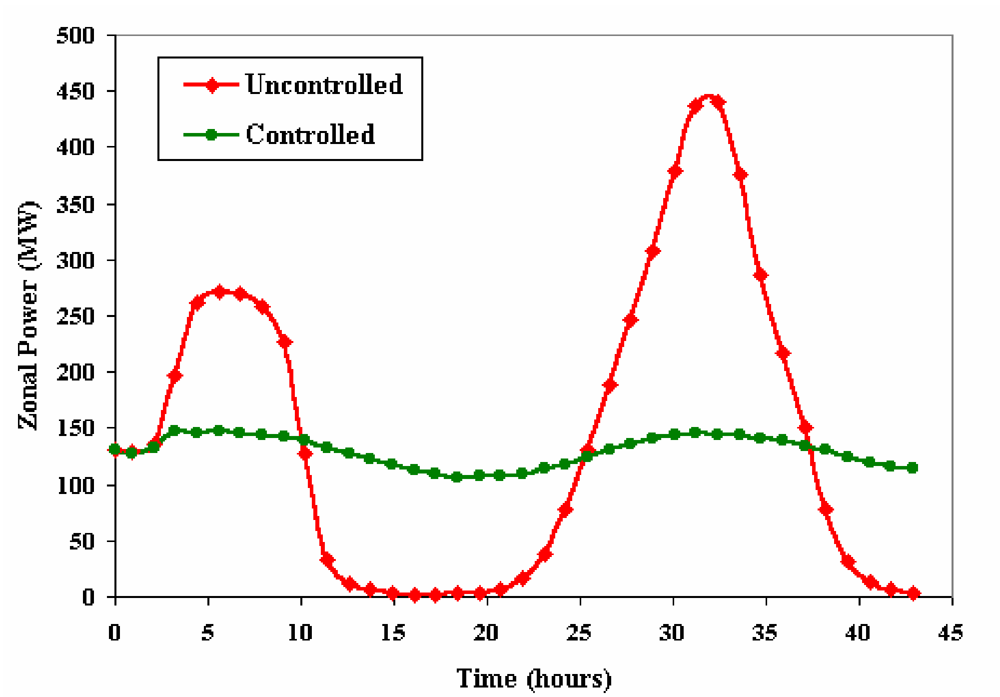
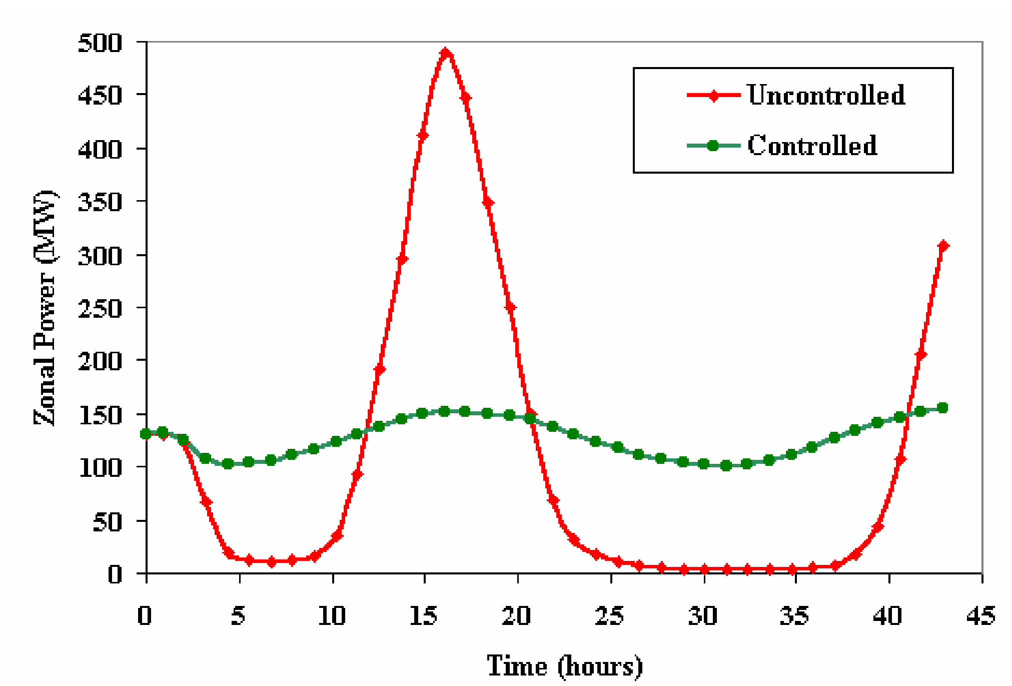


Figure 6: Tilt based Control scheme (Power variation in zone 1)



The maximum zonal power variation is limited to ±11.3 % in the proposed control scheme when the tilt is limited to ±10 %. This is an improvement over ± 20 % variation in the zonal power in the existing control scheme of individual zone monitoring.

5. Conclusions

- Xenon instability is a spatial phenomenon in which any initial perturbation grows and after some time the entire reactor is subjected to sustained power density oscillation. Top to bottom mode of oscillation is the most severe mode of oscillation, which shows maximum power fluctuation from the steady state.
- Location of initial perturbation affects the phase of oscillation, whereas change in the magnitude of perturbation changes amplitude ratio and growth factor but in all cases period of oscillation is unchanged.
- A threshold flux (power) level is necessary for sustained xenon oscillations.
- Existing control scheme, which is based on individual zone monitoring logic, is adequate and robust to suppress xenon induced power density oscillations to safe limit. However, small continuous fluctuations in zonal power remain.
- Proposed control scheme treats xenon instability as spatial phenomenon and hence control actions are generated based on reactor kinetics feedback. This scheme is simpler and involves less control effort for bringing back the system to equilibrium level with smaller variation in power level.
- Monitoring interval can be extended using tilt based spatial control scheme.

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