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Damping Analysis of Xenon Oscillation in CANDU-6 Reactor with DUPIC Fuel

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Abstract

The damping characteristics of the xenon oscillation of a CANDU-6 reactor with DUPIC fuel has been analyzed. In this study, three important harmonic perturbations such as top-to-bottom, side-to-side and front-to-back oscillations were considered. The damping factor has been calculated for each oscillation and compared to that of natural uranium fuel core. The calculation has shown that the damping factor of the DUPIC fuel core is negative and smaller in magnitude than that of natural uranium core. Therefore, the xenon oscillations of the DUPIC core is self-damped as for natural uranium core. Furthermore, this study has also shown that the current zone controller system can damp the xenon oscillation very efficiently.

1. Introduction

The damping of the xenon spatial oscillation is an important aspect of the design and operation of a power reactor. Especially, a large power reactor such as a CANDU reactor is more susceptible to the spatial oscillation. The susceptibility of the large power reactor to the spatial oscillation due to the neutron flux and xenon poison distribution has long been recognized. In general, the susceptibility to the xenon oscillation arises from the out-of-phase interaction between the positive and negative reactivity feedbacks due to the destruction of ^{135}Xe by the neutron capture and its formation by the decay of the fission product ^{135}I. The extent to which a reactor is susceptible to the xenon spatial oscillation depends on the core size, the power level, the shape of the unperturbed flux distribution, the influence of reactivity feedback mechanism of the fuel and the moderator temperature, and, to a lesser extent, the neutron energy spectrum, as it affects the xenon cross-section. In order to operate a reactor within allowable constraints on the power peaking, the core must be stable or self-damped allowing only convergent oscillations. Otherwise, the control techniques must be provided to artificially damp divergent oscillations.

The typical CANDU-6 reactor core (Figs.1 and 2), which is about 628 cm in diameter and 594.4

cm in axial length, is more susceptible to the radial oscillation than the axial oscillation. When the DUPIC fuel is loaded in a CANDU-6 reactor, the power and flux distributions are different from those of natural uranium core (the power distribution is more flattened), which may affect the xenon spatial instability and controllability. In this study, the xenon spatial oscillation of the CANDU-6 reactor with the DUPIC fuel has been analyzed through a comparative study of the reactor with the standard 37-element natural uranium fuel. In addition, the spatial and bulk controllability of the zone controller units (ZCUs) has been assessed for the xenon spatial oscillation.

2. Xenon Oscillation

Under an equilibrium core condition, the concentration of ^{135}Xe throughout a reactor is locally dependent on the power (flux) distribution. If the flux is perturbed from its equilibrium distribution, the interaction between the prompt (positive) and delayed (negative) reactivity feedbacks due to the destruction and production of ^{135}Xe, respectively, keeps the flux to increase until the xenon buildup or the negative reactivity feedback compensates for the flux rise. Then the continued production of the xenon from ^{135}I decay causes the flux to decrease until the decay of the accumulated xenon leads to the increasing local reactivity and the flux level. In this way, the neutron flux and xenon distribution may oscillate between different regions of the core until the oscillations are damped out or appropriately controlled.

The xenon spatial oscillations considered in this study are three typical higher harmonic modes: the top-to-bottom, the side-to-side and the front-to-back oscillations. These three harmonic modes are initiated by withdrawing and subsequently reinserting the adjuster rods (ADJs) to perturb the steady state flux and xenon distribution. The ADJ configurations are shown in Fig. 1. All the ADJs are partially withdrawn and reinserted to induce the top-to-bottom oscillation. The side-to-side oscillation can be induced by withdrawing the ADJ rod numbers 5, 6, 7, 12, 13, 14, 19, 20, and 21 simultaneously. The axial oscillation is induced by partially withdrawing the ADJ rod numbers 1, 2, 3, 4, 5, 6, and 7 together. In this study, the xenon properties are obtained from WIMS-AECL[1], and the core calculations are performed by RFSP[2].

The oscillation characteristics can be represented by power tilts, which are defined as:

$$\text{top-to-bottom tilt (\%)} = \frac{(P_{1,8}+P_{3,10}+P_{6,13})-(P_{2,9}+P_{5,12}+P_{7,14})}{P_{1,8}+P_{2,9}+P_{3,10}+P_{4,11}+P_{5,12}+P_{6,13}+P_{7,14}}\times 100 \quad (1)$$

$$\text{side-to-side tilt (\%)} = \frac{(P_{1,8}+P_{2,9})-(P_{6,13}+P_{7,14})}{P_{1,8}+P_{2,9}+P_{3,10}+P_{4,11}+P_{5,12}+P_{6,13}+P_{7,14}}\times 100 \quad (2)$$

front-to-back tilt(%)

$$= \frac{(P_1+P_2+P_3+P_4+P_5+P_6+P_7)-(P_8+P_9+P_{10}+P_{11}+P_{12}+P_{13}+P_{14})}{P_{1,8}+P_{2,9}+P_{3,10}+P_{4,11}+P_{5,12}+P_{6,13}+P_{7,14}}\times 100 \quad (3)$$

where, $P_{i,j}$ is the power of the zone pair (i, j).

For the top-to-bottom xenon oscillation, which is shown in Fig. 3, the maximum tilt of the DUPIC core is 45.4%, and the oscillation time is about 170 hrs, while the oscillation time of the natural uranium core is 120 hrs with the maximum tilt of 44.5%. For the side-to-side xenon oscillation shown in Fig. 4, it can be seen that the oscillation also continues for 170 hrs with the maximum tilt of 37% at 13 hrs after the perturbation. Unlike the top-to-bottom oscillation, the behavior of the side-to-side oscillation is very similar for both the natural uranium and DUPIC fuel cores because of the symmetric configuration. The oscillatory behaviors are more distinctive for the front-to-back tilt as shown in Fig. 5. For the DUPIC fuel core, the duration time is about 60 hrs with the maximum tilt of 13%. However, there is only a minor axial oscillation for natural uranium fuel core, which is mostly due to the axial power shape that strongly couples the front and rear zone powers.

It is also shown that the top-to-bottom oscillation is more susceptible than any other oscillations for both the DUPIC and natural uranium fuel cores.

3. Damping Analysis

In this section, the damping characteristics are analyzed using the damping factor. The damping factor is a measure of the rate of decay of the oscillation, which is defined by the ratio of the amplitude in oscillation. The xenon oscillation occurs over a specific power level, which is defined as the threshold power. The threshold power for the xenon oscillation is investigated through the oscillation calculations of various power levels. Also, the controllability of the current ZCU system against the xenon oscillation is assessed.

3.1. Damping Factor

The xenon oscillation induced by a small perturbation follows an exponential-sinusoidal behavior, which can be expressed by:

$$P(t) = A_0 + P_0 e^{\xi t} \sin\left(\frac{2\pi}{T} t + t_0\right) \tag{4}$$

where P(t) is the oscillating variable at time t, A_0 is the steady-state value of the oscillating variable, P_0 is the amplitude of the envelope at time zero, T is the period of the oscillation, t_0 is the phase shift, and ξ is the damping factor. In order to obtain a damping factor for the xenon oscillation, the envelope of the xenon oscillation is used, which expressed as:

$$y = P_0 e^{\xi t} . \tag{5}$$

The damping factor is positive for a divergent oscillation and is negative for a damped oscillation.

The damping factors have been determined for the xenon oscillations to give least square fits of the calculated oscillating variables of Eqs. (4) and (5). For the DUPIC fuel core, the damping factor for the top-to-bottom oscillation is $-1.767\times10^{-2}\ \mathrm{hr}^{-1}$, which is 45% smaller than that of natural uranium core. The damping factors of the side-to-side and front-to-back oscillations are decreased by 37% and 40%, respectively, compared to those of natural uranium fuel core. Table 1 compares the damping factors and other parameters for the DUPIC and natural uranium fuel cores.

3.2. Threshold Power

In order to investigate the threshold power for the xenon oscillation, the top-to-bottom oscillations for various power levels have been calculated, which are shown in Fig. 6. It is shown that the threshold power of the xenon spatial oscillation for the DUPIC core is about 10% full power while that of natural uranium core is 20% full power[3]. The damping factors for the different power levels are given in Table 2 for the DUPIC fuel core.

3.3. ZCU Damping Capability

In the previous sections, the xenon oscillations have been assessed with the fixed ZCU levels (no spatial and bulk control). The controllability of the current ZCU system, which is shown in Fig. 2, against the xenon spatial oscillation has been assessed by allowing the ZCU to control the spatial power variations. Figs. 7 to 9 show the ZCU controllability against the top-to-bottom, side-to-side and axial oscillations, respectively. It is clear that the ZCU system suppresses the xenon oscillations very efficiently.

4. Conclusion

The damping behavior of the xenon spatial oscillation for the CANDU-6 reactor loaded with the DUPIC fuel has been assessed. This study has shown:

- The xenon spatial oscillation of the DUPIC fuel core is larger than that of natural uranium fuel core. However, the xenon oscillations are self-damped for both the DUPIC and natural uranium fuel cores.
- The top-to-bottom oscillation is more susceptible than the side-to-side and axial oscillations for both the DUPIC and natural uranium fuel cores.
- Despite the increased instability, the current ZCU system can damp the xenon oscillation completely for the DUPIC fuel core.

In conclusion, the xenon spatial oscillations of the DUPIC fuel core continue for a longer time compared to natural uranium fuel core. Especially for the front-to-back oscillation, the maximum power tilt of the DUPIC fuel core is increased more than five times compared with that of natural uranium fuel core. However, the current ZCU system maintains the damping capability of the xenon oscillation for the DUPIC fuel core

References

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3. "Design Manual : CANDU 6 Generating Station Physics Design Manual, Wolsong NPP 2 3 4", 86-03310-DM-000 Rev. 1, Atomic Energy of Canada Limited, 1995.

Acknowledgement

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Table 1 Damping Factors for Xenon Oscillation

Oscillation	Damping Factor (hr^{-1})	
	DUPIC Core	Natural Uranium Core
Top-to-Bottom	-1.767×10^{-2}	-3.244×10^{-2}
Side-to-Side	-1.594×10^{-2}	-2.635×10^{-2}
Front-to-Back	-2.517×10^{-2}	-1.198×10^{-1}

Table 2 Damping Factors for Different Power Levels (Top-to-Bottom Oscillation)

Power Level (%)	Damping Factor (hr^{-1})
100	-1.767×10^{-2}
80	-2.336×10^{-2}
60	-3.085×10^{-2}
40	-4.391×10^{-2}
20	-1.212×10^{-2}
10	—

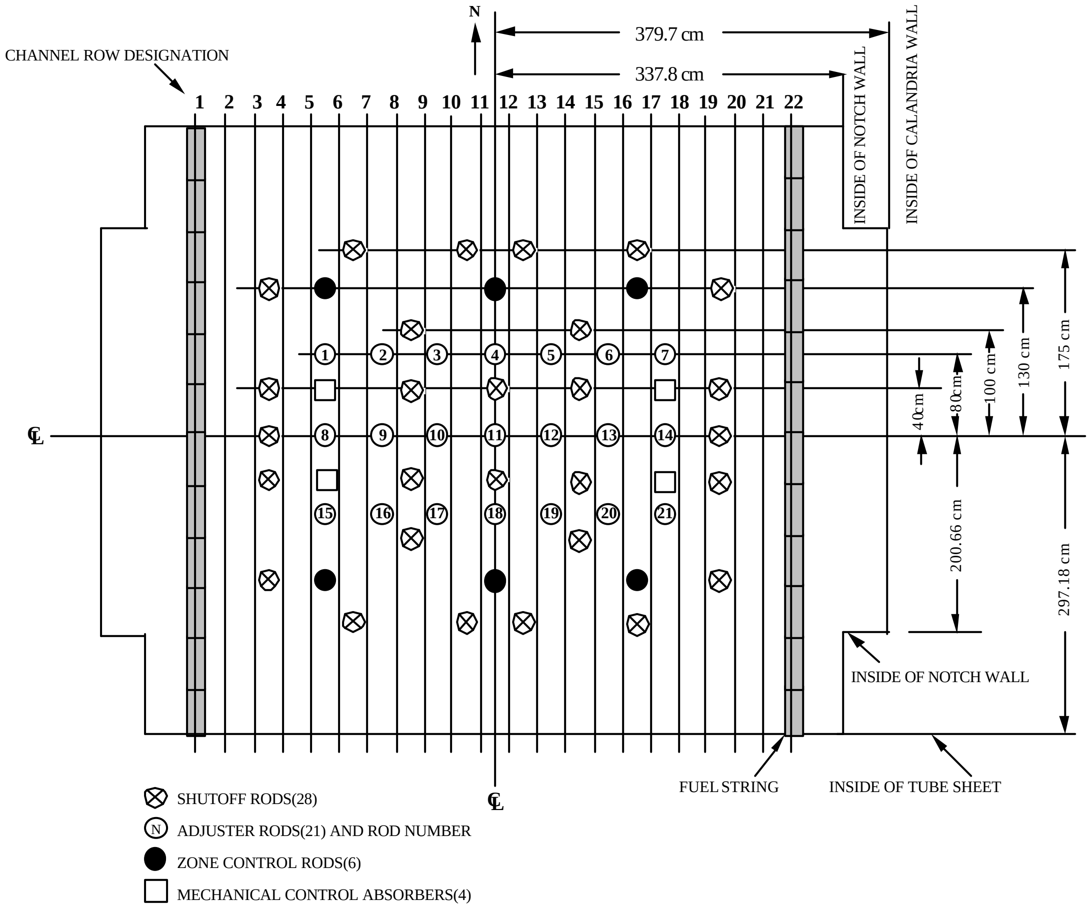

Fig. 1 Plan View of Reactor Showing Reactivity Devices

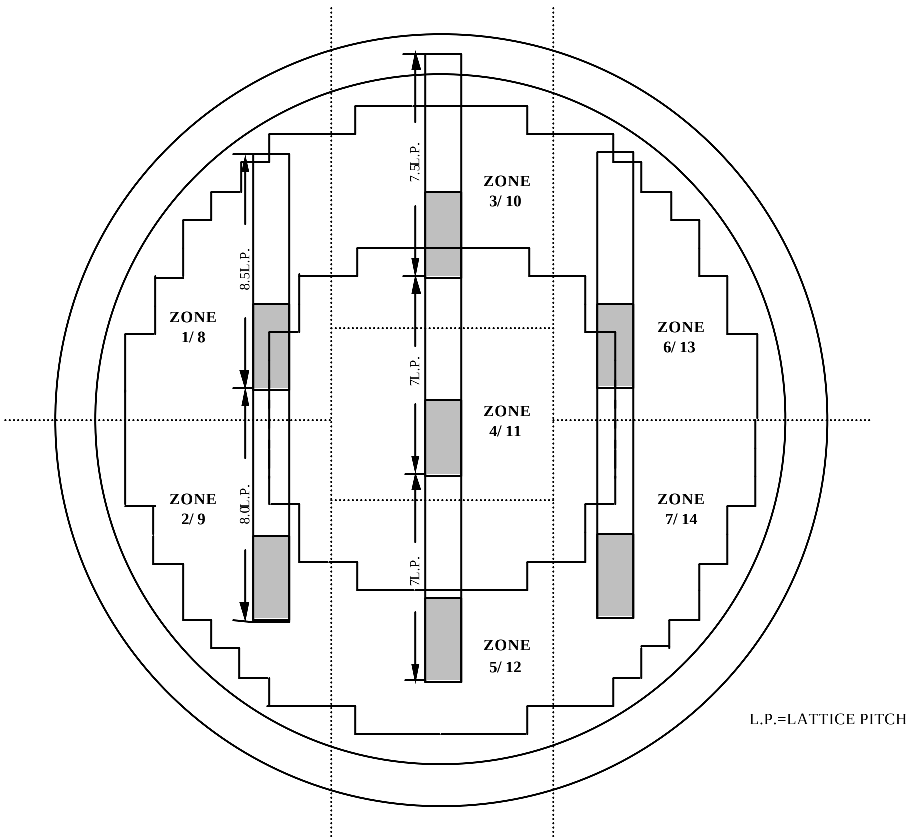

Fig.2 Face View of Reactor Showing Zone Controller Compartments

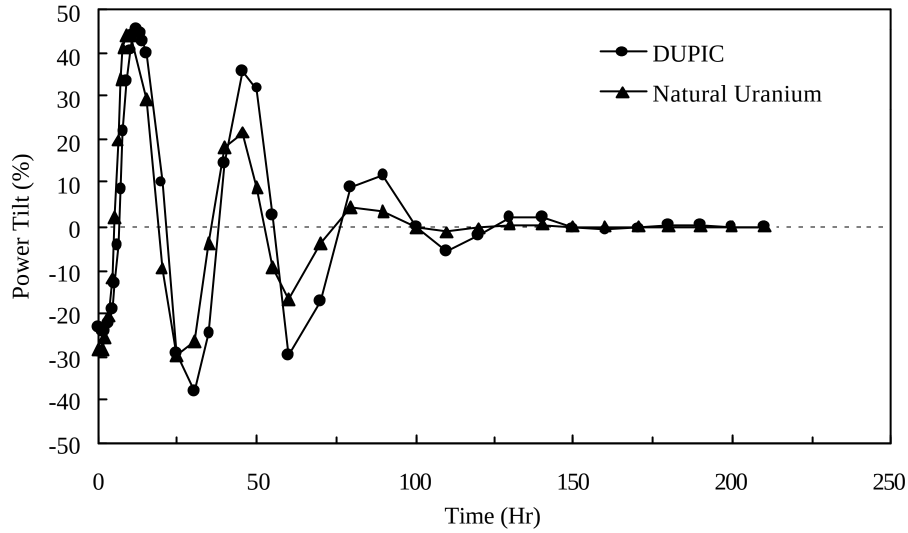

Fig. 3 Comparison of Top-to-Bottom Xenon Oscillation

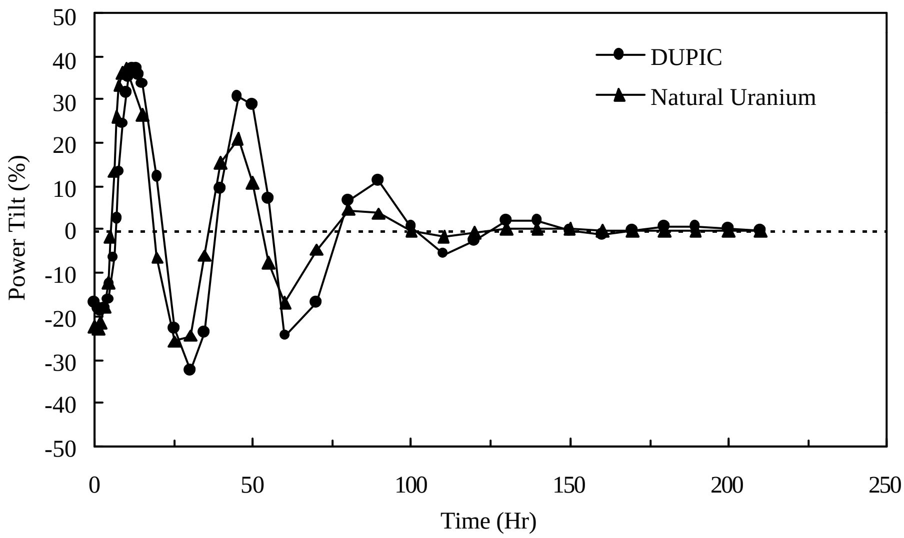

Fig. 4 Comparison of Side-to-Side Xenon Oscillation

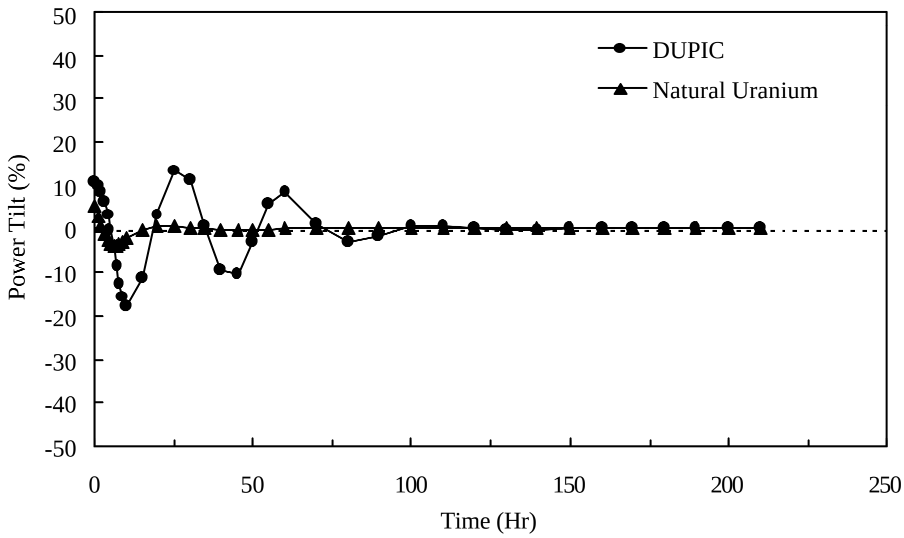

Fig. 5 Comparison of Front-to-Back Xenon Oscillation

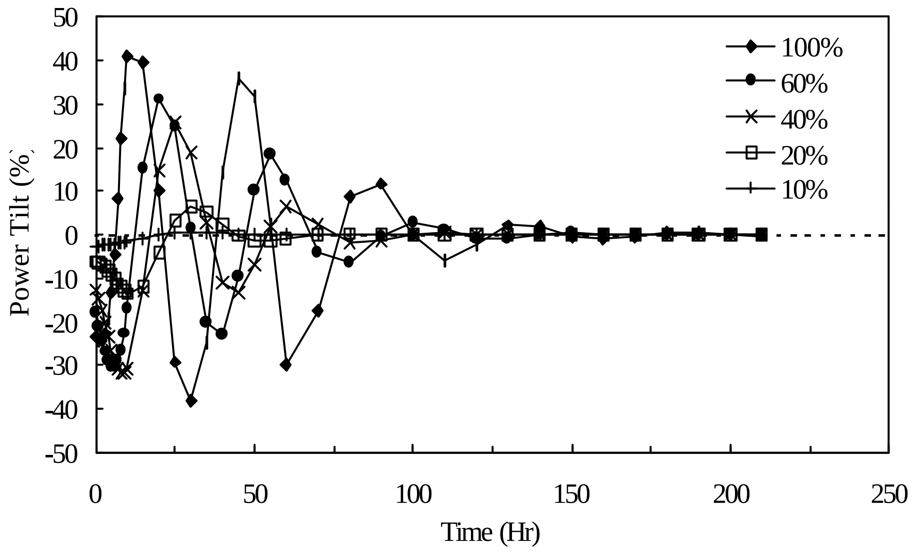

Fig. 6 Top-to-Bottom Xenon Oscillation for Various Power Levels (DUPIC Core)

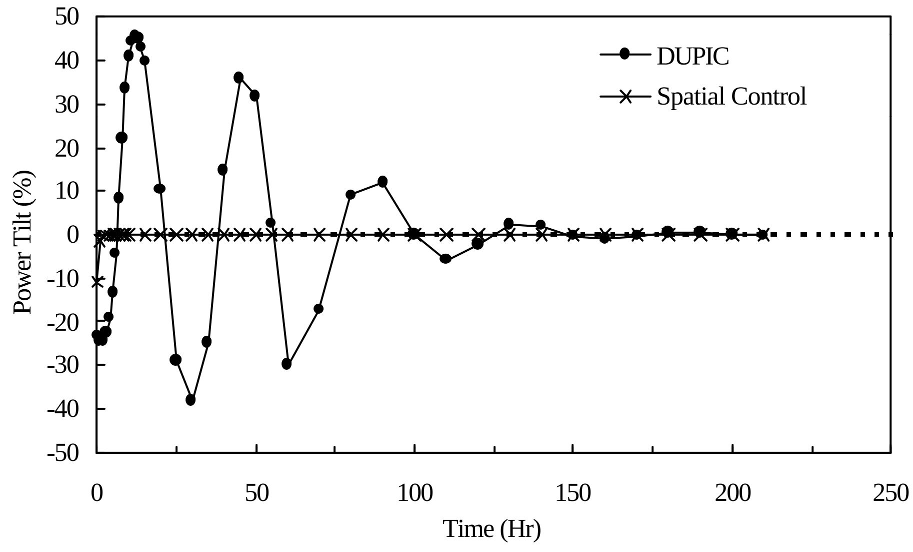

Fig. 7 ZCU Controllability for Top-to-Bottom Xenon Oscillation

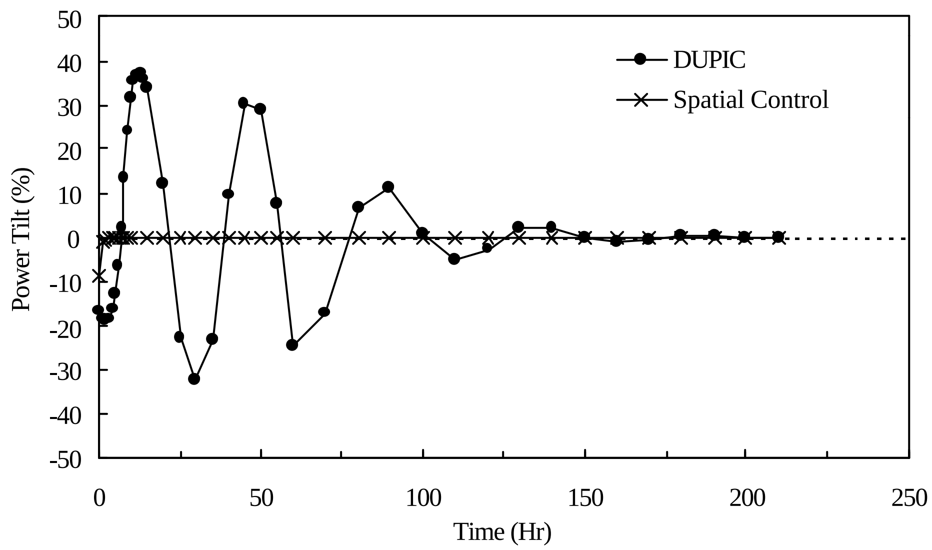

Fig. 8 ZCU Controllability for Side-to-Side Xenon Oscillation

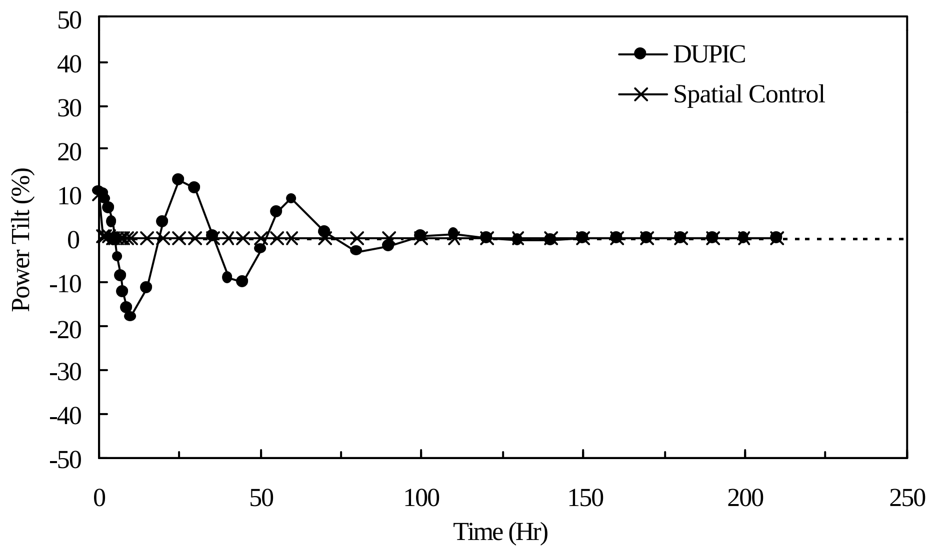

Fig. 9 ZCU Controllability for Front-to-Back Xenon Oscillation