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Technical note

Nuclear power plant instabilities analysis

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ABSTRACT

We studied neutron power instability in BWRs of four different nuclear power plants (NPP). The methodology applied in this study is a properly structured, coherent and expanded use of conventional techniques in spectral analysis, Power Spectrum Density (PSD) analysis and Fast Fourier Transform (FFT). Analyses, based on time–frequency representation, allowed for characterization of time-varying spectral signal components, favoring BWR understanding and monitoring. Results show that in large amplitude events, (i.e. Laguna Verde Unit 1 and Fosmark) two coupled mechanisms are needed. The Forsmark NPP case, similarly to Laguna Verde NPP and Cofrentes NPP, confirms a frequency of 0.5316 Hz for in-phase instabilities and of 1.006 Hz for out-of-phase instabilities. The results of Ringhals NPP support the stated hypothesis that 1 Hz frequencies indicate out-of-phase power oscillations, which could point to the existence of an additional out-of-phase instability mode in Laguna Verde NPP.

1. Introduction

The two oscillation modes commonly associated to density wave instabilities in a BWR are core wide and regional oscillations, also referred to as in-phase or out-of-phase modes, respectively. In core wide oscillations, the power and inlet flow of most core channels oscillate in phase. As for regional oscillations, the power of a core region oscillates out-of-phase compared to the power of other regions. Inlet flows to the different regions are also out-of-phase with respect to each other.

In-phase oscillations result from thermal–hydraulic system lagging caused by the finite speed of density perturbation propagation (Lahey and Podoswski, 1989). At high-core void fractions and low flow conditions, feedback becomes so strong that it induces oscillations at a frequency around 0.5 Hz. As feedback increases, oscillations are higher to the point when oscillatory instability is reached. Additionally, out-of-phase instabilities appear, which has safety implications (i.e., potential large-amplitude out-phase core power oscillation without automatic scram). March-Leuba and Blakeman (1991) examined the stability of subcritical higher harmonic neutron modes potentially leading to out-of-phase power oscillations under certain conditions. In out-of-phase instability, the usually subcritical first harmonic mode dominates reactor response. The BWR out-of-phase stability mechanism is explained as a phenomenon of higher harmonic neutron mode (first azimuthal mode) excitation caused by the thermal–hydraulic feedback effect. Thus, out-of-phase oscillation is dominated strongly by momentum stability in different in-core channel regions. In a large commercial BWR core, the first azimuthal harmonic mode usually appears as the first harmonic with the largest eigenvalue for all but the fundamental mode (Takeuchi et al., 1994). Reactivity feedback causes spatial coupling, which in turn leads to synthesized out-of-phase oscillation in the entire core.

This study presents findings related to neutron power instability in BWRs of four different nuclear power plants:

- Laguna Verde NPP
- Cofrentes NPP
- Forsmark NPP
- Ringhals NPP

The methodology used for this study is based on conventional Power Spectrum Density (PSD) analysis and Fast Fourier Transform (FFT). The goal is to obtain the time-varying spectral signal components for better BRW understanding and monitoring. The results of Ringhals NPP support the stated hypothesis that 1 Hz frequencies indicate out-of-phase power oscillations, which could point to the existence of an additional out-of-phase instability mode in Laguna Verde NPP. However, previous studies by different authors analyzed Laguna Verde NPP using different techniques (e.g., González et al., 1995; Farawila et al., 1996;

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Blazquez and Ruiz, 2003; Nunez-Carrera and Espinosa-Paredes, 2006; Moreno, 2010; Prieto-Guerrero and Espinosa-Paredes, 2014b) without considering the possibility of out-of-phase instability.

2. Methodology

The methodology is aimed at determining the typical frequencies of instability episodes in different boiling water reactor (BWR) plants and at estimating when these episodes may occur.

Once the moments of instability occurrence are determined, they will be correlated to the occurrence moments of specific frequencies. Lastly, the reverse process will be followed to verify if the disappearance of instability episodes leads to the effects resulting from the frequencies identified. A more detailed description of the process is as follows:

Step 1.- FFT calculation for the time series. An FFT is performed on the power series available for the plants under analysis, identifying the main frequencies based on their impact on amplitude. These frequencies are then compared to those described in reference literature and to the experience gained by the industry.

Step 2.- Power Density Spectrum (PSD) Calculation. In the previous step the main frequencies were identified considering their impact on amplitude. Now it is necessary to determine the contribution of each frequency to signal strength, taking into account that frequencies of low amplitude may be really important in terms of power. A double analysis will be carried out in this step: on the one hand, a comparison of the main frequencies identified in the previous step and, on the other hand, a comparison to industry experience and references.

Step 3.- Spectrogram Calculation (Frequency–Time). Once power and amplitude frequency contributions are determined, it is necessary to establish the exact moment when these frequencies occur and begin influencing the signal. Similarly, frequency occurrence will be correlated to the moments when the signals, and the plant for that matter, are affected by instability. The moment when instability disappears, allowing power series and the plant to be normalized, will also be established. This is a triple analysis as it analyzes frequency similarly to the previous steps, but adds a time dimension and the moments of occurrence. These frequencies and their occurrence correlation will be compared to the reference and experience of the industry.

The proposed methodology will be applied to three time series in three nuclear power plants with instability episodes, both in-phase and out-of-phase. Lastly, this methodology is challenged through the use of a series associated to a fourth power plant where oscillation modes are shadowed by the actual signal.

3. Application to real signals

The methodology developed in the previous paragraph will be applied to a set of signals from several nuclear power plants that experienced instabilities events, each of a different nature: Two occurred in-phase (Laguna Verde NPP and Fosmark NPP), one out-of-phase (Cofrentes NPP) and the last one corresponds to a simultaneous out-of-phase and in-phase time series event at Ringhals Nuclear Power Plant.

Every signal will be analyzed, concluding with the presentation of a summary of the main and common features of each signal and frequency.

3.1. Laguna Verde instability event

The event shown in Fig. 1 occurred in 1995 at Laguna Verde Nuclear Power Plant in Veracruz, Mexico (González et al., 1995; Farawila et al., 1996; Blazquez and Ruiz, 2003). Power oscillations occurred during the starting up of Unit 1. When instability took place, unit conditions were 35% thermal power and 38% core flowrate, with the recirculation pump at low speed and the control valves (FCV) of the recirculation system partially open. The operator began to close the FCVs, resulting in a small 2% power reduction. After closing the FCVs, the reactor was placed in the instability region, with power ranging between 30% and 36%. The operator reopened the valves and power amplitude increased (400 s). At $t = 715$ s, the operator decided to scram the reactor. Instability began at 320 s, with a precursor at 240 s.

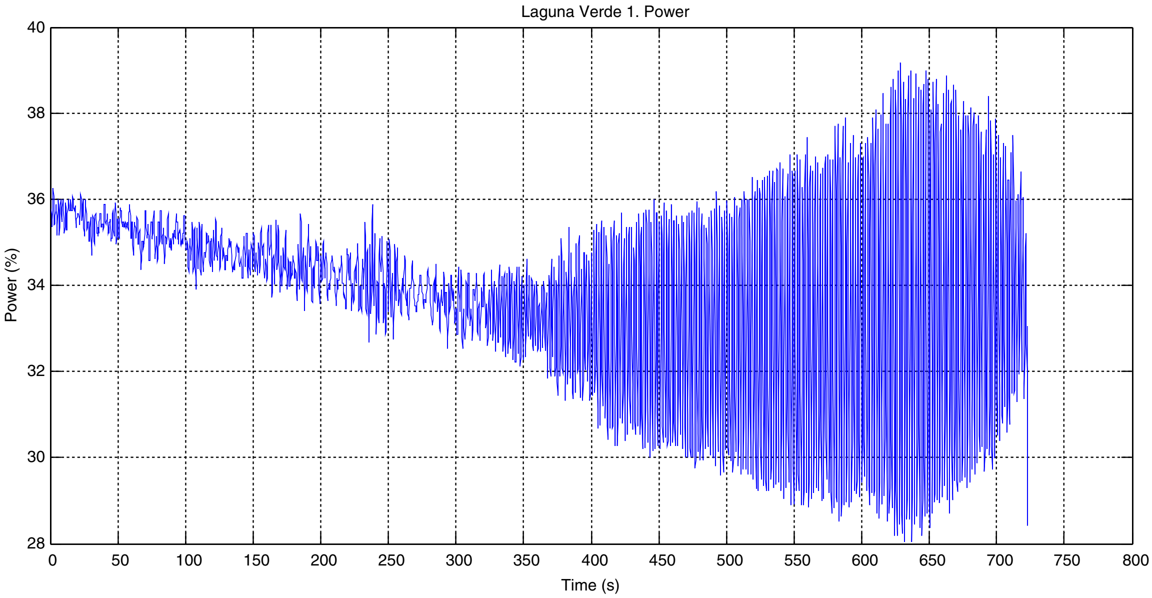

Fig. 1. Laguna Verde instability event.