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Technical note

Boiling water reactor instability analysis using attractor characteristics

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ABSTRACT

The main purpose of this work is to develop an alternative technique to analyze the neutron flux signal with the aim of determining boiling water reactor (BWR) stability or instability. Another benefit would be to demonstrate the intrinsic stability or even reversibility of the BWR neutron flux and hence, of power.

The methodology is based on the attractor morphology analysis. After calculating the time delay and embedded dimension, a tridimensional attractor is constructed. The morphological analysis is based on the attractor center position and the orbit radius value.

Analysis results show that all BWRs analyzed have the same attractor shape, meaning the attractor is a system indicator. The orbit radius is a good stability indicator. It is demonstrated that the limit orbit is not reached in any studied case. Reversibility is justified and intrinsic stability is demonstrated.

1. Introduction

A boiling water reactor (BWR) is a non-linear, deterministic and stationary system (Gavilan Moreno, 2010). This system is dynamic because its condition is influenced by time. It is non-linear because, as a complex system, it responds to a set of differential equations in partial derivatives (Lahey and Moody, 1977; Thie, 1981). The reactor is also deterministic as its evolution is governed by differential equations. A dynamic system is considered stationary if after determining external parameters, time variations do not affect the system, thus meaning the attractor is unique and defined (Small, 2005; Mandelbrot, 1997).

The key concept of this work is the Takens' theorem (Taken, 1980) which develops the delay embedding theorem. Given a system (boiling water reactor), a parameter is measured in specific instants (neutron flux) and a time series is constructed. In this context, this scalar signal (neutron flux) $s(t)$ will correspond to a measurement function $h(x)$ defining $s(t)$ for each state of the system. That is:

$$s(t) = h(x(t)) \tag{1}$$

This means a measured scalar value is needed to reconstruct a higher dimensional state space in order to mimic the true state space.

A delay coordinate function H builds a d_e dimensional vector $y(t)\epsilon R^{de}$ from d_e measurements separated by a delay time τ.

$$\begin{aligned} K(t) &= H(x(t)) \\ K(t) &= (h(t), h(x(t-\tau)), \ldots h(x(t-(d_e-1)\tau)) \\ K(t) &= (s(t), s(t-\tau), \ldots s(t-(d_e-1)\tau)) \end{aligned} \tag{2}$$

Takens' theorem converts a time series $s(t)$ Eq. (2) into a collection of vectors $K(t)$ Eq. (2), with d_e components. These vectors show system status, evolution and behavior.

The attractor is composed of "n" points in a space of d_e dimensions. Points are ordered in time and form orbits defining attractor morphology. Given the limitation of graphic representations, only objects in 2 or 3 dimensions can be represented. This development selects a three-dimensional representation.

The characteristics used in this work are orbit shape, attractor center and orbit radius (diameter), all of which are morphologic features and give information about system behavior and evolution.

The methodology used in this work is described in three steps:

- First Step: Time series description.
- Second Step: Attractor construction (built).
- Third Step: Result analysis. Attractor morphology.

After attractor construction, the correlation with stability or instability is obtained based on attractor morphology and stability analysis results from previous work/research.

2. Time series description

The time series available for calculation correspond to the neutron flux signal of commercial reactors in operation. These time

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Table 1
Reactor type and neutron flux signals characteristics.

Power Plant	Type/model	Manufacturer	Standard Instability	Total time (s)	Sampling (s)
Cofrentes	BWR6	General Electric	Out-of-Phase	250	0.05
Laguna Verde 1.	BWR5	General Electric	In-Phase	700	0.2
Forsmark	BWR (ABWR)	ABB Atom	In-Phase	320	0.08

series have been used to check calculation techniques for other stability parameters, as decay ratio, Hurst coefficient and fractal dimension. The stability, instability and transition conditions are perfectly known (Blázquez and Ruíz, 2008; Castrillo et al., 1991; Gavilan Moreno, 2010; Masashi and Yoichiro, 2005; Prieto-Guerrero and Espinosa-Paredes, 2008, 2014; Prieto-Guerrero et al., 2012; Verdú et al., 2001).

The three time series used are included in Table 1 and their graphic representations in Fig. 1a–c.

The time series (neutron flux signal) selected correspond to 3 instabilities caused by different primary sources in 3 operating nuclear power plants.

Fig. 1a corresponds to an event in Cofrentes Nuclear Power Plant (Table 1) dated January 29, 1991, during unit startup following an emergency shutdown (“SCRAM”). With plant conditions being 41% thermal power and 38% core flowrate, neutron flux oscillations occurred. After operators inserted control rods to a power line below the power-flow map, oscillations were cancelled (Castrillo et al., 1991). Out-of-phase instability was caused by feedwater temperature reduction.

Fig. 1b corresponds to an event at Laguna Verde Nuclear Power Plant in Veracruz (Mexico) on February 24, 1995 (Table 1). Power oscillations occurred during starting up of Unit 1. When instability took place, unit conditions were 35% thermal power and 38% core flowrate, with recirculation pumps at low speed and recirculation control valves partially open. Upon detecting this anomaly, the operator further opened the valves, increasing flowrate and contributing to reduce oscillations and restore stability. In any case, the operator manually performed an emergency shutdown (“SCRAM”). This was an in-phase instability event (Blázquez and Ruíz, 2008).

As for Forsmark NPP, Fig. 1c, conditions were different because it was not a power excursion resulting from plant operation, but rather an intended scenario. The data sets used were those of the “Nuclear Science Committee of the OECD Nuclear Energy Agency (NEA)” project, aimed at comparing different methods to analyze signals applied to BWR stability studies. This case of in-phase instability resulted from operating within the power-flow map instability region (Verdú et al., 2001).

3. Methodology

Boiling water reactors are usually defined in terms of differential equations describing system behavior over a short period of time (Lahey and Moody, 1977). In order to determine system evolution for longer periods of time, it is necessary to integrate equations either analytically or by means of numeric methods. This leads to significant CPU consumption both in terms of analysis

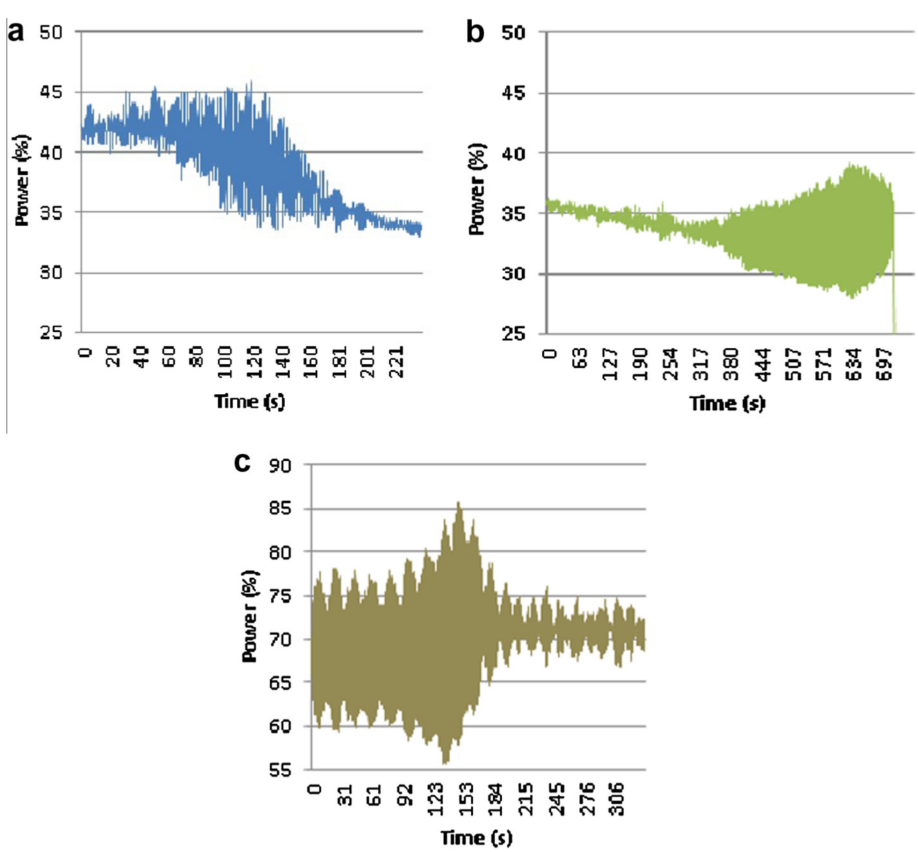

Fig. 1. Power time series corresponding to Table 1: (a) Cofrentes NPP, (b) Laguna Verde NPP, (c) Forsmark NPP.