Annals of Nuclear Energy 64 (2014) 11–20

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

Power probability density function control and performance assessment of a nuclear research reactor

Amir Esmaeili Abharian [a], Amir Hosein Fadaei [b,*]

[a] Department of Electrical Engineering, Islamic Azad University, Garmsar Branch, Garmsar, Iran
[b] Faculty of Energy Engineering & Physics, Amirkabir University of Technology (Tehran Polytechnique), Hafez Street, Tehran, Iran

ARTICLE INFO

Article history:
Received 30 October 2012
Received in revised form 10 September 2013
Accepted 11 September 2013
Available online 12 October 2013

Keywords:
Probability density function (PDF)
Performance assessment
Nuclear research reactor
Stochastic control
PSO
Reactor control

ABSTRACT

One of the main issues in controlling a system is to keep track of the conditions of the system function. The performance condition of the system should be inspected continuously, to keep the system in reliable working condition. In this study, the nuclear reactor is considered as a complicated system and a principle of performance assessment is used for analyzing the performance of the power probability density function (PDF) of the nuclear research reactor control.

First, the model of the power PDF is set up, then the controller is designed to make the power PDF for tracing the given shape, that make the reactor to be a closed-loop system. The operating data of the closed-loop reactor are used to assess the control performance with the performance assessment criteria. The modeling, controller design and the performance assessment of the power PDF are all applied to the control of Tehran Research Reactor (TRR) power in a nuclear process. In this paper, the performance assessment of the static PDF control system is discussed, the efficacy and efficiency of the proposed method are investigated, and finally its reliability is proven.

1. Introduction

Control loop performance assessment is very appreciable for the high efficient advancement of the systems. Lasting whole nuclear plant disturbances, whether oscillating and regular, or non-periodic, are distinguished in nuclear plants. Several developing elective tools techniques, for monitoring and assessing the controller performance, have been proposed in the literature during the last decade. These techniques can be divided into two major categories; that are deterministic and stochastic controller performance assessment methods. A considerable set of these disturbances have periodic fluctuations. The automatic detection of fluctuations initially focused on data that related to a single control loop.

Controller performance assessment and tuning is important industrially, since there are thousands of loops in a typical process plant and many of these will not have been tuned adequately. The investment in control loop Supervisory Control and Data Acquisition (SCADA) systems is also significant and poorly tuned parameters of controllers can waste this investment. Miao and Seborg (1999) have introduced a statistical-based method to detect of beyond measure oscillatory feedback control loops, which should perform better in the presence of noise. They apply tests to the auto-correlation of a signal, on the assumption that the auto-correlation of a fluctuation of signal is also oscillatory. Thornhill et al. (2003) have illustrated a new approach based on the regularity of zero-crossings of filtered auto-covariance data, which determines the presence of fluctuations in pick up frequency ranges.

The commercial interest can be attributed to a recognition in industry that many control loops under perform (Ender, 1993) and that improved control performance can offer significant financial benefits (Brisk, 2004).

Performance assessment methods of closed loop are also accomplished of detecting irregular loops (Harris et al., 1999). However, an augmentation ascribable to Xia and Howell (2003) is necessitated to isolate fluctuations from other configuration of unusual behavior. The performance assessment is conceivable because the nuclear plants are mostly acted with distributed control system (DCS). The operating data can be sampled by a long shot, so the performance assessment can be fulfilled without affect the operation of the nuclear plant. The performance index should be selected firstly to achieve the control loop performance assessment. There are three types of performance assessment indexes till now: the definitive index (Astrom, 1991; Hagglund, 1999; Mia and Seborg, 1999; Jamsa-jounela et al., 2003), the stochastic index and the index defined by the user.

Nuclear plants have many features that affect the civilization, application of advanced control, and performance monitoring techniques:

* Corresponding author. Address: Faculty of Energy Engineering & Physics, AmirKabir University of Technology (Tehran Polytechnique), Hafez Street, Tehran, Iran. Tel.: +98 21 88630644; fax: +98 21 88417576.
E-mail address: Fadaei_amir@aut.ac.ir (A.H. Fadaei).

0306-4549/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.anucene.2013.09.018

- Nuclear processing plants are very complex, i.e. non-linear and stochastic in nature, consisting of neutronic, electrical, mechanic and hydraulic components; transmitters; software and hardware; control systems.
- Nuclear processing plants are usually subject to constraints, e.g. actuator saturations, inequality constraints, couplings, etc., and a wide range of reactor dynamic disturbances and reactor and fuel parameters variations.
- Most of nuclear processes, particularly in research reactor, have fast dynamics with small time constants and dominant time delays, as the many quality of reactor parameters can only be measured some away from the nuclear plant. Moreover, the time delay is usually varying as function of fuel characteristic during the dynamic phases. The determinate index is the requirement of the classical control theory to the performance of the systems, including overshot M_p, settling time t_s, rising time t_r, steady-state error e_{ss}, integral of the square error $\int_0^t e(t)^2 dt$ of the system's unit step response. The stochastic one is a kind of statistic index to describe the control loop performance; the index based on the minimum variance control is the most widely used stochastic index. This index expresses the system performance with the ratio of the closed-loop output variance σ_y^2 and the minimum achievable variance σ_{mv}^2, that is $J = \sigma_{mv}^2/\sigma_y^2$, and $0 \leqslant J \leqslant 1$. If J is close to 1, the performance of the system is good, otherwise the performance is poor. For the stochastic index, the estimation of control loop performance can be performed by analysis the operating data and some prior knowledge of the system. The defined index is defined by user according to the requirement of the system.

The output distribution control is widely exist in nuclear industry, it has a lot of typical nuclear plants, such as the neutron flux distribution in research reactor, the reactor power distribution in nuclear power plant, and the temperatures distribution control in nuclear reactor core. The control of the stochastic systems can be carried out with controlling the mean and variance of the output, but the algorithm is executed with the assumption that the output of the system obeys the Gaussian distribution. This assumption is largely true for many systems. Professor Wang proposed the bounded output distribution control theory (Wang, 2000; Yue and Wang, 2003) to control the output probability density function (PDF) instead of the mean or variance of the system output. For this theory, the assumption of obeying the system's output from the Gaussian distribution is not needed, and the output PDF includes much more information in comparing with mean and variance. This theory makes a big step in stochastic system control. The aim of this paper is to present nuclear case studies of the performance evaluation of control systems in a research reactor. The used methods for the performance monitoring and the obtained results are described and discussed. The novelty of the contribution is to take the stochastic control into a nuclear industrial area, what has not been working on it too much, and show that the control engineers, both in industry and academia, how still have not found the opportunities to improve the controller performance in this industrially nuclear field.

In this paper, the performance assessment of the power PDF control nuclear research reactor is discussed. An index is put forward for the performance assessment of the power PDF, and the method is studied with the simulation power of the Tehran research reactor (TRR) control system.

2. Reactor stochastic modeling

The reactor modeling comprised of several phases. Various models for reactors can be acquired in literary studies, e.g. (Huang and Edwards, 2002). These models become different in some particular way in extension and complexity. In this study, the best feasible model for the reactor under affability was selected. At the first step, the model structure is selected, the next step would be to dwell the selected model structure with Tehran research reactor (TRR) parameters. These parameters were achieved through altered appliances and algorithms (Abate et al., 1990; Hosseini et al., 2010). when the generated model is achieved, the model is supplemented with control rod drive mechanism (CRDM). This model was simulated using MATLAB. Reactor time response was designed for model validation. From reactor experimental data, test vectors were created to tune and validate the retraced model. CRDM part was appropriately tuned to adapt the model application to the achieved test vectors. Different reactor parameters were assessed for TRR. The nonlinear stochastic model of a system contains a comprehensive operating range and supports in better control of the nuclear research reactor.

In this paper, well known of neutronic and thermal–hydraulic model equations are solved concurrently by the reformed Hansen's method in the code (Hansen and Charles, 2007). Two groups of Xenon and Iodine concentration dynamic equations are solved by the fourth order Runge–Kutta method. It is initiative advantageous to derive the point-kinetic dynamic equations in order to differentiate the birth and death processes of the neutron populations. This will assist us in formulating the dynamic stochastic model. Following, the non-stochastic time-dependent equations, satisfied by the neutron density and the delayed neutron precursors, can be illustrated by

$$\frac{\partial n(t,r)}{\partial t} = D\upsilon\nabla^2 n(t,r) - \left(\sum_a - \sum_f\right)\upsilon n(t,r) + [(1-\beta)k_\infty \sum_a - \sum_f]\upsilon n(t,r) + \sum_{i=1}^{m}\lambda_i C_i + S_0 \quad (1)$$

$$\frac{\partial C_i}{\partial t} = \beta_i k_\infty \sum_a \upsilon n(t,r) - \lambda_i C_i \quad (2)$$

For $i = 1,2,\ldots,n$ where $n(t,r)$ is the density of neutrons, r is position, t is time, υ is the velocity, and $D\upsilon\nabla^2 n(t,r)$ is a term accounting for diffusion of the neutrons. The absorption and fission cross sections are $\sum_a$ and $\sum_f$, respectively. The capture cross section is $\sum_a - \sum_f$. The prompt neutron contribution to the source is $[(1-\beta)k_\infty\sum_a - \sum_f]\upsilon n(t,r)$ where $\beta = \sum_{i=1}^n \beta_i$ is the delayed-neutron fraction and $(1-\beta)$ is the prompt-neutron fraction. The infinite medium multiplication factor is k_∞. The rate of transformations from the neutron precursors to the neutron population is $\sum_{i=1}^n \lambda_i C_i$ where λ_i is the delay constant and C_i (t,r) is the density of the ith type of precursor, for $i = 1,2,\ldots,n$. Finally, additional neutron generators are shown by $S_0(t,r)$. In this research, neutron captures are considered deaths. The fission process here has considered as a "pure" birth process where $\upsilon(1-\beta)-1$ neutrons have born in each fission along with the precursor fraction $\upsilon\beta$. For a single energy group model, a neutron is lost in each fission, but $\upsilon(1-\beta)$ neutrons are instantly achieved with the general result that $\upsilon(1-\beta)-1$ neutrons are straightaway "born" in the energy group. However, in a multiple set model, a fission event would be handled as a death of a neutron in the energy group of the neutron causing the fission along with the simultaneous birth of $\upsilon(1-\beta)$ neutrons in individual high energy groups.

let and $C_i(t,r) = g_i(r)c_i(t)$ where we anticipate that $n(t,r)$ and $C_i(t,r)$ are separable in time and space. Now, Eq. (2) becomes

$$\frac{dc_i(t)}{dt} = \beta_i k_\infty \sum_a \upsilon \frac{f(r)n(t)}{g_i(r)} - \lambda_i c_i(t)$$

Note that it is supposed that $\frac{f}{g_i}$ is independent of time. We also suppose that $\frac{f(r)}{g_i(r)} = 1$. Thus we have