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Research on intelligent monitor for 3D power distribution of reactor core

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ABSTRACT

A real-time monitor for 3D reactor power distribution is critical for nuclear safety and high efficiency of NPP's operation as well as for optimizing the control system, especially when the nuclear power plant (NPP) works at a certain power level or it works in load following operation. This paper was based on analyzing the monitor for 3D reactor power distribution technologies used in modern NPPs. Furthermore, considering the latest research outcomes, the paper proposed a method based on using an ex-core neutron detector system and a neural network to set up a real time monitor system for reactor's 3D power distribution supervision. The results of the experiments performed on a reactor simulation machine illustrated that the new monitor system worked very well for a certain burn-up range during the fuel cycle. In addition, this new model could reduce the errors associated with the fitting of the distribution effectively, and several optimization methods were also obtained to improve the accuracy of the simulation model.

1. Introduction

The changes of reactor core power are usually monitored by detecting the neutron flux density, and the measurement system should be more sensitive to the power-change during the load-following operation. Early 3D monitor for reactor power utilized miniature fission chamber neutron detectors which installed in the in-core instrument channels, and the power distribution was computed with the help of a series of neutron flux data, which measured by moving a few fission chamber probes in several in-core instrument channels. Taking a 300 MW NPP reactor core as an example, in the condition of steady power, it takes about 90 min (Liu and Guo, 2008) to complete a 3D power distribution measurement, which cannot reflect the real time changes if the NPP works as load-following operation.

The monitor for 3D distribution of the core power has great significance to optimize reactor design, enhance nuclear safety and improve NPP's operation, for that many scholars have developed a variety of online simulation systems (Zhao, 2006), combined with actual detection and 3D calculation of the core, to monitor 3D core power distribution. In order to improve real-time online monitor, more and more advanced calculation methods and types of reasonable segment division for rapid and effective algorithms have been developed, however, they are largely based on the mathematical and physical models and the complex calculations, not based on the real-time ex-core neutron detection.

In addition, there are still some types of reactors which cannot install in-core measurement system. Such as the pebble-bed gas-cooled reactor, the neutron measurement channels cannot be arranged due to pebble-bed's mobility, the high-temperature and high-pressure environment. Similarly, the detectors cannot be installed in the small experimental reactor core for its limited core size. Consequently, the monitor for 3D power distribution of these reactors can only rely on the ex-core measurement systems.

In this paper, we have proposed a new intelligent 3D core power monitoring method based on artificial neural network. By studying the complex relationship between the 3D core neutron flux change and ex-core neutron detector response, we find out that the artificial neural network could fit complex nonlinear function of this two aspects, and to verify the validity of this method, a series of simulation experiments have been carried out.

2. The model of 3D core power distribution based on ex-core nuclear measurement system

2.1. Ex-core nuclear measurement system of PWR

The neutron detector outside of the PWR reactor together with the matched electronic systems can monitor the core's neutron leakage from a deep shutdown state to 120% FP state. Since the range of the neutron flux around the core is about 10^{-1}–10^{11} neutrons/cm^2 s, the modern PWR usually needs instruments to obtain accurate ex-core neutron flux information. There are three ranges, respectively, the source range, intermediate range and power

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range. The source range uses boron counter tube detectors to survey the reactor start-up neutron flux, as shown in Fig. 1. Source range detector is located at the lower quarter height of the core, approximating to the height of the source rod. The two independent gamma compensated ionization chambers as the neutron-sensitive element of the channel of the intermediate section are mounted in the corresponding instrument pore, and these detectors are installed at the half core height position. Moreover, there are four non-compensated ionization chambers (in channels A, B, C and D, each is divided into upper and lower halves) to detect the leakage neutron flux in the power range.

The main function of the ex-core nuclear measurement system is to alarm timely during steady power operation and achieve accident shutdown when it is needed, by monitoring the neutron flux. And the ultimate purpose is to protect the reactor core. During load-following operation, the core power typically runs between 50% and 100% of its full power, hence, the power range of the neutron detector (non-compensated ionization chamber) can offer one-dimensional core power distribution of the core. This research discusses the use of one-dimensional core power distribution detected by the ex-core axial detector combines with the neural network to achieve the 3D core power distribution prediction.

2.2. The physical process of the 3D power distribution reconstructed

As shown in Fig. 2, the PWR core can be divided into numerous segments. As long as the neutron flux of each segment is obtained, the 3D distribution of the core power can be calculated at a certain power level. When the core power is close to the steady state, each segment can be viewed as a cuboid neutron source, and the leakage neutron number from each segment is almost constant. These leakage neutrons can cross over the surrounding segments, the reflective layer, the steel apron and the pressure vessel and then reach to the detectors. According to the statistical law of neutron measurement principles, when the detector is fixed, its response to the leakage neutrons from one segment is relatively constant. Meanwhile, the count of the detector is the superposition of the neutrons leaked from each segment. Therefore, certain correspondence relationship between the measured value and the neutron flux density value of each segment is exist, i.e., the counts detected by the long ionization chamber in the ex-core nuclear measurement channel can reconstruct the 3D core power distribution.

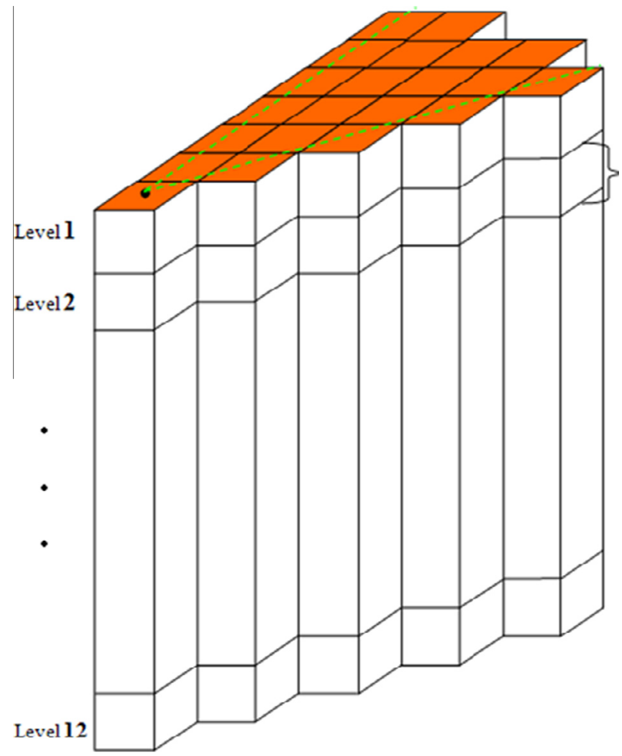

Fig. 2. The partition diagram of 3D reactor core segment.

In addition, there is a strong correlation between each segment for neutron flux, especially between adjacent segments (Zhao et al., 2005). Previous studies have shown that the rigid block does not exist between each segment. The so-called rigid block is defined

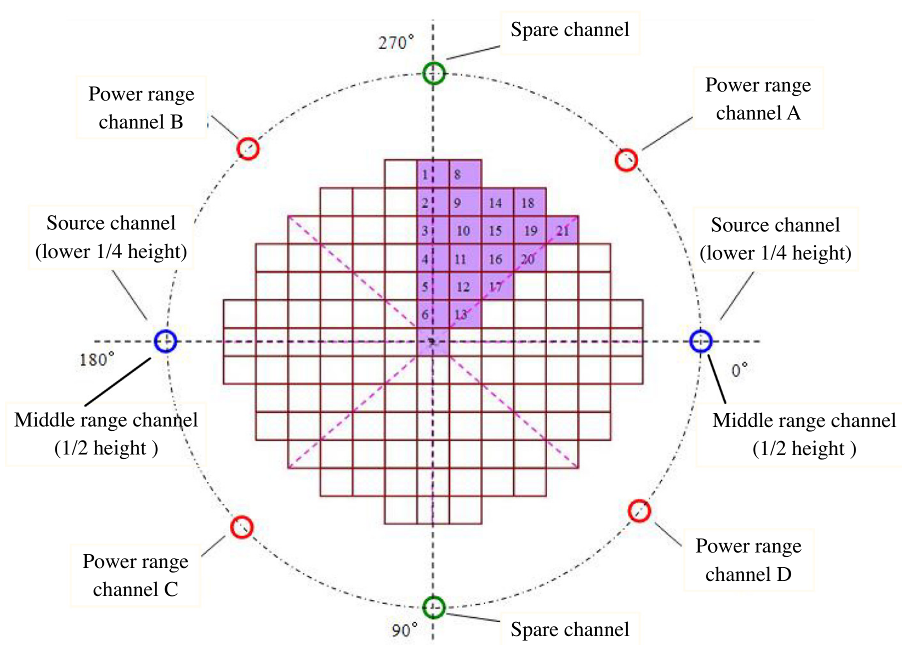

Fig. 1. Arrangement diagram of the PWR's ex-core nuclear measurement system.