A Concept of Fault-Tolerant Control Systems in a Nuclear Plant

Seung-Hwan Seong *, Taek-Kyu Kim, Jae-Kwan Park, Seo-Ryong
Advanced Instrumentation & Control Research Division, Korea Atomic Energy Research Institute
Corresponding author: shseong@kaeri.re.kr

Keywords : fault-tolerant, redundancy, control system, deep-learning, diagnosis

1. Introduction

As current digital control systems are becoming increasingly complex, there is a growing demand for systems with higher reliability due to economic and safety regulations. Therefore, to enhance system reliability and operability, the development of fault-tolerant control logic through configuration reconfiguration is essential.

Redundancy is a core element of fault-tolerant control and can be broadly classified into physical redundancy (hardware redundancy) and analytical redundancy.[1] While securing physical redundancy simplifies fault detection and elimination, it leads to system complexity, difficult installation, and economic disadvantages. On the other hand, analytic redundancy secures fault-tolerant control functions without physical redundancy by utilizing the functional relationships between system inputs and outputs to infer measurement values from other measurements or to infer and analyze dynamic characteristics.[2]

Based on this analytic redundancy-based reconfiguration technique, the concept of a fault-tolerant control system implementable in a controller at a nuclear power plant was conceptually. In addition, a deep learning model was developed to diagnose the state of equipment; when the state of control-related equipment reaches a level equivalent to a fault, the system diagnoses it and responds to the failure of each control system according to the fault-tolerant structure based on the diagnosis results.

2. Methods and Results

2.1 Fault-Tolerant Structure of Power Control System Group

The reactor power control systems include the Reactor Power Control System (RRS) and the Reactor Power Reduction System (RPCS).

The left side of Figure 1 shows the functions handled by each existing system, while the right side illustrates a structure in which the functions of each system encompass all functions necessary for nuclear power control for the analytic-redundant control structure model. Since the current control systems are interconnected via a digital-based communication network, a fault-tolerant structure can be applied without altering the overall structure of the control system.

Under normal operation, each control system performs only its own inherent functions; however, if a fault is diagnosed in a single control system, the functions of the faulty system are simultaneously performed by the unfaulted control system.

The concept of reconfiguration structures of the control systems wase verified through integration with a PC-based Compact Nuclear Simulator(CNS). Figure 2 illustrates the interconnection between systems related to reactor power control. As shown in the figure on the right, the structure allows another normally operating system to bypass a faulty system and perform the functions of the faulty system in the event of a failure.

Since each system incorporates all the functions of the remaining systems based on a dynamic configuration fault-tolerant structure, it is determined that continuous normal operation is possible. In the figure, an X mark indicates a faulty controller; in the event of a system failure, the controller linked by the arrow of the same color additionally performs the functions of the faulty controller in addition to its original functions.

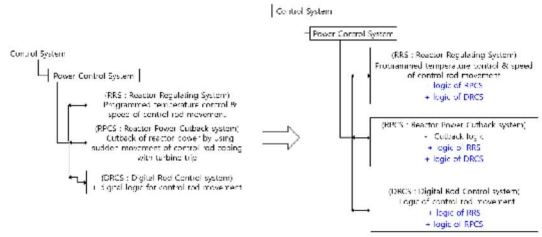

Fig. 1. Function allocation of the suggested method

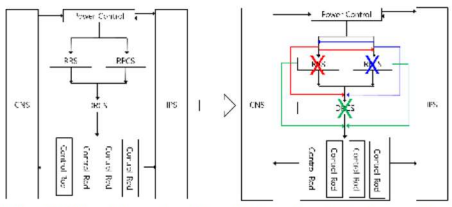

Fig.2 Working logic of the fault-tolerant structure

선진계측제어연구부/2026-08-18 16:52

2.2 Diagnostics based on Deep-Learning

An analysis of the online self-diagnostic capabilities of representative controllers revealed that the fault detection capability based on self-diagnosis at the component level within the controller is sufficient at the current level. Representative online self-diagnostic capabilities include the detection of fuse failures, memory failures, power failures, bus failures, and other faults. Accordingly, this study investigated a technique utilizing deep learning to enable intelligent predictive diagnosis even in cases where the controller is not completely diagnosable online. To validate the predictive diagnosis technique using deep learning, it was assumed that aging had occurred in the input card of the reactor power control system controller.

Uncertainty information from the PT-100 RTD input card temperature measurement device was utilized to determine the criteria for generating an aging signal. For the PT-100 RTD input card, the maximum uncertainty, or accuracy, is defined as ±5.25°C, while the uncertainty in the steady state is defined as ±0.85°C. Since existing fault detection functions can detect failures when the aging of the temperature input device exceeds the maximum uncertainty, a predictive diagnosis technique using deep learning was investigated for abnormal states (±0.85°C to ±5.25°C) that are greater than the steady state but less than the maximum uncertainty. First, we predicted and diagnosed failures caused by input card aging using a Convolutional Neural Network (CNN) deep learning model.[3] Secondly, we conducted a comparative study based on a time-series deep learning model capable of effectively reflecting the characteristics of time-series data. Representatively, the LSTM has a node-to-node connection structure capable of effectively recognizing the system's dynamic behavior over time, so we studied a prediction and diagnosis algorithm based on this.[4]

In this study, we improved the diagnosis rate by using both a CNN deep learning model and an LSTM deep learning model for diagnosing failures in nuclear power plant control systems. The CNN model demonstrated an accuracy of approximately 99.94% under a training condition of learning rate, while the LSTM model demonstrated an accuracy of approximately 99.28%.

In the field of deep learning, ensemble refers to a technique that improves performance by combining the results of various models to produce a final result.[5] The CNN and LSTM models were linked in an ensemble structure to diagnose the fault status of control systems. By connecting the results of the CNN deep learning model and the LSTM model using a filter that takes the average value, we prevented cases where the final nuclear power plant control system fault diagnosis result changed abruptly due to instantaneous abnormal results.

Figure 3 shows the results of the CNS simulation, demonstrating that unstable control rod control is performed initially due to fluctuations in the input signal (temperature), and then returns to normal control through predictive diagnosis and fault-tolerant structure operation. At this point, since the range of temperature fluctuations is within the range (±5.25°C) at which the controller can self-diagnose a fault, no fault diagnosis signal is generated by the controller. It demonstrates that normal operation is possible by diagnosing the abnormal state of the input device and switching the reactor power control from the abnormal Reactor Control System (RRS) to the Control Rod Drive Control System (DRCS) via the developed control switching switch as shown in Fig. 3

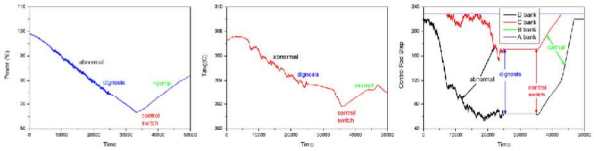

Fig.3 Simulation Result

3. Conclusions

We developed a fault-tolerant structure based on analytical redundancy by utilizing the digital characteristics of nuclear power plant control systems, which lack physical redundancy. In addition, we developed a deep learning-based equipment diagnostic algorithm to diagnose abnormal states prior to complete failure. By integrating the fault-tolerant structure and the diagnostic algorithm, we preemptively detected abnormal equipment states, including complete failures, and ensured continuous operation of the output control system based on analytical redundancy. It is expected that if the developed techniques are applied more broadly, it will be possible to complete a fault-tolerant control system utilizing configuration-reconfigurable redundancy that requires no physical structural changes and incurs no significant cost increase.

REFERENCES

[1] Youmin Zhang and Jin Jiang, “Bibliographical review on reconfigurable fault-tolerant control systems”, Annual Reviews in Control 32, 229–252, 2008.
[2] Vasco da Silva Brito, Fault Tolerant Control of a X8-VB Quadcopter, Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa. Dissertion 2016 september
[3] T. Ince, S. Kiranyaz, L. Eren, M. Askar, and M. Gabbouj, “Real-Time Motor Fault Detection by 1-D Convolutional Neural Networks”, IEEE Transactions on Industrial Electronics, vol. 63, pp. 7067-7075, Nov. 2016
[4] Karim, Fazle; Majumdar, Somshubra; Darabi, Houshang; Chen, Shun (2018). "LSTM Fully Convolutional Networks for Time Series Classification". IEEE Access. 6: 1662–1669. arXiv:1709.05206. Bibcode:2018IEEEA...6.1662K. doi:10.1109/ACCESS.2017.2779939. ISSN 2169-3536.
[5] Kuncheva, L. and Whitaker, C., Measures of diversity in classifier ensembles, Machine Learning, 51, pp. 181-207, 2003.

선진계측제어연구부/2026-08-18 16:52