Development of Nuclear Transient Early Warning System

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1. Introduction

In nuclear power plants, when a problem occurs during operation and an abnormal or emergency condition occurs, an alarm is displayed and the operator takes action according to the corresponding response procedure. It is difficult to recognize and respond to the situation proactively because the operator responds to the abnormal or emergency condition after it exceeds the predefined set-point. Therefore, it is necessary to develop basic technologies to detect abnormal conditions early and support the operator's response in a transitional situation, which means the process of progressing to an abnormal or emergency occurrence.

Transient detection technology can reduce the workload of operators for proactive problem recognition and support operators' decision-making to overcome transients and improve the safety of nuclear power plants through efficient operation. In recent years, advanced artificial intelligence-based diagnosis and prediction technologies can identify insights embedded in complex data and identify changes in the situation from the data.

Recently, studies have been introduced in the field of nuclear power plants to diagnose the status of nuclear power plants based on probability by utilizing deep learning technology [1-5]. In this paper, we propose an early warning system that can recognize changes in the state of a nuclear power plant at an early stage and help operators cope with them by utilizing these advanced diagnostic and prediction technologies. In addition, the interface is designed through the early warning system conceptual design process to provide an early warning to the operator, and the NuTERNS (Nuclear Transient Early Warning System) implemented as a prototype are introduced.

2. Nuclear Transient Early Warning System

2.1Intelligent Early Warning Technique

Alarms in nuclear power plants [6] are determined as true or false by predefined logic based on rules according to instrumentation signals and have high reliability. For each alarm, a response procedure is prepared and strict response measures are taken. Unlike conventional rule-based alarms, AI-based diagnosis is based on probability. Although artificial intelligence technology has been developing rapidly in recent years, it has not yet reached the reliability of traditional rule-based judgment. Depending on the application, they can be very accurate, but in certain cases they can be relatively inaccurate. In particular, it may not yet be appropriate to provide AI diagnostics on par with alarms, as false alarms can be very confusing for operators.

Nevertheless, AI technologies such as deep learning are rapidly increasingly being used to assist humans by identifying hidden characteristics in data that are not visible to the human eye. In some cases, it is already being used in real life, such as driving assistance in autonomous vehicles and X-ray analysis in the medical field. Therefore, in the field of nuclear power plants, it is necessary to take a step-by-step approach to adaptively utilize AI technology at the current level of technological development. In other words, it is necessary to provide intelligent diagnosis results based on data by AI models to operators with a concept that is somewhat less rigorous and attention-grabbing than conventional alarms.

"Intelligent Early Warning" can be defined as such a concept. Intelligent early warning does not necessarily entail immediate action, but it can alert the operator to a trend change in the plant's condition that is gradually deviating from normal and can assist the operator in taking countermeasures, such as monitoring the return to normal, proactively preparing for an alarm, or actively preventing an alarm from occurring. By introducing this concept, abnormal transients can be detected by operators in advance, helping them to manage nuclear power plants more safely, and further contributing to the reduction of abnormal transients.

It is difficult to rely on existing alarm mechanisms for intelligent early warning, as there are no applications in the nuclear field yet and continuous improvement of reliability is required. Early warning for less urgent transients that do not necessarily require manual operator intervention, such as lock-in, is best managed by simpler state changes than alarms. The early warning state control sequence proposed in this paper is shown in Figure 1.

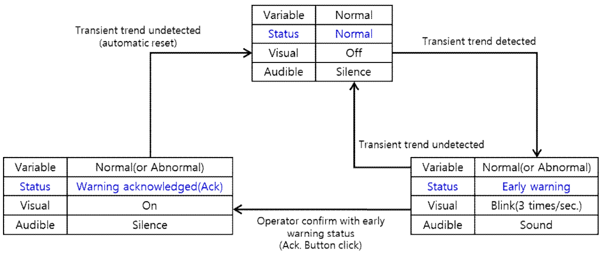

Figure 1. Status transition diagram for early warning.

If a transient trend is detected early during normal operation, the alert status changes to "early warning" and visual and audible notifications are initiated. At this time, the state of the plant process variables may be partially abnormal or still in a normal state. This is different from a conventional alarm, which enters when there is an abnormal condition. When the operator recognizes this through the acknowledgment button (Ack), the warning status changes to "Warning Acknowledged", and the color coding shows on and the sound is silent. Afterwards, if the transient trend changes and is diagnosed as normalized by the diagnostic system, the warning status automatically returns to "normal" without operator intervention, unlike conventional alarms.

In other words, the early warning status can be divided into Normal, Early Warning, and Ack, and the operator can control the early warning as Silence, Acknowledge, Reset, and Test. The visual and auditory coding of early warnings should be designed to be consistent with existing style guides applicable to nuclear power plants. Similar to the visual coding used in existing alarm mechanisms, it can be represented by a blinking light (e.g., 3 times/second) for an early warning (Unack) and a solid light for an operator acknowledgment (Ack). Audible coding can be represented by a sound (e.g., sound for 2 seconds) for early warning (Unack) and silence for operator acknowledgment (Ack). However, the decibel and duration should be different from the existing alarm sounds to ensure that the operator can distinguish between them.

According to the Nuclear Alarm System Design Guidelines [6], manual reset is recommended as the default for alarms in nuclear power plants. Manual reset forces the operator to explicitly acknowledge and disarm an abnormality once it has occurred, so that the event is not missed. This process is called alarm lock-in and explicit reset. Auto-reset, on the other hand, enforces lock-in but not explicit reset, and can be used in situations where the operator must respond to many alarms or needs to return quickly. At the current state of the art, a form of automatic reset that does not enforce lock-in is used to minimize operator burden, but a more stringent approach could be considered in a phased manner as early warning becomes more reliable and the plant becomes more acceptable.

2.2 User Interface for Early Warning System

First, using CNN [4] and LSTM [5], representative deep learning models implemented in previous studies, deep learning models were trained to predict transients for three critical accident situations related to pipeline ruptures: a steam line break (MSLB) inside or outside the reactor building, a steam generator tube rupture (SGTR), and a loss of coolant accident (LOCA).

Figure 2 shows the early warning user screen introduced in this paper. The whole screen is divided into three main parts. First, there is the "Transient Diagnosis Prediction Result" section, which predicts the normal or accident type on the left side of the screen; the "Accident Location" section, which shows the location of the problem in the event of a normal or transient situation; and the "Break Size" section, which shows two fracture sizes that are not displayed in the normal state but have a high probability of intelligent diagnosis results in the event of a transient situation, from a total of 21 fracture sizes (SBLOCA 1 inch to 6 inches, SGTR 1 rupture to 5 ruptures, SLB main steam pipe area 10% to 100%).

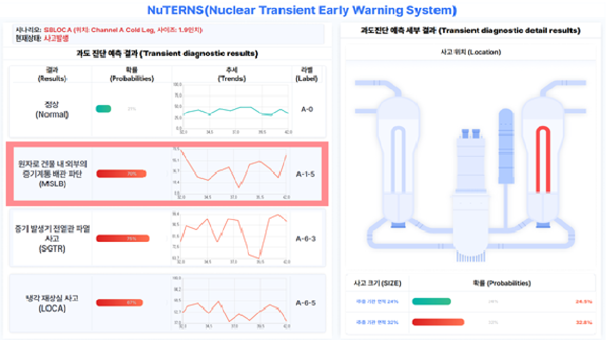

Figure 2. Examples of Intelligent Early Warning.

The "Type of Transient" on the left side of the screen displays the three most likely out of dozens, so it will vary depending on the situation. However, the normal state is always fixed at the top. The trend graph for the steady state is colored green, while the transients are colored red. If the sum of the probability of normal and transient states is 100% and the probability of deep learning prediction is more than 50% among the transient states, it is possible to display indications such as blinking lights and sounds that require the operator's attention.

To support the operator's response, it is effective to provide additional detailed information (accident location/break size, etc.) where possible. For this purpose, "Accident Location" information is provided in the upper right corner of the screen, which shows in red where the transient is predicted to have occurred. In addition, the "Break Size" section in the lower right corner of the screen provides the ability to display the two most probable fracture sizes based on the diagnostic results, among other fracture size information.

3. Conclusions

Artificial intelligence technology with data-driven diagnosis and prediction can realize early condition diagnosis of nuclear power plants, which is very difficult with conventional methods. However, full-scale field application will be possible only when compensation methods for misdiagnosis, improved technical reliability, and acceptance of the technology by conservative nuclear power plant operating groups are in place.

In this paper, we have presented initial directions for applying AI technology to transient diagnostics at the current technological stage. First, we defined intelligent early warnings that are less stringent than conventional warnings to minimize the increased workload of operators while still allowing them to recognize transient events at an early stage. In addition, by implementing a user interface for early warning of nuclear power plant transients, it was shown that it can provide various information such as the type of transient, accident probability, accident location, and accident size required by the operator.

If these AI-based early abnormality diagnosis technologies and information are utilized for user support, it is expected that nuclear power plant safety will be improved.

ACKNOWLEDGMENTS

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (Ministry of Science and ICT) (No. RS-2022-00144150).

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