# Framework to Develop Artificial Intelligent Autonomous Operating System for Nuclear Power Plants

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**Abstract.** As artificial intelligent (AI) technology has been dramatically developed, various industries have been challenged to apply it. In a view of nuclear power plants (NPP), it seems that AI technology applies to NPPs at the last because NPPs are required the most stringent level of regulatory guideline for safety. To overcome it, AI technology should be applied incrementally into the NPPs rather than all at once. According to the unintended shutdown records during startup and shutdown operation from 1997 to 2017 in Korea, it is reported that human errors accounts for 40% of the total. This is because operators feel heavy burden to monitor hundreds of parameters for a long time of operating time. Also, there are lots of startup and shutdown operating history that can be used for correcting the data from the NPP simulator. Therefore, this work proposes a framework to develop AI automatic operating system for startup and shutdown operations of NPPs. Operating procedures of startup and shutdown operations are categorized. In addition, AI technologies will be introduced to find out the most suitable learning algorithm. It is expected that economic loss from human error during startup and shutdown operation will be reduced as AI system developed.

**Keywords:** Artificial intelligent · Startup and shutdown operation
Operating procedure

## 1 Introduction

As data processing and artificial intelligence (AI) technologies have been dramatically improved, automation researches have been carried out in various fields. For a long time, driving on complex city streets has been regarded that only humans can do. However, it becomes one of the successful outcomes of AI technologies now.

Although nuclear power plants (NPPs) are one of the safety-critical infrastructures, NPPs also have been partly automated and even higher level of automation has been investigated.

Figure 1 shows typical operation modes and their automation levels in PWR plants [1]. In startup and shutdown modes, shown as heat-up and cool-down stages respectively on Fig. 1, completely manual operations are conducted. Heat-up and cool-down operation modes are a process that is likely to cause high workload and human error because the operator needs to check lots of plant parameters and control many components in


S. Yamamoto and H. Mori (Eds.): HIMI 2018, LNCS 10905, pp. 508–517, 2018.
https://doi.org/10.1007/978-3-319-92046-7_42

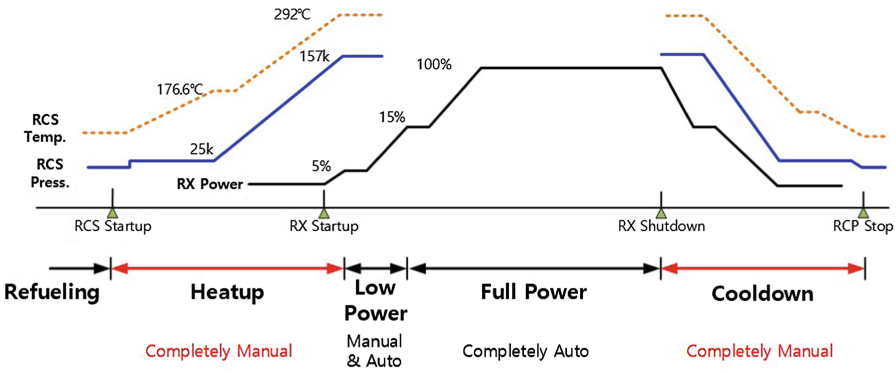


**Fig. 1.** Typical operation mode and automation level in PWR

accordance with the change of the plant power during the operation. This operational environment may cause high probability of human errors. Actually, there have been records about unintentional trip during startup and shutdown operation for 1997 to 2017 from Operational Performance Information System for Nuclear Power Plant developed by Korea Institute of Nuclear Safety, which is a regulatory body in Korea. From the records, human errors account for about 40% of the total trip history. Once NPP is tripped, tremendous economic loss occurs. NPPs are designed to shut down in a hazardous moment taking account of huge economic loss. In general, these factors make operators feel a heavy burden to shut down the plant by their mistake. If a new system that can reduce human error is introduced into a NPP, then it will also be economically beneficial.

Therefore, this work proposes an automated startup and shutdown system for an NPP to minimize possible human operator errors. To develop an automation framework, task analysis of startup and shutdown procedures, investigation of various deep learning techniques, training data collection, and the performance evaluation and validation are necessary. As the beginning of the work, the task analysis and some suggestions related with deep learning techniques will be introduced in this paper.

## 2 Special Characteristics of Nuclear Power Plant Operation

### 2.1 The Need for Operating Procedures of a NPP

In Korea, pressurized water reactor (PWR) is the representative type of NPP operating currently. PWR has two main systems divided into primary system and secondary one. Primary system consists of nuclear core, steam generator, and reactor coolant system with various safety system. The reactor is cooled with pressurized water so that water does not be boiled during the operation. In general, since one steam generator forms one loop with hot leg and cold legs, it is referred to as a loop instead of a steam generator. Secondary system consists of turbine, generator, and condenser. Primary system produces thermal energy by nuclear fission reaction and it is transferred into the secondary side to generate electricity. As well as two systems, there are too many components to be controlled or monitored.

NPPs are operated on main control room (MCR) and worksite where local operators work. To keep the NPP safe, hundreds of parameters are monitored whether they satisfy limits of safety. In MCR, operator group make decisions based on the plant state that plant parameters show on and control target components or system if needed. Since NPPs have enormous numbers of complicated and sensitive devices, it is impossible that operators control the plant with full understanding of parameters without any guidelines. To support operators, there are various operating procedures present to prepare many possible cases.

NPP has three operation modes according to the plant condition; normal condition, abnormal condition and emergency condition. Each condition has its own operating procedure. These operating procedures are resulted from analysis of thermal hydraulic code and reactor analysis code. Since it is not enough to describe the real plant sate from thermal hydraulic code and reactor core analysis code, the results get reliable continuously by comparing with empirical data.

During most of operating time, the plant is on the normal state. Once something goes wrong, it is not determined as abnormal state. Rather than, the plant parameters are checked according to entry conditions listed in the abnormal operation procedures. Operator should select a proper procedure in accordance with combination of alarms and symptoms. Once the plant state enters abnormal condition, operators try to restore normal condition from current state. If it fails, the plant state goes to emergency stage and reactor core must be tripped immediately. The emergency operation procedure is needed in this moment to shut-down the plant in safe.

## 2.2 Startup and Shutdown Operation

Startup and shutdown operating procedures are corresponding to the normal operation mode. Reference operating procedures are based on OPR1000, developed in Korea. Startup operation covers cold shutdown to hot standby mode and shutdown operation has the reverse process. Reactivity maintains subcriticality during whole processes. Cold leg temperature is under 99 °C at cold shutdown state and over 177 °C at hot standby condition. It is known that operating time takes about 20 h to startup or shutdown the plant.

Operators follow instructions on the procedure and decide whether the task should be done or not. The conditions depend on plant operating parameters such as pressure and water level of the pressurizer, water level and pressure of the steam generators and temperature of the reactor. Startup and shutdown operating procedures also provide such parameters informing the plant state. As the beginning of the research, it is important to analyze startup and shutdown operating procedure to find out key parameters that indicate the plant state.

## 2.3 Classification of Operating Procedures of Startup and Shutdown Operations

The procedures consist of 6 sections. The first part declares the purpose of the procedure. In the second part includes reference documents. The third section introduces cautions and limitations during process to keep the plant state safe. It is important part for training AI because these limitations will become indicators when to stop. The forth part is about initial conditions. The fifth part contains the procedure and the last section is an appendix.

While some instructions are simple and straightforward, some instructions require continuous monitoring, dynamic situation assessment, and decision making based on knowledge and experience in the fifth part. Therefore, startup and shutdown operation cannot be automated easily with rule-based code for the reasons above. Those ambiguous statements and tasks in operating procedure that should be determined by skilled operators who have worked long time in this field. To make matter worse, in Korea, the policy to reduce dependency on NPP might lead to lack of startup and shutdown operating experiences for the new operators.

The types of procedure instructions are categorized into two condition judgments and three controls: simple judgment, complex judgment, simple check, simple control, and dynamic control. Each type needs different methods for automation. In a statement, judgement play the role of the entry condition to conduct indicated controls.

1. *Simple judgement.* Simply judge by comparing with given numbers on the procedures. i.e. if reactor coolant temperature reaches 146 °C, trip shutdown cooling system pump manually and arrange the system in safety injection mode.
2. *Complex judgement.* The entry condition is ambiguous or complicated because operator should refer to other system operating procedure. i.e. if needed, conduct ‘long term secondary system purification operation’ according to system-26 ‘condenser system’ or system-27 ‘condenser purification system’ operating procedure to improve the secondary system part of steam generator.
3. *Simple check.* Check the component or system state without action. i.e. Check the level of steam generator is maintained 30 to 50% by startup feedwater pump or auxiliary feedwater pump.
4. *Simple control.* Statements can be done by simple action like binary control. i.e. Close safety injection tank isolation valves at main control room.
5. *Dynamic control.* Control components or system according to other operating procedure to meet the demanded states. i.e. if reactor coolant system pressure reaches under 52.7 kg/cm$^2$A, make safety injection tank pressure to 21.1 kg/cm$^2$ by following system-03 ‘safety injection system’.

Judgement 2 and control 5 are hard to be implemented with rule-based commands. These commands need more information that is not indicated on the procedure. AI algorithm should be able to take a proper decision like skilled human operator do.

According to this classification method, the result of classified startup and shutdown operating procedures of OPR1000 is shown in Table 1.

Since the procedure is designed for the real plant and the simulator which is NPP has, there is a possibility to have more target components and systems in real plant. The operating procedures of APR1400, which is the latest type of PWR in Korea, will be analyzed with the same manner. But the number of targets and types of statements will be similar or increasing because APR1400 is originated from OPR1000. That is, more than 200 or 300 targets will be treated when AI algorithm is trained. Strategies to select the deep learning algorithm and how to train it should consider that the data will continue to accumulate for 20 h, the average operating time for startup and shutdown.

**Table 1.** Categorizing statements of startup and shutdown operating procedures

| Startup operation procedure | | Cold shutdown to hot standby | | | |
|---|---|---|---|---|---|
| Minimum # of target comp. and sys. | | | | 309 | |
| | Judgement | | Control | | |
| Type | 1 | 2 | 3 | 4 | 5 |
| # of instructions | 20 | 31 | 44 | 22 | 33 |
| Shutdown operation procedure | | Hot standby to cold shutdown | | | |
| Minimum # of target comp. and sys. | | | | 194 | |
| | Judgement | | Control | | |
| Type | 1 | 2 | 3 | 4 | 5 |
| # of instructions | 33 | 12 | 11 | 33 | 34 |

# 3 Autonomous Operation Model

## 3.1 Deep Learning Algorithm for Automatic Operation

There is a research to develop an automation system for emergency operating procedures using fuzzy colored Petri net [2]. However, startup and shutdown operator procedures have different forms with emergency operating procedures and more dynamic situations should be considered because plant power and status of various component vary continuously. While conventional neural networks have required large amounts of hand-labelled training data, reinforcement learning algorithms must be able to learn from a scalar reward signal that is frequently sparse, noisy and delayed [3]. In addition, considering characteristics of NPPs, learning algorithms should not assume that data sets are independent.

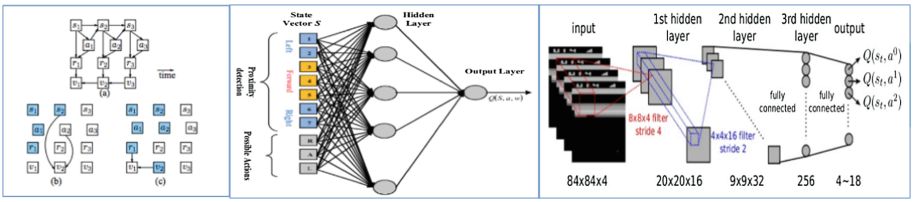


**Fig. 2.** Bayesian reinforcement learning (RL) algorithms (left), artificial neuron network RL algorithm (center), and deep RL (right)

Therefore, to find out the most appropriate learning algorithm for startup and shutdown operations, various methods were investigated as shown in Fig. 2 [3–5]. From the review, it is evaluated that guided reinforcement learning approach is appropriate for startup and shutdown operations. This is because we do not have data that can clearly distinguish between good and bad and there is too much information to be considered. In the future, the outcome of this work would be a group of AI models with multiple layers of hidden layers.

One of the difficulties to apply learning methods to NPP operation is to set score for determining a performed action is appropriate or not. While games have obvious goal (high score), NPP status cannot be easily scored with a specific number. Therefore, there is need to gather the factors that can be used as a score to describe the plant state well. For example, the difference between the target range and the current value of significant plant parameters can be candidates for scoring. Also, operating time could be another option. As far as the operating limits allow, the variables are changed as quickly as possible to finish the entire process earlier than before. Future works will focus on verification of these candidates.

### 3.2 Learning Data Generation Using Full Scope Simulator

Lack of data is one of the main causes which make it difficult to apply deep learning algorithms to nuclear field. For many decades, especially only a few historical data of unanticipated reactor trip have been reported. Even though NPPs have long history, it is not enough to train AI algorithms. Therefore, it is not avoidable to use not only empirical data but also the data obtained from a simulator for training.

Simulator includes hydraulic analysis code such as RELAP and MARS-KS, and reactor core analysis code such as RAST-K and NESTLE neutronic codes to describe the real NPP. To make a result of the simulator as real as possible, empirical data adjust the result. Therefore, even if raw data from system codes are insufficient, simulator results gets better reliability constantly.

Moreover, unlike other accident scenarios, startup and shutdown operation, the target operation modes of this work, have lots of operating records through overhaul period or refueling issue. Considering these advantages, it is appropriate to develop automatic system from these operation modes.

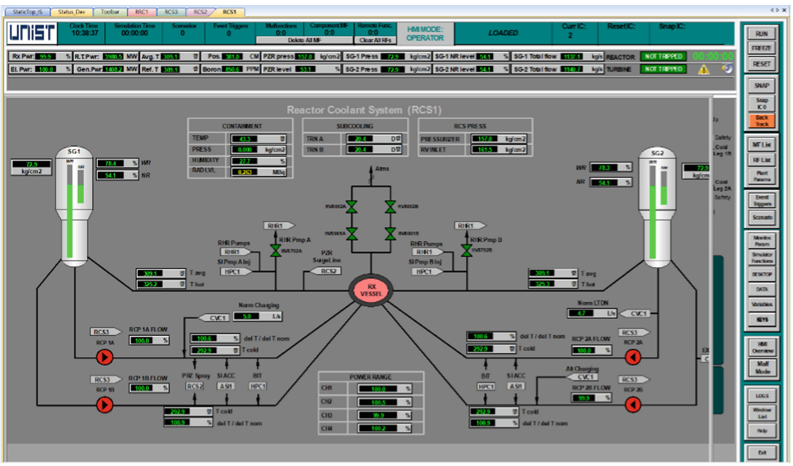


**Fig. 3.** Simulator based on 1400MWe pressurized water reactor

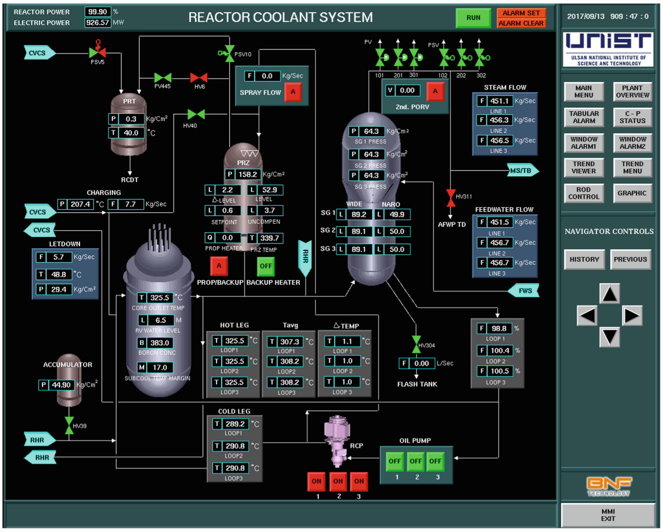


**Fig. 4.** Simulator based on 998MWe pressurized water reactor

In this work, two simulators will be used to make operating data. One simulator developed by Western Service Corporation models 1400MWe PWR as shown in Fig. 3. It will be mainly used because it has the similar structure with APR1400. In addition, since it allows to be run by a script, it is big beneficial to data production. The other simulator developed by Korea Atomic Energy Research Institute models 998MWe PWR as shown in Fig. 4. One of advantages is that the simulator has its own operating procedure. Unfortunately, it does not have script operating function yet.

A scenario file composed of a bundle of script commands can be input in advance to run the 1400MWe PWR simulator. The most common and simplest form of script is as follows.

$$[+]\text{delaytime}\ [\text{ObjectName}]$$

At the first, declare the time when the command line happens. Then write down the object with desired state. For example, '+5 var hsACHIS0268C.iswPos = 0' means that the switch of variable hsACHIS0268C will change its position as 0 (close state) after 5 s. With this function, it is possible to enter numerical values directly as well as simple components operations. However, there is a problem that naming methods of the procedure, the simulator, and the system code, used for script, are all different. For this reason, it takes a lot of time to match their names. Therefore, it must be done in advance before data production stage.

Later, to train the selected algorithm with as many data as possible, an automatic training data generation system was developed connected to 1400 MWe PWR simulator. Data production is big issue because a long operation time is required, and even if the operation time is reduced through simulator function, the reliability of the data may be deteriorated. The automatic data generation system should cover those problems.

# 4 Framework of Startup and Shutdown Operation Procedure

## 4.1 Gradual Approach to Full-Autonomous AI System

The AI autonomous operating system can be divided into three level depending on the degree of utilization of the operating procedure because the procedures do not use all the parameters of the plant. As developing a new system, it is necessary to decide what level it will be made. Three levels of AI system can be categorized as follows.

*Level1: autonomous system based on operating procedure only.*

This is the method to make the tasks automate only appeared in the operating procedure. It is the simplest approach, however, there is no chance to operate the plant more efficiently than the existing procedure does. Only the order of statements or time to take an action could be changed. Therefore, reducing the time it takes to operate will be an indicator of a better system.

*Level2: autonomous system considering plant parameters based on the operating procedure.*

This level basically follows the procedure but makes it possible to consider other related systems. For example, if water level of the pressurizer should be lower, the system will consider not only the components suggested by the procedure but also any components which affects it. From this level, even if the same procedure is performed, the variables to be handled might be different. Likewise, it is possible to develop a new instruction by the AI system.

*Level3: full autonomous system without learning the operating procedure.*

This level guarantees the maximum feasibilities of all controllable parameters without the procedure. Obviously, this level will be the most difficult to be implemented. However, once it succeeds in development, it is expected that the new system will produce a procedure that is completely different from the existing one. As Alpha-Go has made its own strategies, it might consist of something people have not considered ever.

In fact, the operating procedure has high reliability because it is made by experts of a NPP operation and revised continuously. Nevertheless, AI can discover a new way of operation that no one else can think of. The higher level of the system, the greater the likelihood of new discoveries. Obviously, higher level is hard to implement. There are hundreds of controllable components and thousands of parameters to be monitored. Moreover, these parameters make data continuously for about 20 h. That is, there are almost infinite cases to be learned.

Therefore, as feasibility study, the objective of this work is to create a level 1 AI model first. If it succeeds, level of AI model will then be stepped up to the higher level.

## 4.2 Identification of Input Data and End State for AI Algorithm Training

To train AI algorithm, it is important to identify input data type and end state. Input data types can be classified from the fifth part of the operating procedures. It is needed to distinguish which components or systems can be operated because as mentioned in Sect. 2, there are lots of ambiguous statements that needs complex thinking process. End states can be defined by using the third and sixth parts of the procedures which deal with operating and variable limits. AI algorithm should stop the simulator when it meets end states. These termination conditions will check the outcome of operations by AI model.

It feels easy to think so far, however, the procedure suggests only the range of variables. Limitation changes dynamically as the plant state differs. In a data set, a single variable has no meaning. The input variables should be defined considering the combination of the variables. Similarly, termination conditions should be determined in the same way.

In addition, input data type and end state should be change according to the level of the AI system to be developed. The higher the level is, the more complex the variables become. In the level 3 approach, problem is not only the almost infinite number of cases but also termination conditions to be set.

This work cannot be done in the present state because it will be better to declare input data and end state while learning the algorithm, rather than defining them when organizing data.

## 5 Concluding Remarks

In this paper, framework to develop AI autonomous operating system for nuclear power plants is suggested. Since NPP is one of the industries where safety is the highest priority, such automatic system should be applied gradually with thorough verifications. Once startup and shutdown operations succeed to be operated by the AI algorithm, it will be a stepping stone for other operating conditions such as abnormal and emergency conditions.

Considering unique characteristics of NPPs, simple guided machine learning or reinforcement learning has limitation. Rather than, this work suggests guided reinforcement learning for developing level 1 AI model which is based on the present operating procedures. If it is successful to apply to the most sensitive subject, NPP, AI-based autonomous technology is expected to apply to other industrial sectors as well.

**Acknowledgments.** This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) and the Ministry of Trade, Industry & Energy (MOTIE) of the Republic of Korea (No. 20171510102040)

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