Preliminary Study on Improving the Automation Level of Large Commercial Pressurized Water Reactor

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Abstract. Digital instrumentation and control (I&C) system has been widely applied on large commercial pressurized water reactors (PWR), which brings significant convenience to their operation. However, the level of automation and operation efficiency of nuclear power plant is still lower than conventional power plant such as thermal power plant or hydro power plant. On one hand, the safety and reliability requirement of nuclear power plant always chooses the mature and proved technology, but not the emerging technology such as artificial intelligence. On the other hand, the complexity of system design and operation requirement also makes it difficult to improve the automation level of nuclear power plant. To deal with these difficulties, a statistical analysis has been given to identify the challenges on improving the automation level. And a framework of plant level autonomous is given to illustrate how to organize the techniques and algorithms available to reach this goal. For the new functions, algorithms and equipments that involved in the framework, the requirement of nuclear safety should be considered. Therefore related requirements that need to be addressed are also discussed in this paper.

Keywords: I&C system · Pressurized water reactor · Artificial intelligence · Smart plant

1 Introduction

Nuclear energy contributes about 5% of electricity in China. Among the 59 nuclear power units in operation or under construction in China, 55 of them are pressurized water reactor [1]. In recent year, digital I&C system is used in newly built PWR to increase the automation level and operation efficiency. Advanced technologies and concepts such as artificial intelligence (AI) and smart plant that already widely applied in conventional power plant may further improve the automation level of PWR. But the consideration in nuclear safety makes the application of those technologies remain in preliminary stage in PWR [2]. To promote the development of smart nuclear power plant and improve the automation level, safety and economy factor should be focused.

From safety aspect, there are comprehensive safety system design and operation procedure to deal with nuclear accident in PWR, which is not exist in conventional

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power plant. Therefore the automation level of PWR is not only defined by its normal operation condition, but also related to the performance in accident condition. A target automation level of PWR can be defined as “unmanned surveillance, few people on duty”. “Unmanned surveillance” refers to the maximized level of automation when the plant is operated in normal situation. “Few people on duty” refers to the minimized number of staff that should be always ready to deal with nuclear accident, which is the minimized level of automation that need to consider all possible situation that may happen in accident condition. By increasing the automation level, the safety of PWR can be also improved as less human operation will reduce the possibility of human error, which is a main cause of many nuclear accidents.

From economic aspect, the difference in cost distribution between nuclear power plant and conventional power plant also make the target of a smart nuclear power plant different with that in thermal power plant. The fossil fuel is the main cost of a thermal power plant, which makes the optimization in control and automation functions when developing smart power plant is highly focus on fuel efficiency. On the contrary, the fuel cost of PWR only contributes to a small part of its total cost. And once the fuel loaded, its efficiency can be maximized by full power output. The improvement on level of automation contributes to the economic performance from the aspects of reducing number of operation staff and process optimization in auxiliary systems. This can improve the economic performance but is less significant compared with that in thermal power plant. Meanwhile, using smart techniques and equipments to decrease the time for maintenance and periodic shutdown can significantly increase the economic benefit for PWR, but it is not the topic of this paper.

Based on the above condition, this paper analysis the challenges on improving automation level of PWR based on a statistical analysis for the task of operator. To systematic deal with those challenges, a framework of autonomous operation is given to improve the automation level and operation efficiency of PWR. Other than functional design, consideration of nuclear safety is also discussed in this paper to guarantee a reliable implementation of smart nuclear power plant.

2 Current Status

Improving the automation level of large commercial PWR is too general to discuss and provide focus point for implementation. To make it more specific, a statistic analysis about task of control room operator has been carried out to find what kind of task limit the level of automation and how to solve it. The operation task of control room operator generally includes monitoring and control through HMI of I&C system, communicate with other staff, decision making and use 3rd party equipment (e.g. physical protection or grid coordination equipments). The basis for statistic analysis is selected from the emergency operation procedure of HPR1000 PWR. HPR1000 is a third generation PWR with digital I&C system and control room. It has eight units under construction in China and may represent the mainstream PWR technology in China for the following years. The reason that selects emergency operation procedure for analysis is that it contains many complex situations that the operator need to deal with in accident situation, which is difficult to realize by automation logic. From the analysis result, operation tasks that divided to procedure step level can be identified as: “Automatic logic alone”, “Require AI or advanced algorithm”, “Require local operation”. Table 1 shows the statistical result.

Table 1. Statistic analysis for operation tasks

	Automatic logic alone	Require AI or advanced algorithm	Require local operation	Require both	Total steps
Number of steps	791	243	132	25	1191
Percentage of steps (not overlapped)	66.4%	20.4%	11.1%	2.1%	-
Percentage of steps (overlapped)	66.4%	22.5%	13.2%	-	-

About “automatic logic alone” that takes about 66.4% of steps, it means the task can be completed by traditional automatic approach such as sequence control, group control or close loop control. The reason that this kind of tasks is not automatically implemented is that the operation procedure in accident situation involves complex decision branches and parallel tasks that cannot be realized by traditional sequence control. And those steps are separated by other steps that cannot be automatically implemented, which brings break point on control sequence. To improve the level of automation for those steps, a schedule mechanism is required and the break points between steps should be addressed by other approach.

About “Require AI or advanced algorithm” that takes about 22.5% of steps, this kind of tasks may require knowledge or experience based decision making of human operator. It can be implemented by artificial intelligence model that use operation record as input, or can be implemented by advanced control algorithm such as fussy controller, adaptive controller, model recognition etc. [3–5]. The fast development of artificial intelligence brings an alternative approach to improve the level of automation, which has been proved to be effective in thermal power plant but remains in research stage for nuclear power plant. For the application in PWR, on one hand safety and reliability should be considered. On the other hand, there are still some tasks such as decision making based on experts or external information, cannot be automatically implemented by AI or advanced algorithm. Improve the automation level in this aspect need task based application of AI or advanced algorithm, as well as I&C equipments with the capability to implement those algorithms.

About “Require local operation” that takes about 13.2% of steps, it generally contains two kinds of situations. One is the capability of I&C system cannot execute field tasks within I&C system, so that it need to be done by local operator. The other is manual confirmation of task execution for safety purpose. To deal with these situations, a smart I&C system that extend the capability on instrument, actuator and automatic field inspection device can reduce the workload of manual operation in field. Speech recognition can also be used to reduce the workload of control room operator when assigning job to field operator or conducting communication tasks with staff outside control room.

Similar analysis has also applied on normal operation procedure with similar conclusion, while it need more support from local operation and less support from AI or advanced algorithm. To address these detail challenges, it may begin with fully make use of the capability of digital I&C system to implement tasks that requires "automatic logic alone" in automation system. And a frame that can organize these tasks should be established. Then extend the hardware and software capability of I&C system to provide platform for the implementation of advanced automatic functions. Then software related to AI or advanced algorithm, and hardware that can improve the efficiency of local operation, can be gradually implemented in PWR as their reliability grow with application experience.

3 Framework on Improving the Automation Level

As the operation tasks are analyses in step level and can be solved by individual technologies, a framework that can organize those individual functions to complete a plant level operation task or process is necessary to improve the level of automation for PWR. A classic structure of intelligent control by Saridis has three levels: organization level, coordination level and execution level [6]. Based on this model, Fig. 1 shows how this structure matches with the function analysis and organization in an I&C system of PWR with the capability of autonomous operation.

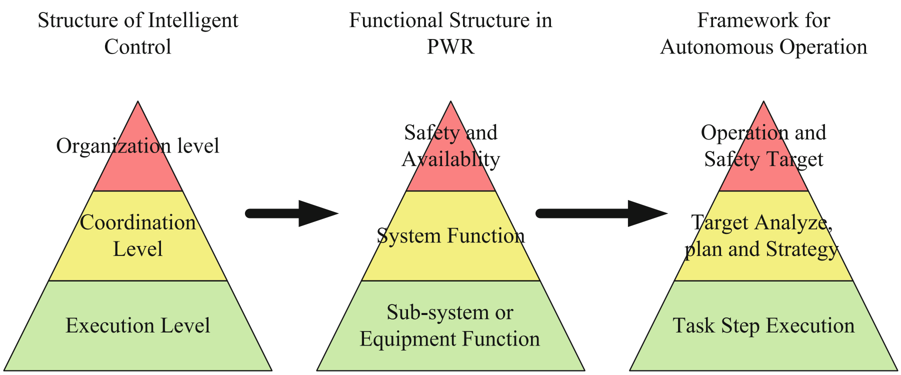

Fig. 1. Functional structure of a framework on improving the automation level

When apply this three-layer structure to the operation requirement of nuclear power plant, the organization level will plan the safety and availability target, such as set the plan of electrical power, which is the top level requirement of nuclear power plant. Then in the design of nuclear power plant, the top level target will be broken down into system level requirement following a functional analysis process. And the coordination level will implement these functions, determine the feasibility of functional targets, and carry out the plan and strategy to reach the operation goal. Execution level contains the functional module for each individual steps and can be called to perform desired task when necessary. Under this structure, the application of AI, advanced algorithm and equipment will gradually increase the percentage of task steps that can be automatically executed by I&C system. Then the level of automation can be improved with a schedule mechanism in coordination level to link each single step to a plant level process. For a long term goal, with a deeply application of AI and other advanced technology that enable nearly all tasks in execution level (some tasks such as get suggestion from technical support center, coordinate with emergency response, chemical sampling and analysis may still need human operation, but the interface with control room operator can be automatically implemented by speech recognition), a coordination level automation that can automatically complete plant level process and procedure will be achievable. Then the operation interface for operator will remain in organization level to set the target for power generation and monitor the safety status of the plant.

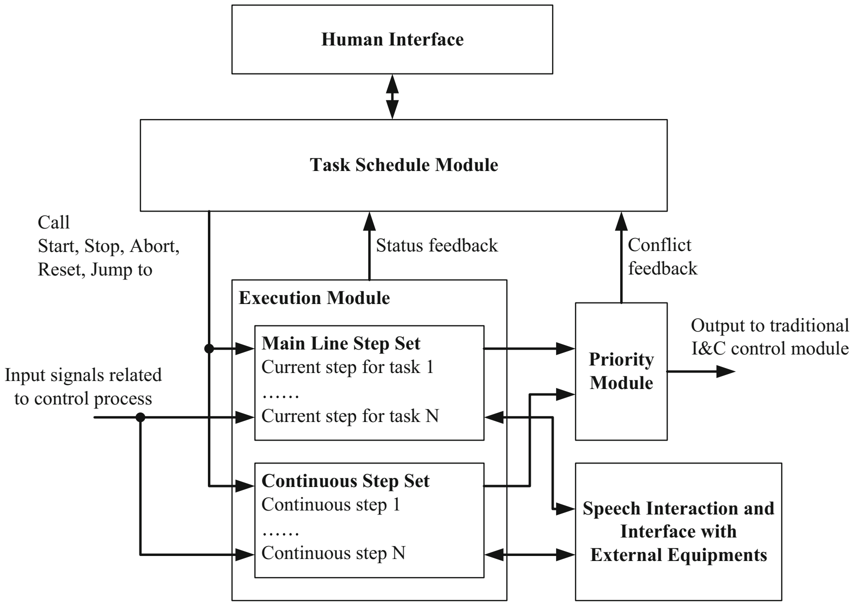

Fig. 2. Framework for schedule mechanism in coordination level

For the schedule mechanism in organization level, Fig. 2 shows a framework that will address the following issues arisen in challenges analysis:

- Complex procedure sequence with decision branches and continuous steps;
- Parallel tasks execution with confliction and priority management strategy;
- Speech recognition and interface with equipment outside I&C system.

In this framework, a task schedule module will manage all of the processes in execution. It will keep track of the current step in each process. If confliction on command appears, it will analysis the priority of tasks and reschedule them by start, stop, abort, reset or jump to steps that currently under execution.

As the confliction has been addressed, execution module will process multiple parallel steps and provide status feedback to task schedule module. For each plant level process or procedure, it has a current step to indicate current position and progress of that process or procedure, while it may have multiple continuous steps that need to be addressed within a period of time. These kinds of steps are managed by two step sets: main line step set and continuous step set. Conventional logic, AI or other advanced algorithm are embedded in a standard interface for the implementation of each step, so that they can be controlled and managed by task schedule module and execution module. The algorithm in each step will process related input signal, then output control command through I&C system or other external interface such as automatic speech interaction with field operator.

For multiple tasks that send conflict command to one equipment, a priority module will detect the confliction, give conflict feedback to task schedule module and output command with higher priority to equipment level logic in I&C system. For field operation that out of the scope of I&C system, a speech interaction system can complete communication task for control room operator to field operator or other related staff. And an interface with external equipment such as unmanned aerial vehicle (UAV) or robot for field inspection will reduce the number of break point due to local operation.

Based on this framework, if the research and development on algorithm and equipment can automatically execute each step in the operation task, then a management and schedule framework will provide the function of plant level autonomous operation, and the operator task will remain on setting the operation target and monitoring the safety status of PWR.

4 Discussion and Conclusion

For the framework and corresponding new functions, algorithms and equipment that involved in the framework, the requirement of nuclear safety should be considered.

Industry level I&C system that support AI or advanced algorithm has been widely applied in conventional power plant and many other industry areas. But nuclear safety has higher requirement on reliability than other industry area. From hardware aspect, equipment qualification should be carried out to ensure the equipment can withstand earthquake, radiation, electromagnetic interference or other extreme environment. From software aspect, a verification and validation process should be carried out to ensure the correctness and effectiveness of advanced algorithm [7]. Without these qualification processes, it cannot be used to perform safety related operation task in accident situation. Therefore the number of staff for operation will not be reduced and the level of automation of PWR cannot be significantly improved. So these processes are necessary for the advanced algorithm and equipment to deeply applied and improve the level of automation of large commercial PWR.

The improvement on level of automation may reduce the possibility of human error and increase the safety of nuclear power plant. However, possible negative impact of advanced I&C functions should also be considered. Advanced algorithms such as neural network are black box model and their uncertainty should be considered. A general principle of this kind of application is using sufficient test cases and a safety analysis to ensure it should not have negative effect on the original safety function [8]. A priority control and manual override approach also can be used to eliminate possible negative effect. Beyond the consideration of I&C system design, too few manual operations may also lower the awareness of human operator, which may have negative effect on human factor engineering and therefore impact the safety of nuclear power plant. So the human factor should also be reevaluated during the implementation of advanced I&C functions.

As a summary, latest development and application of AI and smart plant technologies make it possible to further improve the level of automation of large commercial PWR. To approach this goal, task based algorithm application and a framework to organize plant level autonomous operation should be implemented, while the impact on nuclear safety should be considered during this process. With the growing application experience of AI and other advanced technology, the autonomous operation of nuclear power plant may stepwise enter into industry application.

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