

# Parallel System Method to Improve Safety and Reliability\* of Nuclear Power Plants

Gang Xiong, Jiachen Hou and Feiyue Wang

Key Lab. of Complex Systems and Intelligence Science  
Institute of Automation, Chinese Academy of Sciences  
Beijing, China, 100190  
gang.xiong@ia.ac.cn

Jialin Zhang

Beijing Institute of Nuclear Engineering  
Beijing, China, 100840  
zhangjialin21th@126.com

Timo R. Nyberg

BIT Research Centre  
Aalto University  
Aalto FI-00076, Finland  
timo.nyberg@tkk.fi

ManChang FU

State Nuclear Power Automation System Engineering Corp.  
Shanghai, China, 200233  
fumanchang@snpas.com.cn

**Abstract** - The safety and reliability are the soul of nuclear power plant. Until now, the solution to assure the safety and reliability is still not smart and reasonable enough because its strict management, standards and law are made and executed with human's experience and knowledge. By using of the latest IT technology, "Product Lifecycle Management" software can be developed where "top-down" plan method is combined with "down-top" design method to assure the safety and reliability of the product. Nuclear power system is a typical complex system consisting of many dynamic factors, and the conventional control, simulation and management technology can't assure the safety and reliability of its operation and management. Then, parallel system method is proposed in the paper, where includes the basic principle and its successful applications, ACP method, i.e. Artificial systems, Computing experiments, and Parallel execution methods, which is applied in PnTS, PnES and PnMS for nuclear power.

**Key Words** - Nuclear power plant, Safety and reliability, Artificial systems, Computing experiments, Parallel execution

## I. INTRODUCTION

In Copenhagen Climate Conference 2009, carbon emission reduction has become a worldwide common view. Due to Chinese energy depends mainly on coal, the current energy structure is like Figure 1, emission reduction and sustainable development energy has strong demands and huge development spaces in China. Nuclear power, as one of the best choices, has more advantages than other types of new energy. Generally, nuclear plants can be built close to the centers of demand, whereas suitable wind energy and hydro plant sites are normally remote from demand. Due to these reason, nuclear power will obtain its fast development chance in the next decades. More than 16 provinces, regions and municipalities in China have announced their intentions to build nuclear power plants (Figure 2) during the period of Chinese 12th Five Year Plan (from 2011 to 2015). At present, China has 11 nuclear power plant units in service; nuclear power installation capacity is 9.16 million kw now and will achieve 60 million kw in 2020. Therefore, how to assure nuclear plant's security and reliability is the first

priority among those priorities of Chinese nuclear sustainable development, so independent research and development of Chinese nuclear technology has become more and more important [1].

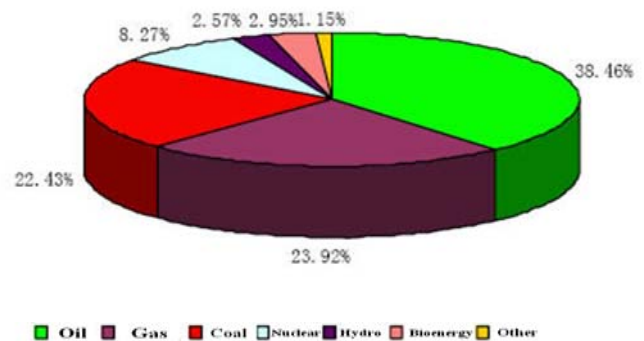


Fig. 1 Current Energy Structure in China



Fig. 2 Chinese nuclear plants plan

China has accumulated the experience of decades in nuclear technology research and nuclear power application. In 1950s and 1960s, China has designed atomic bomb, hydrogen bomb and atomic submarine successfully with the promotion of self-reliance, hard struggle spirit. Nowadays, either Chinese finance or its industrial technology has the solid foundation to develop nuclear technology independently. Long term strategy requirements of China's sustainable development is to realize nuclear power's fast

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development, to import and absorb the advanced nuclear system and technology, and to develop nuclear power plant with Chinese own technology and system which have independent intellectual property rights.

Nuclear power technology's digestion and independent innovation looks contradicting, in fact consistent of two stages and two aspects. Introduction & digestion, and independent innovation, must proceed and coordinate at the same time [2]. China is importing American Westinghouse Company's AP1000 and French AREVA's EPR, which are the representatives of third generation nuclear technologies, where instrument & control system and protection system are included. This paper uses instrument & control system and protection system of nuclear power plant as the main research topic, to research the advanced safe and reliable design and production method for the nuclear plant, provide new and innovative ideas for the localization of nuclear power technology.

## II. ANALYSIS ON THE PRESENT SITUATION AND COUNTER MEASURES OF NUCLEAR PLANTS

At present, Chinese existing nuclear plants mainly apply those nuclear technologies from France, United States, Canada and other countries. Qinshan Nuclear Power Station is the first nuclear power plant built in China, its third heavy water reactor has selected CANDU 6 heavy water reactor which is mature nuclear technology from Canadian. Daya Bay Nuclear Power Station is the first one million kilowatts large commercial nuclear power station in China to import French technology. Zhejiang Sanmen and Shandong Haiyang nuclear power stations, which are under construction, mainly use Westinghouse's AP1000, the third generation nuclear power plant technology based on the "passive" concept. Taishan power plant, which is under construction, use French's EPR technology, which is the third generation advanced pressurized water reactor nuclear power technology. Chinese third generation nuclear power technology is mainly imported from Westinghouse and French which will improve Chinese nuclear power comprehensive level and promote the industrial development. In 2007, China built up State Nuclear Power Technology Corporation Ltd (SNPTC), which are responsible for organizing and implementing the importation, digestion, absorption and innovation of Chinese third generation nuclear power technologies, striving to initiate third generation nuclear power industrial development way of "standardization design, industrialized prefabricate, modular construction, professional management, and self construction" [3].

Sellafield, Three Mile Island, Chernobyl, Maihama and so on, each heavy name represents one of the darkest disasters in nuclear power history. All these events are mainly caused by safety and reliability problems of design and operation phase. For these reasons, safety and reliability is definitely the first target of nuclear power plant, all of economic, efficient, stable, long lifecycle, and full load etc. are secondary objectives. At present, nuclear power domain

has formulated hundreds of national and international regulations and standards [4]. Nuclear power plant should also follow some principles, such as single accident criteria, multiple redundancy criteria, diversity criteria, safety design criteria, testing and maintenance standards, equipments stop standards. But for AP1000 and EPR, the typical representatives of the third generation nuclear power plant technologies, their design, construction and operation management are still not perfect [5]. For example: Their safe and reliability are still guaranteed by the experience of formulating and executing stricter management, standards, regulations and design method, so their intelligence and scientific conscientiousness are not enough. Many of safety and reliability parameters are estimated by using people's experience, which are not reasonable. In addition, strict management and hundreds of related standards & regulations, are also relying on experts to formulate and implement, it is difficult to demonstrate quantitatively its scientificity. With the development of information technology, computing technology is becoming the main research method; related modeling and simulation technology are being increasingly accepted and widely applied. The core idea of innovation design and operation control of nuclear power plant proposed in this paper, mainly uses these three methods comprehensively.

According to complex internal and external factors of nuclear power plant, this paper proposed strategies to necessarily achieve the safety and reliability goals, including: (1) In nuclear power plant design stage, by using the combination method of bottom-up plan and top-down design, the nuclear power plant reliability plan is made and correspond software package is developed to include those data, models and experiences across time and space, thus nuclear power plant has its scientific basis of safety and reliability evaluation before its construction. (2) In nuclear power plant operation stage, based on the existing instrument & control system, and protection system, parallel system are developed by using ACP method, to assure nuclear power plant to adapt for internal and external changes more intelligently, forecast more accurately, and to prevent from various risks, so as to further enhance and ensure the safety and reliability of nuclear power plant.

## III. RELIABILITY PLANNING AND DESIGN OF NUCLEAR PLANT

Taking nuclear power plant instrument & control system as an example, many design and development aspects have already been applied the practical experience of the high reliability, high utilization rate, and high anti-interference and high resistance to damage. Various types of instrumentation, instrument & control, and protection systems applied in nuclear power plants are quite similar.

Famous Chinese scientist Xuesen Qian once said: "The product's reliability is the result of its design, production and management", more and more people can comprehend this ideology. Reliability work experience among many

countries prove that the reliable product design have important influence on the product's reliability. According to Japanese electronics industries' statistics about the root reasons of unreliable product, unreliable design occupies 80%, unreliable components occupy 15% and unreliable manufacturing occupies 5%. According to US naval laboratory's statistics about the root reasons of unreliable products, unreliable designs occupies 40%, unreliable components occupy 30%, unreliable use and maintenance occupy 20%, unreliable manufacturing occupies 10%.

In the past, popular ideas and views among product designers are: "good performance represents good quality" and "products meet performance requirements means products meet quality requirements". Now, more and more concerns will concentrate on product's reliability and maintainability and its life cycle cost. In order to guarantee nuclear power plant's safety and reliability, scientific plan and design must be implemented during its design stage. This paper gives "system effectiveness" concept which is concerned the reliability plan and design, this is systematic and comprehensive reflection of availability, dependability and inherent capacity. The formula is as following:

$$E=A \cdot D \cdot C \quad (1)$$

In the formula: E—system Effectiveness; A—Availability; D—Dependability; C—inherent capacity;

A (Availability) means operational readiness, which means the system can start at any time when operations are needed, i.e. system can work when press START button. D (Dependability) means successful mission, i.e. the system's dependability is given before the task begins, and the system can succeed when it starts to work, or can complete the required function. Relationship among E (Effectiveness), R (Reliability) and M (Maintainability) can be expressed in Figure 3. From Figure 3, both of A (Availability) and C (Credibility) are the functions of R (Reliability) and M (Maintenance). Therefore, the function among E (Effectiveness) and R. M. C is  $E: f(R, M, C)$  [6].

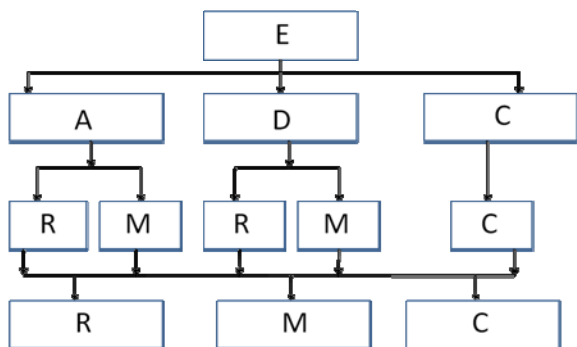


Fig. 3 Relationships among system effectiveness, reliability and maintainability

Nuclear plant reliability planning and design methods are simply explained here:

#### A. Primary selection of system structure

The preliminary design stage is the most effective time for reliability design, because the structure of the nuclear power plant is decided at this point. In the meantime, reliability considering will affect the design decision of nuclear plant, and then can guarantee the selected structure to meet reliability requirements. This is a progressive process to constantly select and test different system structures till all the constraints are satisfied. Other constraints, including capacity, size, shape, weight, price and progress must be fully considered and met. Reliability analysis provides a disciplinary framework, under which researches can satisfy other various constraints well. Such design can assure a more reliable system, and a better system according to all other applicable criteria.

#### B. Detailed system design of reliability concept

The preliminary design of the nuclear power plant, is selected or recommended by potential reliability evaluation, requires its detailed design further. Try every possible way to build up the simulation models, which assure to satisfy the related properties assumptions. If the model assume that a component or a set of components faults have no relationship with other component faults, then the designer should realize the assumption in the product's design. For example, assume that two detecting instrument channels are independent from each other, then they should build and calibrate independently, and then both channels fails at the same time becomes nearly impossible. Simple and direct system is easy to understand, easy to simulate, and has high reliability. Simply to say, reliability design means to add reliability analysis and design into the detailed design program of nuclear power system, and the reliability design concept and its mathematical relationship are hardly to understand.

#### C. Design scheme evaluation

The main values of nuclear power system reliability analysis are to assure that certain common parts have no accidental and groundless contribution to the system's unreliability. If such problems or faults are found, the solution to make up this deficiency includes: to choose better components, to execute more numerous and comprehensive test, to reasonably choose redundant components and modules. Based on the above mentioned nuclear power plant reliability plan and design idea and method, " nuclear power plant reliability plan and design software package " can be created and developed, which is equivalent to the existing software products like CAD, PLM and PDM. Meanwhile, it can become artificial system part of parallel system after suitable modification.

### IV. PARALLEL SYSTEM METHODS INTRODUCTION

Parallel system refers to a common system constitute of a natural actual system and its corresponding one or multiple virtual or ideal artificial systems. Modern control theory is one successful application example of parallel system concept, it firstly establishes accurate enough model, and then analyze its characteristics, predicate its behavior,

control its development. However, actual system control often use artificial systems formed by various mathematical models, which are offline, static, and supplementary form. After Fel'dbaum proposed dual control concept, parameter or structure's adaptive change control theory, the position and function of artificial system has breakthroughs finally, but this can't change artificial systems' non-dominant position from concept and scale point of view. For this purpose, Chinese scholars brought up parallel system framework (Figure 4) a few years ago; this provides a new thinking and perspective for complex system control's research [7]. This framework's first characteristics is to change the non - dominant position of artificial system, change the artificial system's role from passive to active, static to dynamic, and offline to online, so that the two systems can finally up to equal status, the artificial system can give full play in complex actual system control.

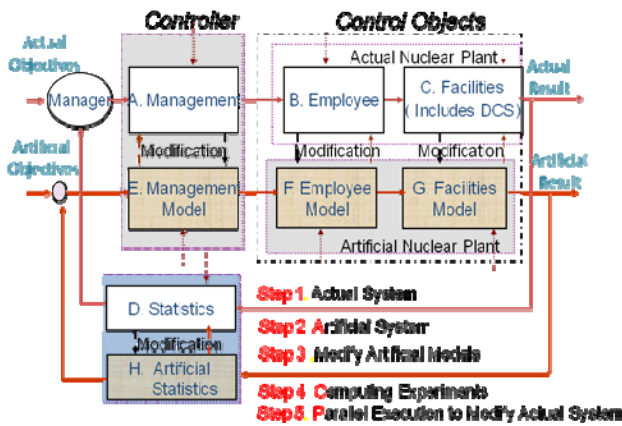


Fig. 4 Double control loop principal of parallel system

ACP method under parallel system theory framework include Artificial systems, Computing experiments and Parallel execution, ACP's basic principles and methods can be described as: To resolve actual system modeling problems, various factors are considered comprehensively, intelligent modeling method and data based modeling method are added to build up artificial systems which are equivalent to actual system [8]; Based on artificial systems, computing experiments are done to understand the relationship among various elements of actual system's normal and abnormal evolutions and interactions. Through parallel systems' interconnection, compare and analyze parallel systems' behaviors, study their future "reference" and "estimation" condition, accordingly adjust their control and management respectively; Finally, by using of the relationship rule found with computing experiments, double closed-loop parallel executions can be realized: under normal circumstances, the understanding of complex systems' ever-changing rules can help actual system optimize its control and management, continuously adapt for changes, forecast and prevent the occurrence of abnormal situation; under abnormal circumstances, artificial system can be applied to find rapid and optimal emergency and recovery management methods, to help people correctly

deal with the problem, to help actual system return from abnormal to normal state rapidly [9-10].

## V. PARALLEL SYSTEM METHODS IMPROVE THE SAFETY AND RELIABILITY OF NUCLEAR POWER PLANT

Based on the above mentioned theoretical and practical achievements, PnMS (Parallel nuclear Control and Management System) is taken as example (figure 5) to introduce the specific applications of parallel system methods, which can enhance the reliability and safety of nuclear power plant,. PnMS includes two parts: actual system and artificial systems. Actual system mainly refers to those existing nuclear power plant instrument & control system, and protection system etc. Artificial systems have three subsystems including A (Artificial systems), C (Computing experiments) and P (Parallel execution). The paper will describe in detail as following [11].

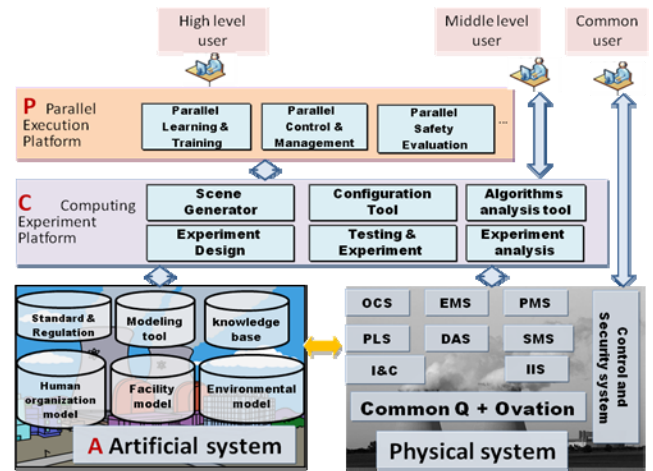


Fig. 5 nuclear power plant's parallel control and management system (PnMS)

### A. Actual system

Take AP1000 nuclear power plant instrument & control system, and protection system as example, which are shown in the right bottom part of figure 5. The actual system means the existing physical systems of nuclear power plant, including OCS (Operation and Control System), DDS (Data Display and Processing System), PMS (Protection and Safety Monitoring System), RTS (Reactor Emergency Trip System), PCS (Power Plant Control System), SMS (Special Monitoring System), DAS (Diverse Actuating System) and IIS (Incore Instrumentation System) and so on, instrument control & system software platform is Common Q, and protection system software platform is Ovation.

The control of nuclear power reactor is executed through the "small" closed-loop, such as instrument & control system, and protection system, which can guarantee the safety and reliability of the reactor. Based on the small closed-loop control, the management of nuclear power plant should add other nuclear power plant management factors, staff factors and environment factors to form a "big" closed-loop control, to adapt for the ever-changing social

and physical environment, assure those targets like security, steady production and environmental protection etc.

Currently, the nuclear power plant's management relies on the strict standards and management systems made with people's experience. Afterwards, "big" closed-loop management is executed still through human beings, there are many inadequacies. For example, (1) Without considering complex social factors, such as people, management and environment, then the precise and real-time "big" closed-loop management can't be realized by informationization means. Therefore, staff false operations can happen easily; (2) Existing system conditions can not conduct those experiments to find and solve many possible problems, like those experiments in abnormal circumstances, potential problems, unpredictable events and so on; (3) Existing nuclear power systems lack scientific analysis and enough research achievements for all types of control methods and emergency management plans.

In fact, the safety and reliability operation control and management of nuclear power plant is a dynamic optimization problem of an intractable multi-constraints, multi-objective complex system. Parallel system method is necessary to assist actual system development, to enhance and ensure the safety and reliability operation of the nuclear power plant [12].

#### *B. Artificial systems*

Modeling of actual system, and its artificial system construction, is the foundation of parallel system. According to the "simple components are consistent" principle, the simple components of nuclear power plant and their interaction are normally consistent. After understanding the basic agreement, fully considering the initiative and randomness of simple component, the nuclear power plant's various factors and components can be modeled with bottom to up method, through comprehensive integration, from the perspective of behavior generation. Such as modeling the instrument & control system, modeling protection system. Modeling methods include agent, complex network and linguistic dynamic and so on.

Afterwards, it can implement interaction between actual system and artificial systems. The first modeling step is focus on nuclear power system structure modeling, under the premise of rational structure, specific parameters can have some deviations. Through learning from actual system, parameters deviation can gradually be reduced or eliminated.

Second step mainly researches how artificial system can learn from actual system, including the offline learning for original data and online learning for real-time data. Artificial system is generated from and trained by actual system; through continuous learning from actual system, artificial system can continuously adjust internal structure and parameter, recursively improve the model accuracy and its effects.

Furthermore, artificial system and actual system can connect to each other through protocol, realizing the virtual and reality interaction, then parallel system can preliminary

be constructed. It must be clarified that there are not only one actual system simulation model, a cluster of artificial models should be established where actual system's model is naturally included.

#### *C. Computing experiments*

After assuring the artificial systems to be equivalent to actual system, thereby various characteristics and behaviors of actual system can be analyzed by using computing simulation and computing experiments on artificial system, to verify all possibilities and assumptions. Here artificial system can be regarded as a controllable and repeatable laboratory, where various experiments can be design to introduce various uncertain factors, even those elements and events which are difficult to quantify by traditional way. Experiments are repeated to collect the statistics results and analyze them, thus traditional simulation is extended to systematic experiment, and quantitative analysis of complex process system becomes a reality. In computing experiments, traditional simulation becomes one test case of computer lab's experiment cases, and become means to produce all kinds of emergency scenes, and actual event is just one of all possible results which can happen in computing experiments [13].

Based on artificial system, by using artificial society thoughts and methods, through computing simulation and avalanche method to easily "grow" various complex phenomena of nuclear power plant, produce and analyze complex system behavior, and then establish computing experiments theory and method, so as to overcome the difficulties to execute experiments of complex nuclear power system, establish a foundation for deeply analyzing the behavior of complex nuclear power system and the effects of effective evaluation decision. Computing experiments of various scenarios and existing problems can be carried out through various types of event-driven system and scene generator, such as climate's, earthquake's influence on the nuclear power plant, potential problems caused by all errors of instrument & control system and protection system, the actual execution of protection system, problems caused by artificial manipulation; At the same time, evaluating and analyzing various solution options, so as to find the best security plan.

#### *D. Parallel execution*

Parallel execution between actual system and artificial system can be realized with computing experiments' results. On the one hand, various results of computing experiments can guide actual system, so as to achieve the optimal goal. On the other hand, actual system's results can feedback to artificial systems for its amendment, so as to achieve the current improvement goals of actual system and artificial system. Different parallel execution systems can be developed in order to achieve different objectives, such as training, evaluation, control, management, optimization, and so on. Parallel systems are commonly used in three ways [14]:

[1]. PnTS (Parallel nuclear Training System) for learning



and training purpose. In PnTS, artificial system is mainly used to train nuclear power plant staffs. Through proper connection combinations of actual system and artificial systems, PnTS can help the staffs quickly become familiar to nuclear power plants' all kinds of status, and the corresponding actions, the related theoretical and technological knowledge. Especially, the efficiency and quality of comprehensive learning & training can be improved by using of the virtual scene environment.

- [2]. PnES (Parallel nuclear Evaluation System) for experiment and evaluation purpose. Firstly, nuclear power plant's complex social factors (environment, management and personnel) is combined with engineering factors (physical equipment, instrument control system and protection system) to form an organic whole. Then, all types of experiments and evaluations can be carried out according to the overall and classified objectives. In this process, artificial system is used to conduct computing experiments, and analyze behavior and reaction of complex system in different circumstances, validate and evaluate the different effects of environmental factors, management system, personnel behavior and production plan solution, provide the basis of selecting and supporting the decision-making of management and control.
- [3]. PnMS (Parallel nuclear Management System) for control and management. In this area, artificial systems try to simulate the actual system as good as possible, predict its evaluation, in order to find an effective solution of actual system or to provide suggestion for the current plan improvement. Furthermore, a new round of optimization and evaluation can be started by observing the different states between actual system and artificial system, producing error feedback signal, amending artificial evaluation methods or parameters. To meet the requirements on nuclear power plant's safety and reliability, PnMS can optimize its control, management and protection, and enhance its emergency management capability.

Development sequence of various parallel systems is decided by the practical requests and the development progress of artificial systems. To assure the safety and reliability of nuclear power plant, PnTS, PnES and PnMS can be recursively developed to meet and improve the functional requirements of instrument & control system, and protection system. Afterwards, this same method can extend to other parts of the nuclear power plant, such as electricity, nuclear island etc. This arrangement is realistic and reasonable.

#### E. Parallel system realization

Take PnMS as an example, its hardware components selects the embedded system with high reliability design, and make it easier to simplify system design and improve its reliability. PnMS software components take reliability as their target, using intelligent total solution based on ACP

method to ensure that all units can complement with each other. PnMS design target: the core task of instrument & control system and protection systems can still be executed well even only one measurement unit, one network unit; one control unit and one execution unit survive [15-16].

## VI. CONCLUSIONS

The combination method of top-down plan and bottom-up design is proposed in this paper. The method brings scientific basis for the safety and reliability of nuclear power plant's design stage, and before its construction stage. Once the method is proven to be valid and applicable, it will promote the localization of automation system and informationization system of third generation nuclear plant, and realize the plant's modular construction and online configuration. And finally become actual systems of various parallel systems with high reliability. Parallel system method has been successfully applied in the petrochemical production field and urban transportation. Once parallel system method is applied to automation and information systems of third generation nuclear power plant, it will further improve the whole system's intelligence and scientific level. This paper describes a bright future, but the proceeding road is tortuous.

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