Development of nuclear power plant real-time engineering simulator

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Abstract A nuclear power plant real-time engineering simulator was developed based on general-purpose thermal-hydraulic system simulation code RELAP5. It mainly consists of three parts: improved thermal-hydraulic system simulation code RELAP5, control and protection system and human-machine interface. A normal transient of CHASHMA nuclear power plant turbine step load change from 100% to 90% of full power, was simulated by the engineering simulator as an application example. This paper presents structure and main features of the engineering simulator, and application results are shown and discussed.

Key words Nuclear power plant, Simulation, Engineering simulator, RELAP5, Safety analysis

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1 Introduction

Nuclear power plant (NPP) engineering simulator is a very powerful tool in the safety analysis, plant design validation, operator training, and for NPP with the nuclear power development, engineering simulator becomes more and more important. Some general-purpose thermal-hydraulic system simulation codes, which enable a more realistic simulation of process systems of NPP, were traditionally just focused on the NPP safety, such as RELAP5, RETRAN, MAAP, MELCOR, etc[1-4]. Now, they are applied as simulation tool to develop visual and realistic engineering simulator due to the enhancement of computer and modeling technology.

An engineering simulator was developed based on RELAP5 code. The transient analysis code for light water reactors, RELAP5, was developed at the Idaho National Engineering Laboratory (INEL) for the U.S. Nuclear Regulatory Commission (NRC). RELAP5 code was used to support rulemaking, licensing assessment, evaluation of accident mitigation strategies, evaluation of operator guidelines and experiment planning analysis. It has been widely used to analyze pressurized water reactors (PWR) in Chinese research institutes for many years. Although RELAP5 is very powerful for the reactor system analysis, some problems need to be solved before it can be used for reactor simulator systems, such as function of real-time calculation, dynamic data communication and the computation process controlling. Besides, RELAP5 cannot completely simulate control and protection systems (CPS) of an NPP in detail. A visual human-machine interface is also needed for an engineering simulator.

This paper focuses on structure and main features of the NPP engineering simulator and simulation results of NPP normal power transients.

2 Development

2.1 Structure

The engineering simulator consists of three main parts, i.e. 1) improved thermal-hydraulic system simulation code RELAP5, 2) CPS and 3) human-machine interface. Structure is shown in Fig.1. Firstly, thermal-hydraulic transient calculations are performed in RELAP5, and then the results, i.e. plant thermal-hydraulic parameters, are transferred to CPS. CPS makes correct response to these parameters by the

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automatic control and protection logics, and then transfers the display parameters to human-machine interface. If any manual operation is done in the interface, it will return to CPS. After combining the manual control with the automatic control, the ultimate control instructions are sent back to thermal-hydraulic simulation code, and process system, i.e. RELAP5, will respond accordingly. During these courses, data are communicated among these parts via a shared database.

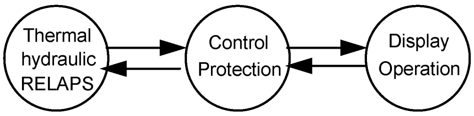

Fig.1 Structure of the engineering simulator.

2.2 Thermal-hydraulic simulation code

Thermal-hydraulic simulation code RELAP5 is the base of the engineering simulator. Main components of the primary and secondary system in a NPP are modeled by RELAP5 code. As an example, RELAP5 model of CHASHMA PWR was shown in Fig.2[5]. The primary system is a closed system, and the secondary system is an open one. Feedwater inlet and steam outlet are the main boundaries.

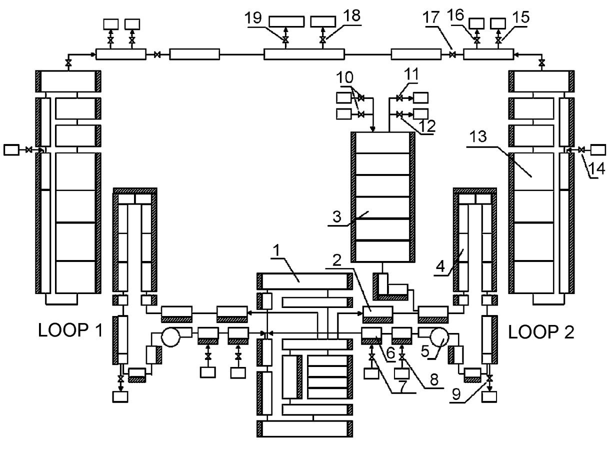

Fig.2 RELAP5 CHASHMA PWR model nodalization scheme.
1. Reactor vessel; 2. Hot leg; 3. PRZ; 4. U tube; 5. Reactor coolant pump; 6. Cold leg; 7. Charging flow inlet; 8. Safety injection flow outlet; 9. Letdown flow outlet; 10. PRZ spray valve; 11. PRZ relief valve; 12. PRZ safety valve; 13. SG; 14. SGFW inlet; 15. Steam atmospheric relief valve; 16. Steam safety valve; 17. Steam line isolation valve; 18. Steam dump valve; 19. Main steam governor and throttle valve.

The original RELAP5 code is improved in the following three aspects to meet the requirements for engineering simulator.

2.2.1 Real-time simulation function

Real-time operation is a basic requirement for a simulator, but original RELAP5 does not have the capability of performing real-time calculation. The time cost in RELAP5 calculation is always shorter than the physical time of the problem solved by RELAP5 code. Based on this fact, in every time step, computer keeps waiting during redundant time period until the real time is equal to the physical time. Thus, the real-time computation is achieved.

2.2.2 Dynamic data communication function

In engineering simulator, thermal-hydraulic parameters presenting the transient process of an NPP need to be outputted dynamically from the RELAP5, and some parameters have to be inputted and modified dynamically by commands. However, both input data and output data of original RELAP5 are arranged in an off-line format, which cannot be easily transferred to other programs. Therefore, the I/O processing functions of RELAP5 were improved to realize a dynamic data communication.

2.2.3 Simulation process control function

In original RELAP5, once it enters into the calculation cycle, user is unable to control the progress, and has to wait until the program terminates by itself as it is a batch operation mode. Therefore, it does not fully meet the requirements for working as a thermal-hydraulic calculation code in an engineering simulator. In improved RELAP5, the code can accept and execute commands from the user in every calculation cycle, which includes: 1) keeping running; 2) resetting the simulation process; 3) freezing the simulation process; 4) snapshoting current results; 5) terminating the simulation process. Thus, the simulation process can be freely controlled.

2.3 Control and protection system

For an engineering simulator, it is not enough to simulate NPP's main transients only with thermal-hydraulic calculation code. A CPS is also necessary. Because RELAP5 code cannot completely simulate an NPP CPS in detail, an independent CPS has been developed.

Main control systems simulated include pressurizer pressure control, pressurizer liquid level control, steam generator feed water control, reactor power control, and steam dump control. Protection systems simulated include 21 reactor trip signals, 2 turbine trip signals, 5 safety injection signals, 10 permissive (P) signals, 14 interlock (C) signals, 6 main feedwater isolation signals, 5 steam isolation signals, and 3 auxiliary feedwater startup signals. The relevant logic calculation elements include “OR”, “AND”, “NOT”, 2/4 voting logic, 2/3 voting logic, “PID”, delay circuit, high/low setpoint, etc[6].

2.4 Human-machine interface

Human-machine interface simulates the display and operation in NPP main control room. It provides graphical simulation information and operation platform to users. Diagrams, figures and curves are the main display mode, while text and sound are also used. There are about 30 frames, including system flow charts, trend curves figures, simulation sketch maps, instrument dial, etc. There are three major concerns in the human-machine interface design. The first is large screen display and the system flow chart design. Large screen display must only include necessary and important information, such as nuclear power, electric power, reactor trip information, etc., as shown in Fig.3. The system flow charts are arranged according to the simplified system just including some components and its information. The second is parameter display and alarm display. Parameter is represented by text or curve mode. Alarm is displayed by text, color and sound mode. The third is interface program expansion. C++ is selected as main basic programming language. Layout of the interface can be modified for different purposes, such as operator training, safety analysis, etc. Because of graphical display and operation, engineering simulator becomes more visual, realistic, and user-friendly.

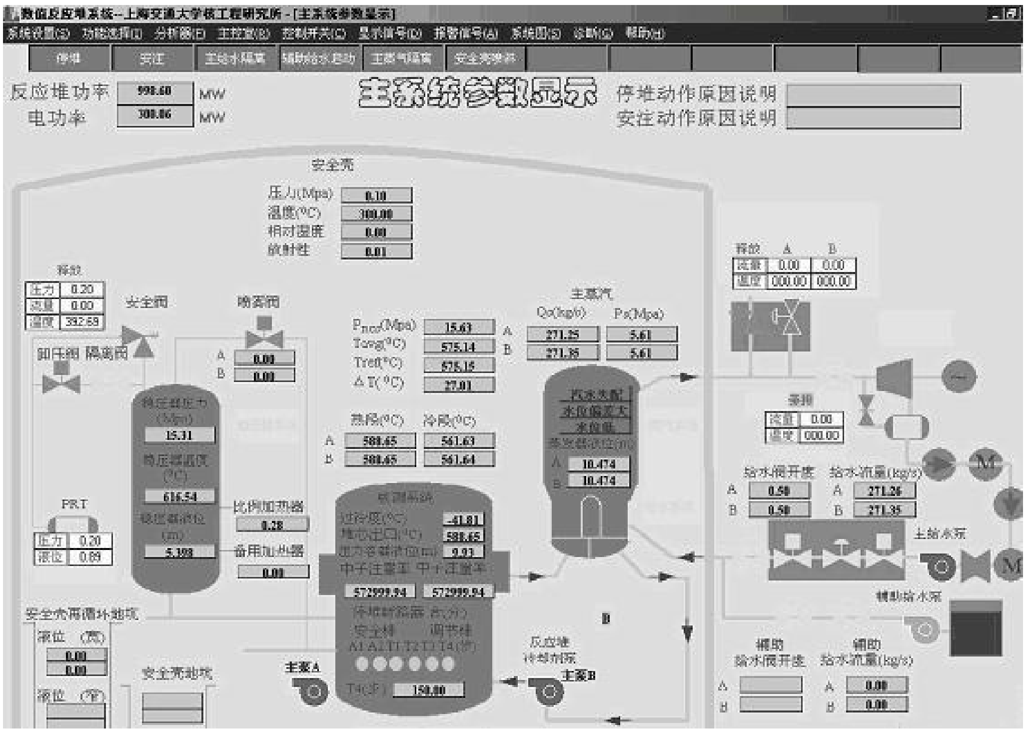

Fig.3 Large screen display of human-machine interface.

3 Application

About 200 experiments of CHASHMA PWR were performed, including normal and accident transients. As an example, the engineering simulator is applied to simulate a normal transient, turbine step load change from 100% to 90% of full power.

At the time of 0s, the NPP runs steadily at 100% power level, and the PRZ pressure is 15.3MPa, TAVG is 575.15K, SG water level is 10.474m. This steady state is broken at the time of 100s due to user’s operation in human-machine interface to make turbine step load change from 100% to 90% of full power. Under the function of CPS, until the time of 1100s, the NPP changes to run steadily at 90% power level. The PRZ pressure and SG water level maintain original value, and TAVG changes to be 573.65K. The results of turbine step load change transient are shown in Fig.4.

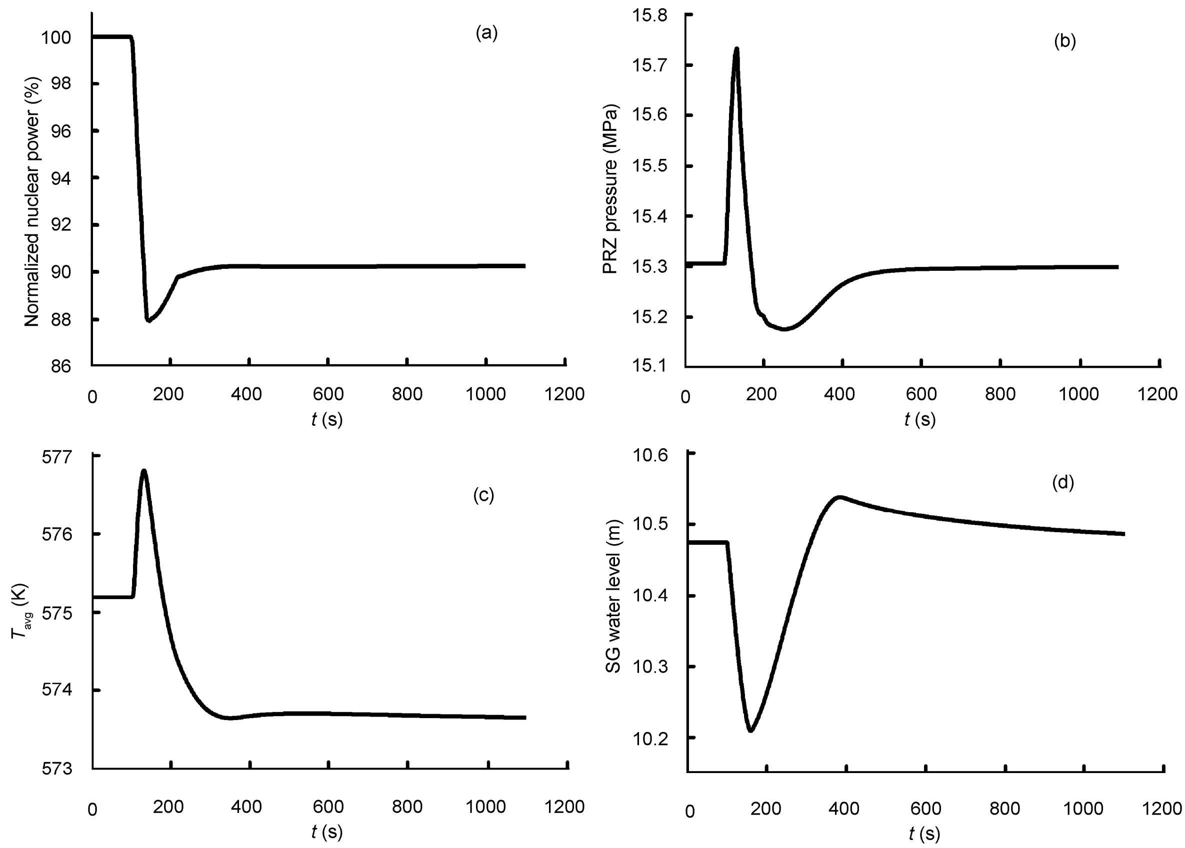

Fig.4 Results of turbine step load change from 100% to 90% of full power transient: (a) Normalized nuclear power; (b) Pressurizer pressure; (c) Average temperature of the primary system; (d) Steam generator water level.

4 Conclusions

A NPP real-time engineering simulator was developed based on general-purpose thermal-hydraulic code RELAP5. The original RELAP5 code was improved in three aspects to meet the requirements for simulator: function of real-time calculation, dynamic data communication and computation process controlling. RELAP5 can ensure accuracy of the thermal-hydraulic calculation. CPS was independently developed in detail to enable the engineering simulator be capable of simulating NPP’s main transients. Graphical human-machine interface provides a visual, realistic, and user-friendly work environment. Many experiments of CHASHMA PWR were performed, and the results showed that the real-time engineering simulator is a very powerful tool in NPP transient simulating, safety analysis, plant design validation, operator training, etc.

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