Design of Test Platform for Thorium-based Molten Salt Reactor Protection System

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Abstract. This paper summarizes the characteristics and test requirements of the thorium-based molten salt reactor protection system, and proposes a test platform design for the fourth-generation thorium-based molten salt reactor (TMSR) protection system. It mainly includes system design, hardware selection, software design and system interface. Based on the Producer-Consumer software architecture built by virtual instrument technology, the test platform uses the NI PXI hardware platform to realize channel testing, functional testing, online debugging and other functions. This design can fully test and verify the protection system without the process system, and can be extended to test other reactor-type protection systems or monitoring systems.

1. Introduction

The thorium-based molten salt reactor (TMSR) nuclear energy system is a fourth-generation nuclear energy system. It is a high-temperature reactor that uses fluoride salt as a coolant and works at atmospheric pressure. Compared with general pressurized water reactors, thorium-based molten salt reactors have inherent safety. However, through the analysis of major nuclear reactor safety accidents that have occurred in the past few decades, the safety of thorium-based molten salt reactors is still a major issue that must be considered[1]. Thorium-based molten salt reactors need a safe, stable and reliable protection system to improve safety.

2. Introduction to the protection system

During the startup and operation of the reactor, the purpose of the protection system is to ensure that the reactor’s three safety barriers (fuel element cladding, primary circuit pressure boundary, and containment) are intact, limit the reactor’s operation within the allowable range or mitigate the consequences of the accident, and protect the reactor, Environment, and personnel safety[2]. Therefore, the function of the protection system can be summarized as: the protection system monitors the operating status of the reactor in real time through a series of sensors. If an abnormal state exceeding the limit occurs during operation, the protection system can immediately and automatically generate corresponding protection signals, Trigger shutdown and start related safety special facilities to minimize the consequences of the accident.

In general, the protection system should meet the following requirements:
1) The system's mean time between failures T≥10^6h;
2) The average recovery time of all functions of the system TB≤1h;
3) The probability that the system will not act due to random failures should be less than 10^-5.
3. Test platform requirements
The TMSR protection system implements emergency rod drop and safety-specific drive when the protection variable exceeds the limit. At the same time, it executes the post-accident monitoring function to monitor and record the relevant design variables, and is designed to realize the online maintenance function of the protection system hardware[3]. It is planned to realize all reactor protection system functions, including emergency reactor shutdown function, post-accident monitoring function, maintenance and testing function, and other support functions such as interface with non-safety level systems. Although the new generation of digital protection system can make use of its powerful self-diagnosis performance to ensure its function is intact, according to the requirements of nuclear regulations, the protection system is a safety level 1E system[4]. In addition to self-diagnosis, the channel accuracy and logic of the system are required. Factory testing of functions, response time, etc. And it is necessary to adopt hardware different from the protection system to avoid common cause failures to improve the validity of verification.

4. Test platform system design
The overall system design includes hardware equipment selection, system construction, automatic test software development, and system interface design. The system hardware is based on modular products of the PXI platform, and the software is designed based on the producer-consumer architecture of LabVIEW. The system interface is mainly RS422/485 and optical fiber.

![Conceptual design of test platform](image)

The test platform adopts a modular layout and a customized signal adapter box to redistribute signals, which improves the integration, miniaturization and portability of the entire platform, and facilitates on-site debugging.

5. Hardware selection
The hardware includes an 18U cabinet, a PXI chassis and its internal corresponding cards, signal simulation card and acquisition card, UPS uninterruptible power supply. At the same time, the device also includes a VPC connection kit for the simulated signal to be transmitted to the interface adapter device, and other appropriately matched air switches, wiring terminals, wires and other accessories. The main hardware list is as follows:

| Serial number | Hardware name                        | Specification model |
|----------------|--------------------------------------|---------------------|
| 1              | Cabinet                              | customization       |
| 2              | Industrial control chassis            | PXIe-1075           |
| Serial number | Hardware name                      | Specification model        |
|---------------|-----------------------------------|----------------------------|
| 3             | Controller                        | PXIe-8135                  |
| 4             | Circuit board card                | PXI-6704                   |
| 5             | Circuit board card                | PXI-2569                   |
| 6             | Circuit board card                | PXI-6289                   |
| 7             | Circuit board card                | PXI-6511                   |
| 8             | Uninterruptible power supply      | APC smart-ups 1000         |
| 9             | High-speed serial port card       | customization              |
| 10            | Photoelectric converter customization | customization          |

6. Design of system interface

6.1. Hardware interface:
The PXI signal chassis is connected to the signal adapter box through the D-Sub connectors, and the other side of the signal adapter box is connected to the Harting connector. The signal is classified and re-layouted through the signal adapter box. Secondary distribution and sorting.

![Figure 2. Conceptual design of signal adapter box](image)

6.2. Communication Interface:
In order to meet the requirements of the single failure criterion, the communication module adopts a dual-redundant design in combination with the safety features and operational objectives of the TMSR reactor, which can simulate the communication between dual sequences and achieve the "two out of one" test of the TMSR reactor logic.

Serial communication card is suitable for PXI bus platform, each channel supports RS422/485 protocol. The serial port card supports 16 channels of transceiver functions, and the baud rate can reach 5Mbps. The baud rate, data bit length, stop bit, parity bit, received data frame header, etc. can be set by software\[5\]. The serial port card is converted into a 5Mbps optical signal through a photoelectric converter and connected to the protection system.

7. Software design
The software is developed using NI's LabVIEW software development platform. The software design architecture is the Producer-Consumer automatic test architecture based on the multithreading technology\[6\], and the upper computer software modules are designed according to different software requirements, and the hierarchical management method is adopted to achieve the functional requirements of high efficiency and high stability of the system software. The system software includes the main control program, TXD thread, DAQ thread, COM thread, and exception handling.
thread to jointly realize system management, signal excitation, data acquisition, and communication processing. Different processes use queue communication to transfer commands and data.

1) The main control program, Main main thread, mainly provides user account management, operation menus, buttons, signal table loading, test procedure import, instruction issued to child threads, execution status and result display;

2) The hardware management module includes TXD thread and DAQ thread. TXD calls PXI-6704/PXI-6612 and other cards to perform analog and digital signal excitation, and DAQ thread calls PXI-6289 to realize analog output and digital output. Collection function, each thread runs independently, executes different test functions separately, commands and configuration data interact in a queue;

3) The communication management module, including the COM thread, is mainly responsible for the sending and receiving of communication data. The sending function is based on the configuration signal table and is translated into the HEX data format required by the RS422/485 protocol and sent to the protection system. The receiving function receives the serial port data sent by the protection system, parses the HEX data into engineering quantities and sends it to the main program.

4) Exception handling process, monitor the error flow between different programs, record the error code for minor errors, and clear the error content to ensure the normal progress of the program; provide pop-up prompts for moderate and severe errors, and confirm to continue or interrupt the program execution.

The test interface design supports automatic test buttons, which can support full and single step, custom step testing. The test injection page, the output page and the response time pages, using custom X-control, achieve free conversion of the interface, support reactor shutdown, after accidents monitoring functions, maintenance and testing functions, and recording the injection and output results throughout the process.

The test interface can display whether the test conclusion is PASS or fail, and can record the details of the error.
8. Concluding remarks

The thorium-based molten salt reactor protection system test platform simulates the steady-state working conditions and possible transient working conditions of the protection system through the design of automatic test software and test cases, using the producer-consumer model plus modular programming software[7]. The architecture ensures the scalability of the system, and the multi-threaded queue communication mode ensures the concurrent characteristics of the test and the ability of sequential logic simulation, which can meet the functions of factory testing and on-site debugging. The graphical and friendly human-computer interaction interface is convenient for the operator to perform test cases editing, user management, hardware configuration, database query and other functions. Through certain design test cases, it can also meet the periodic test requirements of the protection system.

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