CONTROL SYSTEMS FOR SPALLATION TARGET IN CHINA INITIATIVE ACCELERATOR DRIVEN SYSTEM*

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Abstract

In this paper, we report the design of the control system for the spallation target in China initiative accelerator driven sub-critical (ADS) system, where a heavy-metal target located vertically at the centre of a sub-critical reactor core is bombarded vertically by the high-energy protons from an accelerator. The main functions of the control system for the target are to monitor and control thermal hydraulic, neutron flux, and accelerator-target interface. The first function is to control the components in the primary and secondary loops, such as pumps, heat exchangers, valves, sensors, etc. For the commissioning measurements of the accelerator, the second function is to monitor the neutrons from the spallation target. The three-layer architecture has been used in the control system. In the middle network layer, in order to increase the network reliability, the redundant Ethernet based on Ethernet ring protection protocol has been considered. In the bottom equipment layer, the equipment controls for the above-mentioned functions have been designed. Finally, because the main objective of the target is to integrate the accelerator and the reactor into one system, the integration of accelerator's control system and the reactor's instrumentation and controls into the target's control system has been mentioned.

INTRODUCTION

Driven by the national demand for safe disposal of nuclear waste as well as the potentials for advanced power generation, the Chinese Academy of Sciences initiated an accelerator driven sub-critical (ADS) program in 2011 under the frame of "Strategic Priority Research Program". The ultimate goal of the China ADS program is to build an industrial demo facility for ADS technology. In the China ADS system, a heavy metal spallation target located at the centre of a sub-critical core is bombarded by the high-energy protons from an accelerator. An overall control system is required to exactly couple the high-energy beam from the accelerator to the spallation target in the reactor core, by controlling and coordinating three facilities, i.e. an accelerator, a spallation target and a reactor.

In this paper, we report the design of control system for the spallation target. When designing this control system, the following two objectives have to meet. The first objective is to control the demo facility of spallation target during the commissioning of the target without proton beam. The commissioning without beam may be performed either within the reactor core or outside the core. The second objective is to control the spallation target as a part of the China ADS system, when three facilities, the accelerator, the spallation target and the reactor, have been integrated into one system. Therefore, the same architecture as the overall control system should be used in the control system for the spallation target.

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ARCHITECTURE OF CONTROL SYSTEM

The spallation target used in the China ADS system includes several sub-systems. According to the locations of the devices, the subsystems can be classified as the target core subsystem, the primary cooling loop, the secondary cooling loop, the target window and its cooling loop, fill and drain subsystem, cover gas subsystem, and other auxiliary subsystems. The control system for the spallation target controls and coordinates these subsystems during startup, ascent to power, power operation, and shutdown conditions of China ADS system. The control system provides automatic as well as manual controls, monitoring and diagnostics capabilities for these subsystems. Furthermore, since the spallation target is a critical part of the ADS system, its control system should be able to be integrated into the overall control system for the China ADS system.

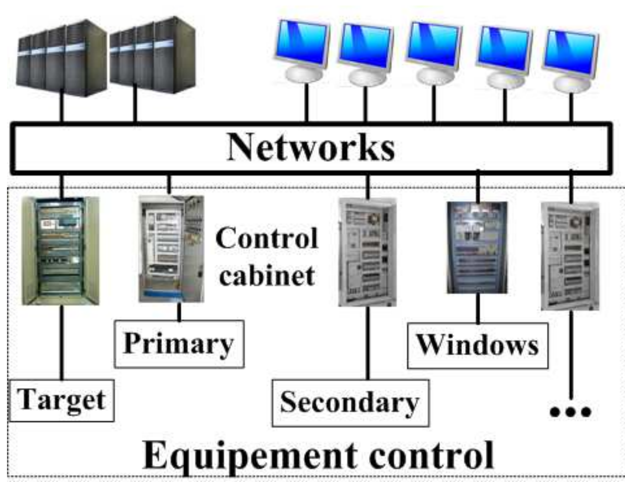

Figure 1: The three-layer architecture of the control system for the spallation target. The legends target, primary, secondary, and window represent the devices for these subsystems.

As shown in Fig. 1, the three-layer architecture is used in the control system, i.e. the top operation layer for the

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human machine interface, the middle network layer for the data communication and the bottom equipment layer for the devices in each subsystem. In the bottom layer, the legends target, primary, secondary, and window represent the devices for the target core subsystem, the primary cooling loop, the secondary cooling loop, the target window and its cooling loop, respectively. The control system provides control support for all phases of each subsystem's life-cycle, including commissioning and operation.

It is noteworthy to mention that there are an overall control system and several local control systems in the China ADS system. The main functions of these local control systems are to control the auxiliary subsystems for the accelerators, the target and the reactor. For example, the following operations can be controlled in the local control system, such as the maintenance of the target, the handling and storage of the coolants in each cooling loop, and so on.

NETWORKS IN THE MIDDLE LAYER

A communication network is the backbone of the networked control systems. Six networks have been suggested to use in the overall control systems for the China ADS facility [1]. Among these six networks, three networks are required in the control systems for the spallation target, i.e. a central operation network, a personnel protection network, and a data archiving network. In the central operation network and personnel protection network, network reliability is the critical issue while choosing the communication type. The redundant Ethernet based on Ethernet ring protection (ERP) protocol has been considered for the central operation network [1].

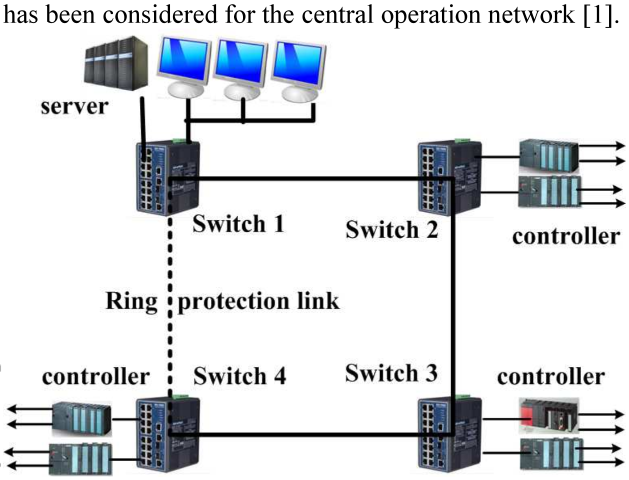

Figure 2: Redundant Ethernet used in the control network for the spallation target. The four switches are equipped with Ethernet ring protection protocol, with which users can establish a redundant Ethernet network with ultra high-speed recovery time.

The ERP protocol, defined in ITU-T G.8032 [2], builds a logical ring topology while maintaining a loop-free forwarding mechanism by logically blocking a link port in the ring, referred to as ring protection link (RPL). Figure 2 shows the redundant Ethernet based on Ethernet ring protection protocol for the spallation target. Although multiple rings may be used in the central operation network for the China ADS facility, only one ring is considered for the spallation target.

The four industrial switches in Figure 2, named as switch EKI-7657C, come from Advantech company (http://www.advantech.com/). The EKI-7657C supports seven Fast Ethernet ports and three Gigabit combo ports with 2x Digital Input and Digital Output ports. To create reliability in the network, the EKI-7657C is equipped with a proprietary redundant network protocol, which provides users with an easy way to establish a redundant Ethernet network with ultra high-speed recovery time.

Based on the report in the user manual of switch EKI-7657C, the redundant Ethernet in Figure 2 can recover from network connection failure within 10ms or less and make the network system more reliable. The algorithm in the redundant Ethernet is similar to spanning tree protocol (STP) and Rapid STP (RSTP) algorithm but its recovery time is less than STP/RSTP algorithm. The ring protection protocol maintains a loop-free forwarding mechanism by logically blocking a link port in the ring, referred to as ring protection link (RPL) in the ERP protocol or X-ring backup path in the user manual of switch EKI-7657C. As shown in Fig. 2, the leftmost link from switch 1 to switch 4 is blocked as a ring protection link. Once a link fails, the vertices adjacent to the failure block the failed link, and the backup path is unblocked. For example, if the link from switch 2 to switch 3 fails, the switches 2 and 3 block the failed link, and the ring protection link from switch 1 to switch 4 is unblocked. Then, the protocol recovers the failed link from switch 2 to switch 3 within 10 ms or less.

EQUIPMENT CONTROL IN THE BOTTOM LAYER

The main function of the equipment layer is to control the devices in the above-mentioned subsystems. In this section, we discuss two main parts of I&C (the instrumentation and controls) used in the equipment layer, i.e. I&C for monitoring the spallation neutrons from the target and I&C for the cooling loops.

I&C for Neutron Monitoring

I&C for the target core subsystem provide both neutron and temperature monitoring for the target. In the China ADS system, a solid tungsten target based on a granular flow method is used. The temperature monitoring for the target core can be done by attaching some thermocouples on the target container. The temperature monitoring method with a thermocouple will be discussed in the next subsection.

The monitoring for the neutron flux level of the spallation target can be done by detecting leakage neutrons from the target core. Since the target is located vertically at the centre of the reactor core, the neutron

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detectors (e.g. fission chambers) should be put within the reactor core. As discussed in [3], the spallation neutron flux should be measured at multiple vertical locations, because the neutron flux at the central location is more than two orders of magnitude higher than the flux at the lower locations. The multi-point measurement of the spallation neutrons can be performed either by several fixed detectors at the fixed locations or by a movable detector.

When using a movable detection system, the drive system for the insertion and withdrawal of the movable detectors is similar to the incore neutron monitoring system used in the pressurized water reactor. It consists of drive units, limit switch assemblies, rotary transfer devices, and isolation valves. Each neutron detector is attached to a flexible drive cable in the drive units that can be driven into selected core locations by the operating staff.

I&C for Cooling Loops

I&C for three cooling loops, the primary cooling loop, the secondary cooling loop and the cooling loop for the target window, are similar to the I&C in the cooling loops for a reactor. Currently, the analogue I&C systems are used in the reactors of most nuclear power plants. In order to successfully integrate three systems, an accelerator, a target and a reactor, into an entity, digital I&C technology has to be used in the equipment layer for the target. In this subsection, as an example, we study digital I&C technology for the temperature control of several cooling loops.

A temperature control system comprises one or multiple temperature sensors and one or multiple temperature controllers. Two types of temperature sensors, the thermocouple and the resistance temperature detectors (RTD), are used commonly in the temperature control system. The temperature controller applies a dynamic analysis to a plurality of measured temperature parameters, and then, to generate a set of control values by considering the temperature ranges. For different cooling loops, e.g. the primary or secondary cooling loop, the models for the dynamic analysis are different. Finally, the switch-on or switch-off of the valves, the flow speed of the coolants, and the operation of the pumps in the cooling loops are driven by the temperature controllers.

Figure 3 shows the three-layer architecture of a temperature control system. In the middle network layer, several switches EKI-7657C have been used. In the bottom equipment layer, the following products from National Instruments (NI) company are used. PXIe-4353 32-channel thermocouple input module and TB-4353 front mounting and isothermal terminal block are used for the temperature measurement with a thermocouple, while PXIe-4357 RTD input module and TB-4357 terminal block accessory are used for RTD. For the measurement of flow speed and the control of valves, a multifunction data acquisition (DAQ) board PXI-6238 is used. The PXI-6238 can be used to read from encoders, flow meters, and proximity sensors as well as control valves, pumps, and relays; and connect up to other common 20 mA sensors. The green device in Figure 3 is a screw terminal connector for the PXI-6238.

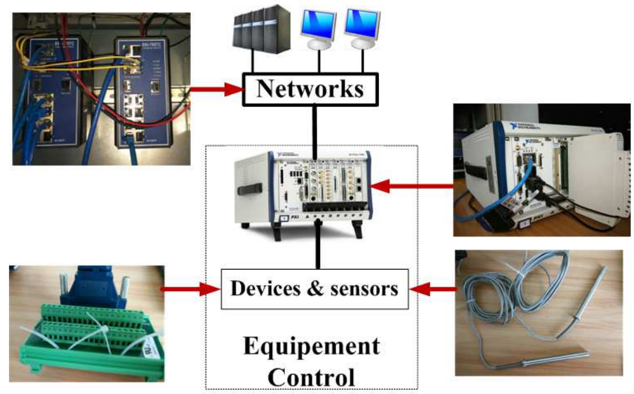

Figure 3: The three-layer architecture of a temperature control system used in the cooling loops. It can be used for the measurement of temperature and flow speed, as well as the controls of valves and pumps.

The temperature control system in Figure 3 is managed with EPICS (experimental physics and industrial control system) software [4]. The control system studio (CSS) is used as a user interface framework for the control systems. Figure 4 shows the temperature values measured with two thermocouples. During the measurement, a thermocouple was put in the room temperature, while the other was put in the water. The red line in Figure 4 shows the water temperature when the water was heated from 20°C to 60°C.

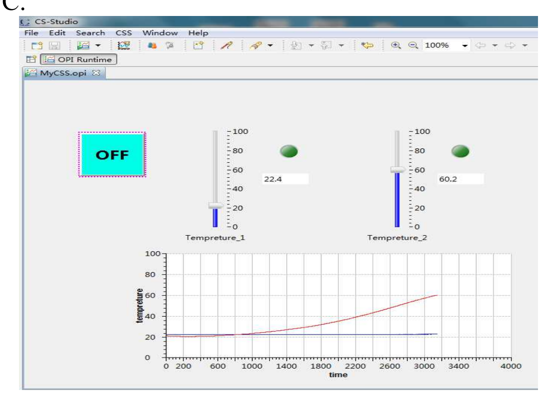

Figure 4: The temperature measurement displayed in the control system studio. Temperatures 1 and 2 represent the values measured with two thermocouples.

Robust Electronics for Equipment Controls

In the China ADS system, the spallation target is located at the centre of a sub-critical reactor core and the control electronics in the equipment control layer for the spallation target has to be put in the reactor room. As shown in Figure 3, the 8-Slot 3U PXI express chassis, PXIe-1082, is used in the equipment control layer. The Intel Core i7 Processor with the lithography of 22 *nm* is used in the control chassis. To be used in the field, a compact control chassis, such as cRIO-9033, can be used

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to reduce the space occupied by the controller. cRIO-9033 includes a Kintex-7 FPGA device produced by Xilinx company.

An important issue for the application of these advanced semiconductor devices, including RIO-1082 and cRIO-9033, in the radiation environment of the ADS reactor room is how to mitigate the radiation effects caused by nuclear radiation exposure. In the China ADS system which will demonstrate the ADS concept at 10 MW power level with the maximum incore neutron flux of 2×10^{14} *neutron* $/cm^2/s$, the total excore neutron flux in the reactor room is estimated to be 10^7 *neutron*$/cm^2/s$. Our researches in [5] have indicated that these advanced semiconductor devices can be used in the reactor room after being shielded with the thick polyethylene material, where the thickness of the polyethylene should be several dozen centimeters.

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INTEGRATION OF ACCELERATOR CONTROL SYSTEM AND REACTOR I&C

As a critical part of the China ADS system, the spallation target is used to integrate two totally different facilities, an accelerator and a reactor, into one system. When designing the control system for the target, we have to consider the difference between the accelerator's control system and the reactor's I&C. The following are two examples.

Control Software

The EPICS control system framework, running on a Linux operating system, has been used for the control software in the two accelerator injectors of the China ADS system. Furthermore, EPICS will also be used in the main accelerator of the China ADS system. An open question is whether EPICS control system framework can be used in the reactor. Are the modules used in the reactor's I&C compatible with EPICS? If two sets of software have to be used for the accelerator and the reactor, which one will be used in the overall control system of the China ADS system?

Naming Convention

The naming convention used in the accelerator of the Chinas ADS system is based on a standard developed for the Superconducting Super Collider in the U.S. in the 1980s, and later adopted by other large research facilities, including SNS, FRIB, ITER, CEBAF, and ESS (e.g. [6]-[7]). The format of the naming convention is:

SSSS-BBBB:DDDD-III:TTTIIIXXX

where SSSS is the system name, BBBB is the subsystem name, DDDD is the device identifier, III is the device qualifier, and TTTIIIXXX is the signal part of the name with type (TTT), instance (III) and suffix (XXX).

On the other hand, other naming conventions have been used in a reactor or a power plant, such as CCC (common core code) in England, EDF code proposed by Electricite De France, EIIS (energy industrial identification system) in USA, ERDS (European reliability data system) in European, and KKS (Kraftwerk Kennzeichen system) code in Germany. If two sets of naming conventions have to be used for the accelerator and the reactor, the same naming convention as in the reactor will be used in the spallation target, because the target is located in the center of the reactor core and the cooling loops for the target are put in the reactor room.

CONCLUSION

For the first time, we have reported the design of control system for the spallation target used in an ADS system. The three-layer architecture has been used in the control system, i.e. the top operation layer, the middle network layer and the bottom equipment layer. In the subsystems for the target, such as the target core subsystem, the primary and secondary cooling loops, and the target window and its cooling loop, the main functions of the control system are to monitor and control thermal hydraulic. Therefore, the instrumentation and controls (I&C) for the cooling loops, including the temperature control system, have been discussed in detail. Finally, we discuss the issues about the control software and naming conventions used in the two totally different facilities, the accelerator and the reactor.

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