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Novel design of a personnel safety system for Hefei Light Source-II

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Abstract The Hefei Light Source-II (HLS-II) is a vacuum ultraviolet synchrotron light source. The personnel safety system (PSS), which is a personnel access control system, is a crucial part of the HLS-II, as it protects the staff and users at HLS-II from radiation damages. The prior version of HLS-II PSS was based on an access control system called SiPass. This lacked the personnel management function. Meanwhile, as the prior PSS is a turn-key system, it was not effective for sharing information. To overcome these drawbacks, the novel design of PSS for HLS-II is proposed based on the Siemens redundant programmable logic controller under the Experimental Physics and Industrial Control System. The proposed PSS consists of a safety interlock system, access control system, and a radiation monitoring system. The safety interlock system is used to define the interlock logic. The access control system is designed to restrict the access of staff and users at HLS-II, and to provide a personnel management function. The radiation monitoring system is used to monitor the radiation dose rate in both the light source and the surrounding areas. This paper details the architecture and the specific design of the novel PSS. The off-line test results demonstrate that the proposed system has achieved the design objectives.

Keywords Personnel safety system · Personnel management · Redundant programmable logic controller · PROFINET · Experimental Physics and Industrial Control System

1 Introduction

The Hefei Light Source-II (HLS-II) is a dedicated synchrotron radiation facility, which can emit radiation from the infrared to the vacuum ultraviolet in both top-off and decay operation modes. It is composed of an 800 MeV linac, 800 MeV storage ring, and a transport line connecting the linac and storage ring [1].

The personnel safety system (PSS) is a crucial part of the HLS-II. It is used to protect the staff and users at HLS-II from radiation damage. The SiPass system is a TCP/IP-based distributed access control system developed by the Siemens Building Technologies Company [2]. It was adopted to process the interlock signals in the prior version of HLS-II PSS. However, this HLS-II PSS could not provide a personnel management function, and it was ineffective for sharing information. To overcome these drawbacks, a novel PSS was designed for the HLS-II in 2017.

The programmable logic controller (PLC) and redundant technology are widely used in the design of the PSS at large scientific facilities to fulfill the requirements relating to high reliability and stability. These facilities include the Japan Proton Accelerator Research Complex [3], European Spallation Source [4], CERN with the Super Proton Synchrotron (SPS) and Large Hadron Collider [5], Stanford Linear Accelerator Center with the radiation safety systems

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[6], and the Institute of Nuclear Energy Safety Technology with the high intensity D-T fusion neutron generator [7].

To fulfill the requirements of the China National Standard GB18871-2002 (international basic standards for protection against ionizing radiation and for the safety of radiation sources) [8], the main design principles of the proposed HLS-II PSS are defined as follows: (1) The system needs to be hardware based; (2) it needs to adopt a failure-safety and redundant design; and (3) it must be based on classified protection. The novel HLS-II PSS is designed based on the Siemens redundant PLC S7-412-5H under the Experimental Physics and Industrial Control System (EPICS). EPICS is a set of open-source software tools, libraries, and applications that are widely used in large scientific facilities [9–12]. The novel HLS-II PSS comprises three parts: a safety interlock system, access control system, and a radiation monitoring system. The safety interlock system is used to define the interlock logic to be implemented. The access control system is designed to restrict the access of staff and users at HLS-II, and to provide a personnel management function. The radiation monitoring system is used to monitor the dose rate in the light source and the surrounding areas.

In this paper, Sect. 2 introduces the system architecture of the novel HLS-II PSS and Sect. 3 provides the details about the design of the safety interlock system and the personnel management function in the access control system. Section 4 demonstrates the design of the operator interfaces (OPIs) and the off-line performance tests of the novel HLS-II PSS, and Sect. 5 describes the development of the PLC programs and EPICS driver.

2 System architecture

The proposed HLS-II PSS ensures personal safety by monitoring the radiation dose rate, controlling interlock signals, and executing the interlock actions. We integrated the safety interlock system, access control system, and the radiation monitoring system under the EPICS environment to enable information sharing. Meanwhile, we used the existing data archiver and alarm toolkits provided by the EPICS community to archive the historical data and publish the alarm information [13]. The system architecture of the novel HLS-II PSS consists of three layers: the EPICS layer, controller layer, and the devices layer, as shown in Fig. 1.

The EPICS layer comprises the EPICS input/output controllers (IOCs) and the OPIs. The novel HLS-II PSS consists of two IOCs, out of which the first one was responsible for monitoring and analyzing the real-time data of the safety interlock system and access control system using the PLC. The data of the radiation monitoring system

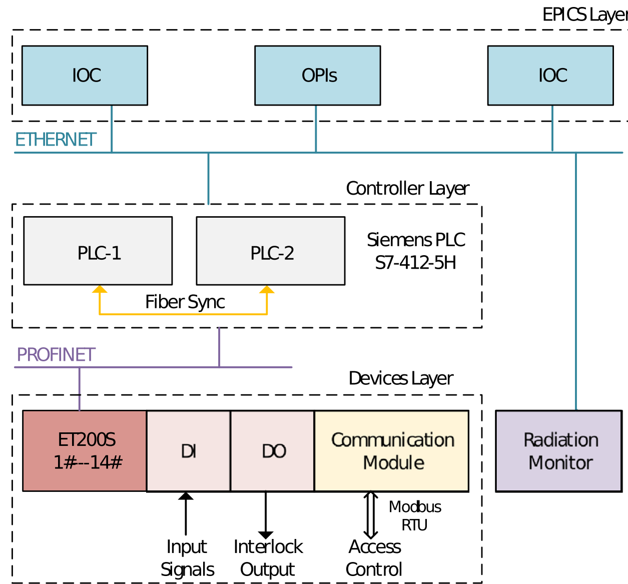

Fig. 1 System architecture of the novel HLS-II PSS

were transmitted into the second IOC. In the EPICS environment, the first IOC could retrieve the radiation monitoring data from the second IOC conveniently. The operation commands and radiation monitoring data were downloaded to the PLC. The interfaces were developed by Phoebus/Display Builder and executed on the OPIs. Phoebus is an update of the Control System Studio toolset that employs generic tools and technologies available as part of the JAVA ecosystem [14].

The controller layer included only one pair of the Siemens redundant PLC S7-412-5H. The PLC could gather the IO signals and access data from a total of 14 IO stations (using fiber optic cables), and receive the radiation monitoring signals and commands from the EPICS layer. The redundant PLC pair included two high-performance PLCs that backed up each other. One of them performed the function of the MASTER PLC, while the other one acted as the SLAVE PLC. During the operation, these two PLCs synchronized the programs and the real-time data over a high-speed fiber, and their roles could be switched whenever the MASTER PLC failed. As the design principle requires the system to be hardware based, all the interlock logic and access algorithms were processed in the PLC.

In the devices layer, 14 Siemens ET200S IO stations were distributed adjacent to the 14 security doors. The input signals of the search buttons, emergency buttons, and the security doors were collected into the IO stations through the digital input (DI) modules. The signals of the audible and visual alarm devices, button lamps, and the interlock actions were output through the digital output (DO) modules. In addition, the data of the card reader were transmitted into the IO station via the Modbus-RTU protocol.

According to the design, 134 input signals were monitored, including 41 for search buttons, 25 for emergency stop buttons, 42 for security doors, and 26 for radiation monitoring purposes. All the signals (except for radiation monitoring) were transmitted from the IO stations. The communication between the PLC and IO stations was enabled using the PROFINET real-time protocol, and the communication cycle time was defined as 2 ms. PROFINET is the standard for industrial networking with respect to automation in data communication, and it is widely used in accelerator control systems [4, 15, 16]. The communication between the IOC and PLC was enabled using ETHERNET with a communication cycle time of 100 ms. The radiation monitoring signal was used to monitor the average of the radiation dose over a period of 5 s. Therefore, the real-time performance of this signal was not high. It was transmitted between the IOCs over the EPICS Channel Access protocol.

3 Design of the safety interlock system and access control system

The radiation monitoring system was developed based on EPICS and deployed at HLS-II in 2017 [17]. This section focuses on the design details of the safety interlock system and the access control system.

3.1 Safety interlock system

The safety interlock system is a crucial system that processes the interlock logic. The operation of the safety interlock system comprised the following three operation states: released state, searching state, and the interlocked state. Figure 2 shows the workflow chart of the safety interlock system. Table 1 lists the definitions and actions of the different operation states.

When the facility was turned on, the safety interlock system entered into the released state. The HLS-II included three safety interlock areas: the linac, ring center, and the ring hall. In the released state, the interlock system of these three areas was released. All the interlock signals were reset and the search lamps were turned off.

The search state was aimed at establishing the interlock. When the search state was initiated, the operator would inform all the individuals to leave the interlock areas using audible and visual alarms. Then, the interlock areas in the linac, ring center, and the ring hall were searched consecutively by the operator. If all the search buttons were pressed and the security doors were locked, the operator provided the beam permit command to transfer the operation state into interlocked state.

For the HLS-II, after the beam was injected and the beam current of the storage ring reached 360 mA, two types of operation modes, such as the top-off mode and decay mode, could be considered. The top-off mode is a high-performance operation mode, in which the beam is injected every few minutes [18]. Thus, the linac and ring center were maintained in the interlocked state in the top-off mode. In the decay mode, the beam was injected every few hours, and the interlock of the linac and ring hall could be released, while the ring center was maintained in the interlocked state.

During the interlocked state, if the interlock system was released by the operator or triggered by the interlock signals, such as the emergency buttons were pressed or the radiation monitoring system detected an excessive radiation dose, the safety interlock system would cut off the timing signals of the electronic gun as well as the microwave system and transit into the released state.

3.2 Access control system

The design of the access control system in HLS-II is based on the principle of classified protection. The interlock areas could be classified into three types, such as the high radiation area, radiation area, and the safety area, according to the radiation dose rates. If the radiation dose rate was higher than 10 μSv/h, the interlock area was defined as the high radiation area. If the radiation dose rate ranged between 1 μSv/h and 10 μSv/h, the interlock area was defined as the radiation area. It was defined as the safety area, if the dose rate was less than 1 μSv/h. Table 2 lists the safety classifications of the interlock areas in different PSS states. In the high radiation area, the access of the security doors was prohibited, and no personnel was allowed to open the doors under any condition. In the radiation area, only the staff were provided with the restricted access authority. In the safety area, staff, users, and all other personnel could open the security doors with their respective access cards.

In HLS-II, the security doors could be opened using the respective access cards. When the access card was swiped, the card information was transmitted to the PLC. Then, the PLC determined the access permission according to the access authority of each card and safety classification of the interlock areas. The card number and authentication information were transmitted to the IOC and archived in the EPICS database as an event for recording and tracking. Meanwhile, the OPIs could display the access state synchronously.

In the access control system, the personnel count function was realized in the EPICS IOC using the state notation

Fig. 2 Workflow chart of the safety interlock system

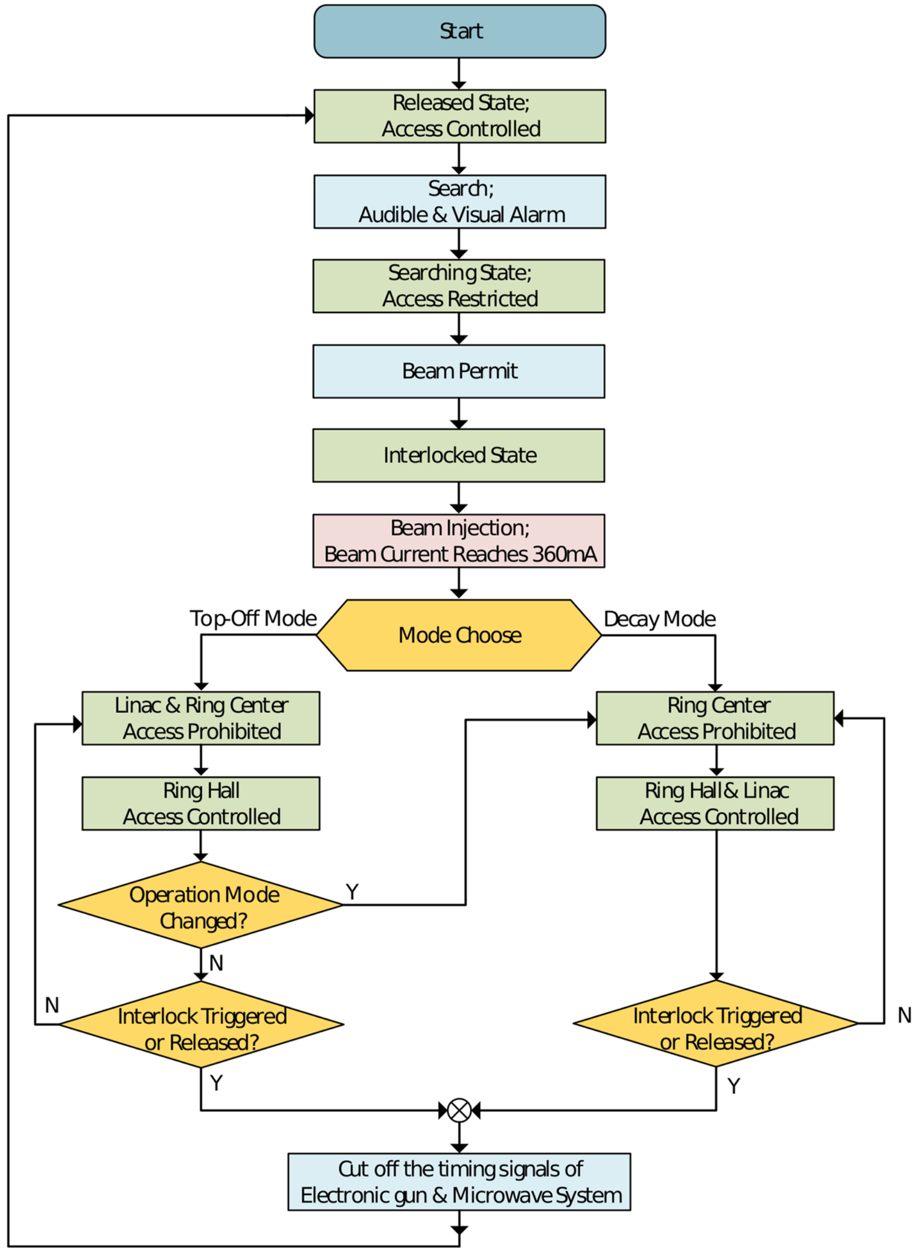

Table 1 Operation states of the safety interlock system

States	Definition	Actions
Released state	Release the interlock	Reset interlock logic
		Turn off search lamps
Searching State	Process to establish the interlock	Audible and visual alarm
		Search the interlock areas
		Turn on search lamps
		Lock the security doors
Interlocked State	Interlock is established	Beam injection
		Choose the operation mode

language (SNL). SNL is a domain-specific programming language, which can provide a simple yet powerful tool for sequential operations in a real-time control system [19]. The number of personnel in each of the interlock areas was

Table 2 Safety classification of the interlock areas in HLS-II

Operation states	Linac	Ring center	Ring hall
Released state	Radiation area	Radiation area	Safety area
Searching state	Radiation area	Radiation area	Radiation area
Interlocked state			
Beam enable	High radiation area	High radiation area	High radiation area
Top-off mode	High radiation area	High radiation area	Safety area
Decay mode	High radiation area	Radiation area	Safety area

counted by the SNL program, and the count results were recorded into the EPICS records.

4 Software development

4.1 PLC programs

As shown in Fig. 3, the PLC programs include two types of blocks, such as the data block and function block. The data block is used as the storage block for the PLC programs. The input and output data are stored, respectively, in the data blocks "DI Data" and "DO Data." The function block is used to process the safety interlock and access control signals and communicate with the EPICS IOC.

In the PLC programs, the input signals from the IO devices and the input data from the data block "DI Data" were retrieved using the receive function. Two types of flags, such as the lock flag and bypass flag, were defined for each signal in the preprocess function to process different types of input signals. The lock flag was designed to latch onto the transient signal, such as the signal of the search button. The bypass flag was used to ignore the related signals in the scenario of system test or maintenance.

The execution of the interlock logic and the PSS state transition among the released state, searching state, and the interlocked state were managed by the safety interlock function. The access control function was used to process the access algorithms and control the security doors. The send function was used to output the interlock signals to the IO devices and record the output data to the data block "DO Data."

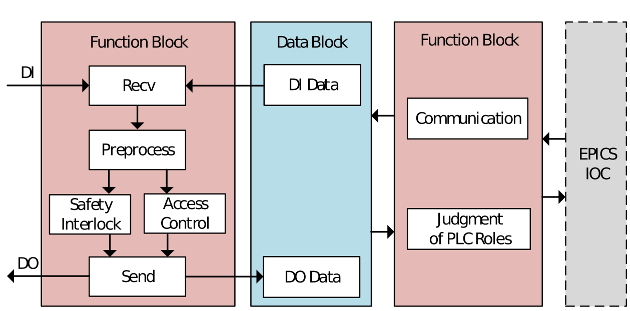

Fig. 3 Structure of the PLC programs

The communication function was used to define the communication cycle and the size of the communication frame, establish the communication links, and exchange data with the EPICS IOC. The role of the PLC could be determined by its state parameters. Only the MASTER PLC was used to transmit the data to the EPICS IOC.

4.2 EPICS driver of redundant PLC

The development of the EPICS driver for the Siemens redundant PLC is based on the EPICS driver "S7plc" [20, 21]. The driver was intended to connect to the PLC via the TCP/IP protocol. The EPICS IOC was set up as the TCP client, and the PLCs were set up as the TCP server. Figure 4 demonstrates the structure of the EPICS driver.

The EPICS driver includes four types of threads, such as the manager thread, link thread, data receive thread, and the data send thread. After the IOC driver was initialized, the two link threads attempted to establish the TCP circuits with the redundant PLC pair periodically. Once successful, only the MASTER PLC transmitted data to the IOC. This behavior was used to distinguish the role of the redundant

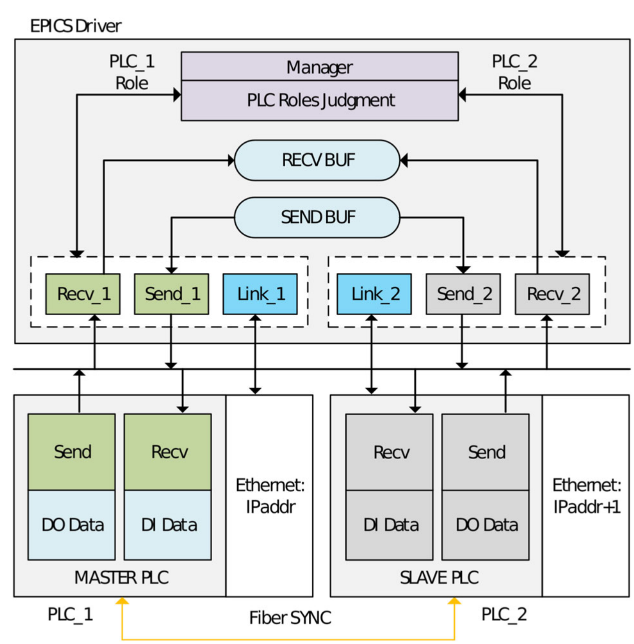

Fig. 4 Structure of the EPICS driver

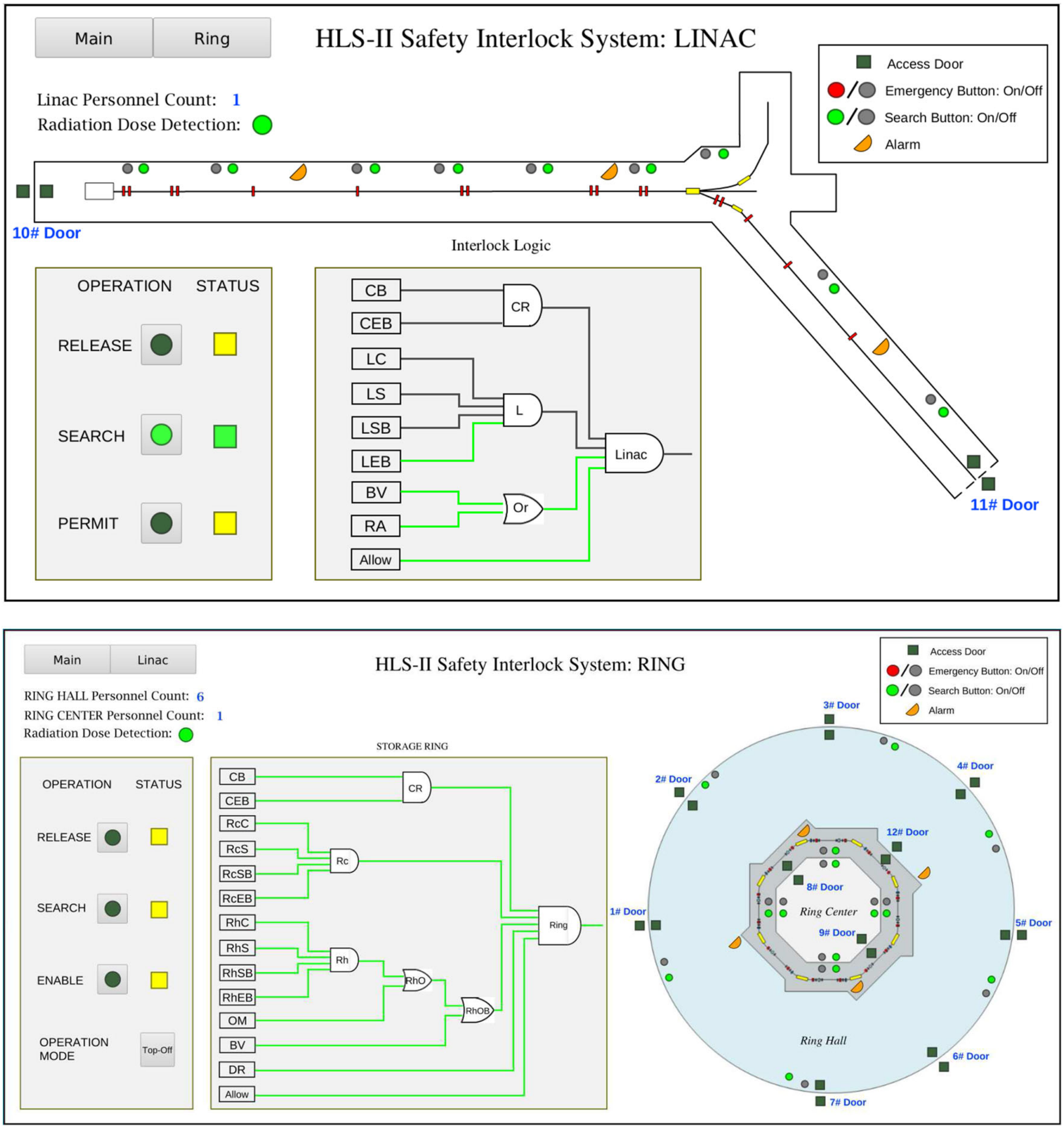

Fig. 5 (Color online) OPI of the linac (up) and OPI of the storage ring (down)

PLCs in the manager thread. The data receive thread and the data send thread were used to exchange data.

During the communication, the SLAVE PLC did not transmit data to the IOC. To check whether the SLAVE PLC was operational or not, the IOC transmitted the "ping" command periodically to the SLAVE PLC. If the MASTER PLC failed, the IOC would not receive any data. Once the SLAVE PLC switched to the new MASTER PLC, it transmitted data to the IOC. After the IOC received the data again from the new MASTER PLC, it could determine that the roles of the redundant PLCs were switched and the data were exchanged with the new MASTER PLC.

5 Off-line tests of the developed system

5.1 OPI design

The OPIs of the proposed HLS-II PSS comprise the OPI of the linac area and that of the storage ring area, as shown in Fig. 5a, b, respectively. The linac area includes the linac tunnel and transport line tunnel. The storage ring area includes the ring center and ring hall.

The OPI could be divided into the following four parts: (1) the distribution and state of the security doors, emergency buttons, search buttons, and the alarm devices; (2) personnel count and the radiation dose monitoring state in the interlock areas; (3) interlock logic diagram; and (4) the

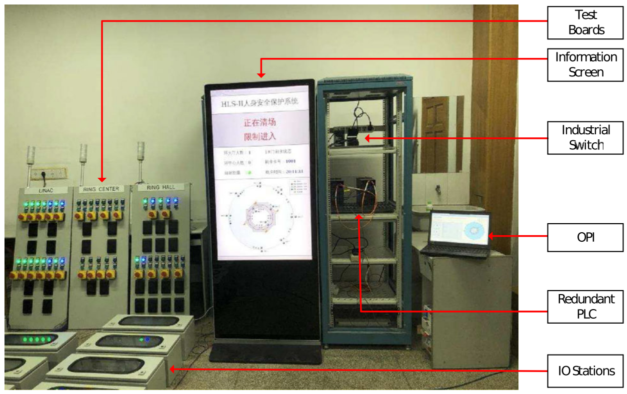

Fig. 6 (Color online) Photograph of the test platform of the novel HLS-II PSS (In the information screen, the search button in blue that is adjacent to the door is also called the registration button)

operation commands and related states. The line color in the interlock logic diagram is variable depending on the logic value. It is gray when the logic value is 0 and green when the logic value is 1.

5.2 Off-line tests

The development of the novel HLS-II PSS is complete. To ensure that that this system could function as per the design, we set up an off-line test platform, as shown in Fig. 6. In the platform, the redundant PLCs and the industrial switch were installed in the cabinet. According to the location of the IO devices at HLS-II, all the buttons, lamps, and the card readers were mounted on three boards with the names "LINAC," "RING HALL," and "RING CENTER." The information screen was used to display the state of the security door and the personnel count results. In Fig.6, the OPI and part of the 14 IO stations are also shown. The IOC is not shown in the picture.

The off-line platform was continuously tested according to the real operation situations for one month. The test results demonstrated that all the devices could function in a proper and stable manner, interlock actions could be executed effectively, and the top-off mode and decay mode could be supported successfully. Moreover, it was observed that the off-line platform could function properly during the redundant PLCs switchover.

6 Conclusion

In the novel design of the HLS-II PSS, the safety interlock system, access control system, and the radiation monitoring system were integrated under the EPICS environment. With this design, it is easy to share information and use the existing toolkits provided by the EPICS community. In the access control system, the personnel management function was designed for monitoring the entry and exit of the staff and users. Therefore, the HLS-II management requirements were also fulfilled.

Currently, the development of the novel HLS-II PSS is complete. The system was tested under an off-line test platform for a month, and the results indicated that the novel HLS-II PSS could function according to the design requirements. The novel HLS-II PSS will be deployed during the next shutdown of HLS-II.

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