Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

Preliminary Design of Monitoring System of ITER Static Magnetic Field Test Facility

To cite this article: Mi Pan *et al* 2021 *J. Phys.: Conf. Ser.* **1894** 012083

Preliminary Design of Monitoring System of ITER Static Magnetic Field Test Facility

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Abstract—The structure and characteristics of the ITER static magnetic field test facility is introduced. The preliminary design scheme of the monitoring system of the facility is proposed. According to the characteristics of the facility that it includes several subsystems, multiple signal types and is suffered from electromagnetic interference, the solution given combines NI CompactRIO embedded system, NI PXIe and Ethernet exchange technology. It can realize signal acquisition, status monitoring, safety interlock, parameter setting and other function. Also, the scheme covers the methods to weaken the interference from the surrounding magnetic field on the system itself and improve the stability of the system. The preliminary design scheme complies with control, data acquisition and communication specifications from ITER, and meets the SIL level assessment requirements in the concept phase.

1. Introduction

The ITER Organization (IO) is an international joint research and development project. The project aims to demonstrate the scientific and technological feasibility of nuclear fusion for peaceful purposes, and to obtain necessary data for the design, construction and operation of the first fusion power station. For all components entering the ITER experimental site, PIC (Important Protective Components) and non-PIC identifications are required, and different protective measures are taken according to the identification results to ensure the stable operation of the components and systems related to the fusion facility, thereby ensuring stable and reliable operation. Therefore, a static magnetic field test facility will be designed and manufactured to complete the qualification task [1]. EUT (Equipment Under Test) covers any type of electrical and mechanical equipment used at ITER site will be tested in accordance with the test requirements established by IO.

The key components of ITER static magnetic field test facility include PS (Power Supply) system, magnet coil, water cooling system, EHS (EUT Handling System) and other auxiliary equipment. It can provide maximum magnetic field strength not higher than 275mT, and the test area is 1m×1m×1m. The scheme adopts NI CompactRIO embedded system, NI PXIe data acquisition and Ethernet exchange technology, which can realize remote monitoring and safe operation of the entire facility, and improve the stability of the system that exposed in a special magnetic field environment [2]-[6]. This article focuses on the demand analysis of the facility monitoring system, introduces the hardware framework design, and gives the SIL assessment and certification results.

2. Analisis of Functional Requirements and Signals

The static magnetic field test facility is composed of a PS system, a magnet coil, a water-cooling system, an EHS and other auxiliary equipment.

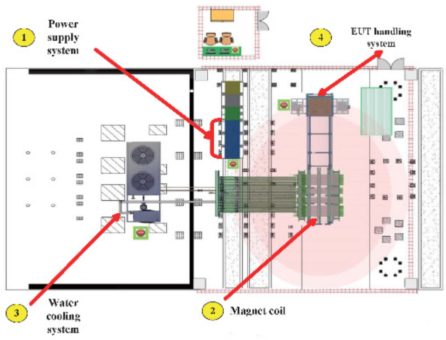

Figure 1 Components and layout of static magnetic field facility.

The components and location distribution of the entire facility are shown in Figure 1. The following will give the design requirements and signal analysis of the monitoring system of the static magnetic field test facility based on the comprehensive consideration of the independent work of each subsystem and the collaborative completion of the test.

2.1. Analysis of Functional Requirements

The programmable PS system consists of two power supply cabinets and a control cabinet to provide the necessary power for the magnet coil. The nominal current of 12.23kA corresponds to the maximum magnetic field strength generated by the magnet coil of 275mT. The local controller has the function of electric parameters adjustment and local protection. while the remote-control system has the function of power start-stop, real-time data acquisition and display of current and voltage, and interlocking with other subsystems to realize protection for the facility.

The magnet coil adopts a 4-coil mode, and the turns ratio is 20:12:12:20. The current within the specification range can generate a static magnetic field test zone with a uniformity of less than 1.1. When the magnet coil is energized to generate a static magnetic field, it will cause the temperature of the coil rising. In order to prevent the overheating of the coil from causing the facility to lose control, it is necessary to acquire the magnetic field strength and coil temperature and display them in real time.

The water-cooling system consists of heat exchange equipment, closed-loop cooling tower, water pumps, pipelines and other related equipment, and is an internal circulating water system. Its main function is to cool the high-temperature coil through circulating water to keep the coil temperature within the design range. For the water-cooling system, on the one hand, it is necessary to acquire the water temperature, water flow and water pressure data of the main pipeline and determine whether it exceeds or falls below the set threshold. On the other hand, it is necessary to set up remote start-stop and interlock protection signals to protect the entire facility.

The EHS consists of an EUT bracket, a track, and a rotating and tilting facility. It is used to transport, rotate and tilt the EUT to ensure it can be tested in six directions. Its control system is mainly composed of transportation control, lifting control, rotation control, clamp control, flip control, remote control and human machine interface (HMI). Remote control includes remote start and stop of the EHS, sending and receiving face-changing instructions, participating in interlocking protection, etc.

Other auxiliary equipment includes power distribution cabinets, safety fences, safety doors, etc., which are mainly involved in the safety interlock of the facility to ensure the safety of personnel on-site.

Based on the above description and function analysis of each subsystem, the monitoring system of the static magnetic field test facility includes routine status monitoring, data acquisition and display, remote operation, safety interlock, threshold setting, and data export functions.

2.2. Analysys of Signals

On the basis of the analysis of functional requirements, in order to realize the function of the monitoring system, sensors are configured locally in each subsystem. Dry nodes are placed to acquire the required signals, and thus the IO mode is adopted. The subsystems equipped with local controllers are communicated through communication protocol of Modbus TCP to do read and write operations. All signal types, parameters and quantities communicated between the facility and the monitoring system are shown in Table I.

Table 1 Statistical Table of Monitoring System Signal of the ITER Static Magnetic Field Test Facility

Control Type	**Object Names**	**Signal Type**	**Quantity**
Analog input signal	Current/Voltage Sensor	0~±10V	2
	Magnetic field probe	0~±10V	20
	Temperature Sensor	4~20mA	99
	Flowrate/pressure sensor	4~20mA	34
Digital input signal	Switch box of cooling facility	24VDC	21
	Flowrate/ Temperature switch	24VDC	5
	Local PLC of EHS	24VDC	1
	Controller of PS system	24VDC	7
	Emergency stop button, limit switch of safety door, circuit breaker	24VDC	7
Digital output signal	Relay switch of cooling system	24VDC	6
	Local PLC of EHS	24VDC	1
	Controller of PS system	24VDC	1
Modbus TCP-read/write	Local PLC of EHS	-	12/6
	Controller of PS system	-	3/6

3. Scheme Design of Monitoring System

Based on the analysis of function requirements and signals, the hardware framework of the system will adopt a high-performance industrial computer as the upper computer of the system. Each local controller will be implemented as the structure of the lower computer. The choice of software development platform takes into account the cooperation with hardware, which can give full play to the advantages in test and measurement and improve development efficiency. The choice of communication medium and communication protocol will also be given in this section, mainly considering the influence of special environmental magnetic fields.

3.1. Design of Hardware Frame

The monitoring system of ITER static magnetic field test facility coordinates the operation of its various subsystems to ensure the safe and stable operation of the facility and the smooth completion of the test task. The monitoring system needs to process fast signals with a sampling rate of more than 10kHz and slow signals with a large number of nodes under 10kHz, and realize the communication with the subsystem has a local controller.

Figure 2 shows the hardware design structure of the monitoring system. The fast acquisition module is composed of a high-performance industrial computer, an NI PXIe chassis and a multi-functional fast data acquisition card. It acquires signals above 10kHz and performs calculation processing inside the industrial computer. The fast acquisition hardware structure is highly expandable, and there are enough signal processing unit slots in the PXIe chassis to meet the expansion of the acquisition function. Two NI CompactRIO embedded controllers are equipped with NI C-series input and output modules to process analog signals and other digital signals below 10kHz. Through the Ethernet switch, a local network including a high-performance industrial computer, NI CompactRIO embedded controllers, PS system controller and EHS local PCL is formed to realize network communication and data exchange between subsystems.

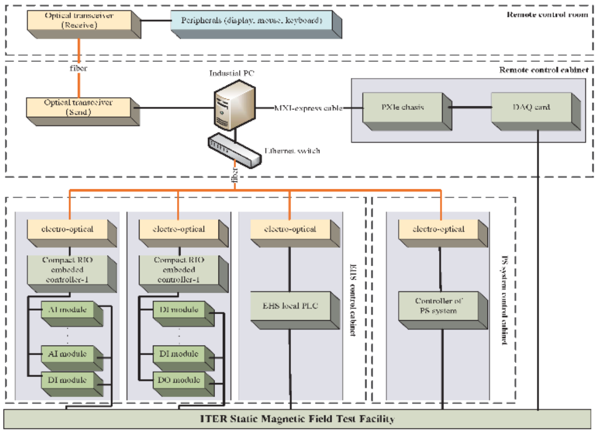

Figure 2 Structure and layout of static magnetic field facility.

When the equipment is installed and configurated, the actual function and space size shall be considered. The hardware to realize the monitoring system function are mainly distributed in 4 different locations, the EHS control cabinet, the PS control cabinet, the remote-control cabinet and the remote-control room. The NI CompactRIO system consists of a controller containing a processor and a programmable FPGA, and multiple signal conditioning I/O modules, which are all installed in the EHS control cabinet. The CompactRIO lower computer 1 monitors and alarms the state of the waterway and magnet coils, mainly including receiving the upper computer's threshold information, uploading fault data and fault location, and uploading all data acquired from the sensors. The CompactRIO lower computer 2 performs the safety interlock logic processing of the entire facility, acquires the fault signals and operating signals of the PS system and the EHS, receives the status of the water-cooling facility, and sends the control command.

The two CompactRIO controllers, the EHS local PLC and the PS system controller are respectively connected to the optical-electrical transducer to realize the network port to the optical port. Then they can exchange data with the Ethernet switch using optical fiber as the communication medium. The software program of the ITER static magnetic test facility runs on a high-performance industrial computer, using the transmitting and receiving ends of the optical transceiver to connect to the computer peripherals in the remote-control room. By connecting the peripherals with the optical transceiver, it takes advantage of the strong anti-interference of optical fiber transmission, ensuring the quality of signal transmission. At the same time, it can increase the receiving end to facilitate the expansion of peripherals.

3.2. Selection of Software Development Platform

LabVIEW is a graphical compilation platform developed by NI (National Instruments). Its good graphical programming environment and visual interface make it widely used in industrial automation, process processing and other fields. Programming is efficient, flexible, and object-oriented, which helps improve project development efficiency and reduce system costs. LabVIEW has many industrial interfaces. In the local area network established by the system's Ethernet, it can communicate with PLC, CompactRIO and other lower computers. Therefore, LabVIEW is used as the software development platform, which can not only achieve good data exchange with two NI CompactRIO controllers, but also can completely replace the traditional configuration software of the PLC system.

3.3. Selection of Transmission Medium and Communication Protocol

According to calculations, most of the control equipment are exposed to the magnetic field conditions of 3mT-0.5mT. The control cabinet itself has the function of shielding magnetic field interference. Therefore, the selection of long-distance transmission media needs to consider the particularity of the environment. Optical fiber transmission has the advantages of low loss, large capacity, strong anti-interference, and long relay distance, and is suitable for data transmission in long distances and special environments. Therefore, optical fiber is selected as the transmission medium for the connection of each subsystem and switch in the local area network constructed by the use of Ethernet technology in the monitoring system. It can enhance the anti-interference ability and avoid the problem of electromagnetic interference in the long-distance transmission of electrical signals.

Modbus is a communication protocol developed by MODICON in 1979. Based on the hardware design architecture characteristics of this system, the Modbus TCP protocol is used to establish high-performance industrial computer communication with other facility via Ethernet [7]. The industrial computer end is the client, which sends the data frame specified by the Modbus TCP protocol to the lower computer controller to realize the acquisition and status monitoring of the lower signal, and issue control commands to the lower computer.

3.4. Workflow Design of the System

The main task of the ITER static magnetic field test facility is to provide magnetic field condition, complete the test of each EUT and give the judgment result. In order to ensure the smooth progress of the task test, it is necessary to set up the system self-check step before, including the communication connection check of each subsystem, the important status check, the important safety interlock signal check, etc. To improve the operating efficiency, upon completing the regular debugging, it is not necessary to debug the subsystem every time it runs. It is enough to debug when the self-check fails. As shown in the figure 3, the main workflow of the system includes several important steps: login, system self-check, EHS/PS debugging, and task test.

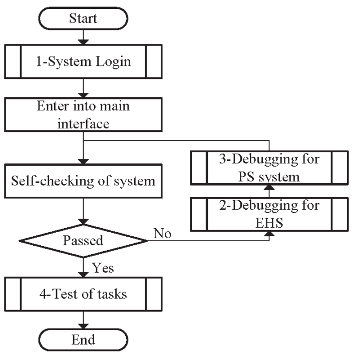

Figure 3 Workflow chart of the monitoring system.

Among them, the design of the task test process is the most critical part. As shown in the figure 4, it describes the steps required for a complete task test using this facility. The EUT is tested in 6 directions during a complete task. The EUT will move in 4 areas, namely the initial zone, the load zone, the power link zone, and the test zone. In these different zones, each subsystem will complete the corresponding operation, and the key steps need to be manually confirmed and completed instructions can be sent to the next step. This operation process makes the cooperation of various subsystems more efficient, and the addition of manual confirmation steps also improves the safety of facility operation.

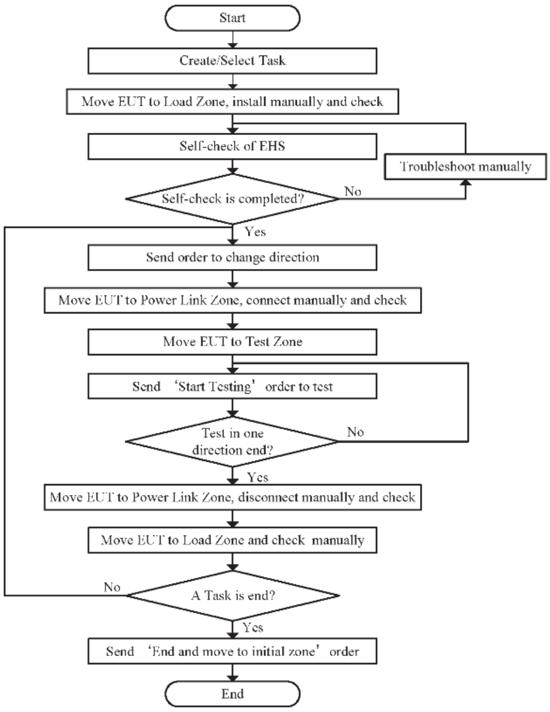

Figure 4 Work flow chart for implementing a test task.

4. Analysis of System Realiability

Mainly from the aspect of failure, the SIL level assessment of the system is carried out to analyze the reliability of the system. This method is used to verify the rationality and reliability of the preliminary design of the monitoring system, and to provide a basis for further design of the system.

4.1. Failure Level and Handling Mechanism

The monitoring system of ITER static magnetic field facility divides the hazards of the fault into three levels, and adopts corresponding handling mechanisms for different fault levels [8][9].

1) Level- I failure. High-risk faults, including overcurrent at the input side of the PS system, and safety door opening faults. In the event of a level-I fault, the interlock mechanism is to cut off the power input circuit breaker.

2) Level-II failure. Moderate-risk faults include overcurrent, overvoltage, overtemperature at the output side of the PS system, the temperature of the magnet coil exceeds the first-level threshold, and the waterway temperature exceeds the first-level threshold. When a Level-II fault occurs, the interlock mechanism is to press the emergency stop button or click the interface power stop button to cut off the power output current.

3) Level-III failure. Low-risk faults include the temperature of the magnet coil exceeds the secondary threshold, the temperature of the water circuit exceeds the secondary threshold, and if any subsystem's software and hardware equipment cannot perform the system's monitoring function correctly. The interlock mechanism is an interface error or alarm prompt, and the operator is notified the prescribed protective measures.

4.2. SIL Determination for the System

The SIL (Safety Integrity Level) is defined as the possibility of a safety-interlock system performing its specified safety function under a certain time and certain condition. Safety interlock is an indispensable safety system in modern factories. The design of the monitoring system of this facility comprehensively considers the interlock signals issued by each subsystem and the corresponding interlock actions [10][11].

The HAZOP analysis method is used to analyze the danger and risk of all levels of faults during the operation of the facility to identify the hazardous events and their risk categories. Through the method, the SIL level of the monitoring system is determined as SIL2.

Table 2 Reference Table for Minimum Hardware Failure Margin and Safety Interity Level

Minimum Hardware Fault Tolerance	SIL Level
0	1
1	2
2	3
3	Special requirements apply

According to the relationship between the SIF (Safety Instrument Function) operation mode and the time interval, the operation mode of the monitoring system can be regarded as a high-demand operation mode. The design of the monitoring system leaves a certain fault margin in the hardware structure. Refer to the TABLE II, the sensor and the final execution element meet the minimum Hardware Fault Tolerance (HFT) of 1, and its safety integrity level can reach SIL2.

5. Conclusion

The design of the monitoring system of the ITER static magnetic field test facility fully considers the characteristics of the facility's several subsystems, multiple signal types and strong environmental magnetic field interference, and provides a reasonable hardware solution. The selection of software platform and communication transmission method has increased the integrity of the program design. Failure analysis and evaluation of SIL verified the reliability of the system scheme design. At this stage, detailed requirements and design documents of the monitoring system, hardware structure and cabinet integration drawings can be output as a guide for the manufacturing stage.

Acknowledgment

This work was supported by Comprehensive Research Facility for Fusion Technology Program of China under Contract No.2018-000052-73-01-001228. The view and opinions expressed herein do not necessarily reflect those of the ITER Organization.

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