ISBN: 978-3-95450-193-9 doi:10.18429/JACoW-ICALEPCS2017-THPHA060

CONCEPTUAL DESIGN OF THE CRYOGENIC CONTROL SYSTEM OF CFETR COIL TEST FACILITY

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Abstract

China Fusion Engineering Test Reactor (CFETR) is superconducting Tokamak device which is next-generation engineering reactor between ITER and DEMO. It is now being designed by China national integration design group. In the present design, its magnet system consists of 16 Toroidal Field (TF) coils, 6 Center Solenoid (CS) coils and 8 Poloidal Field (PF) coils. A helium refrigerator with an equivalent cooling capacity of 5kW at 4.5K for CFETR TF coil test facility is proposed. It can provide 3.7K & 4.5K supercritical helium for TF coil, 50K cold helium with a 10g/s flow rate for High Temperature superconducting (HTS) current leads and 50K cold helium with a cooling capacity of 1.5kW for thermal shield. This paper presents the conceptual design of cryogenic control system for CFETR TF coil test including of architecture, hardware design and software development.

INTRODUCTION

China Fusion Engineering Test Reactor (CFETR) is superconducting Tokamak device which is next-generation engineering reactor between ITER and DEMO [1].It is now being designed by China national integration design group. CFETR is envisioned to provide 50~200M fusion power and a demonstration of long pulse or steady-state operation with duty cycle time not less than 0.3~0.5 and the full cycle of tritium self-sustained with TBR not less than 1.2 based on the existing EAST and ITER physical and technology. Magnet system of CFETR consists of 16 TF coils, 6 CS coils and 6 PF coils and another 2 PF coils (CC1 and CC2) at the bottom of the device to produce the snowflake and super-x equilibrium shape[2]. The Fig.1 shows the structure of the superconducting magnets system. The toroidal magnetic field of CFETR is generated by 16 D-shaped superconducting coils which is winded with 132Nb3Sn CICCCs with a height of about 14m and about 11m width[3].

CFETR TF test facility includes cryogenic system, cryostat, vacuum system, power supply system, magnet protection system, instrumentation and control system. Helium refrigerator is key component of the cryogenic system which provides adequate refrigeration power to cool down and maintain the testing coil in superconducting state under normal test phase. So the 5kW/4.5K helium refrigerator is designed at ASIPP. This paper presents the conceptual design of cryogenic control system for CFETR TF coil test including of architecture, hardware design and software development.

CRYOGENIC SYSTEM OF TF COIL TEST FACILITY

The CFETR TF coil will be installed in a large cryostat and mechanically fixed by low thermal conductivity material when in the process of cold test. In order to further reduce the heat load to 4.5K, a 60K thermal radiation shied between the magnet vessel and the cryostat shell is designed and cooled by 50K cold helium gas. All of cold components of the CFETR TF coil test facility will be refrigerated by a helium refrigerator. The heat loads of the whole system consist of heat radiation, residual gas heat conduction box, control Dewar, cryogenic transfer lines, HTS current lines and super critical helium(SHe) circulators, Joule heat from superconducting joints and eddy current loss of the testing coil[4]. According to the estimation of the heat loads, a certain refrigeration capacity margin and a reserved ability to supply 3.7 K sub-cooled helium to test CFETR cryopumps, the helium refrigerator is designed at a capacity of 1500W/3.7K +2500W/4.5K +10g/s/50K+ 1.5Kw/50K, which is approximately equivalent to a helium refrigerator with the capacity nearly 5kW at 4.5K.

The cryogenic system of CFETR coil test facility consists of compressors, oil removal system, cold box, pure gas helium(GHe) storage, helium external purifier, impure GHe storage, recovery compressor, LHe dewar, LN2 tanks gas bags and distribution system and so on, which is shown in Fig. 2. The refrigeration system is based on Modified Claude refrigeration cycle and possesses of one optional LN2 pre-cooling stage, several reverse Brayton refrigeration stages and J-T valve throttle cooling stage. The helium refrigerator system has three operating mode. (1) Standard refrigeration mode. (2) Peak refrigeration mode. (3) Liquefier mode. LN2 pre-cooling stage only runs in cool down phrase, peak refrigeration mode and liquefier mode. In standard refrigeration mode, the HP(high pressure) helium is cooled down by turbines T1&T2 while LN2 pre-cooling stage is cut off, which largely reduces the consumer of LN2. When the coil test facility is put into operation, the helium refrigerator should supply enough cold sources to cool down all cold components in coil cryostat, including superconducting coil, HTS current leads, thermal shield and so on. At this time, the helium refrigerator works at standard refrigeration mode. Without the supply of LN2, there is no heat exchange in HX3 &HX4. The HP helium is cooled down to 132.8K in counter-current heat exchanger HX1. At the outlet of HX1, the flow rate is divided into two flows: one to the turbines T1 & T2 and the other

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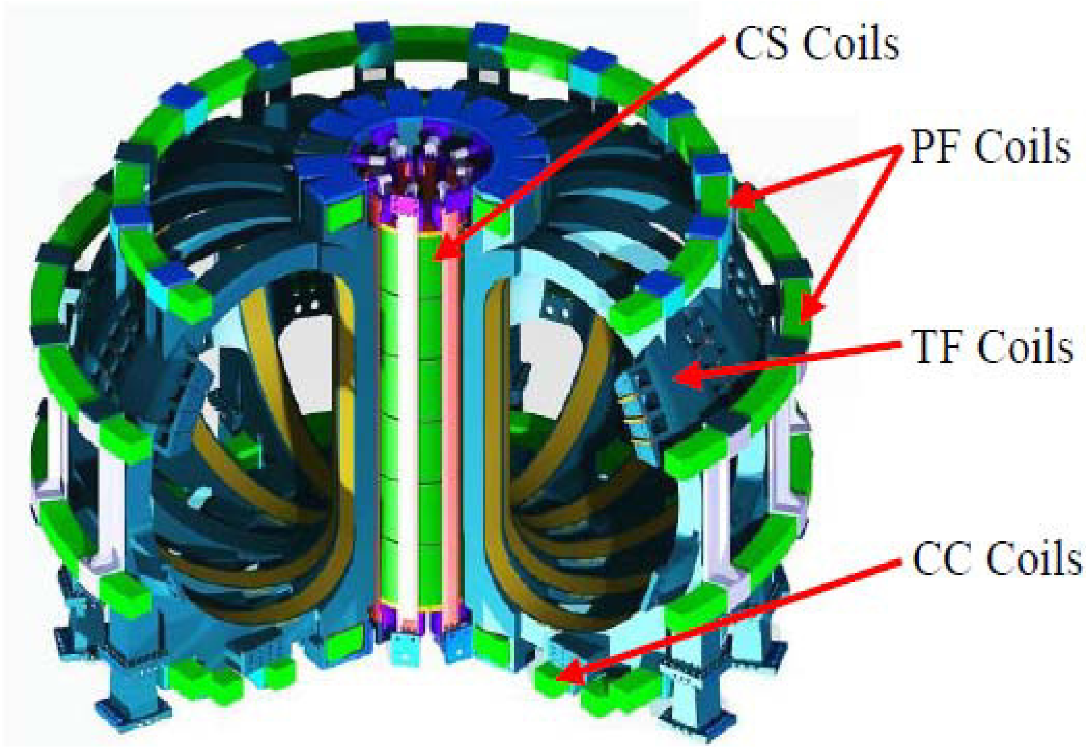

Figure 1: Magnets system of CFETR.

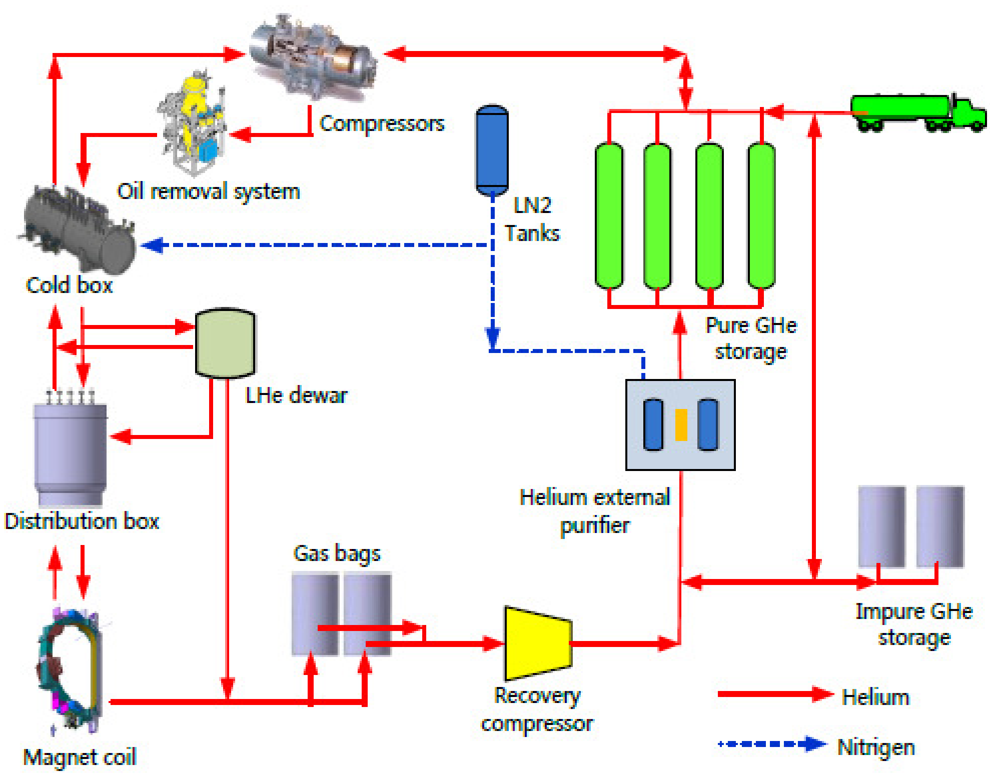

Figure 2: Cryogenic system of CFETR TF coil test facility.

dedicated to the colder turbines. Then the HP helium flow is cooled down to 91.2K by refrigeration power produced by turbine T1 & T2 and cold return helium at HX2. At the cold end of HX5, the temperature of HP flow is 52.5K, part of which is dedicated to cool the thermal shields while the MP (medium pressure) flow is 50K and 4bara,

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part of which (10g/s) is used to cool HTS current leads. Return helium from thermal shields is expanded in turbine T3 & T4. The helium gas is cooled down to 4.921K through HX7~12, T5 and T7. During this operation mode, turbine T6 doesn't run. Some helium then liquefies at 1.2bara through J-T valve and liquid helium accumulates in S1 dewar. Another part of supercritical helium is cooled down to 3.7K through heat exchangers immersed in 4.5K S1 dewar and 3.6K S2 dewar. The 3.6K sub-cooled helium is realized by a cold compressor to lower the saturation pressure to 0.47bara. The cold helium in MP & LP flow is warmed by heat exchangers and sent to the suction of compressors. The PFD of helium refrigerator is shown in Fig.3.

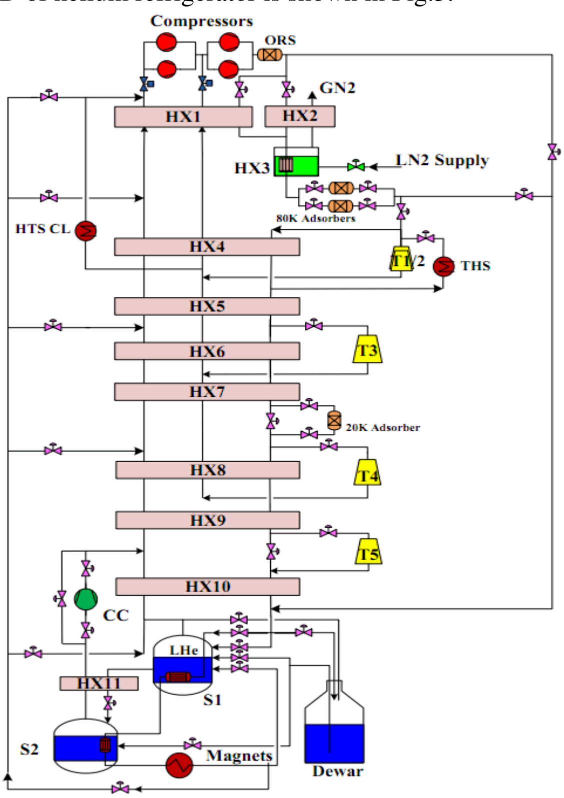

Figure 3: PFD of helium refrigerator.

DESIGN OF CRYOGENIC CONROL SYSTEM

The control system of cryogenic system must meet the following function:

- Full and semi-automatic operation in all specified steady state and non-stationary modes as well as transitions between the modes.
- Visualization of the system parameters via an operator-friendly and easy for interpretation display of the surveys, symbols, trend-diagrams and reports.
- Adjustment parameters of the system and its separate components.
- Developing of new software and downloading it into the control system without interruption of the helium refrigerator operation.
- Safe shut-down of the helium refrigerator in case of a fault as well as restart after fixing the fault.
- Automatic notification of the concerned parties such as main control room, the helium refrigerator control room, stand by operators, etc. about a failure via hard wired interlocks, SMS and as software signal.
- Archiving the data.
- Possibilities of an easy extension of the control system (e.g. interface for additional client stations, possibly remotely situated).

The control system of cryogenic system of CFETR TF coil test facility is based on EPICS (Experimental Physics and Industrial Control System). The architecture of control system is shown in Fig. 4. The control system is divided into three layers: field device control layer, process control layer and supervisor layer. The structure software of Programmable Logic controllers (PLC) will be used in the filed device control layer for the implementation of process and operational modes. There are five PLC sites to be responsible for the subsystem of cryogenic system including of recovery system, compressor system, turbine system, coldbox and distribution system. Process control layer is the core of the control system for the functions of real time data acquirement/storage, parameters setting/adjustment, physical/engineering data conversion, etc. Furthermore, process control layer need to respond to data requests from supervisor layer and deal with external events from device layer.

The hardware configuration of IOC in process layer selects the cPCI bus industrial computer with VxWorks or Linux operating system. Real time database in memory is the core of IOC including of records and structure of description records. Supervisor layer is responsible for the HMI, alarm system, events record, history trend and administration license. The hardware configuration selects HP workstation and business PC with Linux system. The HMI is developed based on CSS(control system studio) which is open source software provide by EPICS. CSS based on Eclipse Public License(EPL) is a OPI tool with the functions of operator interface, data storage and processing, alarm and drawing[5]. Communication between supervisor and process control is based on LAN with fiber Ethernet. The I/O data exchange is between process control and device layer. The communication of PLC master controller and subsystem is based on Profibus. The redundant control system for cryogenic system makes the system more reliable and stable.

The software structure was designed according to the requirements of system in order to realize the automatic operation of cryogenic system. The main program of

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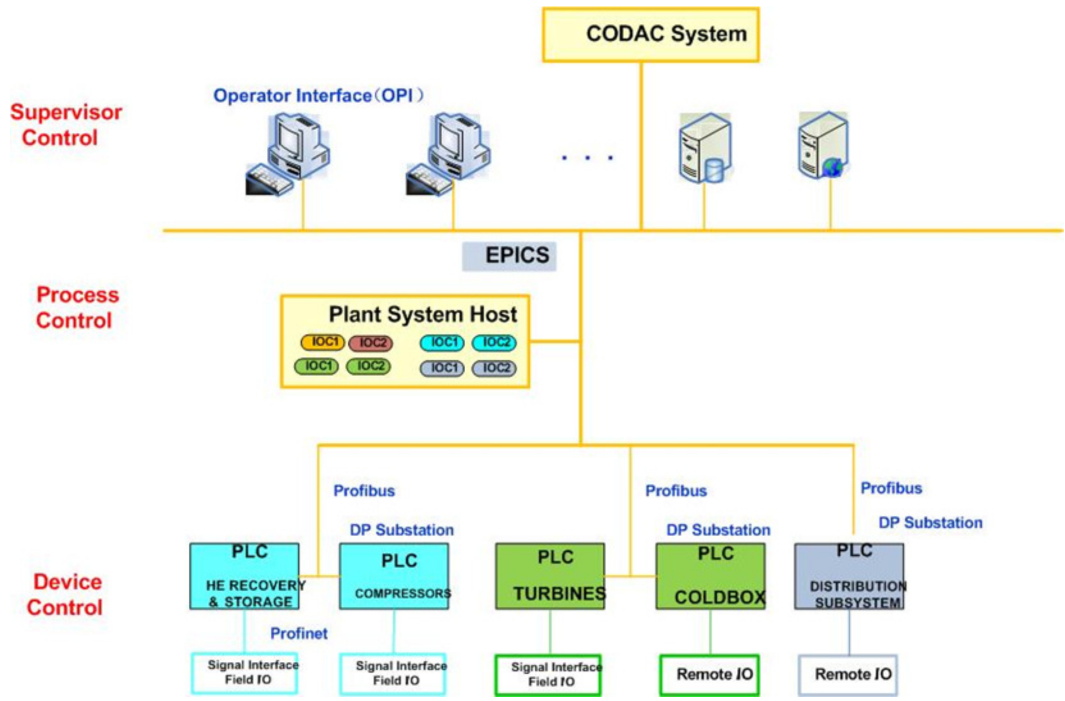

Figure 4: Structure of cryogenic control system.

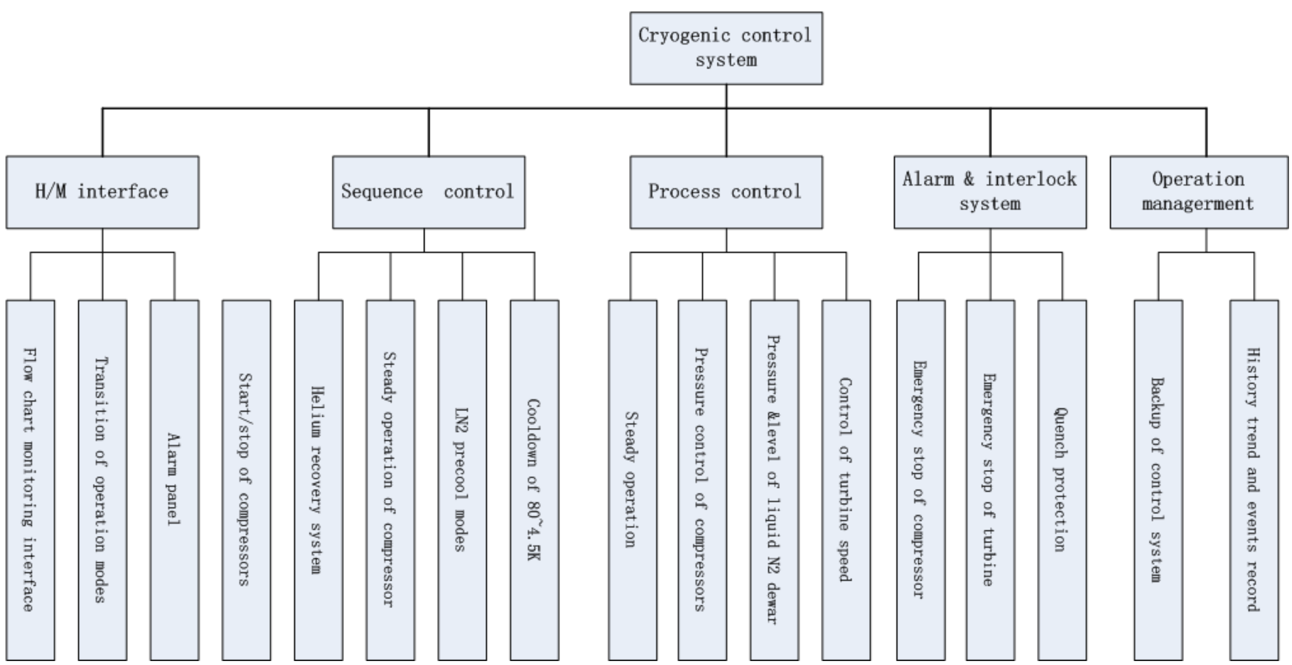

Figure 5: Software structure of cryogenic control system.

the cryogenic control system includes human/machine(H/M) interface, process control, sequence control, alarm and interlock system and operational management. Fig.5. shows the structure of the cryogenic control system software. The H/M interface is to monitor the operational status and manipulate the system. The design of process control performances depend on the closed loop control according to the PID algorithm. The sequence control is according to the operation modes of cryogenic system, such as cool down, standby and steady operation and warm up. The alarm and interlock system is to protect the important components and quench protection. The operational management is to maintain the system and analyze the process data.

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CONCLUSION

CFETR TF coil test facility is to test the electromagnetic and stability of TF coils at nominal operating current and cryogenic temperature to minimize the risk of malfunction. The cryogenic control system for CFETR TF coil test facility has been developed based on EPICS. This conceptual design will be conducive to the engineering design. The control logic and process modes will be analyzed in detail in next step.

ACKNOWLEDGMENT

Financial support by the key fund for outstanding youth talent of Anhui Educational Commission of China (NO. 2013SQRL099ZD) are gratefully acknowledged.

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