Circuit Controller for PF Converter System Based on CODAC Core System

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Abstract. The poloidal field converter system of the International Thermonuclear Experimental reactor, which is developed, assembled, and tested by the Institute of Plasma Physics of the Chinese Academy of Sciences, uses the CODAC core system provided by ITER organization to design its control system. This paper completes the design of the circuit control system as well as realizes the transmission, state transition, and real-time control of the operating status of the poloidal field converter system to meet specific requirements for the control cycle of the control system. This paper provides solutions to some key problems, such as the state transition, real-time transmission, and operating state display, and real-time control of the converter circuit control system. The system designed by this paper has been successfully tested in the ITER PF prototype and ITER PF test platform.

1. Introduction

The "International Thermonuclear Experimental Reactor (ITER) Program" is currently one of the largest and most influential international scientific research cooperation projects. The ITER device is a superconducting Tokomak that produces large-scale nuclear fusion reactions, commonly known as "artificial sun". It is jointly built and developed by China, the European Union, India, Japan, South Korea, Russia, and the United States. This project aims to put controllable fusion energy into technological and engineering practice. [1][2]

The ITER device is composed of many subsystems, which are all critical components. Control Data Access and Communications (CODAC) Core System (CCS), a software package developed by the ITER organization (IO), which provides the necessary environment for developing and testing software. CODAC system is composed of a central regulatory control system and several subsystem control systems. IO has published the Plant Control Design Handbook (PCDH), which sets out the development criteria and control system framework for the subsystem. CCS is based on Experimental Physics and Industry Control System (EPICS) and Red Hat Enterprise Linux (RHEL). [3]

The Poloidal Field (PF) is one of its subsystems, consisting of 6 sets of magnet coils, and there are 14 four-quadrant Converter Units (CU) are required to supply for them [4], as shown in Figure 1. For PF1 or PF6, there is one four-quadrant converter unit to feed the coil, and for PF2–PF5, there are four-quadrant converter units in series to feed the each coil.

The control system of the ITER PF Converter system is designed based on the ITER standard, which is responsible for the real-time operation and the converter system monitoring, interlocking and protection, and communication with the upper-level control realization. The overall structure of the control system for the PF converter system is shown in Figure 2, which is composed of two levels: the Local Control System Level (LCSL) and the Main Control Level (MCL). The MCL comprises Circuit
ControleR(CCR), MasteR Controller (MRC), and Mini-CODAC controller. According to the IO’s (specify what is IO here!) schedule, China is responsible for the development and installation of the CCR, which is the lowest level in the MCL hierarchy and provides interfaces to PON (Plant Operation Network), SDN (Synchronous Data-bus Network), and DAN (Data Archiving Network) for the LCSL.

According to the location of the PF converter system in the IO site, the Local Control System (LCS) of PF1 and PF6 is managed by one CCR, and the LCS of PF2 to PF5 is managed by the other CCR. Therefore, these LCSs are managed uniformly by two sets of CCRs. The function of the circuit controller is to manage and summarize the status of the LCS, data archive and alarm, voltage reference dispatch, real-time data transmission with MRC and state transition, and realize the process monitoring experimental data processing, alarm processing, data archiving, operation interface offering, and remote control functions. As a result, it can finally realize centralized management and decentralized control in the experiment. [5]
2. Architecture of circuit controller

According to the demands of Plant Control Design Handbook (PCDH) by ITER CODAC team, CCR is defined as fast controller, and adopt MRG-R of RHEL kernel as Operator System (OS). As shown in Figure 3, based on the special conditions set by IO CODAC team, the CCR has four network interfaces with CODAC, which are PON, SDN, TCN, and DAN. CCR transmit data with MiniCODAC through PON, including configure parameters and timing control of ITER PF converter system, receive data the safety signals and the currents and voltages from Local Conventional Controllers (LCC), and then upload them to PON CCR also subscribes the voltage reference from MRC through SDN, then multicasts them to LCCs, and publishes the Q value to SDN. What is more, CCR also provides transient recorder management and publishes them to DAN so that it will be convenient to double check in the later time. Last but not least, CCR can obtain the time stamp from the TCN server via the TCN to synchronize the system time of the CCR.

The key points while designing the CCR is to transmit and convert signals of different data formats between CODAC and LCCs so that CODAC can monitor the conditions within ITER PF converter system, dispatch voltage reference to different LCC, and archive data at 1ms control cycle, in order to manage and transmit the transient recorders to DAN archive server, and to implement the state machine transition in different LCCs.

3. Design of circuit controller

3.1. Data transmission between CCR and LCCs

The System platform of the circuit controller is the CCS, provided by IO, which is a distributed control architecture based on Experimental Physics and Industrial Control System (EPICS) [6] proposed by ITER to regulate the cooperation of various countries, but the project of LCCs is written based on an open source by using Eclipse, C/C++ based extensible development platform as the development tool. Thus, it can be seen that CCR and LCCs are develop by different operating system and different software, which causes their signal formats to be different and cannot be directly utilized between each other. Therefore, CCR developed a method to realize a cross-platform data transmission of control system based on EPICS to solve the problems caused by transmission and conversion for different data formats because of different operating systems and different development software.
As shown in Figure 4, CCR uses the device/driver support of EPICS to realize signal transmission and conversion between CCR and LCCs. CCR receives data packets from the LCC via the private network, and the device/driver support converts these signals into a valid Process Variable (PV) of EPICS, which is stored in the run-time database. The client accesses CCR IOC through CA protocol to obtain the PVs and monitor it on the Human-computer Interaction Interface (HMI). At the same time, the client changes the value of PVs, CCR IOC converts these PVs into the signals type which the LCCs can identify them, and then CCR IOC sends them to the LCCs through the private network, so as to realize remote control of the equipment at the field layer of the converter system. It is convenient for the client to realize monitoring, alarm, and data archive of the field equipment in the HMI.

3.2. Dispatching real-time control data
The dispatching real-time control data from CCR subscribed periodic transmission from the MRC via SDN, and the control cycle is 1 millisecond. According to the design requirements of IO, the time for dispatching the real-time control data from the MRC to the local controller (LCC) should be less than 200 s.

As shown in Figure 5, the dispatching of the real-time control data includes two parts: the real-time control data published by the MRC to CCRs, and CCRs multicast the real-time control data to the LCCs. The data is published and subscribed over SDN, which is a real-time high-speed Ethernet based on 10G network card. [7] The MRC utilizes User Datagram Protocol (UDP) to publish the real-time control data of the ITER PF converter system, and CCRs join into the multicast group and subscribe the real-time
control data. The delay time will be $t_{A1}$; CCRs utilize UDP protocols to multicast these dispatching real-time control data, and the LCCs will join into the multicast group to receive their corresponding real-time control data respectively, and the receiving time will be $t_{Bn}$. (‘n’ is the number of the ITER PF number).

After testing, the MRC and the CCRs send voltage control data every millisecond, and take 1000 seconds as a statistical period. Then statistical analysis shows that there is no packet loss in each cycle. According to Figure 6(A), the maximum delay time of $t_{A1}$ is 65.7μs and the average delay time is 37.36μs. As shown in Figure 6 (B), the maximum delay time between CCR and LCCs of $t_{Bn}$ is 76.5μs and the average delay time is 51μs.

![Figure 6. Delay time of 1000 seconds of sampling.](image)

In conclusion, the maximum delay time of the real-time control data from the CCRs to the LCCs is 142.7μs, which is less than 200μs. As a result the real-time transmission scheme of the CCRs can meet the requirement of the high-speed transmission and real-time control of the ITER PF converter system.

3.3. Transient Recorder Management

The DAN is a real-time high-speed network based on TCP/IP protocol for delivering high-throughput data stream, the clients to send data to the DAN archive server through the DAN, which stores the data as HDF5 files. Data archiving technology is an important service provided by CCS. [8] According to the requirements of PCDH established by CODAC system group, CCR should collect and archive the transient recorder from the LCCs in case of ITER PF Converter System’ failure. As shown in Figure 7, the LCCs sends the transient recorder to CCRs which runs the data archiving process provided by the CCS and the DAN Publisher process developed using the data archive interface function. The DAN Publisher is responsible for receiving packets of transient recorder from the LCCs, creating a new data buffer for storing the transient recorder, and then notifying the DAN Sender to read the transient recorder and send them to the DAN archive server. The DAN archive server is responsible for the storing and browsing the transient recorder, which is subscribed over the DAN and stored on disk as an HDF5 files.

![Figure 7. Structure of DAN archive system for CCR.](image)
3.4. State machine transition

The working state of ITER Plant system I&C is determined by its timing sequence, while the working state of the PF converter system is determined by the CCS. [9] According to the characteristics of ITER PF converter system, there are five states are designed, namely Shutdown, NotReady, Ready, Starting, and Running, which are shown in the Figure 8 (B). MRC sends request of state machine to CCRs, CCRs then broadcast it to LCCs after receiving the request. The STATUS of LCCs are aggregated by CCRs and then upload them to MRC. Thus, the state machine transition of ITER PF converter system is realized, which is shown in Figure 8 (A).

As shown in Figure 9, the state machine transition of CCRs wait for the Finite State Machine (FSM) request of MRC to check whether the state and request are consistent with each other. If it is inconsistent and is the next request, the CCRs will send the request to LCCs, and then start to collect and integrate the FSM status which is uploaded from LCCs. Otherwise, CCRs will wait for the next request. If the state received by CCRs is 'Fault' uploaded from LCCs, CCRs will send the 'Fault' state to MRC and at the same time sends 'NotReady' request to LCCs, while waiting for the MRC state machine to process.
3.5. Software architecture of CCR

The control project of CCRs follows the PCDH of CODAC system team, CCS provides a powerful and convenient development environment and driver. What is more, IOC for fast controller is written in SDD-Editor. The project of CCR includes three IOC: PON IOC based on EPICS, SDN IOC based on C++, and DAN IOC based on C++. What is more, the IOCs are running independently.

As shown in Figure 10, the signals of ITER PF converter system is converted to EPICS PV by PON IOC, and published to PON for real-time archiving and monitoring in HMI. Meanwhile, the SND IOC subscribes and publishes the real-time control data over SDN, so that the LCCs achieves the real-time control of ITER PF converter system after receiving the real-time control data through Private network. The transmission of transient record of ITER PF converter system is achieved by DAN IOC. The transient record is received in real-time through private network and publish to DAN, which is managed and stored by DAN archive server.

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4. Conclusions
The CCR of ITER PF converter system is designed based on the standards of ITER Plant System I&C template by the PCDH. It achieves monitoring status, data archiving, time machine control, and real-time control, as well as transient record of ITER PF converter system. The system is designed based on CODAC framework, and the software and hardware are in line with ITER specification. As a part of a large scientific engineering project, this is necessary to facilitate the integration of CCR into the entire IO CODAC control system in the future. The design scheme has completed the debugging and testing on the ITER PF prototype in 2014. By the end of 2019, fourteen ITER PF converter units have been successfully completed and tested, which proves that the project and the entire network of ITER PF CCR are stable and reliable and have passed various performance tests required by IO.

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References
[1] Pan Chuanhong. The international thermonuclear experimental reactor and the future of nuclear fusion energy. Physics, 2010, 39(6): 375-378
[2] Feng Kaiming, Controlled nuclear fusion and ITER project. China Nuclear Power, 2009, 2(3):212-219

[3] Stepanov D. CODAC core system user manual[R]. Cadarache: ITER Organization, 2015

[4] Zhu L L, Fu P, Gao G, et al. Development of data acquisition management system for ITER DC testing platform[J]. Journal of Fusion Energy, 2015, 34: 1100–1104. DOI: 10.1007/s10894-015-9924-5

[5] He S, Huang L, Gao G, et al. Design of Master Control System for ITER PF Converter System Based on CODAC Core System[C]// IEEE International Power Electronics and Application Conference and Exposition. 0.

[6] He S, Huang L, Gao G, et al. Design of Monitoring and Control System in Poloidal Field Power Supply Based on EPICS[C]// the 3rd International Conference. 2019.

[7] He S, Huang L, Gao G, et al. Design of Master Control system for Poloidal Field Power Supply Based on Real-time Linux[J]. Nuclear Fusion and Plasma Physics, 2018.38 (1):93-9

[8] Feng S, Peng F U, Huang L, et al. Application of ITER data archiving system for PF control system[J]. Nuclear Techniques, 2015.

[9] Zhang B. Application Research of CODAC Core System in ITER Radial Soft X-ray Camera[D]. University of Science and Technology of China, 2017