Design of Central Controller for EAST ECRH System Based on FPGA

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Abstract. Electron cyclotron resonance heating is one of the important heating methods for controlled nuclear fusion reactions, which can make up for the shortcomings of the traditional heating methods. To this end, a 4MW long pulse electron cyclotron heating system was designed on the Experimental Advanced Superconducting Tokamak device. This paper mainly introduces the design of the gyrotron controller of ECRH system based on FPGA chip. The control logic of the central controller is based on state machine. Throughout the entire control process, each signal in the system is monitored in real time. Once an abnormality occurs, the main control logic will cut off the high voltage power of the gyrotron as required to protect the gyrotron from damage. In addition to the normal control logic, the FPGA also embeds abnormality diagnosis logic, which monitors the control state transitions of the main control logic and various input signals in real time to determine whether an abnormality has occurred in the system and can diagnose the cause of the abnormality. Timing simulation was done to the FPGA program. The result shows that the controller can respond to the total control trigger signal in real time, accurately control the switching of the cathode and anode high voltage power supply, diagnose and handle various abnormal conditions, and meet the control requirements of the ECRH system.

1. Introduction
Electron Cyclotron Resonance Heating (ECRH) is one of the important heating methods for controlled nuclear fusion reactions. It has high coupling efficiency, good localization of power deposition, simple structure of microwave transmitting antennas, and high transmission power density. Many advantages, such as easy control of the cyclotron resonance layer, can make up for the shortcomings of the limited heating temperature of traditional heating methods.

The DIII-D Tokamak experimental device built by General Atomic Energy is equipped with an ECRH system with 2MW output power and 10s pulse duration in the initial version [1], which was upgrade to 6 MW later [2, 3]. On the basis of the Chinese Circulator New No. 1(HL-1M) [4], the China Circulator No. 2A (HL-2A) unit has gradually developed from a total of 1MW output power of two 500kW gyrotrons in 2005 to a total of 3MW output power of 6 in 2009 [5, 6]. As an upgraded version of China’s first superconducting Tokamak HT-7 [7], the EAST (Experimental Advanced Superconducting Tokamak) tokamak device is equipped with a 4MW long pulse electronic cyclotron heating system [8-10].
The EAST ECRH system consists of a gyrotron system, a transmission line antenna system, a monitoring and protection system, a high voltage power system, a water cooling system, and associated vacuum and low temperature subsystems, which is shown in Fig. 1.

![Figure 1. EAST ECRH system](image)

Each gyrotron is equipped with a superconducting magnet and its auxiliary system such as power supply, filament power supply, titanium pump power supply, and superconducting magnet power supply. The high-power microwave generated by the gyrotron system is sent to the cluster antenna system through a vacuum wrinkle waveguide transmission line system, and a high-power millimeter wave is coupled to the plasma to realize plasma heating and current driving. The monitoring and protection system is responsible for controlling system operation and detecting system operation status, including central controller, system status monitoring and interlock protection, video monitoring, overcurrent protection, spark protection, polarization feedback control, data acquisition and power monitoring, data management and Release subsystems. Transmission line antenna systems include wrinkle waveguides, dummy loads, antennas, and waveguides, power monitoring elbows, polarizers, and other transmission line functions that are responsible for transmitting microwaves into the plasma. The water cooling system is responsible for the heat dissipation of the various components, and the vacuum system is responsible for maintaining the internal vacuum of the transmission line system and the superconducting magnet interlayer.

As the gyrotron is the core device of the entire ECRH system, the control of the gyrotron needs to follow strict requirements. One of the important principles is: when power is applied, the cathode high voltage should be applied first, and then the anode high voltage; when shutting down, turn off the anode high voltage first, and then turn off the cathode high voltage, that is, the anode high voltage can only be loaded when the cathode high voltage is already loaded, and it cannot be loaded separately. The central controller is a component that directly controls the gyrotron. In order to ensure the reliable operation of the gyrotron and not to be damaged by various accidents, its control logic is complex and the input and output signals are numerous. If an abnormal situation is encountered during installation and debugging, it is difficult to locate where anomalies occur. If there is no abnormality diagnosis function, when an abnormality is encountered, an oscilloscope is needed to capture the abnormality again. Due to the large number of signals, difficult wiring, and the low frequency of some abnormalities, the debugging work is very cumbersome, the efficiency is low, and the work progress is seriously delayed. Therefore, it is imperative to design a real-time online abnormality diagnosis logic. This paper is organized as follows. Section 2 describes the control principle of the central controller of the ECRH system and the logic design of the abnormal diagnosis. The timing simulations of the
normal control and abnormal diagnostic logics, and experimental testing waveform, are presented in Section 3. Finally, we give the conclusions of this paper in Section 4.

2. Design of Gyrotron Controller

2.1. Control signals

The main function of the central controller is to control the switching of the cathode high-voltage power supply and anode high-voltage power supply of the gyrotron according to the trigger signal and the plasma current signal sent by the general control of the EAST device. Because it must be strictly guaranteed that the anode high-voltage is not separately loaded on the gyrotron, it is necessary to detect the output state of the cathode high-voltage source in real time. Once an abnormality is detected, the anode power would be quickly turned off. The input and output signals of the central controller are shown in Fig. 2.

![Figure 2. Main signals for ECRH control system](image)

The signals named TriggerIn_-60, TriggerIn_0, and Ip are sent by the EAST total controller. TriggerIn_-60 is a negative 60-second trigger pulse signal, which is used to notify the ECRH system to prepare for a discharge experiment, because some components in the ECRH system (such as the cathode high-voltage power supply) take a long time from start to ready. TriggerIn_0 is a 0-second trigger pulse signal used to notify the central controller that it can immediately turn on the gyrotron to deliver high-power microwaves to the EAST device. Ip is the plasma current signal sent by the EAST total controller. When the gyrotron outputs microwaves, the Ip signal is valid. When the Ip signal becomes invalid again, it indicates that the discharge process is over. The gyrotron should be closed immediately.

NegHVPre_-60 is the negative 60-second preparation signal of the cathode high voltage power supply, and DAQCtrl_OnOff is the data acquisition control signal, which is synchronized with NegHVPre_-60 at all times. NegHV_OnOff is the output switching signal of the cathode high-voltage power supply, NegHV_Ready is its ready signal, NegHV_OutputState is its output status signal,
NegHV_Voltage is its output voltage signal, and this signal indicates whether the output voltage meets the requirements by the level. PosHV_OnOff is the output switching signal of the anode high-voltage power supply. PLC_Ready is a PLC ready signal. Wave_OutputState is a real-time wave output status signal. Its level indicates whether there is a wave output from the gyrotron. Because the analog signal output by the microwave power detector is noisy, it may cause pulse interference to the Wave_OutputState signal. Therefore, this signal needs to be confirmed two or more times to determine the true state of the wave output more reliably.

Wave_OutputState_Down is the diagnostic output signal when the wave output state is abnormal, IpNull is the diagnostic output signal when there is no plasma current abnormality, NegHV_Down is the diagnostic output signal when the cathode high-voltage output abnormal state occurs, and PLC_Ready_Down is the diagnostic when the PLC ready state abnormality occurs Output signal, NegHV_Ready_Down is a diagnostic output signal when a cathode high-voltage ready state abnormality occurs.

In addition to the above signals, there are various protection and emergency stop signals, collectively called Protection Stop Signals. When any of these signals are valid, the central controller will immediately close the gyrotron and output a diagnostic output signal corresponding to the signal. Collectively referred to here as protection signals.

2.2. Normal control flow

The control flow of the central controller can be represented by the status diagram shown in Fig. 3:

1) Power-up initialization: within 100ms of power on the system, the reset signal is valid, at this time in the "Idle" state, the system is initialized, FPGA will put all output signals in an invalid state (NegHVPre_-60, NegHV_Onoff, PosHV_Onoff, DAQCtrl_OnOff, IpNull is low, Wave_OutputState_Down, NegHV_Down, PLC_Ready_Down, NegHV_Ready_Down, Protection Signals are high);

2) When the PLC ready signal (PLC_Ready) is high, it enters the "Ready" state, and if the -60s trigger signal (TriggerIn_-60) is valid and enters the "TRIGGER_NEG_60" state, the signals NegHVPre_-60 and DAQCtrl_OnOff are set to high so that the cathode high-voltage power supply begins to be prepared and the signal data begins to be collected, and when the cathode high-voltage power supply is ready, the signal NegHV_Ready becomes high;

3) In the “TRIGGER_NEG_60" state, when the NegHV_Ready signal becomes high, if the 0s trigger pulse signal (TriggerIn_0) becomes valid, the signal NegHV_OnOff will be set to high, to load cathode high-voltage power supply for gyrotron. then, the program enters"WAIT_NEGHV_OUTPUTSTATE" state;

4) After waiting for 1ms, the program automatically enters the "CHECK_NEGHV_OUTPUTSTATE" state to detect whether the signal NegHV_OutputState is normal. If the NegHV_OutputState is abnormal (indicating that the cathode high-voltage power supply is not loading properly), the program will jump to the "SHUTDOWN" state, and if the NegHV_OutputState is normal, the program enters the "WAIT_POSHVON" state. 50ms after, the program automatically enters the "WAIT_WAVEOUTPUTSTATE" state, and the signal PosHV_OnOff is set to high, to load anode high-voltage power supply for gyrotron;

5) When the signal PosHV_OnOff is issued, the program waits 1ms in "WAIT_WAVEOUTPUTSTATE" state, and then enters the "CHECK_WAVEOUTPUTSTATE" state to check whether the signal Wave_OutputState is normal. if Wave_OutputState is detected as abnormal, the program enters "WAIT_WAVEOUTPUTSTATEAGAIN" state, wait 1ms, then enter "CHECK_WAVEOUTPUTSTATEAGAIN" state, detect whether the signal Wave_OutputState is normal again. If the signal Wave_OutputState is detected as abnormal again, then the program enters the "SHUTDOWN" state. If the Wave_OutputState detection (or re-detection) is normal, then the program enters the "WAIT_IP" state. After waiting 1ms, the program enters the "CHECK_IP" state, to check whether the signal Ip is normal;
5. If the signal Ip is normal, the program enters the "WAIT_SHUTDOWN" state. If abnormal, goes directly to "SHUTDOWN" state;

7. In "WAIT_SHUTDOWN" state, the program waits for the signal Ip to become invalid (indicating the end of a discharge process) and then normally enters the "SHUTDOWN" state. If a wave output exception is detected at this time, the program enters "CHECK_WAVEOUTPUTSTATE_AGAIN" state. If detected normally, goes directly back to "WAIT_SHUTDOWN" state. When the program enters "WAIT_WAVEOUTPUTSTATE_AGAIN" state and "CHECK_WAVEOUTPUTSTATE_AGAIN" state from "WAIT_SHUTDOWN" state, then if the Ip signal becomes invalid, it is also determined that the discharge process ends normally and immediately enters the "SHUTDOWN" state;

8. When the program enters the "SHUTDOWN" state, the PosHV_Onoff will be set low to turn off the anode high voltage power supply, wait 2ms and then enter "SHUTDOWN2" state, and in "SHUTDOWN2", the NegHV_Onoff will be set low to turn off the cathode high-voltage power supply and wait for 200ns to enter "SHUTDOWN3" state. In "SHUTDOWN3" state, NegHVPre_ -60 and DAQCtrl_OnOff are set to low, and then the program finally returns to Idle State.

2.3. Abnormal diagnosis

In addition to the main control logic described in previous, an exception diagnostic logic is also embedded in the FPGA chip. During the operation of gyrotron, various abnormalities may occur. Without the abnormality diagnosis function, when an abnormality is encountered, an oscilloscope is needed to capture the abnormality again. Due to the large number of signals, difficult wiring, and the low frequency of some abnormalities, the debugging work is very cumbersome, the efficiency is low, and the progress may be seriously delayed.

The abnormal diagnostic logic is to determine whether an anomaly has occurred and the cause of the anomaly is based on the state before the program jumps to the "SHUTDOWN" state and the level of each input signal. When the main control logic is in the idle, ready or shutdown states, the input status signal is abnormal or the protection emergency stop signal is valid will not be determined as an abnormal condition. Only during one discharge progress, an abnormal input status signal may cause an abnormal situation. Exceptions can be divided into 6 cases shown in Table 1.

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**Figure 3.** State machine of the main control logic
### Table 1. Exceptions in the operation of gyrotron

| Type of exception                       | The state before jumping to the "SHUTDOWN" state & Input signal status | Abnormal indication signal |
|-----------------------------------------|-----------------------------------------------------------------------|-----------------------------|
| PLC ready state abnormal                | States 2 ~ 12 & PLC_{Ready} is low                                    | PLC\_{Ready\_Down}          |
| Cathode high-voltage ready state abnormal| States 2 ~ 12 & NegHV\_{Ready} is low                                 | NegHV\_{Ready\_Down}        |
| Cathode high-voltage output state abnormal| States 4 ~ 12 & (NegHV\_OutputState signal or NegHV\_Voltage signal is low) | NegHV\_{Down}               |
| Wave output state abnormal              | State "CHECK\_WAVEOUTPUTSTATE\_AGAIN" & Wave\_{OutputState} is low    | Wave\_{OutputState\_Down}   |
| No plasma current protection signal is valid | States 2 ~ 12 & any protection stop signal is valid                  | The corresponding protection signal |

3. Simulation and Experimental Testing

The design was implemented on Cyclone II [11] series chips using Quartus II software. We chose VerilogHDL as the programming language. The FPGA system clock uses an external high-precision active crystal to generate a clock signal with a frequency of 29.2412MHz. Since each input signal is asynchronous to the system clock, a two-step sampling of the system clock for all input signals is taken in order to avoid metastability [12, 13]. Timing simulation was performed on the program to verify the correctness of the design. In simulation, the various time intervals involved are appropriately shortened to reduce simulation time and to observe the waveforms more convenient. Fig. 4 is a simulation timing diagram of normal operation. Fig. 5 is a simulation timing diagram when a wave output state anomaly occurs. And Fig. 6 is an experimental testing waveform of one completed discharge process captured by oscilloscope. Fig. 6(a) shows the beginning of a discharge process, and Fig. 6(b) shows the end of a discharge process.

![Figure 4. Normal operation simulation timing diagram](image-url)
4. Conclusion
This paper mainly describes the design of the central controller of the electron cyclotron resonance heating system for the EAST Tokamak device. For the high reliability, high time control precision and fast response requirements of the central controller, FPGA is used as the main control chip. A complex and rigorous gyrotron control flow is designed to detect the important signals of each stage in real time. Once there is a signal abnormality, the abnormal processing is performed or the power supply is directly turned off to protect the gyrotron. For the problem that the gyrotron wave output signal has a large noise, after detecting the abnormality of the wave output signal, two consecutive detections are performed, and only when the two are abnormal, the wave output is abnormal. In addition, on the basis of the main control functions, abnormal diagnosis was also added to locate the cause of the abnormality in runtime. Finally, timing simulation was performed on the FPGA program, which verifies the correctness of the design.

Acknowledgments
This work was supported by the National Key R&D Program of China (Grant Nos. 2017YFE0300200, 2017YFE0300503, 2017YFE0300401, 2017YFE0400600).
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