Steady-State Operation Control of EAST ECRH System

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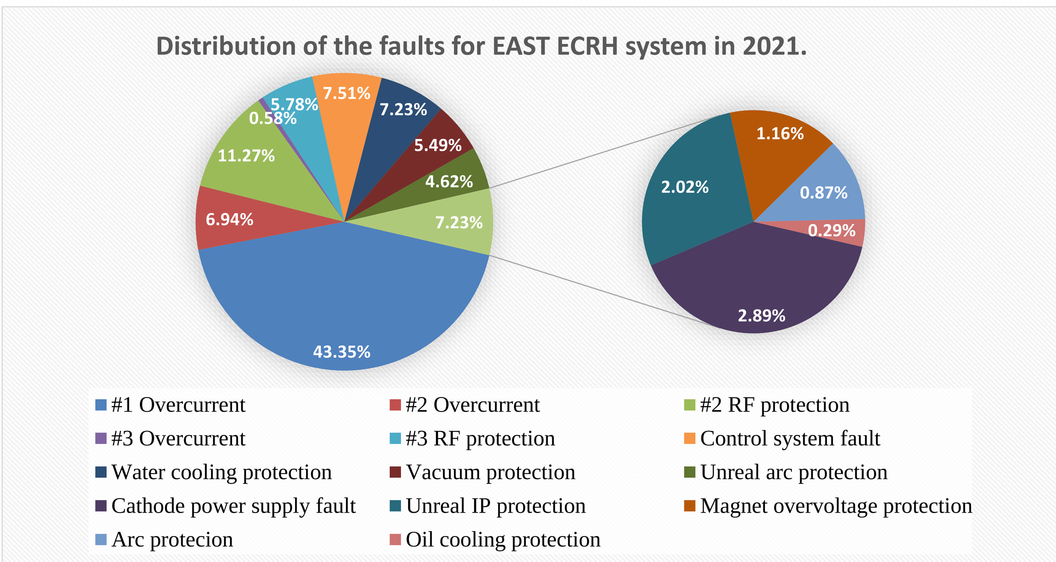
I. INTRODUCTION

- The tokamak is one of the most promising solutions to achieve magnetic confinement nuclear fusion [1]. ECRH is an attractive plasma heating method for tokamaks, which has the advantages of high coupling efficiency, good localization of power deposition, etc. Gyrotrons are high-power microwave sources used in ECRH systems.
- Due to the electromagnetic interference in the actual experiments, especially the gyrotrons are prone to overcurrent in the long-pulse operation [2], it is difficult for the ECRH system to achieve 1000s long-pulse operation. We designed an ECRH system operation scheme, which can realize the 400s~1000s long-pulse steady-state operation of the ECRH system without affecting the safety and stability of the original system.
- In order to achieve 1000s long-pulse operation of the EAST [3] ECRH system, we designed an ECRH system operation scheme, which can realize the 400s~1000s long-pulse steady-state operation of the ECRH system without affecting the safety and stability of the original system. The distribution of the faults for the EAST ECRH system in the 2021 campaign is shown in Fig. 1. The most two encountered types of faults for the EAST ECRH system are overcurrent (include the arc inside the gyrotron and the body current above the threshold limit) and RF protection (dropping out of the RF generation mode). These two faults accounted for 68% of the total faults. The unreal arc protection means the arc protection is not real, but due to the electromagnetic interference, it accounted for 4.6% of the total faults. We designed the steady-state control scheme for the three protections of overcurrent protection, RF protection, and unreal arc protection.



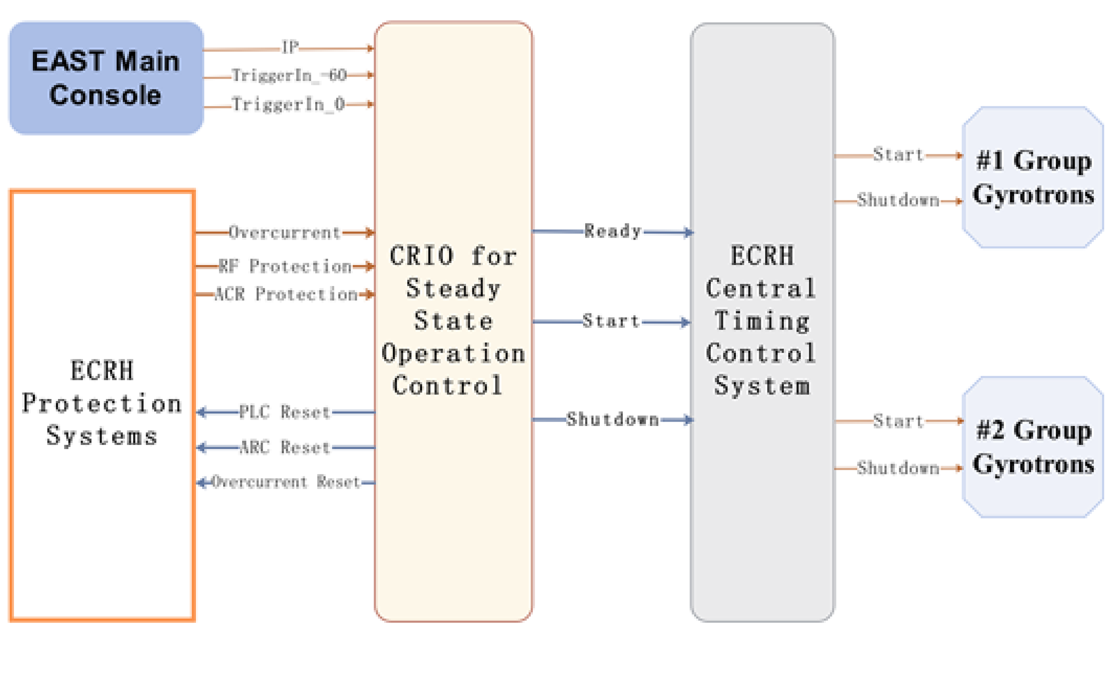
The distribution of the faults for the EAST ECRH system. Unreal arc protection means the arc protection is not real, but due to electromagnetic interference.

II. STEADY-STATE OPERATION CONTROL SYSTEM ARCHITECTURE

The 140GHZ/4MW ECRH system developed by the Institute of Plasma Physics, Chinese Academy of Sciences uses four gyrotrons as the microwave sources [4]. There are three gyrotrons available now in the EAST ECRH system. The 3 gyrotrons are divided into two groups, #1 gyrotron and #3 gyrotron from GYCOM are the #1 group, #2 gyrotron from CPI are the #2 group. Each gyrotron has a separate anode high voltage power supply, and the two gyrotrons in the same group share one cathode high voltage power supply.

In order to realize the 1000s long pulse operation of the ECRH system, the new steady-state operation real-time control system was developed. In order to meet the requirements of signal response speed and sampling frequency, we chose NI cRIO as the hardware that can realize real-time processing and high-speed input and output. It includes the NI Linux Real-Time operating system and reconfigurable FPGA. The NI cRIO-9116 is used as the chassis, the NI cRIO-9039 is used as the controller, and multiple hot-swappable high-speed bidirectional digital modules NI 9401 are used for digital input and output.

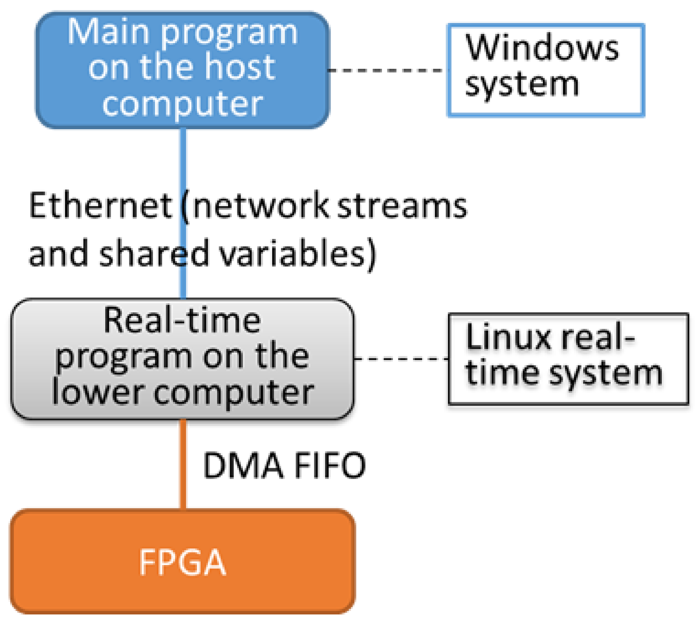
We upgraded the original manual reset to automatic reset. The ECRH steady-state operation control system can output different reset signals under the corresponding protection conditions. The ECRH central timing control system receives a plurality of trigger signals from the ECRH steady-state operation control system, including a ready signal, a start signal, and a shutdown signal. After receiving the corresponding trigger signal, the ECRH central timing control system sends a start-stop command to the power supplies of the gyrotrons to control the working sequence of the gyrotrons.



The signal interactions between the subsystems.

III. LOGIC AND PROGRAMMING

The control software is written based on Labview. It is divided into three parts: the host computer human-computer interaction interface VI, the lower computer real-time VI and the FPGA VI. The host computer host VI and the real-time VI carry out data transmission through shared variables and network streams, and the real-time VI and the FPGA communicate through DMA FIFO (Direct Memory Access First Input First Output). We can set the activation, pulse time and working mode of the gyrotrons on the main program of the host computer. Four working modes were designed, namely manual restart mode, automatic restart mode, timed alternate operation mode, and protection trigger alternate operation mode.



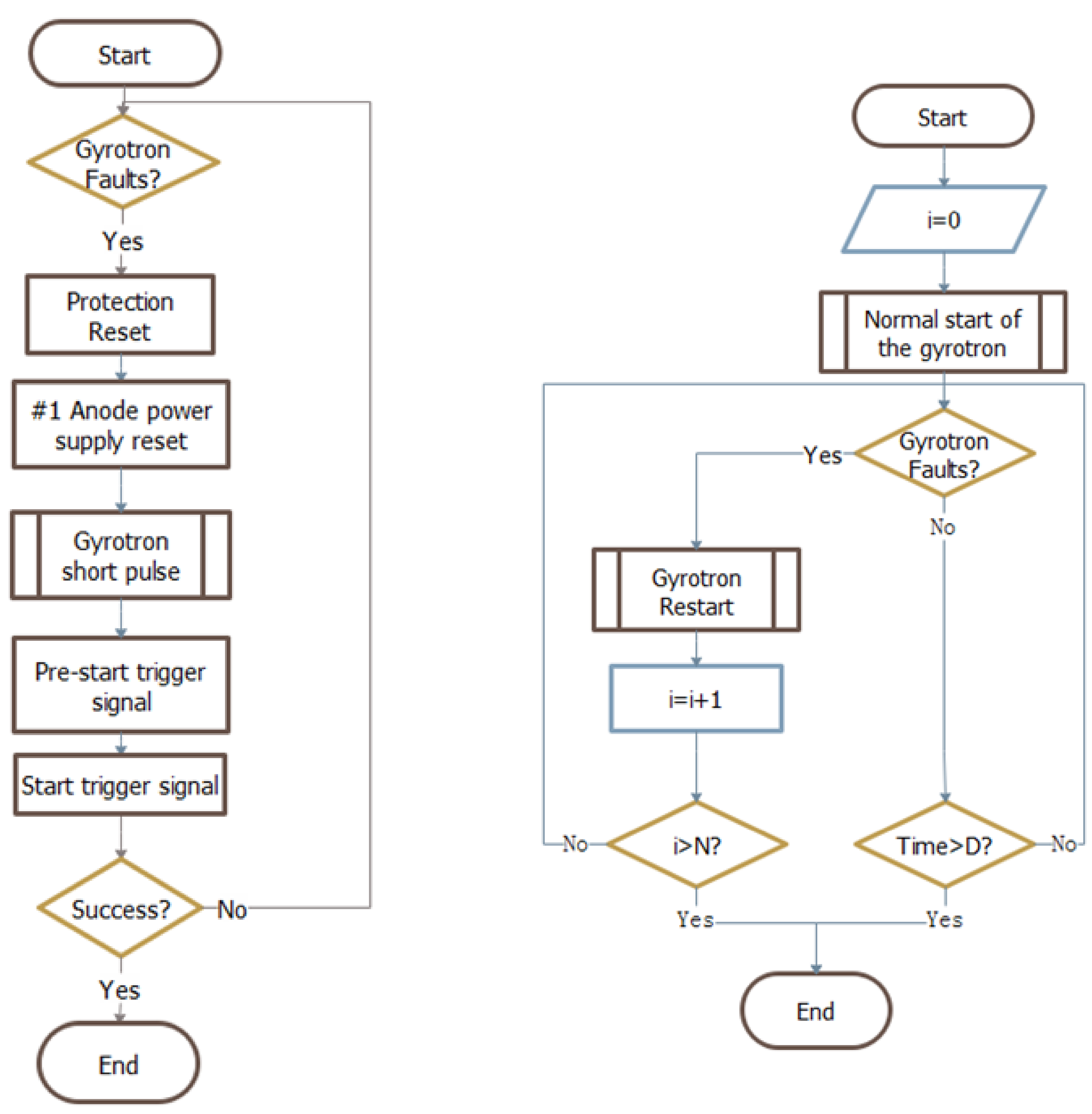
Software architecture for steady state operation control.

The manual restart mode was developed for the test of the steady-state operation control system. The restart of the gyrotron includes three parts: reset, short pulse discharge, and start trigger. A 100ms short pulse discharge can be performed before each long pulse of the gyrotron to improve the stability.

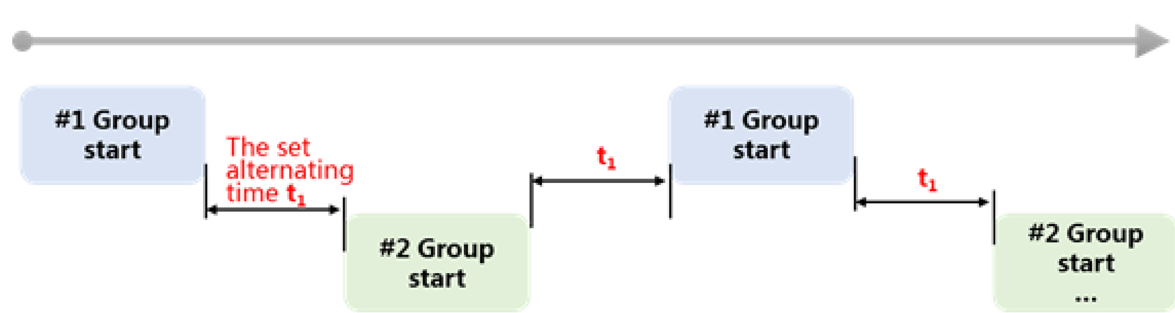
In order to further improve the automation degree of the system and the simplicity of operation, the automatic restart mode was developed. When the protections are detected, the related equipments are automatically reset, and the controller immediately sends out the restart commands. The steps of reset and restart are the same as the manual restart mode, but it becomes the automatic processing of the system.

When the system is in the timed alternate operation mode, the system first starts the #1 group of gyrotrons by default, and the #2 group of gyrotrons is ready for standby. When one group runs for longer than the set alternating time, another group will be activated. In the timed alternate operation mode, the probability of occurrence of gyrotron faults is greatly reduced. The gyrotron will not be restarted if the gyrotron faults occur during the alternate operation time.

An protection trigger alternate operation mode was developed. When one group of gyrotrons stops working due to the protection, another group will be started to take over and continue to run, so that the whole system can run uninterruptedly.



The flow chart of the gyrotron manual restart and the automatic restart mode.



The flow chart of the timed alternate operation mode.

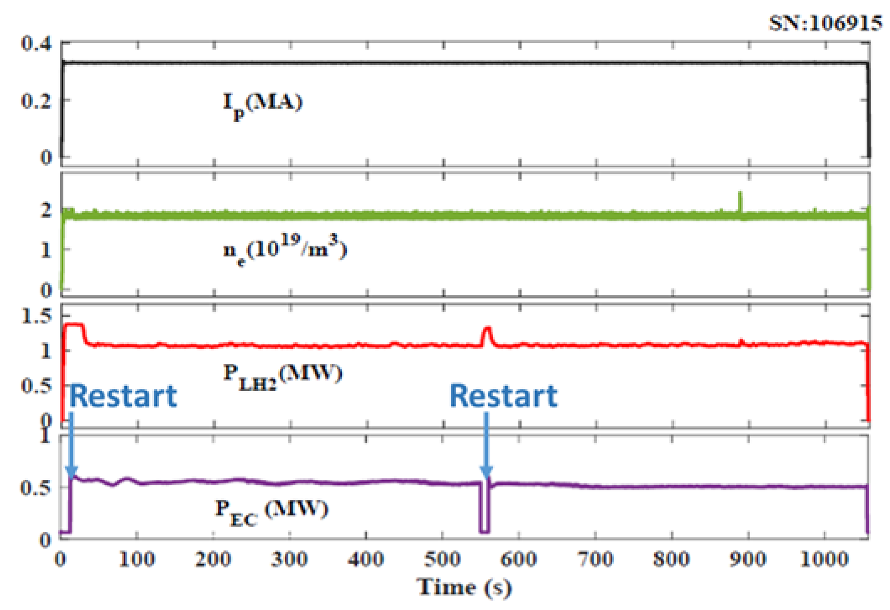
The flow chart of the protection trigger alternate operation mode.

IV. TESTS AND RESULTS

The logic analyzer was used to test the steady-state operation control system. The CRIO sends a ready signal and a start signal to the central timing control system 20.001ms after receiving the Trigger_-60 signal, Ip signal, and Trigger_0 signal of normal timing. A variety of protections have been tested. For example, when the RF protection occurs after normal startup, the CRIO outputs a reset signal after the system is turned off for 11ms. Taking into account all the hardware system delays, it takes a total of 810.006 ms from the occurrence of protection to the restart of the #1 group of gyrotrons.

Test of the steady-state operation control system that was based on CRIO.

The steady-state operation control system has been verified in nearly two rounds of EAST experiments. For example, in shot 106915, the overcurrent occurred at the beginning of discharge and at the time of 550s. The gyrotron restarted after 10s and finally helps EAST to complete the 1056s long pulse discharge. The new developed ECRH steady-state operation system can improve the long-pulse operation capability of the gyrotrons up to 1000s.



EAST ECRH system running for more than 1000s, relying on the automatic restarts.

CONCLUSIONS

We developed an ECRH steady-state operation control system for the 1000s long pulse operation of the EAST ECRH system. Four working modes were designed, namely manual restart mode, automatic restart mode, timed alternate operation mode, and protection trigger alternate operation mode. Three types of faults for the EAST ECRH system are considered, i.e., the overcurrent protection, RF protection, and the unreal arc protection. The NI CRIO and its components were used as the lower computer, and the LabVIEW was used to write the program.

References

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[3] J. Li, and Y. Wan, "The Experimental Advanced Superconducting Tokamak," Engineering, vol. 7, no. 11, pp. 1523-1528, 2021/11/01/, 2021.
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