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RELIABILITY ANALYSIS OF DIGITAL CONTROLLER FOR MAGNET POWER SUPPLY BASED ON OPTOCOUPLER FAILURE

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Abstract

Digital controller is widely used in accelerator power system because of its flexibility and reliability. However, with the accumulation of running time, the power shutdown caused by the fault of the digital controller occurs from time to time, which affects the running efficiency of the accelerator. Through the analysis and detection of the digital controller where the fault occurs, it is found that the reason of the fault is basically the optical coupling failure. In this paper, the fault will be analysed, combined with the nature of the optical coupling failure to reveal the factors affecting the life of the controller. Finally, the problem of optical coupling failure is improved by increasing the heat dissipation means, and the reliability of the controller is improved.

INTRODUCTION

In the China Spallation Neutron Source （CSNS）, there are more than 350 accelerator power supply provide precise excitation current for the magnet of the linac and the fast cycle synchrotron respectively, so that the magnet generates magnetic field in the vacuum tube through which the proton beam passes, and controls the motion path of the proton beam. Therefore, the stable operation of the accelerator power system is an important premise to ensure the beam quality. It is also one of the necessary conditions for the normal operation of the whole spallation neutron source [1,2].

The basic control structure of the power system is shown in Fig. 1. In the face of a large number of power loads, the digital controller becomes the best scheme to achieve these indicators because of its advantages such as high reliability, small temperature drift, convenient parameter setting, high integration and good consistency.

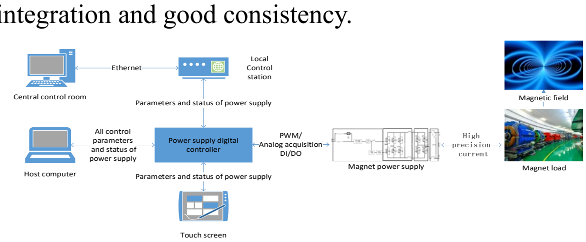

Figure 1: Basic structure of power supply system.

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STRUCTURE OF POWER DIGITAL CONTROLLER

Figure 2 shows the power supply digital controller used by CSNS. The main functions of the controller are showed in Fig. 3, it includes receiving digital acquisition board signals, communication of upper computer, touch screen communication, high-precision PWM output, fault signal reception, fault protection signal output, etc. According to these functions, the hardware circuit of the main control board is divided into driver module, protection module, communication module, storage module, debugging module, fault signal detection module, data acquisition module, and on-board power supply module.

Figure 2: The control board used by CSNS.

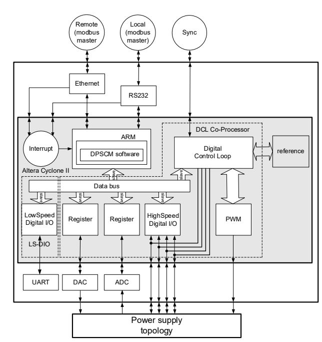

Figure 3: The functional block diagram of the controller used in CSNS.

According to the reliability analysis theory [3], the controller hardware is divided into function modules. As shown in Fig. 4, the controller is a typical series system, and its reliability expression is shown in Eq. (1).

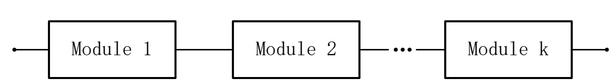

Figure 4: Equivalent model of controller in series.

$$R_{sys} = \prod_{i=1}^{k} R_k \qquad (1)$$

In series system, the failure of any module will lead to the failure of the whole system. In the operation process of CSNS in recent years, it is found that there are almost no power failures caused by controllers in the early stage of

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project investment. However, in the past two years, power failures caused by controller factors have gradually increased. The detection of the controller board itself shows that the faults are all caused by optical coupling isolation devices. Therefore, it is necessary to study and optimize the problem of optical coupling failure.

FAILURE ANALYSIS OF OPTICAL COUPLER

Through the analysis of the controller hardware, high-precision PWM output, fault signal reception, fault protection signal output module in order to achieve the isolation of strong and weak electricity, reduce the interference of power frequency signal on the controller signal in the design of the optocoupler isolation and external circuit connection. The principle of isolation application circuit is shown as follows:

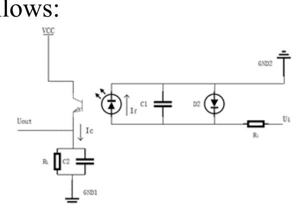

Figure 5: Application circuit of optical coupler in controller.

When used as fault signal input and output, in order to ensure reliable transmission of the circuit when fault occurs, it is set as "1" normal "0" fault, that is, when the fault occurs, the coupling is in the off state, and the rest of the normal running time is in the on-state. For the accelerator, which is a large device running all year round, the optical coupling in the controller is almost constant, which brings a test to its reliability. Since the lifetime characteristics of the optical coupler are closely related to its structure, material characteristics and manufacturing process, the failure of the optical coupler is analysed, which is mainly shown as the current transfer ratio (CTR) decreases (can be calculated by Eq. (2)). When the CTR exceeds the lower limit of the specification range, the output driving capacity of the optical coupler weakens, which will lead to the low level recognized by FPGA, and thus the fault occurs. Fig. 6 (a) is the measured output waveform when the optical coupler is normal/faulty. Figure 6 (a) is the test waveform when the optical coupler is normal, the external input is high level and the FPGA receives the low-level signal after inverting the buffer, and Fig. 6 (b) is the test waveform when the optical coupler is faulty. After the buffer is reversed, FPGA receives a high-level signal, resulting in wrong judgment and false alarm of power failure. Some studies have shown that the failure is mainly caused by the thermal effect of the filling material inside the photocoupling. When the photocoupling conducts heating for a long time or the environment is overheated, the internal wafer will have obvious thermal effect of thermal expansion and cold contraction, resulting in dislocation of the internal wafer, weakening IR light intensity and decreasing CTR.

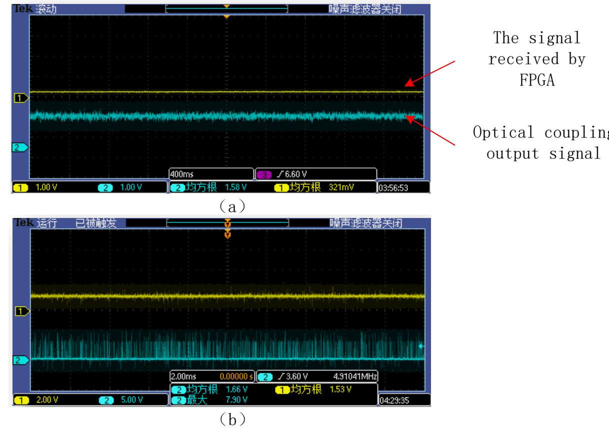

Figure 6: Signal comparison between normal and failed Photocoupling device.

$$CTR = \frac{I_c}{I_f} * 100\% \quad (2)$$

The generalized Eyring model, Arrhenius model and voltage acceleration model are used for acceleration life analysis[4], and voltage is converted into current. The life model is described by Eq. (3).

$$AF = A\exp(\frac{E_a}{kT}) * I^{-n} \quad (3)$$

Where, AF is the life characteristic of the product and is described as the acceleration factor; A is a constant; n is the current coefficient; Ea is the activation energy; T is the temperature; k is the Boltzmann constant, 8.62 × 10-5 eV; I is current x duty cycle. Duty cycle refers to the percentage of the on-off time of the optical coupling in the entire working cycle of the optical coupling. With the acceleration of temperature or current, the overall life of the optical coupler will decrease, thus affecting the life of the entire controller.

In the controller, the photocoupler works in saturation state, its current value is selected according to the product manual, so the main cause of its failure is temperature. Since the power supply adopts the cooling mode of forced air cooling, and the control case is embedded in the power supply cabinet, a large amount of heat will be transferred to the control case during the operation of the power supply. Thermal analysis software is used to model the power supply and analyse the temperature at the controller, as shown in Fig. 7.

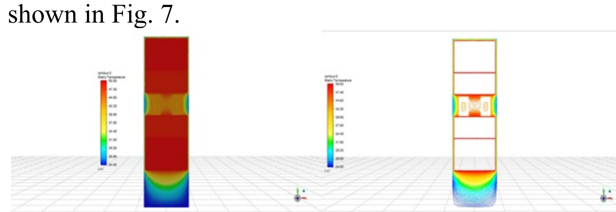

Figure 7: Temperature distribution simulation diagram of power supply.

It can be seen from the simulation diagram, there is a high temperature at the control box when the power supply is running, and the thermoelectric couplers are used to measure the actual power supply. The measurement results

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show that the temperature at the surface of the optical couplers reaches 65℃, and the service life of the optical couplers is reduced because of long-term operation at high temperature. Therefore, in order to extend the service life of the optical couplers and improve the reliability of the power supply, we add heat dissipation measures in the control box. Figure 8 shows the simulation of heat distribution after a cooling module is added at the bottom of the control chassis. It can be clearly seen that the temperature at the control chassis is effectively reduced. The heat dissipation parts were made and installed and tested. Figure 9 shows the temperature comparison of the heat dissipation fan before and after opening in the laboratory. As shown in Fig. 10, the deployment is finally completed on the actual power supply, and long-term measurement is carried out. The results show that after the addition of heat dissipation measures, the temperature at the optical coupling decreases by 10℃, effectively extending the life of the device.

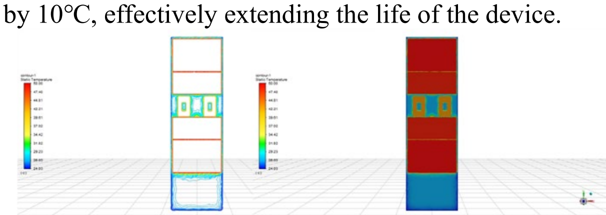

Figure 8: The temperature field distribution of the power supply after the heat dissipation module is added.

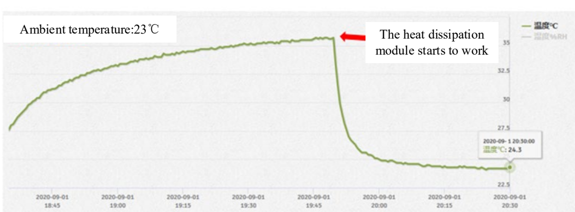

Figure 9: The laboratory measures the controller temperature comparison after the heat dissipation module began to work.

As shown in Fig. 10, the designed heat dissipation module is finally installed on the power supply and has been running for a long time. No fault has occurred.

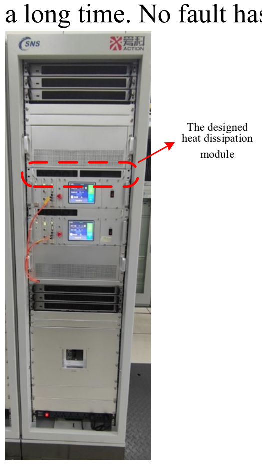

Figure 10: The power supply after the heat dissipation module is installed.

CONCLUSION

In this paper, through the analysis of the optical coupling failure in the power controller, the main reasons affecting the life of the controller are obtained. The design of a special cooling module can reduce the temperature of the controller in the power cabinet, which can effectively improve the reliability of the controller.

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