Research on Precise Servo Control Technology for Integrated Aircraft Utility System

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Abstract. In this paper, stepper motor servo valve is selected as the execution unit to adjust environmental variables, such as temperature, pressure and flow of the aircraft environmental control system and fuel thermal management system, to meet new generation aircraft requirements of the reliability of the servo valve, the controllability of the opening and closing angle, as well as the controllability of the opening and closing angle requirements. Since there are a large number and great variety of stepping motor controllers in the airborne system, a unified architecture design is adopted, and it is integrated into the Remote Execution Unit (REU) of the supporting equipment of the aircraft utility system, reducing the aircraft weight and improving the integration level. To enhance the accurate positioning and rapid isolation of stepper motor faults, a fault diagnosis method for inverse-time protection power drive circuit and hierarchical interface are designed to improve system safety and testability. To tackle the temperature rise, noise, torque ripple, start out-of-step and stop overshoot, caused by the stepper motor drive current distortion, high-deterministic command transmission technology and constant current drive technology based on fixed duty cycle and segmented pneumatic technology are developed to perfect the control accuracy of stepper motor servo valve. The test results show that the stepper motor servo control system designed in this paper has high control accuracy and better engineering application value.

Keywords: Utility system · Servo control · Stepper motor · Inverse-time protection · Constant current drive

1 Introduction

There is a large number of click-driven valves in the aircraft environmental control system and the fuel thermal management system. These are able to adjust control parameters in the system, to adjust the temperature, to adjust the pressure and to control the flow and other functions within a time limit [1–3]. Stepper motor servo valve has become the first choice for electric servo valve because of its high control precision with flexible and convenient control method [4]. Stepper motor is a servo motor that can realize precise angle control. Through the cooperation of controllers, the valve angle can be adjusted with time limit. Its essence is an actuator that converts the electrical pulse signal into the corresponding angular displacement [5]. By controlling the frequency

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and quantity of the pulse signal, the adjustment of speed and position can be fulfilled, which can meet requirements of reliability, controllability of opening and closing angle and environmental resistance of new generation aircraft servo valve [6].

To deal with the large number and variety of stepping motor controllers in the airborne system, a unified architecture design is proposed and integrated into the Remote Execution Unit (REU) of the supporting equipment of the aircraft utility system to reduce the aircraft weight and improve the integration level. Aiming at accurate positioning and rapid isolation of stepper motor faults, a fault diagnosis method for inverse-time protection power drive circuit and hierarchical interface are designed to perfect system safety and testability. Targeting at the temperature increase, noise, torque ripple, start out-of-step and stop overshoot caused by the stepper motor drive current distortion, high-deterministic command transmission technology, constant current drive technology based on fixed duty cycle and segmented pneumatic technology are developed to improve the control accuracy of stepper motor servo valve. The test results show that the stepper motor servo control system designed in this paper has high control accuracy and better engineering application value, which therefore can be widely applied in aerospace and other industrial fields.

2 Overall Design

Figure 1 shows the block diagram of the stepper motor servo control system. Three isomorphic Control Computers (CC) constitute the computing center of the utility system, which is used to deal with the motor rotation direction, speed and position information. There are five isomorphic Remote Interface Unit (RIU), distributed in various locations of the aircraft to collect regional temperature, pressure, flow information, and etc., 10 isomorphic REUs are used to receive control commands, to generate a fixed pulse sequence, and to drive the motor to rotate to the predetermined position, to realize the real-time adjustment of the aircraft am temperature, pressure and thermal energy. Each REU contains three stepping motor interfaces. CC, RIU and REU utilize the IEEE-1394 bus for data and command interaction to achieve highly deterministic data transmission and action control of the control system. The internal stepping motor servo control system of REU mainly includes servo controller, double H power bridge driver with inverse time protection function, double H power MOSFET bridge, phase current, voltage acquisition circuit, output feedback and position feedback.

The system adopts the structure of DSP + FPGA, in which DSP is able to realize the algorithm control and bus communication, while FPGA can fulfill the state information acquisition and BIT calculation. The dual H power bridge driver with inverse time protection function can generate the driving signal of the dual H power MOSFET bridge, and realize the inverse time characteristic protection of the current position range, and the output feedback are realized to complete the BIT detection of the system based on the current.

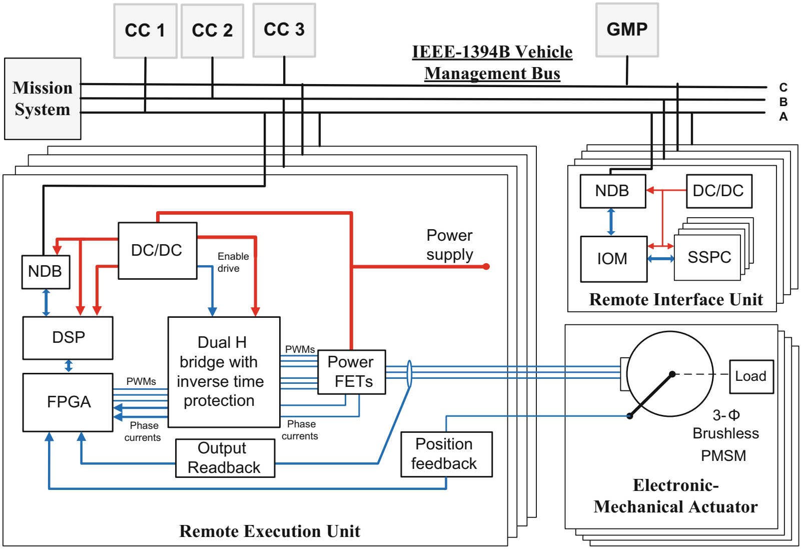

Fig. 1. Block diagram of stepper motor servo control system.

3 Drive System Design with High-Reliability

3.1 Hardware Design

Figure 2 illustrates the hardware functional block diagram of the stepper motor control system. The system mainly includes stepper motor DSP controller, FPGA controller, upper bridge power drive with inverse time protection, lower bridge power drive, power main loop, and current monitoring. The phase current acquisition circuits are fulfilled by current Hall, and the output acquisition circuits are implemented by an 8-channel configurable discrete input chip. The FPGA controller receives motor drive instructions sent by the DSP controller. The tube MOSFET is turned on and off by the driving circuit, and the driving current acts on the motor winding to drive the motor to rotate. The main power circuit can be configured as 4 groups of 28 V/open discrete output interface or 4 groups of ground/open discrete output interface individually to achieve the interface usage, reducing diversification within products, and reducing aircraft weight. The upper-bridge power drive circuit with inverse time protection function is able to monitor the current of the single-phase bridge arm in real time, to calculate the energy accumulation and dissipation of the current, and to realize Trip protection when the duration of the current amplitude reaches the protection threshold. The Trip state will be reported to CC through the bus in real time, while CC will judge the Trip state comprehensively and therefore generates a command to clear the Trip state or lock the interface.

3.2 Power Drive Design Based on Inverse Time Protection

Both stepper motor interface over current and short circuit protection are able to prevent abnormal short circuit damage to the motor or interface. However, traditional current

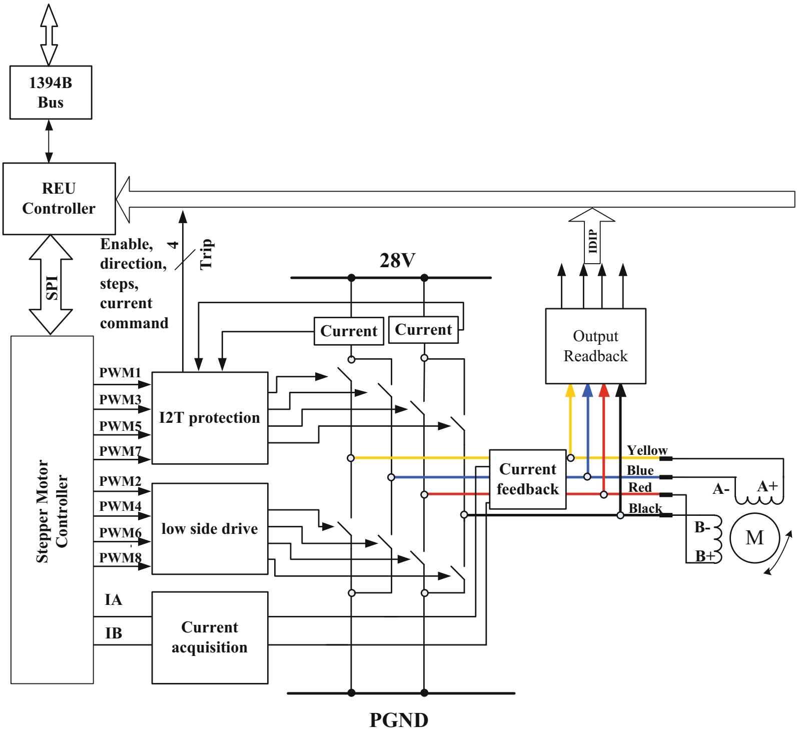

Fig. 2. Hardware functional block diagram of stepper motor control system.

protection hardware circuit is complex and the protection action is hysteretic, which reduces the reliability and security of the system [7]. Figure 3 shows the block diagram of the inverse time limit protection of the 28 V/on discrete output interface, which is mainly composed of sampling resistors, current amplification, current comparison arrays, inverse time limit controllers and power drive parts. The control commands are sent from the DSP controller to the inverse-time controller. The inverse-time controller accumulates energy according to the output state of the current comparison array. When the energy accumulation reaches the threshold value, the output is turned off, and a Trip signal is sent to set the hardware in a safe state until CC contact Trip. In order to improve the real-time performance and reduce resource overhead, the traditional A/D conversion circuit is not applied in this paper to collect the voltage corresponding to the power current, but it is compared with a given reference voltage matrix to generate a current indication signal array. The level inversion state is an overcurrent state. The system has 11 inversion thresholds. Different inversion thresholds represent different energy accumulation step values. When the energy accumulation is greater than the protection threshold, the Trip protection signal is output.

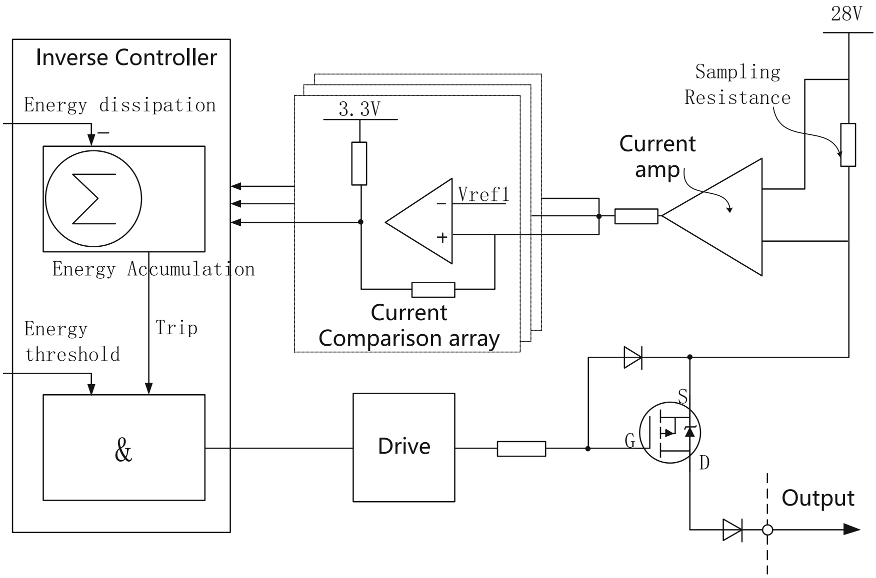

Fig. 3. 28 V/ON discrete output interface inverse time protection principle block diagram.

3.3 Fault Diagnosis Technology of Hierarchical Interface

Stepper motor fault diagnosis technology mainly includes hardware electric furnace detection, motor online status monitor and isolation as well as location of short-circuit fault [8]. When the stepper motor interface fails, the system tube adopts the fault diagnosis technology of fault detection and isolation of the graded interface to realize the rapid location and isolation of the fault. The basic principle of the hierarchical interface fault diagnosis technology is to divide the stepper motor faults into three types that is, the internal interface fault, the external load fault, and the three-chamber REU fault. The internal interface fault is used to diagnose the internal double H-bridge fault, the external load fault is used to detect the motor disconnection and short-circuit fault, while REU fault is used to Fig. out the control part fault. The system utilizes the internal interface of REU to realize fault detection through table configuration technology.

The timing of fault detection is when the interface is in normal operation. There is no need to apply special fault detection operation to the fault detection of the interface, and the normal operation of the old interface is carried out synchronously. The fault detection method is low power consumption, short path and high coverage. Table 1 shows the fault judgment logic of the stepper motor interface of the hierarchical interface.

4 High-Precision Stepper Motor Control Technology

4.1 Command Response Technology with High Deterministic

REU utilizes the IEEE-1394 bus to realize the highly reliable and deterministic transmission of control commands and responses [9]. The IEEE-1394 bus pre-assigns fixed

Table 1. Hierarchical interface stepper motor interface fault judgment logic.

Fault level	Fault type	Detection method
Internal interface failure	28 V/on	Output readback
	Ground/open	Output readback
	Readback circuit failure	Readback circuit BIT
	Current monitoring circuit failure	Voltage acquisition
	Current compare array failure	Array voltage self-test
External interface failure	Short	Abnormal current
	Disconnection	Single upper arm output, H-bridge readback status is inconsistent
Remote actuation unit failure	Electricity failure	Voltage acquisition judgment
	Processor failure	Processor BIT
	Bus communication failure	Bus BIT
	FPGA failure	Answer handshake

transmit offset, receive offset and data pump offset to each node, and plans the number and size of asynchronous flow packets, as well as provides the ability to change the time offset of remote nodes [10]. In the first bus cycle, REU can change its own predefined time offset according to the packet tail information of the asynchronous stream sent by the effective bus controller, and can arrange the system communication sequence reasonably with the help of the time offset and pre-allocated bandwidth, to ensure that the key data has a deterministic time delay that can be designed during the transmission process. Figure 4 shows the description of the de-qualification delay of the system. It is assumed that it takes $\Delta T1$ for RIU to collect flow pressure information to complete the asynchronous flow packet grouping, and $\Delta T2$ for CC to calculate the special and rotational speed position commands from receiving RIU data, the time spent by REU from receiving CC command to starting to drive the actuator is $\Delta T3$, and the transmission delay of asynchronous flow packets between bus nodes is $\Delta T4$. By rationally designing the time offset of RIU, CC and REU, it can be guaranteed that the response time delay of the motor control command in the utility system is able to be controlled at ($\Delta T1 + \Delta T2 + \Delta T3 + 2*\Delta T4$).

4.2 Constant Current Drive Technology Based on Fixed Duty Cycle

Figure 5 shows a schematic diagram of a two-phase four-beat stepper motor with a fixed duty cycle chopper drive. In each continuous shooting control, the first beat implements a 100% duty cycle drive signal, and the second beat implements a fixed duty cycle drive signal. The fixed duty cycle is 0.4–0.6, and the frequency is 6–20 kHz. The first beat

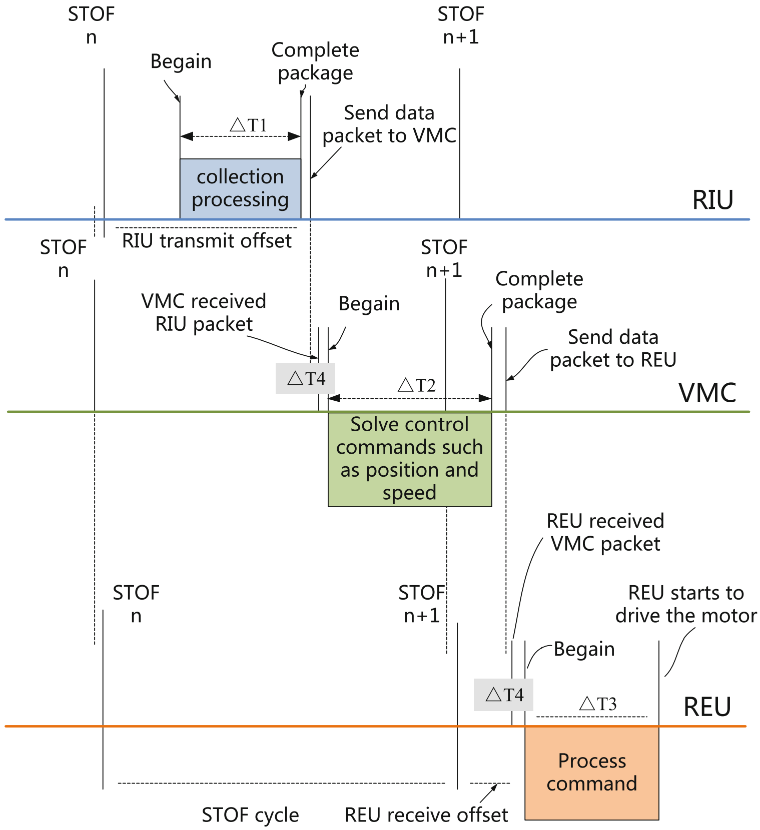

Fig. 4. Description of system deterministic delay.

control is used to increase the start-up capability. When the click turns the equilibrium position, a fixed duty cycle driving signal is applied, which can reduce the overshoot current as well as the torque ripple, and improve the control accuracy and reliability of the system effectively. The constant current drive of the stepper motor based on the fixed duty cycle is realized by an all-digital controller, omitting the complex PID control algorithm. The hardware is simple, the software is flexible with strong portability and expansibility.

4.3 Segmented Startup Technology

The traditional motor startup generally requires the design of complex acceleration and deceleration curves and rotor position positioning methods [11]. According to the motor load condition, this paper proposes a low-complexity segmentation determination method, which includes:

The first stage: Execute the last rotation command of the last rotation, the starting frequency is half of the rated operating frequency, and the number of starting step is 1,

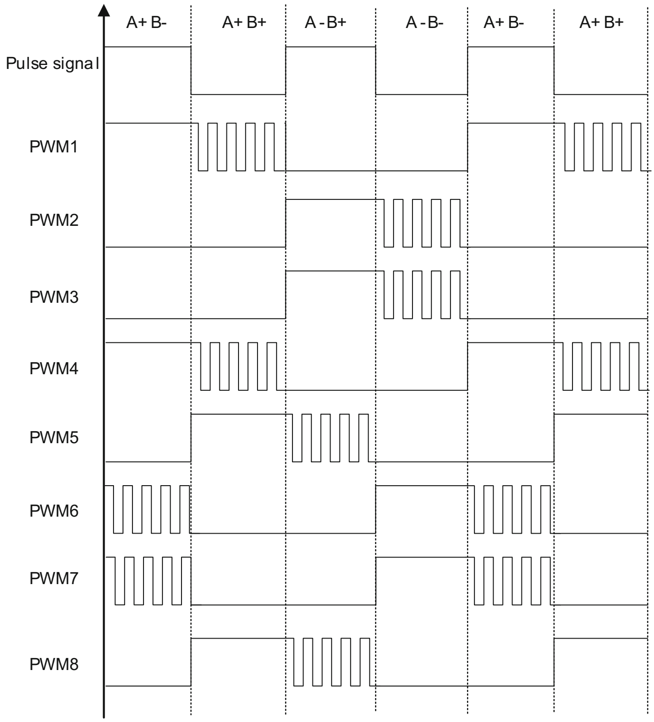

Fig. 5. Schematic diagram of a two-phase four-beat stepper motor with a fixed duty cycle chopper drive.

by which the motor can realize the starting positioning and obtain the low-frequency oscillation kinetic energy;
The second stage: the execution start frequency is 3/4 of the rated frequency, and the number of start step is 4;
The third stage: The motor runs at the rated frequency, and the number of rotation step is (total steps-4).

After the above simplification, the minimum starting step of the motor are only 5, and the rotation out-of-step probability of small steps can be controlled below 0.1%, which improves the control accuracy of the system.

5 Software Design

The stepping motor software sets three different working modes, which are normal working mode, safe working mode and testing mode. In the normal working mode, the software generates the driving sequence according to the pulse distributor. In the safe working mode, it is used for fault handling, and the interface is in a safe state. In the test mode, the 28 V/on discrete output test, ground/on discrete output test are completed. The system adopts stepper motor when appearing and mixing, which supports two-phase four-beat control. The forward rotation logic of the motor is AB-AB‘-A‘B‘-A‘B, while the reverse logic is AB-A‘B-A‘B‘-AB‘. Figure 6 shows the operation diagram of the motor control software in normal operating mode. After the initiation of system, the valid of the rotation enabling signal is checked. When the rotation enable is valid, the PWM peripheral module is turned off, and the step-by-step command is further judged. When the command is valid, different pulse distributors are called according to the rotation direction, and send out driving signals. During the rotation, when the output of two consecutive beats is valid, the first beat implements a 100% duty cycle drive signal, and the second beat fulfills a fixed duty cycle drive signal, in which the fixed duty cycle is 0.4–0.6, and the frequency is 6–20 kHz. If the above rotation process is disabled or the step-by-step command is invalid, all drive signals will be turn off to ensure that the motor work is in a safe state.

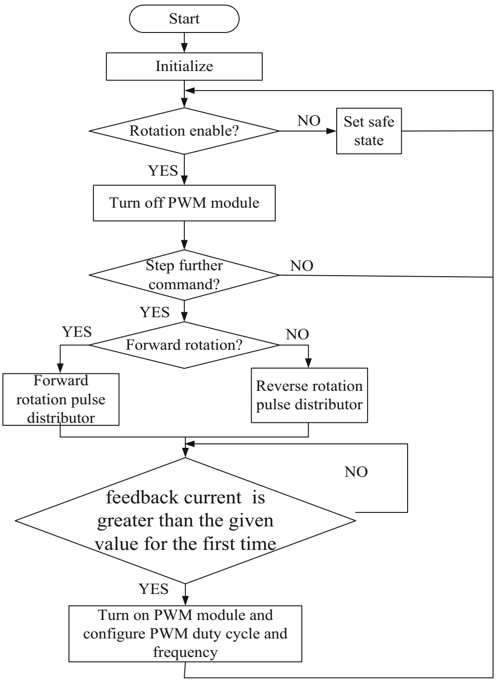

Fig. 6. Software running flow chart.

6 Experiments

A two experimental verifications are carried out in this paper. In order to verify the inverse-time protection strategy of the power output circuit, the experimental environment shown in Fig. 7 is constructed. The working voltage of REU is provided by an external DC power supply with an amplitude of 28 V. The power electronic load is used to simulate different Real load under current, and IEEE-1394 bus monitor is applied to monitor REU Trip status. The time-current inverse-time protection test waveform fitting curve is shown in Fig. 8. When the load current is more than 8 times the rated current, the turn-off protection time is 90 μs. The higher the current value, the shorter the protection time, ensuring the safe and reliable operation of the system.

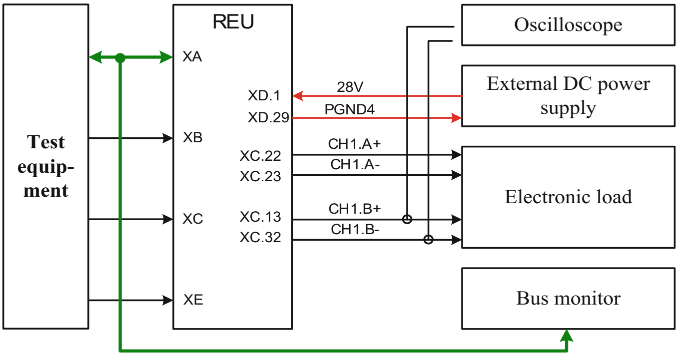

Fig. 7. Inverse time protection test configuration.

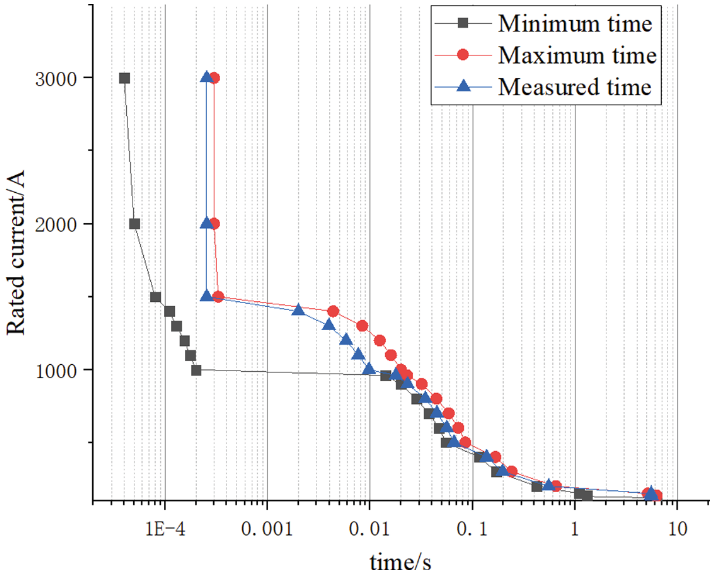

Fig. 8. Time-current protection fitting curve.

In order to verify the control accuracy of the stepper motor servo valve, the torque test environment shown in Fig. 9 is established. The parameters of the stepper motor used in the test are that the maximum speed is 750 steps/s, the rated speed is 600 steps/s, the rated current 3 A, the step angle is 5°, the reduction ratio is 600:1, A-phase winding resistance is 4.6 Ω (measured 4.88 Ω), and B-phase winding resistance is 4.6 Ω (measured 4.52 Ω). Figure 10 demonstrates the 50% fixed duty cycle phase current waveform. The fixed duty cycle frequency is 10 kHz and the duty cycle is 50%. Test results show that the stepper motor servo control strategy developed in this paper can limit the current fluctuation within 10%, and the current fluctuation and torque fluctuation can be decreased, with high control accuracy.

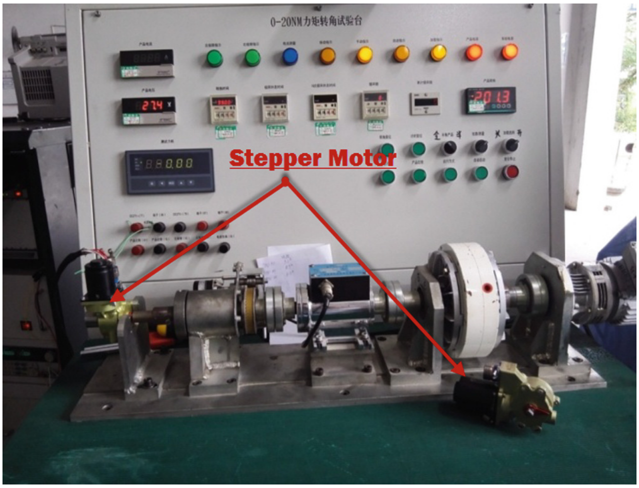

Fig. 9. Torque torque test bench.

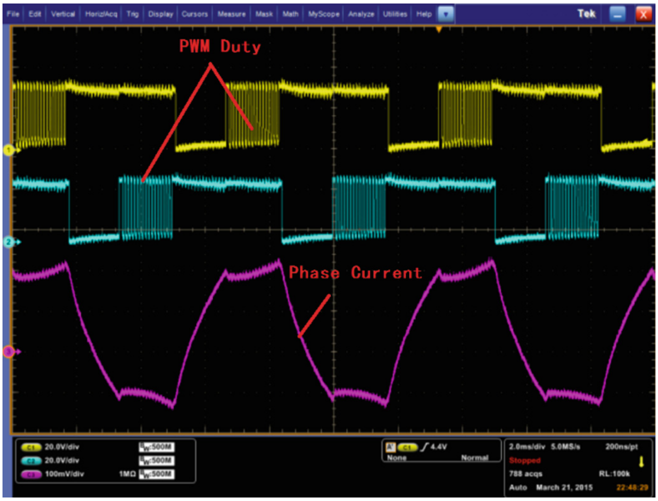

Fig. 10. 50% fixed duty cycle phase current waveform.

7 Conclusion

In this paper, stepper motor servo valve is selected as the execution unit to adjust environmental variables. A unified architecture design is adopted, and stepping motor controllers are integrated into REU of the supporting equipment of the aircraft utility system, reducing the aircraft weight and improving the integration level. To enhance the accurate positioning and rapid isolation of stepper motor faults, a fault diagnosis method for inverse-time protection power drive circuit and hierarchical interface are designed to improve system safety and testability. To tackle the temperature rise, noise, torque ripple, start out-of-step and stop overshoot, the high-deterministic command transmission technology and constant current drive technology based on fixed duty cycle and segmented pneumatic technology are developed. The test results show that the stepper motor servo control system designed in this paper has high control accuracy and can be widely applied in aerospace and other industrial fields.

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