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Design and Implementation of a DC Switch Machine Electronic Control Module

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Abstract: The electronic interlocking system offers advantages including flexible configuration, reduced cost and space requirements, and simplified debugging and installation compared to traditional relay-based interfaces. In order to realize the electronic control of DC switch, a DC switch machine electronic control module was designed, which adopts two-out-of-two security architecture, and The switch interface unit utilizes a heterogeneous design combining a mechanical contactor and an electronic switch to mitigate common-cause failures. The software, developed in compliance with the EN 50128 standard, comprises five components: initialization, communication control, state machine calculation, driving and application program. Reliability analysis demonstrates that the module meets the requirements for Safety Integrity Level 4 (SIL 4), and has passed a series of experiments. The electronic control module of DC switch has high reliability and availability, and meets the requirements of all-electronic computer interlocking system of rail transit.

Keywords: DC Switch Machine; Electronic Control Module; Redundancy; Heterogeneous Structure; Reliability; Two Out of Two; Functional Safety; Railway Signalling
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1.Introduction

All-electronic computer interlocking system has the advantages of high electronic integration, high intelligence, simple system structure, powerful functions, flexible configuration and wide control range, etc. It has emerged as a key development trend in rail transit signalling systems[1]. Compared with the widely used relay interlocking system at present, the electronic interlocking system has many advantages such as eliminating relay interface circuits, providing a clearer system architecture, reducing equipment quantity, lowering maintenance intensity, and enhancing the system's informatization and intelligence levels[2], and has been widely used in foreign railways [3,4]. For example, the control unit of Siemens' electronic interlocking system is two out of three, which can realize regional interlocking[5]. However, due to the restriction of electrical characteristics of domestic signal equipment, foreign all-electronic computer interlocking system cannot be readily integrated into domestic rail transit control systems through simple adaptation. Therefore, the autonomous development of all-electronic computer interlocking system is therefore urgently required. The full electronic execution module of computer interlocking developed by Lanzhou Jiaotong University, a domestic signal manufacturer, employs a electronic computer interlocking system featuring a communication interface with the central interlocking computer, which has been applied in a few railways in China[6], and the full electronic interlocking system made by China Railway Signal and Communication Corporation has been applied in the field section of power plant[7].

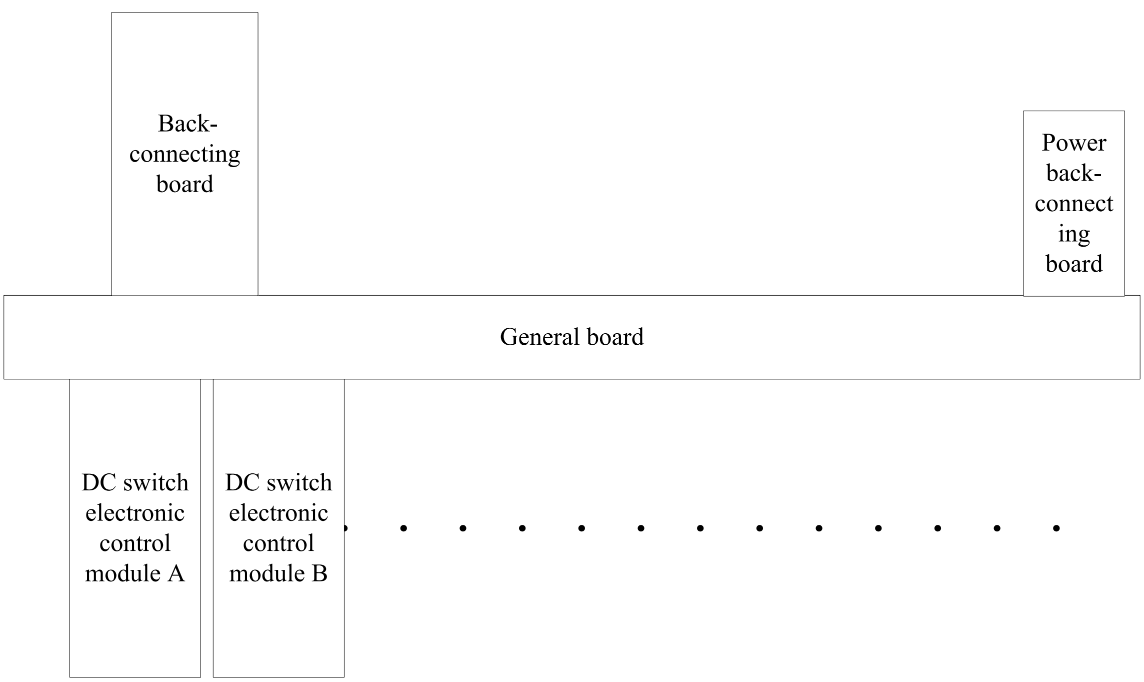
Switch is widely used in rail transit signal equipment, electronic control module should have high reliability and safety[8,9]. At present, the electronic control unit of switch adopts two-out-of-two isomorphic architecture, which realizes the control and state acquisition of switch switch circuit[10,11]. Isomorphic control architectures carry a risk of common-cause failures. In order to improve the reliability and availability of equipment, a heterogeneously redundant electronic control module for DC switch machines was designed and implemented, prioritizing safety. After a series of tests and experiments, it is integrated into an autonomous all-electronic computer interlocking system, which has been successfully applied to some domestic field sections and urban rail transit projects, and the availability of the electronic control module is verified.

2.Overall System Architecture

The development of an electronic computer interlocking system aims to extend the interface function of safety relay and related relay circuit in the executive layer of computer interlocking system at present, and replace the digital quantity acquisition driving executive layer circuit and safety relay interface layer circuit with various intelligent electronic executive units to directly control the wayside equipment such as switch machine and signal machine[12].

The switch electronic control module system structure is composed of main and standby DC switch electronic control module, back-connecting board, general board and power back-connecting board. Each electronic control module on the universal board is equipped with two sets of address jumpers to configure a unique CAN address ID of the electronic control module and complete the communication with OCU (Object Controller Unit). The electronic control module of DC switch controls the switch after receiving the switch control command, and at the same time performs self-diagnostics on the output state. If the read-back state is inconsistent with the driving command, it initiates a safety shutdown procedure. Dynamic pulse signals generated by the master and slave CPUs control the vital relay, causing it to drop, cutting off both the internal power supply of the DC switch electronic control module and its external output. The backplane facilitates the connection of output lines. The universal board provides the power connection of the electronic control module of DC switch, and interconnections between the module and the rear connecting board. The system structure diagram of DC switch electronic control module is shown in Figure 1.

Figure 1 System Architecture Diagram of DC Switch Electronic Control Module



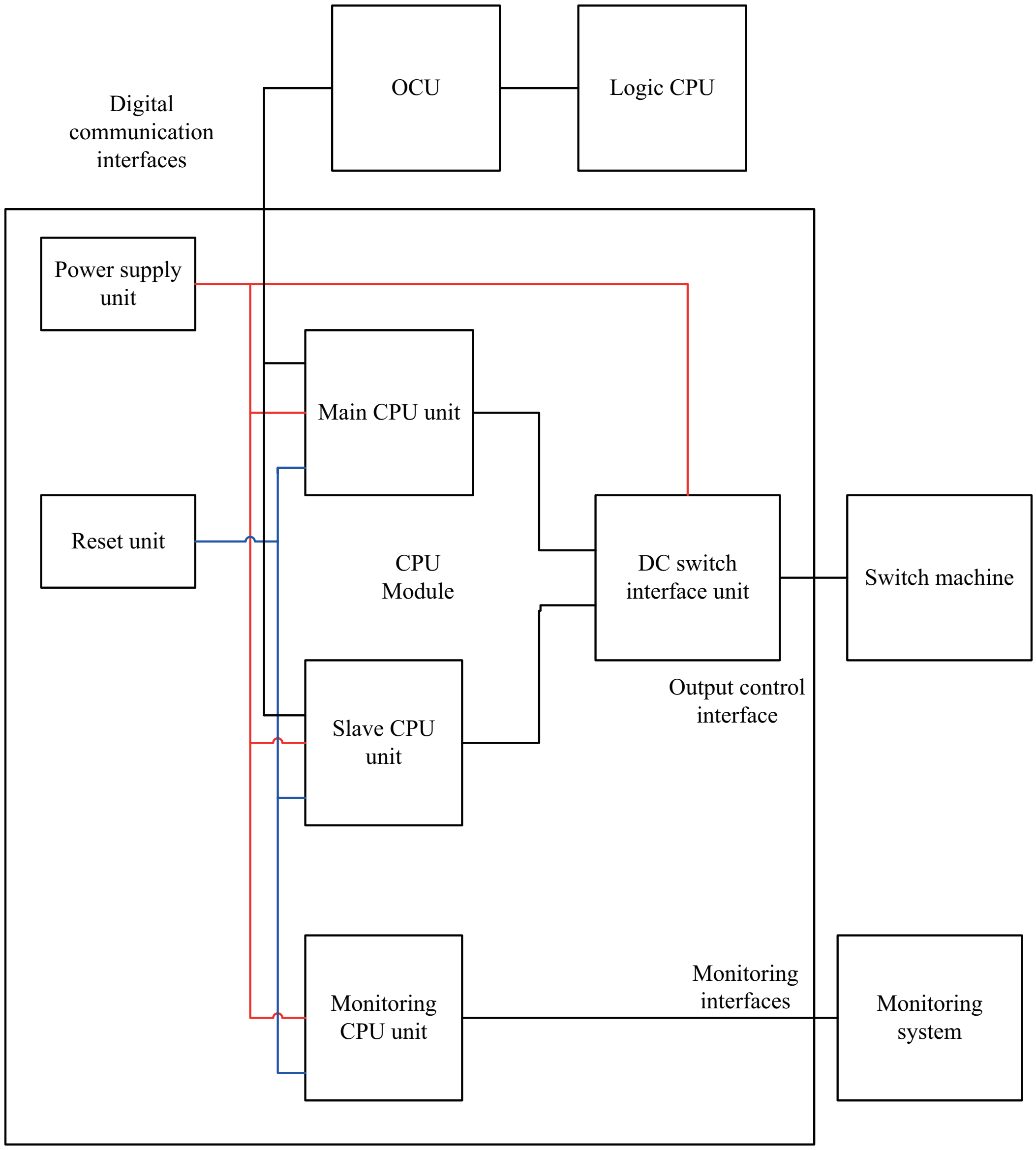
3.Hardware Circuit Design

3.1 Hardware Architecture

The DC switch electronic control module is composed of CPU unit (including main CPU unit, slave CPU unit and monitoring

CPU unit), power supply unit, reset unit and DC switch interface unit. The master and slave CPUs exchange information via a serial port, and complete two-out-of-two safe calculation by real-time comparison. The master and slave CPU units communicate with the Object Controller Unit (OCU) via a digital communication interface, and receive switch operation commands issued by interlocking logic and return switch state information. The DC switch interface unit of the module completes the drive and state acquisition of the wayside switch machine through the output control interface. The monitoring CPU reads the status of the master CPU unit and the slave CPU unit via a serial port, and transmits the status information of the DC switch electronic control module to the monitoring system via a dedicated monitoring interface. The hardware composition and external system connection of DC switch electronic control module are shown in Figure 2.

Figure 2 Connection Diagram of Internal Unit and External System of DC Switch Electronic Control Module



3.2 Digital Communication Interface

Electronic interlocking logic communicates with DC switch electronic control module through OCU. OCU utilizes an IP-based network control mode. Compared to existing relay interfaces, the standard IP network interface offers advantages of wide adoption, lower cost, and greater convenience. This digital interface facilitates the sharing of field data collected by the electronic control module in the rail transit control network, thereby enhancing compatibility and interoperability of the interlocking system, extending its control distance, simplifying future upgrades and transformation of the interlocking system in the future, and providing a foundation for interconnection and intercommunication with other systems. The digital control interface protocol of electronic interlocking is shown in Table 1.

Table 1 The Digital Communication Protocol of DC Switch Electric Control Module

Control message	Content
The general header of switch electronic control module from the interlocking logic unit	Target Controller ID, Communication Protocol Version, Data Version, Control Module Number, CRC, Switch Electronic Module Control Command
Control command of switch electronic control module	Mode type, module type, control (lock protection relay, normal operation relay, reverse operation relay) command, switch machine type, start-up sequence
Electronic control module of switch-general header	Target Controller ID, Software Version, Communication Protocol Version, Data Version, OC Working State, Module Number, CRC, Switch Electronic Control Module State Information
Status information of switch electronic control module	Mode type, module type, switch relay (lock protection relay, protective relay, normal indication relay, reverse indication relay) status

3.3 Output Control Interface

Integration of Driving and Indication Power Supplies: A rectifier circuit integrated within the module eliminates the need for an external DC driving power supply, driving power supply and indicating power supply share a 220V AC power supply.

“Take 2”(1oo2) Power Drive Architecture: The driving circuit implements a “take 2” safety-redundant structure: the power drive adopts the safety redundancy structure-”take 2” structure. In order to avoid the simultaneous failure of homogeneous devices due to the same reason, the motor control path is governed by two series-connected power devices: an electronic switch and a mechanical contactor, and the two power devices are controlled by the master CPU unit and the slave CPU unit respectively. Only when the two devices are turned on at the same time can the switch be operated. Electronic switches and mechanical switches form a complementary relationship. The mechanical contactor’s normally-open contacts prevent false outputs in the event of an electronic switch failure, and the electronic switch suppresses arcing across the mechanical contacts, thereby extending the contactor’s service life. At the same time, the output device of the driving circuit carries out real-time state self-checking. State monitoring circuits are implemented for both the electronic switch and the mechanical contactor, which can find the abnormal state of each output device in real time.

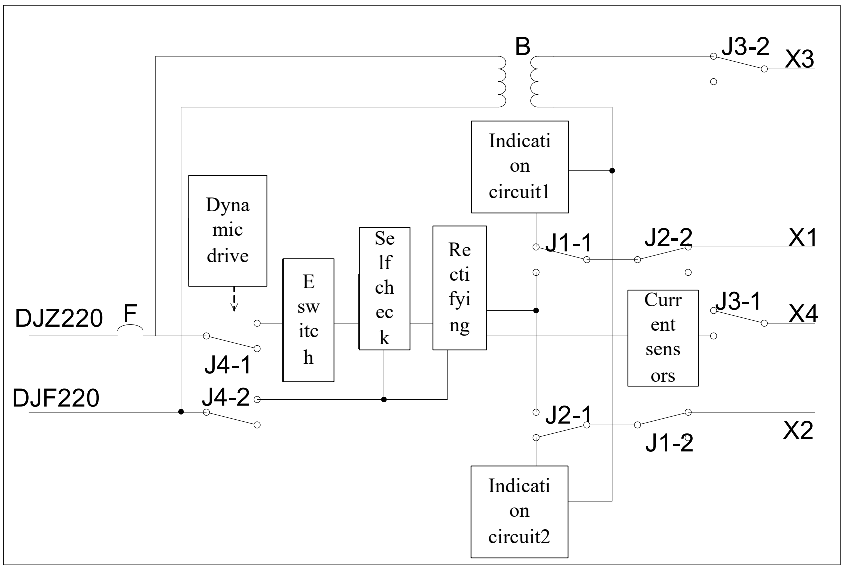
A current sensor in the acquisition part provides the monitoring CPU with real-time measurements of the motor control path current, which is used to record the action current curve of each switch operation.

The switch position detection employs two independent circuits, each utilizing full-wave rectification. When the switch machine is in the normal position, one circuit receives full-wave rectified voltage, while the other receives half-wave rectified voltage. By comparing the states (full-wave/half-wave) of these two detection circuits, the position state of the switch can be determined. At the same time, the change of full-wave and half-wave state of each representation circuit at different positions of switch also tests the quality of the representation circuit.

In safety design, each switch control module incorporates a vital relay, which is driven by a dual-input dynamic circuit, and the inputs of the double-input dynamic circuit are controlled by the master and slave CPU respectively. The vital relay picks up only if the master and slave CPUs simultaneously provide synchronized dynamic pulses of identical frequency but opposite phase to the dual-input circuit. On the one hand, The vital relay serves a dual purpose: (1) to cut off the control power supply under fault conditions, and (2) to detect potential loss of control in the master or slave CPU. In the event of overcurrent, a magnetic circuit breaker disconnects power to the switch machine. The module incorporates a lightning protection unit for the switch control lines. Overvoltage protection devices are integrated between the drive lines and the indication lines.

The structure diagram of switch interface unit of DC four-wire switch electronic control module is shown in Figure 3. In the figure, DJZ220 and DJF220 represent the live line and zero line of switch power supply; F is safety, B is rectifier bridge, and J1 ~ J4 are relay contacts. X1 ~ X4 is the switch control and indication line.

Figure 3 DC Switch Interface Unit Diagram of DC Switch Electronic Control Module



3.4 Monitoring Interface

The electronic control module of DC switch realizes the monitoring interface with the monitoring system through CAN communication mode, which is used for monitoring and maintenance. The monitoring system and the electronic control module of DC switch adopt two data exchange modes: master-slave response mode and active data transmission mode. When the monitoring system needs to obtain the current and power value of the switch, the working state of the module and the change curve of the switch, the DC switch electronic control module works in the master-slave response mode. In this mode, the monitoring system as the host sends the inquiry command, and the DC switch electronic control module as the slave responds to the inquiry command and returns the corresponding information. When the electronic control module of DC switch has alarm data or module reset or work failure, the electronic control module of DC switch works in active response mode, that is, it does not need the monitoring system to issue commands, and actively sends wrong alarm information to the monitoring system.

4.Embedded Software Design

The software was developed in accordance with the EN 50128 standard. Based on functional requirements and software design considerations, the whole software is divided into five parts: initialization unit, communication control unit, state machine unit, driving unit and application program unit. The software implements techniques including fault detection and diagnosis (FDD), error detection codes, rigorously defined interfaces, state machines, and structured programming to meet the design requirements for SIL 4. The functions of the software unit are shown in Table 2.

Table 2 The Function of Software Units in the DC Switch Electric Control Module

Unit Name	Function
Initialization	Performs address initialization, LED control and error handling
Communication control	Serial port communication processing, CAN communication processing and command processing
State machine	Complete the definition of state machine-related state, event and transition relationships
Driver	Initializes hardware peripherals, acquires digital inputs, and drives digital outputs
Applications	Main function program, event trigger processing, action execution processing and the second set of switch inspection program

The application software unit is divided into main function program, event trigger processing, action execution processing and the second set of switch inspection program.

(1)The main function program serves as the entrance and exit of the software, which completes the periodic scheduling of the main program of the software, calls the interface functions with each module, completes the data receiving, logic processing and data sending, the collection of switch values and the output driving of switches.

(2)The event handler triggers actions based on the results of logical processing within each cycle, and drives the state transition of the state machine.

(3)The action executor performs the functions associated with the current state of each state machine, including accident relay drive, command output, state, operation, fixed and reverse operation relay control, etc.

(4)The secondary switch state verification routine operates independently to confirm consistency between issued switch commands and the actual execution state.

The electronic control module of DC switch has four states:

(1)Initialization state. Performs hardware self-tests and initializes communication channels. During power-on reset, under-voltage reset, or manual reset, the reset circuit generates a reset signal to the master-slave CPU and the interface circuit, and clears all outputs to enter the initialization state.

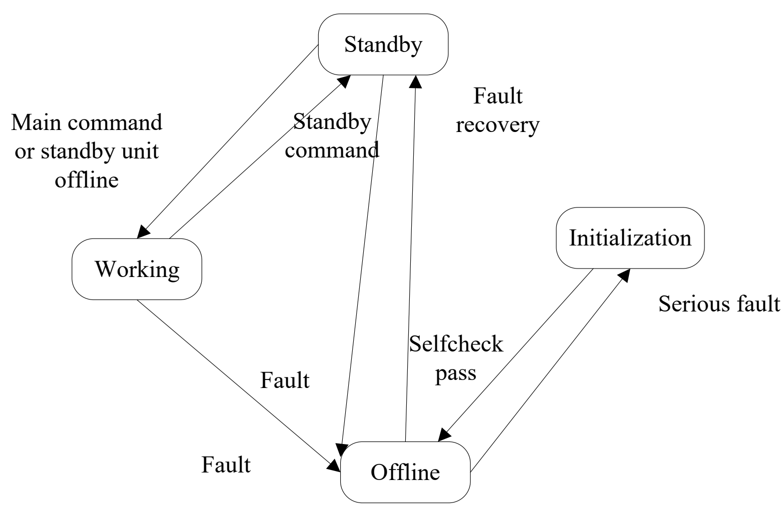
(2)Offline state. When the vital relay drops, it cuts off the action power supply of the switch machine and the 24V power supply of the control circuit.

(3)Standby state. The vital relay is picked up, the action power supply is supplied, and the 24V power supply of the control circuit is supplied, but the output relay drops and the external output line is disconnected, so that the unit has no output capacity.

(4)Working state. From the standby state, when the output relay is picked up, so that the unit has driving ability.

(5)Upon detection of a critical internal fault, the module transitions to the offline state and initiates self-recovery checks. The four operation state transitions are shown in Figure 4.

Figure 4 State Transition Diagram of DC Switch Electronic Control Module



5.Reliability Analysis

The reliability of electronic control module of DC switch affects the performance of the whole electronic interlocking system. Based on the FN2 reliability model from MIL-HDBK-217F, the reliability of the electronic control module of DC switch is evaluated according to the structure and parameters of each component. MIL-HDBK-217F is a reliability prediction handbook published by the Reliability Analysis Center (RAC) under the US Department of Defense. It provides empirically based failure rate models for electrical and electronic components across 14 distinct operating environments, and has been widely used in reliability prediction of complex system design processes such as satellites, aerospace and orbit control. Using a reliability block diagram (RBD), the FN2 model was calibrated by incorporating reference failure rates for system components and applying environmental derating factors resulting in a comprehensive prediction of system reliability [13] .

The failure rate of DC switch electronic control module components is shown in Table 3[14]. The calibration factor is set to indoor work, the duty cycle of the system is 100%, and the working temperature is 40 °C. The calibration factor is obtained in MIL-HDBK-217 manual. The safety index λ of all-electronic DC switch electronic control module is obtained by MTBF calculator software = 7.1293×10^{-8} /h, and the mean time between failure (MTBF) is 14026600 hours, greater than 10^5 hours, which meets the design requirements of all-electronic DC switch electronic control module SIL4.

Table 3 Parameters of component failure rate of electronic control module of DC switch

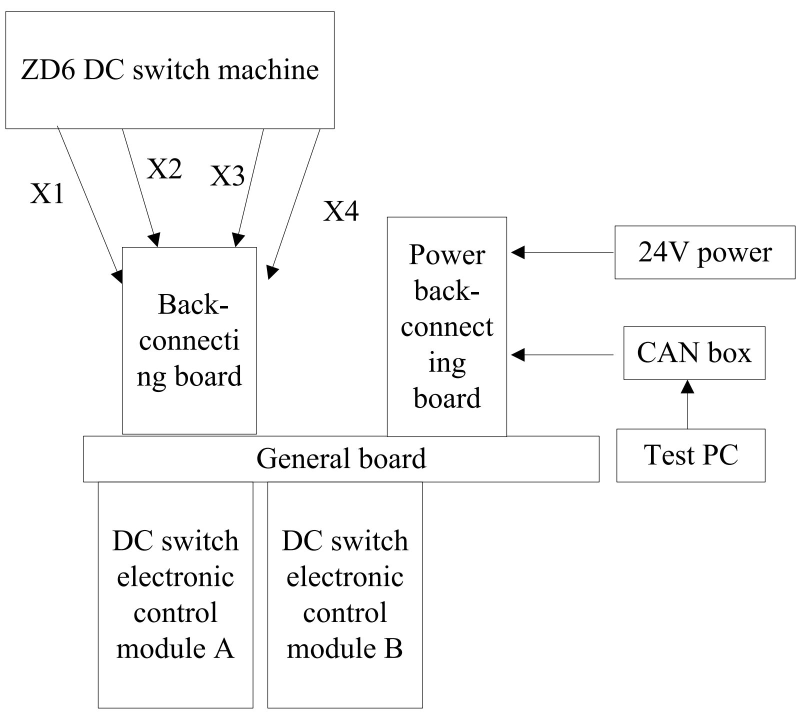
Module name	Quantity	Failure Rate/10^{-6}/h	MTBF/h
Power supply rear connection board	1	0.071102	14064320
Back connecting plate of DC switch	1	0.130837	7643098
DC switch module board	2	6.057192	165093
Communication board	1	0.138317	7229786

6.System Test

6.1 Hardware Test

In order to verify whether the hardware of DC switch electronic control module meets the functional requirements and performance requirements, the test environment is set up as shown in Figure 5. After 24V power supply is connected to the power supply, it is supplied by the board. A test PC sends switch control commands to the DC switch electronic control module via a CAN interface box, observing whether the ZD6 DC switch machine responds correctly. Hardware test items encompass functional and performance verification of DC switch electronic control module working power supply, clock circuit, reset circuit, CAN communication, serial port circuit, DC switch control circuit, switch indication circuit, accident circuit and switching circuit. All hardware test items were successfully passed.

Fig. 5 Hardware Test Environment of DC Switch Electronic Control Module



6.2 Software Test

Software testing is divided into static testing and dynamic testing. In static testing, testing tools were selected and configured based on the test objectives and unit characteristics, and coding rule checks, static analysis, and software quality metrics were performed ensuring each test item met requirements before proceeding to coding style checks. Coding style checks were primarily manual. Coding rule verification, static structure analysis, and software quality metric assessments relied mainly on automated tools, with manual review of the results for each test item.

In dynamic testing, firstly, test cases for each function under test were executed using a combination of manual data input and automated execution, and test execution was documented electronically, capturing input conditions, expected results, and actual outcomes for each test case. The code coverage metrics (statement, branch, and MC/DC) were analyzed alongside the test case execution results of the tested software to assess compliance with design requirements. All software units listed in Table 1 passed both static and dynamic testing.

6.3 Integration Test

The DC switch electronic control module was integrated into the electronic computer interlocking system, and system integration testing was performed. The autonomous all-electronic computer interlocking system includes three cabinets: power cabinet, interlocking cabinet and execution cabinet, as shown in Figure 6. Prior to deployment, comprehensive indoor and outdoor integration testing is conducted, including performance test, interface test, function test, structure test and safety test. Integration testing aims to minimize configuration errors and ensure reliable system operation. The contents of the integration test are shown in Table 4.

Fig.6 Electronic Interlocking System

Table 4 Integrated Test of Electronic Interlocking System

Type	Number of test cases/items	Test content	Test conclusion
Performance test	23	Communication cycle, unit capacity, external output performance of each electronic module, etc.	Pass and meet the needs
Interface test	58	Internal interface, external interface, working power interface, etc.	Pass and meet the needs
Functional testing	49	Safety communication, unit management, wayside equipment control, etc.	Pass and meet the needs
Structural testing	28	Redundant channels, redundant structures, etc	Pass and meet the needs
Security requirements testing	43	Internal communication protocol, parameter configuration, startup process, etc.	Pass and meet the needs

7.Conclusion

The digital communication interface enhances the flexibility of switch machine control, and the heterogeneously redundant output control interface mitigates common-cause failures, which can reliably control the DC switch and collect the state of the switch in the signal system of rail transit. Reliability analysis and comprehensive testing validate the module's performance. The integrated, autonomous electronic computer interlocking system incorporating this module has been successfully deployed in several field applications in China, demonstrating good operational performance. Its excellent and stable performance confirms the efficacy of its safety design and reliability supporting its wider adoption in rail transit engineering projects.

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no

Conflict of Interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

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