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Design and Test of the Electrical System of the All-Electric Subsea Gate Valve Actuator

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Abstract: To bridge the gap in the research on the control and drive methods of the key equipment of the new subsea production control system, all-electric subsea gate valve actuator, and to solve the problems of the valve control and drive system in the traditional subsea production system, this paper proposed a full-featured and feasible electrical system of the all-electric subsea gate valve actuator containing the control system and the drive system. The key functions were realized, including status monitoring, redundant communication, redundant power supply, redundant drive, and low-power open-position holding. The electrical system is suitable for monitoring and controlling all-electric subsea gate valve actuators with various specifications and is highly integrated, open, efficient, and real-time. The electrical system prototype was developed and successfully tested for several functions. The results showed that the all-electric subsea gate valve actuator electrical system was capable of controlling and driving the actuator, monitoring the status information of the internal and external environment of the system, as well as the power output information of the drive system, and having redundancy features.

Keywords: all-electric subsea production system; all-electric subsea gate valve actuator; electrical system; control system; drive system

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1. Introduction

With the development of offshore oil and gas resources towards deeper and farther areas, the traditional Multiple Electric-Hydraulic Subsea Production System cannot meet the exploration requirements [1–3]. Therefore, the All-electric Subsea Production System has been introduced, which has emerged as the preferred direction for development due to its benefits in terms of cost-efficiency, control effectiveness, and environmental friendliness [4–7].

The all-electric subsea gate valve actuator is a key component of the All-electric Subsea Production System, which is utilized to regulate the on–off, flow, and pressure of the production media, thus directly impacting the smooth functioning of the system [8]. Cameron's all-electric subsea gate valve actuator controlled the opening and closing of the valve through electrical means and could maintain the valve in the open position with low power consumption [9,10]. Aker Solutions' all-electric subsea gate valve actuator employed a modular and standardized design with advanced status monitoring capabilities, available in high-load and low-load versions [11]. TechnipFMC's all-electric subsea gate valve actuator used rechargeable lithium batteries as the energy source and was equipped with a battery management system, allowing for high-precision monitoring of valve position and vibration [12,13]. The world's smallest all-electric subsea gate valve actuator from Rexroth Bosch Group had a complete drive and fail-safe system, and its dimensions were the same as existing hydraulic-driven subsea gate valve actuators, allowing for seamless integration with existing subsea production facilities [14,15]. OneSubsea's all-electric subsea gate

valve actuator had a simplified drive and transmission structure and offered high control precision for the output shaft [16,17].

Researchers have also conducted relevant studies on all-electric subsea gate valve actuators. Paul White [18] proposed a configuration concept for opening the subsea gate valve using electromagnetic force without the need for a drive motor by arranging interval windings with alternating polarity at the main shaft of the actuator. Cai [19] proposed a configuration concept for reducing the size of the actuator by using a linear motor as the drive mechanism, eliminating the need for a gearbox and other transmission structures. Garrone Marco [20] proposed an all-electric subsea gate valve actuator which used a clutch and brake combination to maintain the spring in a compressed position. Xiao [21] presented a scheme for the all-electric subsea gate valve actuator applied to the Christmas tree. Liu [22,23] proposed a novel pressure-compensated all-electric control gate valve actuator structure by integrating the subsea gate valve with the actuating mechanism, significantly reducing the high-pressure hydraulic resistance during the valve closing process, then obtained the optimal model for the hydraulic side of the valve and actuator. Volker Phielipeit Spiess [24] designed a docking device for the all-electric subsea gate valve actuators that achieved precise docking between the actuator and subsea production equipment through a guiding mechanism and special-shaped slots. Tian [25] proposed a method for controlling the speed of subsea electric actuators that improves the dynamic performance of the system. Alexandre [26] proposed a subsea electric actuator suitable for small-bore valves whose function is achieved through a combination of electrical and mechanical means. Liu [27] proposed a motor layout for an all-electric subsea gate valve actuator with redundant control. Glenn-Roar [28] introduced the retrofit solution for the world's first subsea electric choke actuators installed on live wells in Statfjord Satellite Field in the North Sea. Carsten [29] proposed the development of a documented qualification program for subsea all-electric actuators based on a foundation of existing industry standards. Wang [30] proposed a concept prototype of the actuator based on this mechanism and successfully tested it for functionality. Markus [31] analyzed and tested the effect of saline water entering the Christmas tree actuator, and applied the research results to novel sensor designs. Leon [32] proposed a wear-optimized PST approach to diagnose all-electric actuation systems, evaluated through experimental tests.

The all-electric subsea gate valve actuator is an electromechanical integrated equipment. Currently, the actuators of various oil companies are still in the experimental stage, and key technologies are immature. The proposed all-electric subsea gate valve actuators by scholars focus primarily on the changes in the driving and transmission mechanism resulting from the switch in the driving mode, with limited research on the control and drive methods of the actuator's electrical system. This present work is aimed at developing a full-featured and feasible electrical system of the all-electric subsea gate valve actuator and carrying out the related test, which satisfies the operational requirements of the All-electric Subsea Production System and the control and drive requirements of the actuator and has the key functions including the status monitoring, redundant communication, redundant power supply, redundant drive and low-power open-position holding, to bridge the gap of the key equipment of the new subsea production control system and to solve the problems of large size, closed software, low driving efficiency, and slow response speed of the valve control and drive system in the traditional Multiple Electric-Hydraulic Subsea Production System.

2. Design of the Electrical System of the All-Electric Subsea Gate Valve Actuator

The electrical system of the all-electric subsea gate valve actuator plays an important role in the All-electric Subsea Production System. The electrical system receives commands from the Master Control Station (MCS) located on the platform to drive and control the all-electric subsea gate valve actuator and collects and feeds back the status information of the subsea production facility to monitor the operation of the subsea production system, realizing the exploitation of deep-sea oil and gas resources.

2.1. Control Object

Before designing the electrical system of the all-electric subsea gate valve actuator, it is necessary to clarify the information about the control object, the all-electric subsea gate valve actuator. In this paper, the all-electric subsea gate valve actuator to be controlled and driven was developed previously by the authors, as shown in Figure 1, which features redundant actuation, fail-safe shutdown, valve override, open/close position indication, and low-power open-position holding [30].

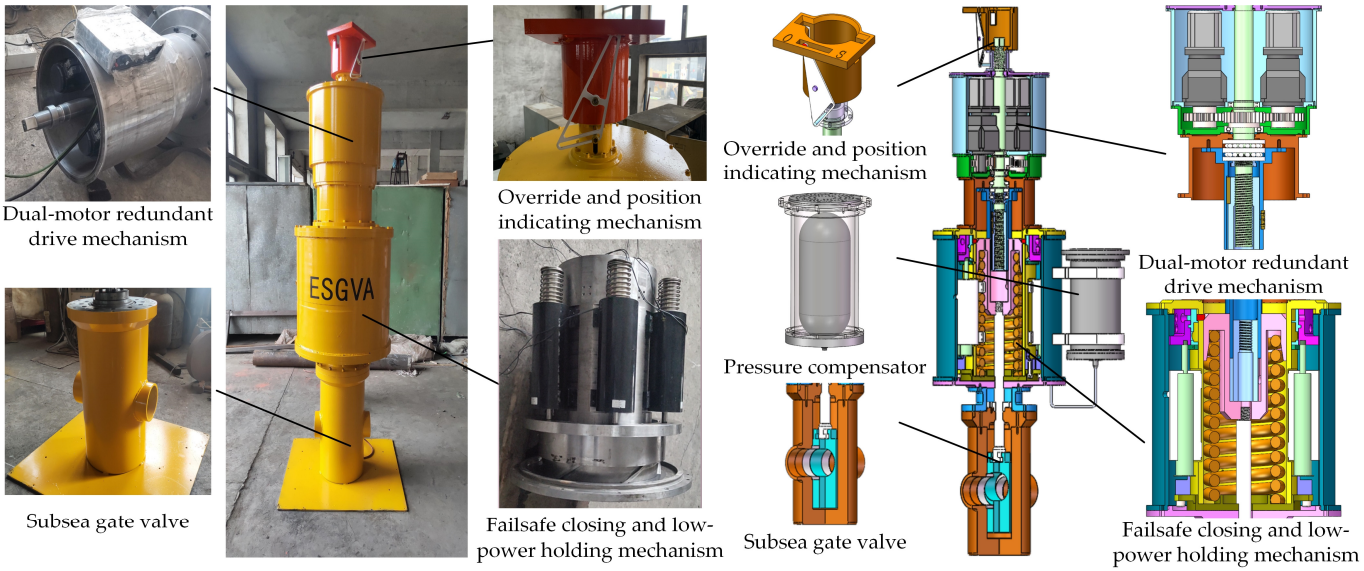


Figure 1. All-electric subsea gate valve actuator as the control object.

As shown in Figure 1, the controlled gate valve is a subsea flat gate valve. The dual-motor redundant drive mechanism is the power output unit of the actuator, which adopts a redundant design form and outputs power through mechanical transmission. The override and position indicating mechanism is used to open and close the subsea gate valve by Remotely Operated Vehicles or divers. The failsafe closing and low-power holding mechanism can automatically and safely shut off the subsea gate valve in case of system failure and is capable of keeping the subsea gate valve open for a long period with small power consumption by utilizing electromagnets as the driving element after the subsea gate valve is fully opened. The pressure compensator is used to eliminate the internal and external pressure difference of the actuator. The parameters of the all-electric subsea gate valve actuator are listed in Table 1.

Table 1. All-electric subsea gate valve actuator parameters.

Parameters	Unit	Value
Working depth	m	500
The nominal bore size of the subsea gate valve	inches	5 1/8
The rated working pressure of the subsea gate valve	psi	5000
Working stroke	mm	144
Opening power	kW	3.68
Holding power	W	180
Opening or closing valve time	s	53
Failsafe closing time	s	6
ROV interface	level	CLASS IV

2.2. Design Requirements

Based on the configuration scheme of the control object, according to ISO 13628 and API 17 standards [33,34] and the control and drive requirements of the actuator, and

considering the working environment of the electrical system, the design requirements of the electrical system of the all-electric subsea gate valve actuator are derived. The design requirements include general requirements and basic requirements.

(1) General requirements:

The electrical system should be capable of redundantly controlling and driving the drive motor of the all-electric subsea gate valve actuator.

The electrical system should be able to operate submerged up to 500 m for extended periods.

(2) Basic requirement:

The electrical system should be able to collect the status information of the production pipeline in the Christmas tree.

The electrical system should be capable of feeding back the status information from the internal control system and drive system.

The electrical system needs to ensure that the low-power holding mechanism of the actuator can be activated after the subsea gate valve is fully opened.

The electrical system should be suitable for supplying power to the control object, namely providing at least 3.68 kW for the drive mechanism and at least 180 W for the low-power holding mechanism of the actuator.

The working stroke of the control object is 144 mm and the single control time is 53 s.

2.3. System Design

According to the above requirements, the electrical system should have the sections of the control, drive, and structural protection.

2.3.1. Control System

The main function of the control section of the electrical system is to receive commands from the MCS and control the actuator drive system, as well as to collect various sensor data and feed them back to the MCS. Based on the design requirements of the electrical system, the working principle of the proposed control system is shown in Figure 2, which is composed of the embedded computer PC104, power supply board card, data acquisition module, CAN communication module, serial port module, stabilized power supply, and various types of sensors.

As shown in Figure 2, the embedded computer PC104 is the "brain" of the control system, which is used to complete tasks such as receiving and sending commands, logic and data operations. The power supply board card is used for supplying stabilized 5 V power to the PC104 and various modules. The data acquisition module is not only used for collecting data from various sensors inside the control system, drive system, and Christmas tree's pipeline, but also for acquiring the status data of the power supply inside the control system and drive system, as well as the displacement data of the subsea gate valve stem. The CAN communication module adopts the CANopen communication protocol to communicate with the drive system for realizing the control of the actuator drive mechanism. The serial port module monitors the real-time status of the well pressure and temperature signals of the Christmas tree by using the Modbus communication protocol. The stabilized power supply can stabilize the power output from the Electrical Power and Communication Distribution Unit (EPCDU) to provide a stabilized 24 V DC for the entire control system, and various sensors and the power supply board in the control system are powered by this power supply. In addition, the control system has reserved external interfaces, which support multiple interface protocols to facilitate communication with various external devices and can be modified or expanded according to changes in demand for the system's functions.

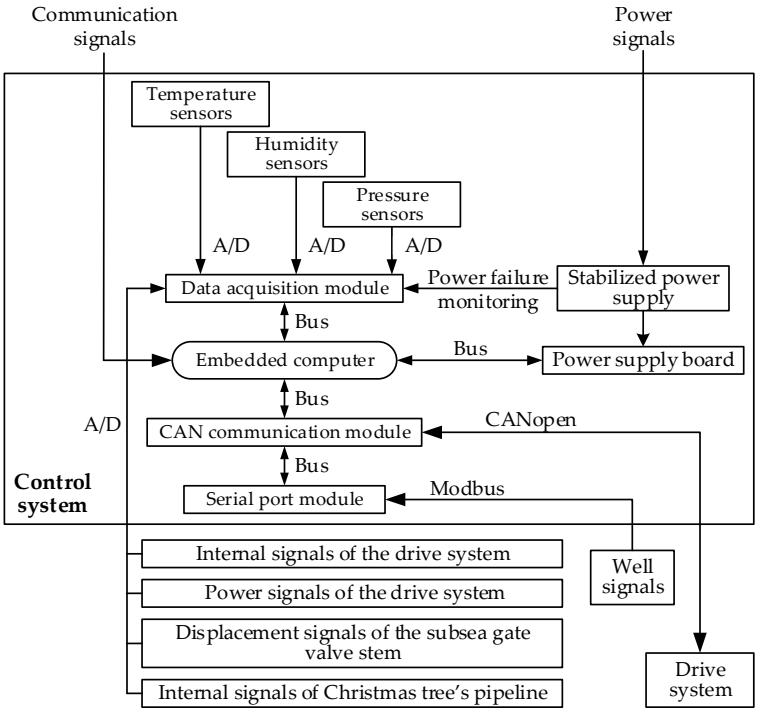


Figure 2. Working principle diagram of the control system.

Based on the working principle of the control system, the composition scheme of the control system is shown in Figure 3. Subsea electrical connectors are installed on the top cover for communicating with the MCS and supplying power. The electronic components inside the control system are mounted on the support plate fixed relative to the top cover.

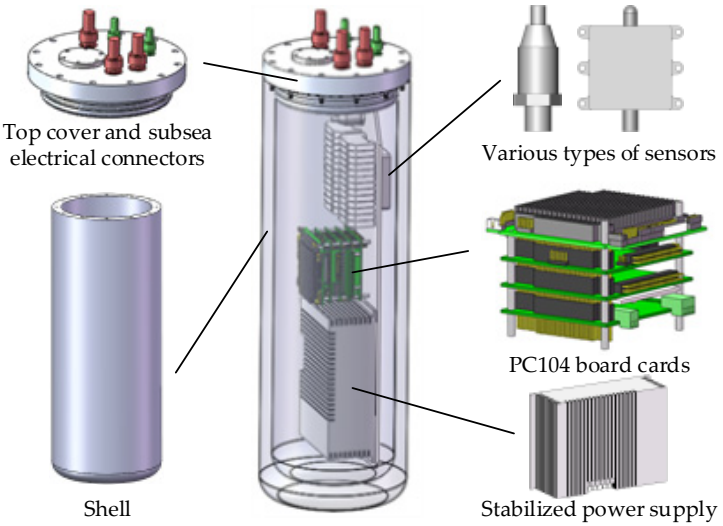


Figure 3. Composition scheme of the control system.

Different from the control system commonly used in the traditional Multiple Electric-Hydraulic Subsea Production System [35], the proposed control system is built based on modular PC104 board cards and embedded with multitasking real-time operating programs, which realizes the miniaturization, open interface, and real-time responsiveness of the control system.

2.3.2. Drive System

The main function of the drive section of the electrical system is to receive commands from the control system and powers from the EPCDU to operate the drive mechanism and low-power holding mechanism of the all-electric subsea gate valve actuator, as well as to provide feedback on the internal status data of the drive system, the drive motor status data of the actuator and the displacement data of the subsea gate valve stem. Based on the design requirements of the electrical system, the working principle of the proposed drive system is shown in Figure 4, which is composed of the drive power supply, transformer, driver, relay, control box, and various types of sensors.

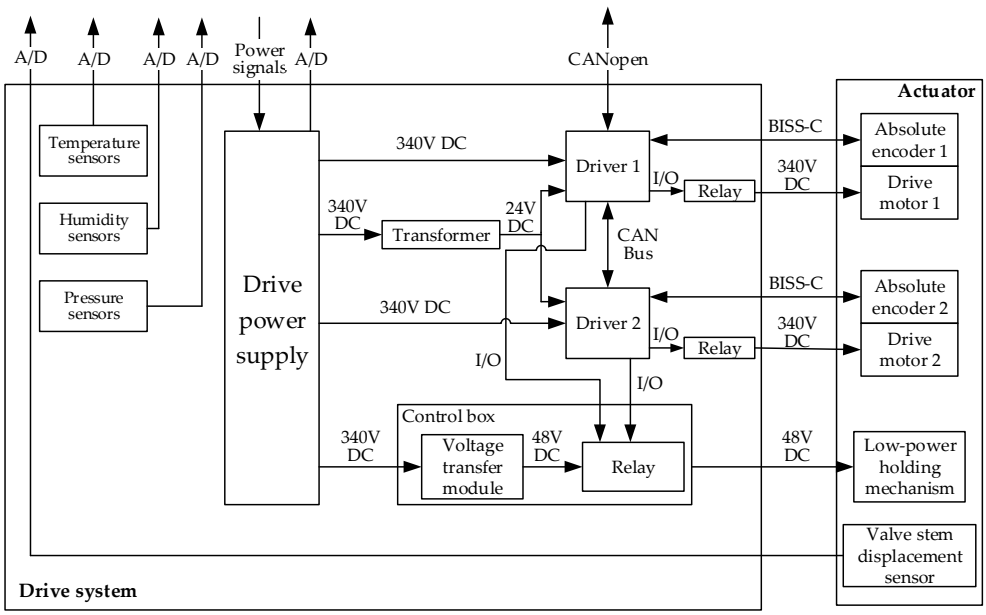


Figure 4. Working principle diagram of the drive system.

As shown in Figure 4, the power of the drive system is supplied redundantly from the EPCDU and is converted by the drive power supply to provide stabilized 340 V DC to the transformer, driver, and control box. The drive power supply has a power monitoring interface that provides feedback on its status information to the control system.

The transformer is used to convert 340 V DC to 24 V DC to provide auxiliary power for two motor drives. Each driver is connected to a relay, a drive motor, and an absolute encoder. The driver receives control pulses from the control system via the CANopen communication protocol. After receiving the control pulse, the two drivers simultaneously control the two drive motors of the actuator through the pulse following control. The two absolute encoders are respectively connected to the end of their respective drive motor spindle and communicate with the drivers via the BISS-C protocol to provide feedback on the motor positions. The relay is used for disconnecting the circuit when a drive motor fails to ensure that the failed motor does not generate power to form a load during single motor operation or override operation. The control box mainly consists of a voltage transfer module and a relay for driving and controlling the low-power holding mechanism of the actuator. The voltage transfer module is capable of converting the 340 V DC provided by the drive power supply to 48 V DC to energize the low-power holding mechanism, while the relay is controlled by the driver's I/O signals and serves as the control switch for the low-power holding mechanism.

The drive system is also equipped with temperature, humidity, and pressure sensors to enable the control system to monitor its internal environmental status. In addition, to facilitate the installation of the wiring harness, the signals from the displacement sensor located inside the subsea gate valve are transmitted via the drive system to the control system.

Based on the working principle of the drive system, the composition scheme of the drive system is shown in Figure 5. The subsea electrical connectors installed on the top cover are used for communicating with the control system and supplying power. The subsea electrical connectors installed on the bottom cover are connected to the all-electric subsea gate valve actuator for delivering power and providing feedback signals. In addition, the electronic components inside the drive system are mounted on the support plate fixed relative to the top cover.

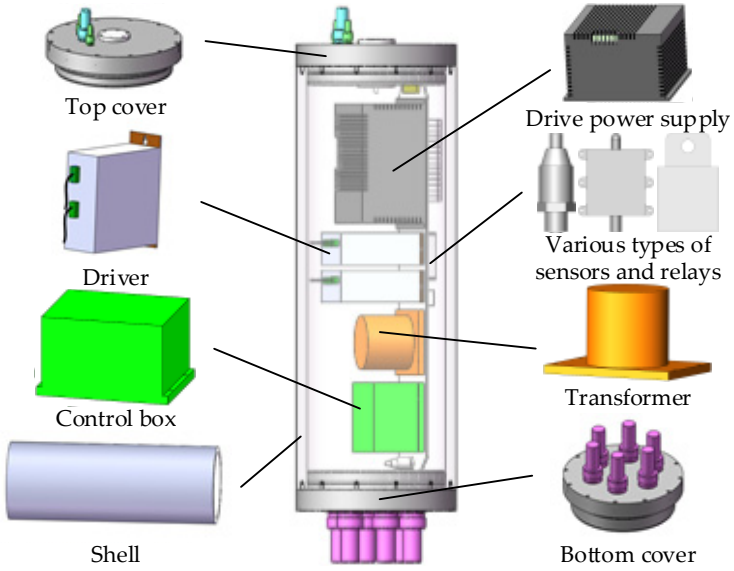


Figure 5. Composition scheme of the drive system.

In the proposed drive system, all drivers are piggybacked onto the CAN Bus, which facilitates the unified control of the control system. The drive power supply is equipped with a built-in redundant input module, which achieves redundancy in the power supply and improves system reliability.

2.3.3. Structural Protection

According to the design requirements, the electrical system of the all-electric subsea gate valve actuator should be able to operate submerged up to 500 m for extended periods, which imposes requirements on the mechanical properties, process performance, and corrosion resistance of the electrical system. The structural protection section of the electrical system is designed as follows:

To ensure the safe operation of the equipment, the control system and drive system adopt the overall sealing design.

Subsea wet-mateable electrical connectors, which are easy to connect and suitable for underwater environments, are selected for data acquisition and communication between the control system, drive system, and actuator.

The working environment of the electrical system is located in deep water. For reliable operation of the system, the internal components of the system should have appropriate corrosion resistance and strength. Therefore, 316 L stainless steel is used as the main material for the control system and drive system.

The shell components of the electrical system are in direct contact with the external environment and are subjected to deep water pressure and seawater corrosion, which requires high corrosion resistance and strength. Therefore, the super duplex stainless steel featuring excellent pressure and corrosion resistance is selected to process the shell components of the control system and drive system, and the surfaces of the shell components are treated with anti-corrosion coatings.

2.4. Design Process

The design process is shown in Figure 6.

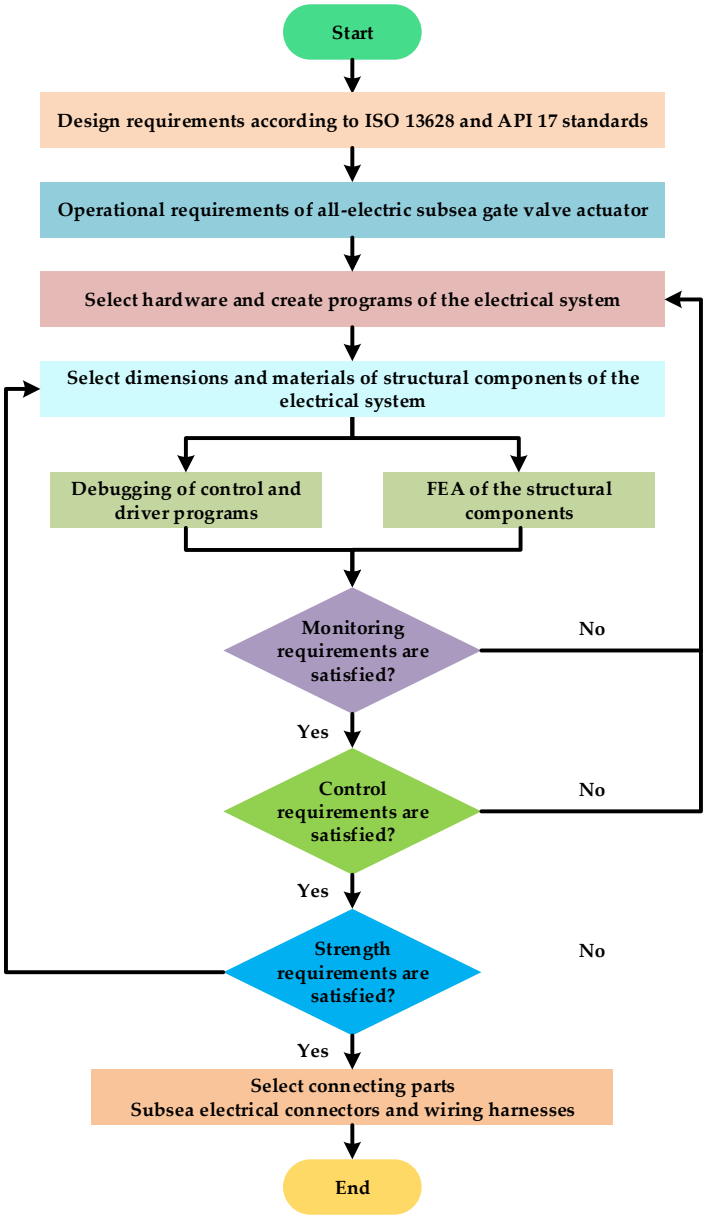


Figure 6. Design flowchart of the electrical system of the all-electric subsea gate valve actuator.

According to ISO 13628 and API 17 standards, the design requirements for the electrical system are specified. Based on the given operational conditions of the all-electric subsea gate valve actuator, select hardware and create programs of the electrical system, and select the dimensions and materials of the structural components of the electrical system. Then, debug the control and drive programs and create the 3D model for Finite Element Analysis (FEA) of the structural components. If the monitoring and control requirements are not satisfied, change the hardware or modify the program of the electrical system and redo debugging of the control and drive programs until the performance satisfies the requirements. If the strength requirement is not satisfied, change the dimensions or materials of the structural components and redo FEA until the performance satisfies the strength requirement. After the control and drive programs of the electrical system and the

dimensions and materials of its structural components are determined, select the connecting parts, including subsea electrical connectors and wiring harnesses.

3. Prototype

Based on the design requirements and system designs, the electrical system prototype is developed as shown in Figure 7. The prototype is a highly integrated electrical equipment, consisting of the control system prototype and drive system prototype which are connected by subsea electrical connectors.

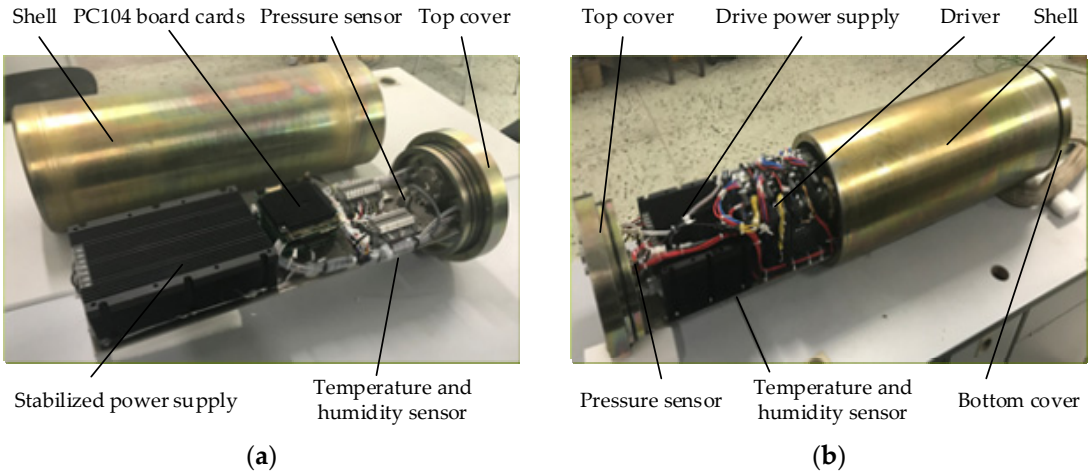


Figure 7. Electrical system prototype for the all-electric subsea gate valve actuator: (**a**) the control system prototype; (**b**) the drive system prototype.

3.1. Parameters

The parameters of the electrical system prototype are listed in Table 2. The prototype operates submerged up to 500 m and is capable of controlling and monitoring the all-electric subsea gate valve actuator with nominal bore size and rated working pressure of 5 1/8 inches and 5000 psi, respectively. The electrical system has functions such as status monitoring, redundant communication, redundant power supply, redundant drive, and low-power open-position holding.

Table 2. The parameters of the electrical system prototype.

Parameters	Unit	Value
Working depth	m	500
Communication mode	/	Fiber-optical
Number of actuator control channels	channel	6
Sensor interface type	/	4–20 mA RS485
Number of sensor function channels	channel	6
Number of actuator power supply channels	channel	2
Actuator drive voltage	V DC	340
Actuator drive power	kW	3.68
Actuator open-position holding voltage	V DC	24
Actuator open-position holding power	W	180
Actuator working stroke	mm	144
Actuator open/close valve time	s	53

At present, the control and drive methods of the electrical system of the all-electric subsea valve actuator have not been systematically studied. Compared with the hydraulic transmission system of subsea valves in traditional Multiple Electric-Hydraulic Subsea Production Systems [36,37], the developed electrical system prototype has a more simplified

structure and smaller size due to the complete use of electronic components for system construction without hydraulic control devices; the prototype is designed with reserved external interfaces, which support multiple interface protocols to facilitate communication with various external devices, and can be modified or expanded according to changes in demand for the system's monitoring and control functions, with a higher degree of openness; the electric drive method is not affected by distance and water depth, so the prototype has significant advantages in terms of drive efficiency and real-time response for more stable, continuous and fast controlling and driving subsea valve actuators.

3.2. Operation Mode

The operation mode of the electrical system of the all-electric subsea gate valve actuator is shown in Figure 8. Firstly, the MCS and the power supply unit located on the platform transmit communication signals and high-voltage power signals to the EPCDU via the umbilical. The EPCDU transmits communication signals to the control system of the electrical system through the internal communication distribution equipment. Meanwhile, through the internal power transmission equipment of the EPCDU, the high-voltage power signals are converted into low-voltage power signals required by the subsea equipment, and the low-voltage power signals are transmitted to the control system and the drive system.

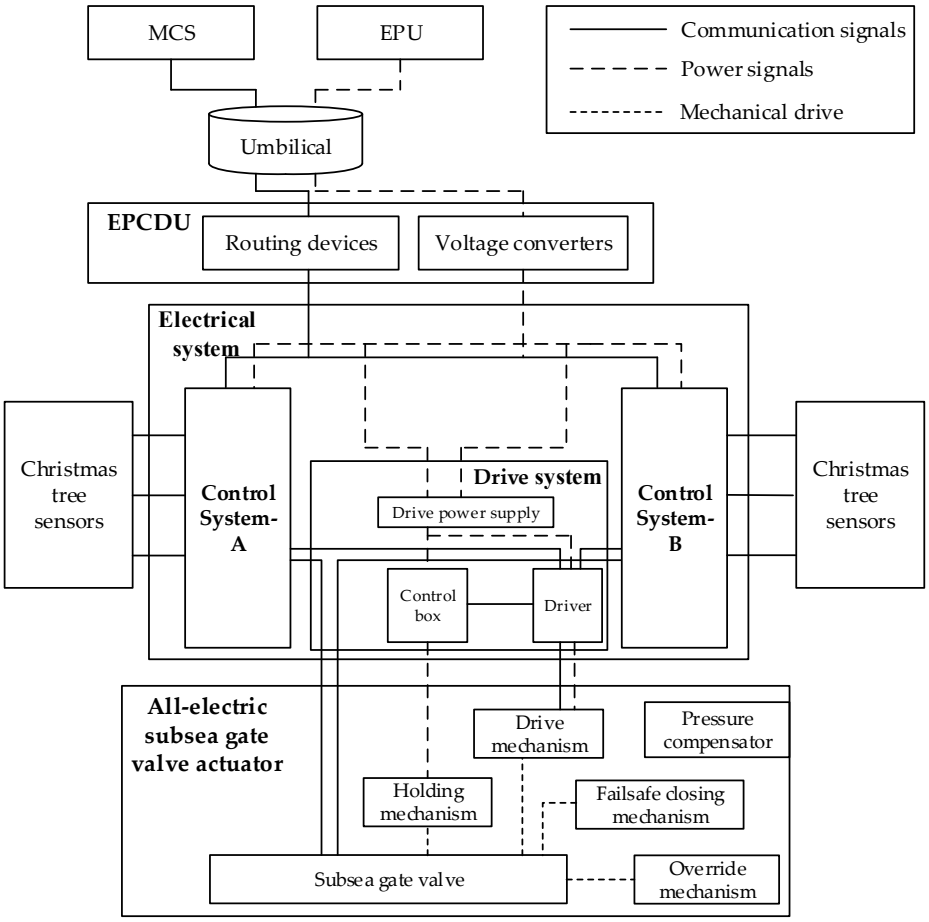


Figure 8. The operation mode of the electrical system of the all-electric subsea gate valve actuator.

Then, the control system receives commands from the MCS to collect and feedback data from various sensors inside the Christmas tree's pipeline, the control system, and the drive system, as well as to communicate with the driver in the drive system for controlling the operation of the all-electric subsea gate valve actuator. In addition, the control system adopts the commonly used dual redundancy configuration [35]. During the operation of the electrical system, both of the control systems are in hot standby mode, so that if

one control system fails, the other control system can still independently complete the monitoring, communication, and control tasks.

Finally, after receiving the commands from the control system and the electrical power from the EPCDU, the drive system controls the dual-motor redundant drive mechanism and the low-power holding mechanism in the all-electric subsea gate valve actuator through the internal drivers and control box to complete the operation of opening and closing the subsea gate valve.

4. Tests

The tests were conducted in the self-developed test system of the electrical system of the all-electric subsea gate valve actuator. The key functions were fully tested, including status monitoring, redundant communication, redundant power supply, redundant drive, and low-power open-position holding.

4.1. Test System

As the concept prototype of the electrical system proposed in the paper was developed synchronously with the actuator concept prototype previously proposed by the author, and the control object of the electrical system is the actuator concept prototype [30], the two research processes are related, especially in terms of functional testing. To save test costs and facilitate the verification of device functionality, based on the testing requirements, the test system was developed by combining the developed actuator body with the electrical system, as shown in Figure 9 [30]. However, it should be noted that there are differences between the test items carried out for the electrical system and those for the actuator. The developed test system is composed of the test MCS, the test EPCDU, the signal generator, the all-electric subsea gate valve actuator, and the electrical system prototype which includes two control system prototypes and a drive system prototype.

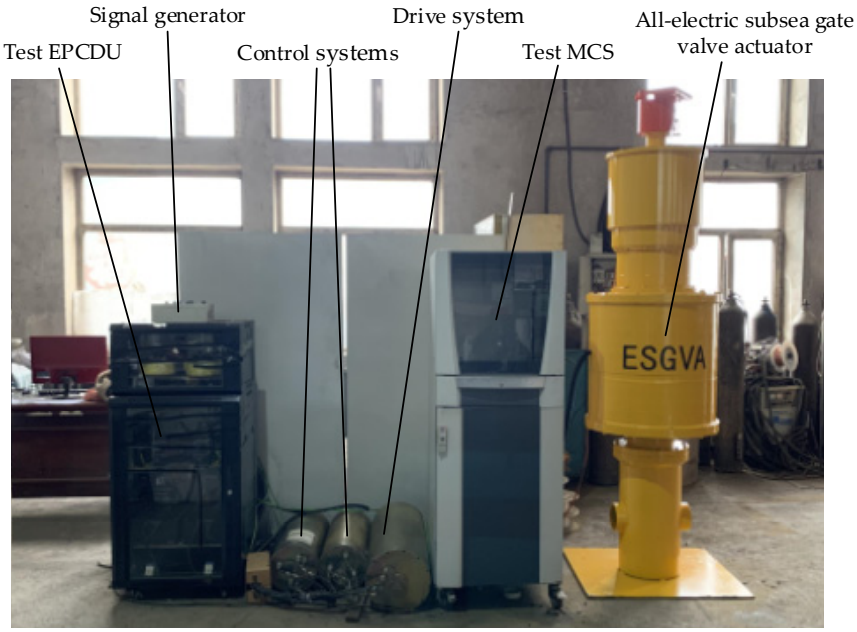


Figure 9. The test system of the electrical system of the all-electric subsea gate valve actuator.

The schematic diagram of the test system of the electrical system of the all-electric subsea gate valve actuator is shown in Figure 10, which is used to simulate the operation of a real All-electric Subsea Production System. The test MCS sends control commands and reads feedback data; the test EPCDU transmits power and distributes communication; the signal generator simulates the temperature, pressure, and humidity signals from the

Christmas tree's pipeline; and the all-electric subsea gate valve actuator is the control object for verifying the function of the electrical system.

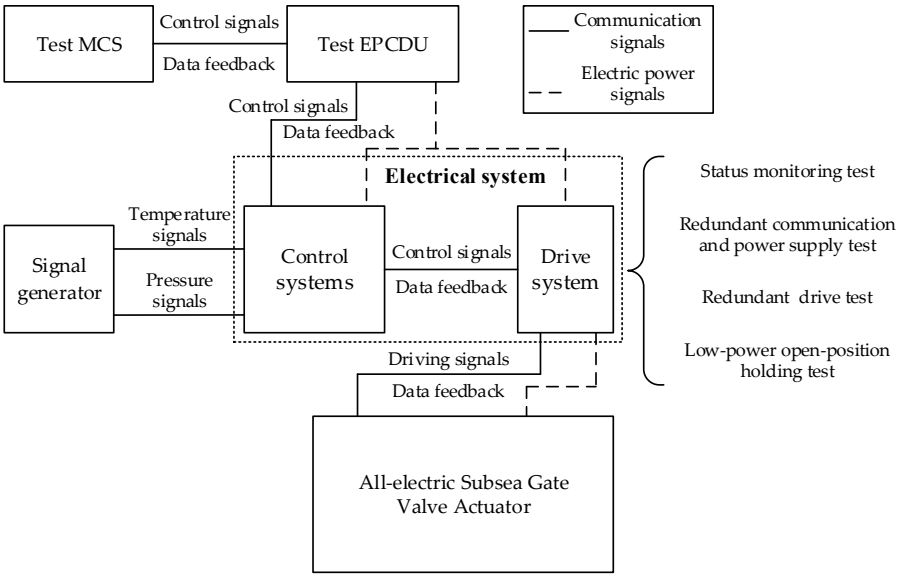


Figure 10. The schematic diagram of the test system of the electrical system.

The main monitoring interface of the test system is shown in Figure 11, which can monitor the internal and external environment status information of the electrical system, the drive system power output status information, as well as the communication and power supply status. In addition, to facilitate status monitoring and data reading, functional monitoring interfaces such as internal monitoring interface, external monitoring interface, drive system power output monitoring interface, and actuator action monitoring interface are developed to satisfy the test requirements.

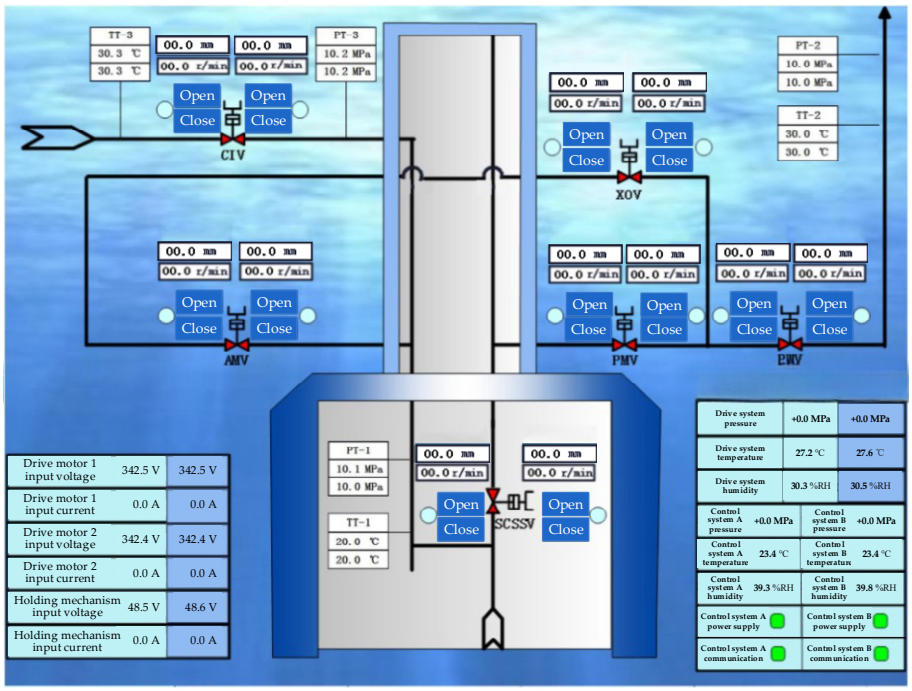


Figure 11. The main monitoring interface of the test system.

4.2. Test Results

The functional test results of the electrical system of the all-electric subsea gate valve actuator are summarized below.

4.2.1. Status Monitoring Test

(1) Internal environmental monitoring test

The internal environmental monitoring test was carried out with the test system. The monitoring data and the test results are shown in Figure 12 and Table 3, respectively.



(**a**)

Drive system pressure	+0.0 MPa	+0.0 MPa	
Drive system temperature	27.2 ℃	27.6 ℃	
Drive system humidity	30.3 %RH	30.5 %RH	
Control system A pressure	+0.0 MPa	Control system B pressure	+0.0 MPa
Control system A temperature	23.4 ℃	Control system B temperature	23.4 ℃
Control system A humidity	39.3 %RH	Control system B humidity	39.8 %RH

(**b**)

Figure 12. The internal environment monitoring data: (**a**) the data in the internal monitoring interface; (**b**) the data in the main monitoring interface.

Table 3. Test results of the internal environmental monitoring test.

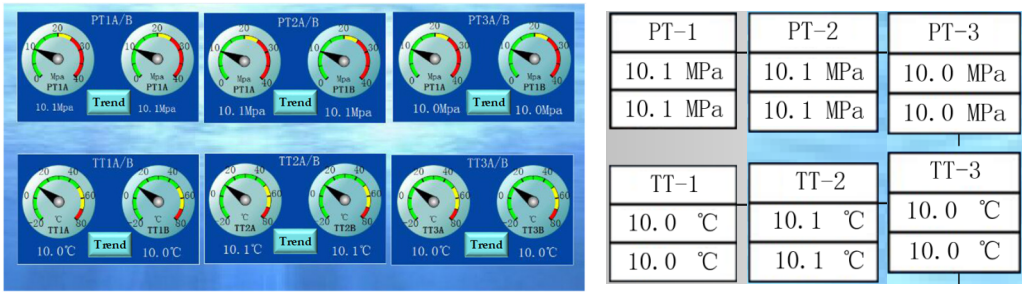
Monitoring Information	Data Range	Control System A	Control System B
Control system internal pressure	−0.1–+0.4 MPa	+0.0 MPa	+0.0 MPa
Drive system internal pressure	−0.1–+0.4 MPa	+0.0 MPa	+0.0 MPa
Control system internal temperature	−40–+100 °C	+23.4 °C	+23.4 °C
Drive system internal temperature	−40–+100 °C	+27.2 °C	+27.6 °C
Control system internal humidity	0–100%RH	39.3%RH	39.8%RH
Drive system internal humidity	0–100%RH	30.3%RH	30.5%RH

Since the pressure data acquired by the electrical system were all relative pressures, the pressure monitoring results inside the control system and the drive system were both 0 which was correct. The control system and the drive system were independent of each other, so the collected temperature and humidity data were not the same; but the monitored status data were within the reasonable range, so the monitoring results were correct. In addition, the monitoring data in the internal monitoring interface matched the data in the main monitoring interface, so there were no anomalies in the data results.

(2) External environmental monitoring test

Figure 13 shows the external environment monitoring data during the test, and the test results are listed in Table 4.

As shown in Figure 13 and Table 4, with the changes in the value of the status signals simulated by the signal generator, the data monitored by the electrical system also changed; and the error of the data values between the monitored value and the simulated value was within 2%. In addition, the monitoring data in the external monitoring interface consistently matched the data in the main monitoring interface, so the data results were not abnormal.



(**a**) (**b**)

Figure 13. The external environment monitoring data: (**a**) the data in the external monitoring interface; (**b**) the data in the main monitoring interface.

Table 4. Test results of the external environmental monitoring test.

Monitoring Information	Standard Value	Control System A	Control System B
Downhole pipeline pressure PT1	10 MPa 20 MPa	10.1 MPa 20.1 MPa	10.1 MPa 20.0 MPa
Christmas tree production pipeline pressure PT2	10 MPa 20 MPa	10.1 MPa 20.0 MPa	10.1 MPa 20.0 MPa
Christmas tree chemical injection pipeline pressure PT3	10 MPa 20 MPa	10.0 MPa 20.2 MPa	10.0 MPa 20.2 MPa
Downhole pipeline temperature TT1	10 °C 30 °C	10.0 °C 30.0 °C	10.0 °C 30.0 °C
Christmas tree production pipeline temperature TT2	10 °C 30 °C	10.1 °C 30.0 °C	10.1 °C 30.0 °C
Christmas tree chemical injection pipeline temperature TT3	10 °C 30 °C	10.0 °C 30.1 °C	10.0 °C 30.1 °C

(3) Drive system power output monitoring test

Figure 14 shows the drive system power output monitoring data during the test, and the test results are listed in Table 5.



(**a**) (**b**)

Figure 14. The drive system power output monitoring data: (**a**) the data in the drive system power output monitoring interface; (**b**) the data in the main monitoring interface.

According to the test conditions, the input voltage and current required for the drive motors in the dual-motor redundant drive mechanism of the all-electric subsea gate valve actuator were approximately 340 V and 3.7 A, respectively, during the test, so the monitoring results of the electrical system were correct. After the actuator's low-power holding mechanism was stabilized, the input voltage and current of approximately 24 V DC and 7.5 A needed to be maintained for a long period according to the mechanism's power

requirements, so the monitoring results were also correct. In addition, the monitoring data in the drive system power output monitoring interface matched the data in the main monitoring interface, so there were no anomalies in the data results.

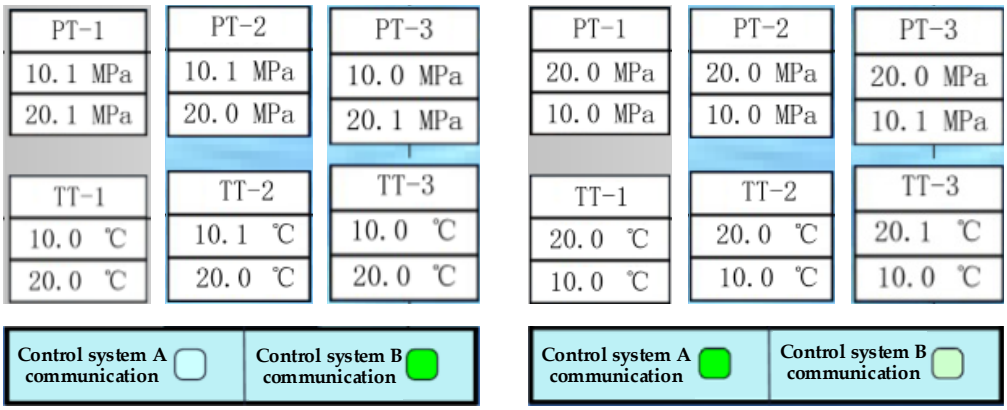
Table 5. Test results of the drive system power output monitoring test.

Monitoring Information	Data Range	Control System A	Control System B
Drive motor 1 input voltage	0–400 V	342.5 V	342.5 V
Drive motor 2 input voltage	0–400 V	342.4 V	342.4 V
Holding mechanism input voltage	0–50 V	24.2 V	24.1 V
Drive motor 1 input current	0–20 A	3.7 A	3.7 A
Drive motor 2 input current	0–20 A	3.7 A	3.7 A
Holding mechanism input current	0–20 A	7.5 A	7.5 A

4.2.2. Redundant Communication and Power Supply Test

(1) Redundant communication test

The monitoring interface and test results of the redundant communication test are shown in Figure 15.



(**a**) (**b**)

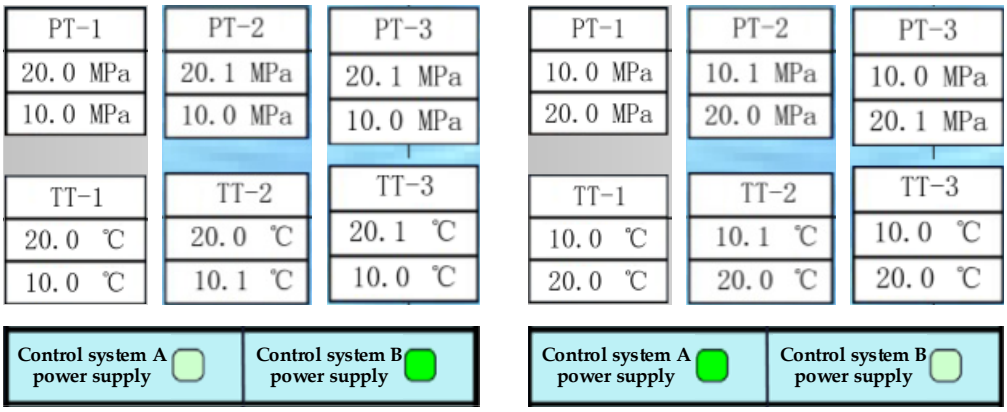
Figure 15. The monitoring interface and test results of the redundant communication test: (**a**) the communication cut-off of control system A; (**b**) the communication cut-off of control system B.

The signals simulated by the signal generator started at 10 MPa and 10 °C and then were adjusted to 20 MPa and 20 °C. As shown in Figure 15, when the communication of a certain control system was cut off, the corresponding communication status light was off, and the monitoring data of this control system did not change when the signal value changed. While the communication status light of the normal control system is working normally, and its monitoring data would still change with the change of the simulated signal value. After the fiber-optic communication line of the faulty control system was restored, the monitoring function of this control system returned to normal.

(2) Redundant power supply test

The monitoring interface and test results of the redundant power supply test are shown in Figure 16. Similar to the redundant communication test, the initial signal values simulated by the signal generator were 20 MPa and 20 °C, and the signal values were adjusted to 10 MPa and 10 °C during the test.

As shown in Figure 16, when the power supply of a certain control system was cut off, the corresponding power supply status light was off, and the monitoring data of this control system did not change. In contrast, the normal control system not only has a normal status light, but its monitoring data always matches the simulated signal value. After the power supply line of the faulty control system was restored, the monitoring function of this control system returned to normal.



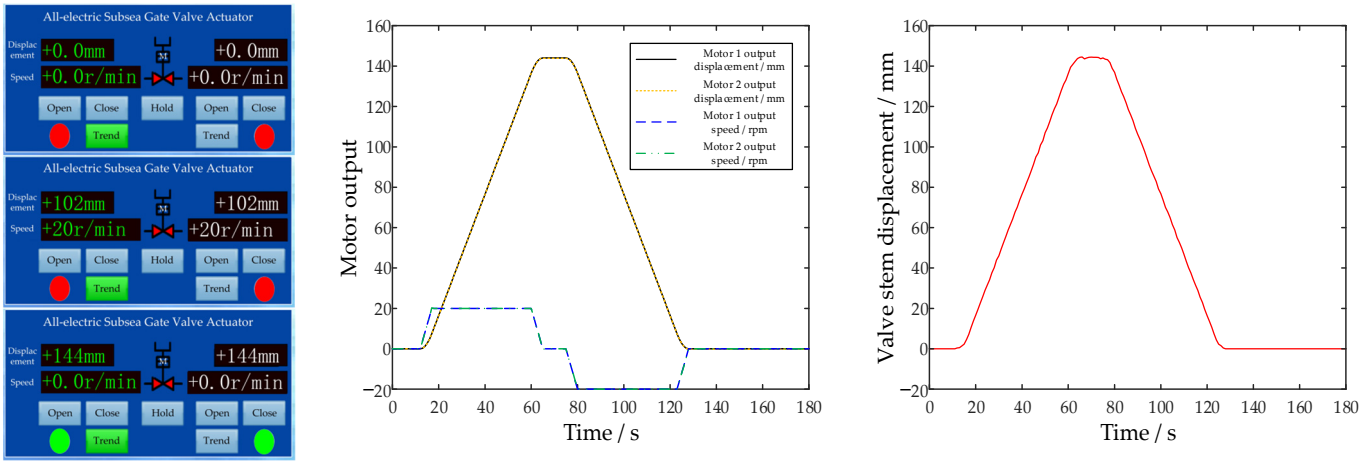
(**a**) (**b**)

Figure 16. The monitoring interface and test results of the redundant power supply test: (**a**) the power cut-off of control system A; (**b**) the power cut-off of control system B.

4.2.3. Redundant Drive Test

The actuator concept prototype previously proposed by the author was tested on the developed test system to verify the redundant drive function of the actuator [30]. However, this function is under the control and drive of the electrical system, which means that the test results can also be used to verify the functions of the electrical system. That is to say, when the function of the actuator body is tested, the function of the electrical system is also proved in reverse. Therefore, the test results of the redundant drive function of the actuator are used in the paper to describe the realization of the redundant drive function of the electrical system, which makes the functional tests of the electrical system complete.

The test results of the dual motor drive test and the single motor drive test of the electrical system are shown in Figures 17 and 18, respectively. Figure (a) was the monitoring interface of the drive test, where the light was on to indicate that the motor was normal, the light was off to indicate that the motor was faulty and disconnected, and the green and red lights indicated that the gate valve was in the open-position and close-position, respectively. Figure (b) and Figure (c) showed the motor output curve and the displacement curve of the valve stem during the test, respectively.



(**a**) (**b**) (**c**)

Figure 17. Dual motor drive test results: (**a**) the monitoring interface, (**b**) the motor output curve, (**c**) the displacement curve of the valve stem.

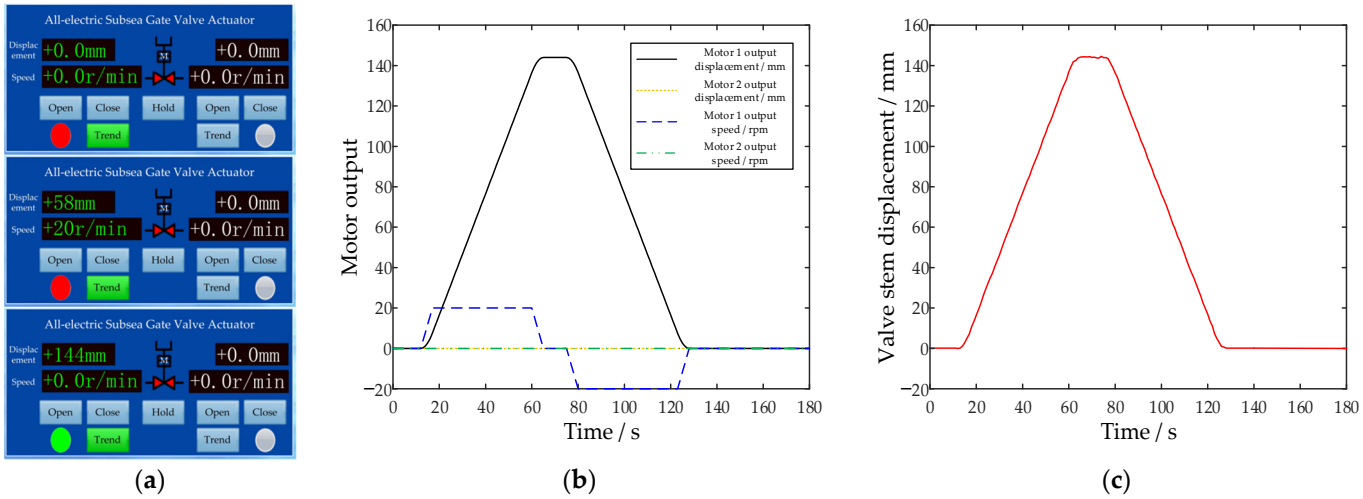


Figure 18. Single motor drive test results: (**a**) the monitoring interface, (**b**) the motor output curve, (**c**) the displacement curve of the valve stem.

As shown in the test results, the electrical system could not only synchronously drive two motors to complete the opening and closing of the subsea gate valve, but also in the event of a certain motor failure, switch the operating mode of the normal motor to enable it to independently open and close the subsea gate valve. During the testing process, the output status of the motor was always good, and the operating time spent satisfied the design requirements. In addition, the electrical system was able to monitor the output data of the motor and the movement data of the valve stem continuously. Both the dual motor drive test and the single motor drive test were repeated 10 times, and every test was successful, indicating that the electrical system had redundant drive functionality.

4.2.4. Low-Power Open-Position Holding Test

Similar to the redundant drive functionality of the electrical system, the low-power open-position holding functionality also requires collaboration between the actuator body and the electrical system to achieve. In the authors' previous original research, this functionality has been tested for the actuator body, and the test results are described in this paper to ensure the completeness of the electrical system functional test content, as shown in Figure 19 [30]. Likewise, the successful realization of the low-power position holding function of the actuator body can also be used to demonstrate in reverse the realization of the low-power open-position holding functionality of the electrical system.

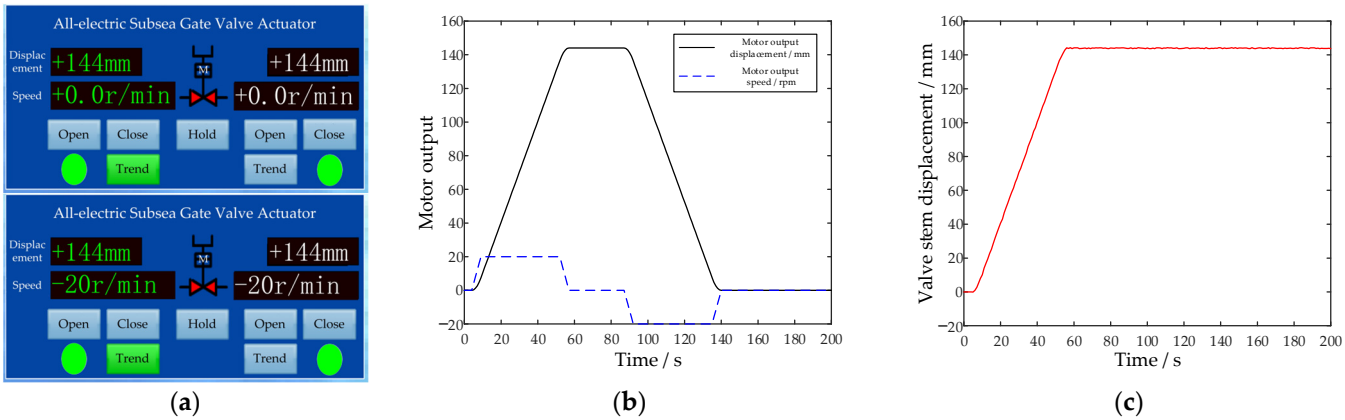


Figure 19. Low-power open-position holding test results: (**a**) the monitoring interface, (**b**) the motor output curve, (**c**) the displacement curve of the valve stem.

As shown in Figure 19, the electrical system could control and drive the low-power holding mechanism of the actuator to keep the subsea gate valve in the open position for a long time after the actuator drive mechanism had fully opened the gate valve. The low-power open-position holding test was repeated 10 times and every test was successful, indicating that the electrical system could control the operation of the drive mechanism and the low-power holding mechanism of the actuator to achieve long-term opening of the gate valve and had low-power open-position holding functionality.

5. Conclusions

To bridge the gap in the research on the control and drive methods of the key equipment of the new subsea production control system, all-electric subsea gate valve actuator, and to solve the problems of the valve control and drive system in the traditional subsea production system, this paper proposed a highly integrated, open, efficient, and real-time electrical system of the all-electric subsea gate valve actuator containing the control system and the drive system, which satisfied the operational requirements of the All-electric Subsea Production System and the control and drive requirements of the actuator. The electrical system prototype was developed and successfully tested in the self-developed test system, fulfilling the control and monitoring of the all-electric subsea gate valve actuator with a nominal bore size of 5 1/8 inches and rated working pressure of 5000 psi. The following conclusions can be drawn:

(1) The proposed control system of the electrical system is built based on modular PC104 board cards and embedded with multitasking real-time operating programs to form a complete embedded control system to realize the monitoring and control functions of the All-electric Subsea Production System. The proposed control system has the advantages of miniaturization, open interface, and real-time responsiveness.
(2) The proposed drive system of the electrical system can realize the power transmission and drive control for the drive mechanism and low-power holding mechanism of the all-electric subsea gate valve actuator. Through piggybacking all drives onto the CAN Bus and equipping a built-in power supply redundant input module, the drive system has the advantages of convenient control, power supply redundancy, and high reliability.
(3) The proposed concept prototype of the electrical system has key functions including status monitoring, redundant communication, redundant power supply, redundant drive, and low-power open-position holding. The prototype is capable of controlling the all-electric subsea gate valve actuator to perform redundant opening–closing and long-term opening operations of the subsea gate valve, as well as monitoring the internal environmental status information, external environmental status information, and drive system power output information.

The electrical system is full-featured and feasible and can be used for monitoring and controlling all-electric subsea gate valve actuators with various sizes and rated working pressures, but the hardware, programs, and structural components of the electrical system need to be reselected and redesigned, as well as the specifications of subsea electrical connectors.

Further research will focus on the association comprehensive test with Christmas trees, subsea oil and gas pipelines, and subsea wellheads in real deepwater environments to verify the long-term application of the electrical system in subsea environments.

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Conflicts of Interest: The authors declare no conflicts of interest.

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