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Fault Tolerant Control Method of Power System of Tram Based on PLC

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Abstract

Due to the large fault classification granularity of tram power system, there is still a problem that the gain coefficient is not reasonable in different control links, so a fault-tolerant control method of tram power system based on PLC is designed. First, the fault classification of the tram power system is carried out, then the fault diagnosis of the tram power system is carried out. Finally, the fault-tolerant control of the tram power system is carried out through the angle fault-tolerant control unit, PID control algorithm model and brake pull fault-tolerant control unit, as to complete the fault-tolerant control of the tram power system based on PLC. The experimental results show that the reasonable value of proportional gain coefficient, integral gain coefficient and differential gain coefficient are 30.00, 15.00 and 29.98 respectively.

Keywords: PLC; tram; Power system; Fault-tolerant control; Fault diagnosis;

1. Introduction

The power system of the tram is composed of power battery, the first and second contactor groups, bidirectional DC / DC converter and motor controller. The power battery is isolated from the high-voltage line network through the controller to avoid the impact of the high-voltage line network current on the power battery and protect the safety of the power system. As for the power system of tram, in case of an accident, it may cause huge losses to people, property, etc. The safety performance of tram power system determines the safety of operators and the economic benefits of tram. In the above background, the research of fault-tolerant control technology has been pushed to the forefront and there has been a rapid development. Fault tolerant control opens a new way to improve the reliability and safety of tram power system.

Fault tolerant control refers to the way that the system can automatically compensate the fault when it occurs, and recover the performance of the system as soon as possible, and as to ensure the stability, safety and reliability of the system operation. Fault tolerant control is of great significance for practical systems, especially for systems with high reliability and safety requirements, such as all kinds of aircrafts, underwater robots, etc. “Fault tolerance” is originally a concept in computer system design technology, which is the abbreviation of fault tolerance. The basic idea of fault tolerance is that a control system will fail sooner or later, so when designing the control system, we should consider how to compensate the failure once the control system fails, to ensure the stability and safety of the system. Fault tolerant control consists of two parts: fault diagnosis and fault compensation. Fault diagnosis refers to the process of using existing knowledge to comprehensively process and analyze the collected information according to the collected various state information of the diagnosed system, so as to obtain the comprehensive evaluation of the system operation and fault condition; fault compensation refers to the process of readjusting the parameters of the controller, namely software compensation or changing the structure of the controller, namely hardware compensation, after the fault occurs, so as to achieve the purpose of fault tolerance.

In recent years, many researchers have put forward many different definitions for fault-tolerant control. Although the expressions are different, the essence of fault-tolerant control is clear, that is, “when the control system fails, the system can still maintain its own operation in a safe state and meet certain performance index requirements as far as possible”. At present, fault-tolerant control is mainly aimed at the aircraft, and the reconfiguration design theory of control law is the main one. The fault-tolerant control of the power system has become mature, but due to the large fault classification granularity of the power system, there is still a problem that the gain coefficient is not reasonable in different control links. Therefore, this paper puts forward the research on the fault-tolerant control method of the power system of the tram based on PLC. PLC is a programmable logic controller, which uses a kind of programmable memory for its internal storage program. It performs logic operation, sequence control, timing, counting and arithmetic operation for the user's instructions, and controls various types of machinery or production processes through digital or analog inpu\t / output.

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2. Fault classification of tram power system

Before fault-tolerant control of tram power system, fault classification of tram power system is required. At present, there are many methods for the fault classification of hybrid electric vehicle power system, most of which are from the fault analysis of a certain part of the tram. However, in order to better pave the way for the fault tolerance of the vehicle control system [1], according to the clue of the functional structure of the tram vehicle control system, the fault can be divided into three levels as shown in the following figure according to the concept of hierarchical system: organization level, coordination level and execution level. The top layer of the hybrid electric vehicle control system is the organization layer, which is the core of the vehicle control system. The fault-tolerant control strategy and fault-tolerant module strategy of the tram system are embedded in the vehicle controller program at this level. The organization layer analyzes driver input signals, accelerator pedal signals, brake pedal signals, vehicle speed signals, gearbox and clutch signals, and outputs command signals of corresponding power sources. The coordination layer is the second layer of the control layer. It is a secondary control system composed of control units of each sub module, including engine, motor, battery management unit, etc. The bottom layer is the executive unit of the control system, which consists of engine, motor, clutch, reducer and other components. The direct fault of the vehicle comes from these devices. The main stratification diagram is as follows:

According to the hierarchical structure of the above tram power system [2], the following layer by layer analysis summarizes the control system faults, mainly including eight aspects, as follows:

1. First, the power box of tram power system is composed of power battery group and super capacitor group. When the power battery or super capacitor fails, the power supply system will fail, causing the power system of the tram to reduce power or stop, thus affecting the normal operation of the tram;
2. Second, the failure of power battery pack, battery failure refers to the loss of charge and discharge capacity. The failure modes include too fast capacity attenuation, shorter service life, premature failure of one or more battery cells in the battery pack, falling off of active substances in the battery plate or partition, etc. in the actual work, the main performance is capacity reduction, internal resistance is too large, charging and discharging temperature is too high. The failure reasons include the poor conductivity of active substance [3] in the battery, the short circuit or open circuit in the battery, and the rapid temperature rise during the operation of the battery. In case when a large number of cells are combined into a battery pack, if one or more cells fail, the failure of the whole battery pack will be accelerated;
3. Third, the inconsistent failure of the power battery pack; the inconsistency of power battery pack is reflected in the difference of voltage and resistance capacity of each cell, which is mainly caused by the difference of battery manufacturing process and the inconsistency of battery voltage caused by long-term charge and discharge of battery. When the capacity of the battery pack is inconsistent, with the frequent charging and discharging of the battery, the small capacity battery will not keep up with the pace of the large capacity battery, resulting in the premature damage of the small capacity battery, and the discharge performance and heat dissipation of the whole battery pack will also be reduced. Usually, the terminal voltage of lithium battery is measured as the basis of diagnosis. When inconsistent single battery is found, the single battery can be repaired and reused; when it cannot be repaired, it shall be isolated and replaced in time. The state changes and phenomena of battery performance parameters are shown in the table below.

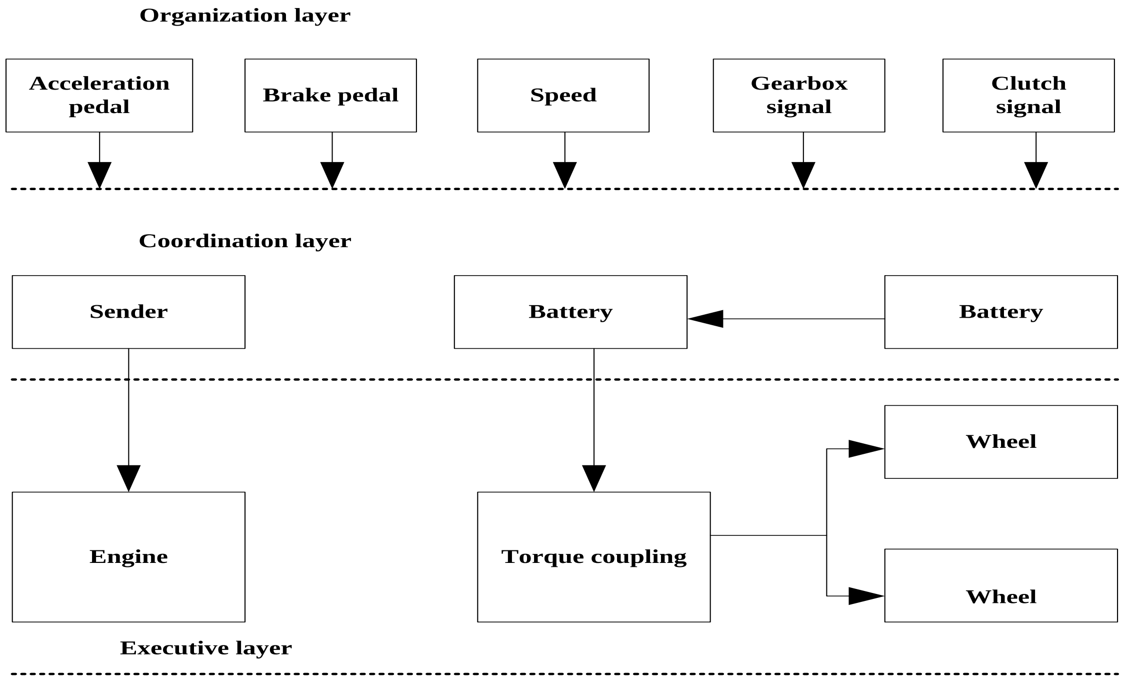

Figure 1. Hierarchical diagram of tram power system control system

Table 1. Parameter change phenomenon and diagnosis method of battery damage

Physical parameter	Phenomenon	Diagnosis method
Temperature change	Short-term temperature rises quickly and then stabilizes	Measure battery temperature
Capacity change	Reduced battery capacity	Detect changes in battery voltage and current
Voltage change	Abnormal closed-circuit voltage	Detection of battery cell voltage under high current charge and discharge
Internal resistance change	Increased internal resistance	Measuring battery internal resistance

4. Fourth, the damage of lithium battery. When the battery is overcharged and discharged for many times, the small damage gradually accumulates and develops into battery failure, and finally the battery will not be repairable;
5. Fifth, power battery voltage and current fault [4]. The power battery control unit is responsible for receiving the current value and voltage value uploaded by the battery sensor in real time and judging whether the power battery fails through the fluctuation of these two values. Taking the power battery voltage as an example, the power battery voltage detection fault includes circuit break and voltage detection accuracy. In order to improve the accuracy of voltage detection, the power battery is divided into several groups. The detection system detects the voltage of each power battery branch and the total voltage of the battery. In case of voltage failure, the power battery will transmit the failure information to the control center and ask for an alarm;
6. Sixth, the power battery temperature fault, including different parts of the temperature is uneven or a part of the temperature is too high and so on. In general, multiple temperature sensors are set in the power battery box. The control unit is responsible for collecting sensor signals and controlling the cooling system. If a temperature fault is detected, the control unit will upload the fault information [5] to the hybrid system control center to decide either power reduction or shutdown;
7. Seventh, the power battery in the power system of the tram has leakage fault. When the insulation between the power supply electrode and the insulation resistance is lower than the specified standard, the information will be fed back to the control center [6], and the sensor will judge the leakage of the power battery and make a decision of shutdown.
8. Eighth, network control system failure. The network control system, including many sensors, actuators and other components, is an important part of the information transmission in the hybrid system, which plays an important role in the stable operation of the tram, especially if the state information feedback of the power box fails, it can lead to overcharge or over discharge of the battery [7] and super capacitor, and damage the power box. The main faults of the sensor are as follows:

Table 2. Sensor failure

Serial number	Classification	Details
1	Classification according to the degree of failure	Hard fault, which means that the sensor structure is damaged, the fault amplitude is large and the change is sudden, this type of fault is easier to identify
		Soft fault refers to the variation of sensor characteristics, the fault amplitude is small and the change is slow, this kind of fault is difficult to identify
2	Classification by fault performance	Intermittent failures, manifested as good or bad sensors
		Permanent failure, manifested as failure to return to normal after failure
3	Classification by failure process	Abrupt fault, large signal change rate
		Slowly changing faults, small signal change rate
4	Classification by fault modeling	Multiplicative failure
		Additive failure
5	According to the breakdown reason	Deviation failure
		Impact failure
		Open fault
		Drift fault
		Short circuit fault
		Periodic failure
		Non-linear dead zone fault

3. Fault diagnosis of tram power system

According to the above classification results of tram power system fault, diagnose the tram power system fault to improve the accuracy of fault diagnosis [8], and provide basis for fault-tolerant control of tram power system. In order to diagnose the fault of the power system of the tram, it is necessary to establish the tram model, use CRUISE to model and simulate the hybrid tram, simulate multiple performance indicators of the vehicle to be controlled, and provide the basis for optimizing fault-tolerant control. CRUISE software is to build the vehicle control system in a modular way, and the driver model can truly reflect the behavior of people operating the car. CRUISE has an interface with Matlab / Simulink, which can embed user designed modules and control algorithms into the vehicle simulation model. This study was conducted through CRUISE. The modules used for building the tram model mainly include: vehicle module, which contains the basic information of the vehicle, the most important information is the equipment quality and full load mass of the tram; FC module, which contains the characteristic curve of the engine, which is designed according to the actual tram parameters; motor module The motor module mainly includes the characteristic curve (MAP) and the efficiency distribution diagram of the motor. From the selection of two main power sources, the tram power in this simulation enjoys a low fuel consumption of 1.2 L; the battery module includes some basic characteristics of the battery. For example, the battery voltage value, SOC of the battery, the maximum charge and discharge current and voltage allowed by the battery, internal resistance of the battery, etc. In this study, the battery pack is matched with the Prius; the driver module, the driver module, is an important information hub connecting the human and vehicle components, and transmits the status of the motor, engine and gearbox to cockpit through the bus bus bus connection unique to the CRUISE software. In the module, the driver module also sends the load signal of accelerator pedal to the vehicle controller module, as well as the output of brake pressure and temperature signals; the vehicle controller is embedded in the module, and the vehicle controller is introduced into the CRUISEsimulation model through the MATLAB API module, in which the MATLAB model is the logic threshold control strategy module designed in this study The bus bus connects the input and output of the API embedded module; the display module contains some commonly used data, such as vehicle speed, acceleration, driving distance, motor torque speed signal, engine torque speed signal, and temperature signal.

According to the built tram model, the fault diagnosis of the tram power system is carried out. The fault diagnosis module in the design strategy uses the generalized observer to get the estimated value of the sensor fault signal, and transmits it to the decision-making body for analysis. In the case of no fault in the original system, without considering the influence of interference, noise [9] or unmodeled part of the system, the initial error of the detection filter will be gradually eliminated, the filter can fully track the response of the original system, and the output error will remain zero. If there is a fault in the original system at a certain time, the output of the filter will not be able to fully track the output of the system after the fault, so there is a residual. The expression formula of this state is as follows:

$$q = a(b) + d / o \tag{1}$$

In formula (1), q represents dimensional state variable, a represents dimensional control vector, b represents dimensional measurement vector, d and o represent constant respectively.

For the actual control system, the premise of fault diagnosis is that the fault can be detected. Only when it is clear that the fault can be detected, the fault diagnosis process can be completed [10]. For the failure of discrete system, the following equation is used to describe:

$$c(t) = x + e / \frac{f}{q} \tag{2}$$

In formula (2), $c(t)$ represents the sudden change of input quantity at t time, x represents the initial value of fault state, and f represents the expandable state variable.

For the unknown fault in the power system of the tram [11], the fault detection observer [12] is used to detect whether the power positioning tram power system has actuator fault:

$$B = k + \frac{c}{y} \tag{3}$$

In formula (3), B represents the state variable of the detection observer, k represents the parameter of the dynamic positioning controller when no fault occurs, y is the output of the system, and c represents the state variable estimation parameter.

Based on the above calculation, it is detected whether the actuator of the tram power system has failed, but it is impossible to know which actuator has failed [13]. Next, separate the failed actuator:

$$W = F / Q + e \tag{4}$$

In formula (4), W represents the initial value of observation error, F represents the actuator fault judgment parameter, and Q represents the function of time.

According to the above diagnosis results, the actuator with failure [14] can be separated. When the thrust is distributed, the actuator with failure [15] will not be distributed with force and torque, while the controller's force and torque will be distributed to the actuator without failure, which provides the basis for fault-tolerant control. The decision-making mechanism can isolate the system output affected by the fault through the control selector [16], and select the controller based on the health system output to form a feedback control loop, to maintain the stability of the system.

4. Fault tolerant control of tram power system

The fault-tolerant control method in this design is generally divided into three parts, namely, angle fault-tolerant control unit [17], PID control algorithm model [18] and brake pull fault-tolerant control unit [19]. The overall framework is shown in the figure below.

It can be seen from the above figure that in the angle fault-tolerant control unit, the tram power system collects the angle sensor and acceleration sensor signals in real time, inputs the detected value of the acceleration sensor into the estimation model to calculate the estimated value of the angle, and then inputs the estimated value of the angle and the detected value of the angle sensor into the fault-tolerant control model for fault diagnosis and fault compensation respectively, Thus, the expected braking force is calculated by the corresponding formula. In the fault-tolerant control unit of braking force, the tram power system collects the signal values of braking force sensor, motor speed sensor and current sensor in real time [20], inputs the detection values of motor speed sensor and current sensor into their respective estimation models to calculate the corresponding angle estimation values, and then inputs the estimated values of braking force and braking force sensor. The detection value of the controller is input into the fault-tolerant control model, and fault diagnosis and fault compensation are carried out respectively, so as to output the actual braking force value. Compare the expected braking force value with the actual braking force value, input the difference into the PID control algorithm model to control the actuator, thus forming a closed-loop control [21-23].

PID control algorithm design. PID control algorithm is the most widely used control algorithm in industrial production. The core of its control algorithm is to calculate the difference between the ideal value of the controlled object and the feedback value according to the three links of proportion, integration and differentiation, and adjust the parameter values of the three modes through its linear combination to achieve the control of the output value of the controlled object. As a classical numerical control method [24], PID control has the following advantages: first, the principle is simple, easy to operate and master; second, it can be widely used in various industrial process control fields; third, it has good control effect and strong robustness. The conventional PID controller is a kind of linear controller composed of Pro controller [25] and controlled object. Its control system schematic diagram is as follows:

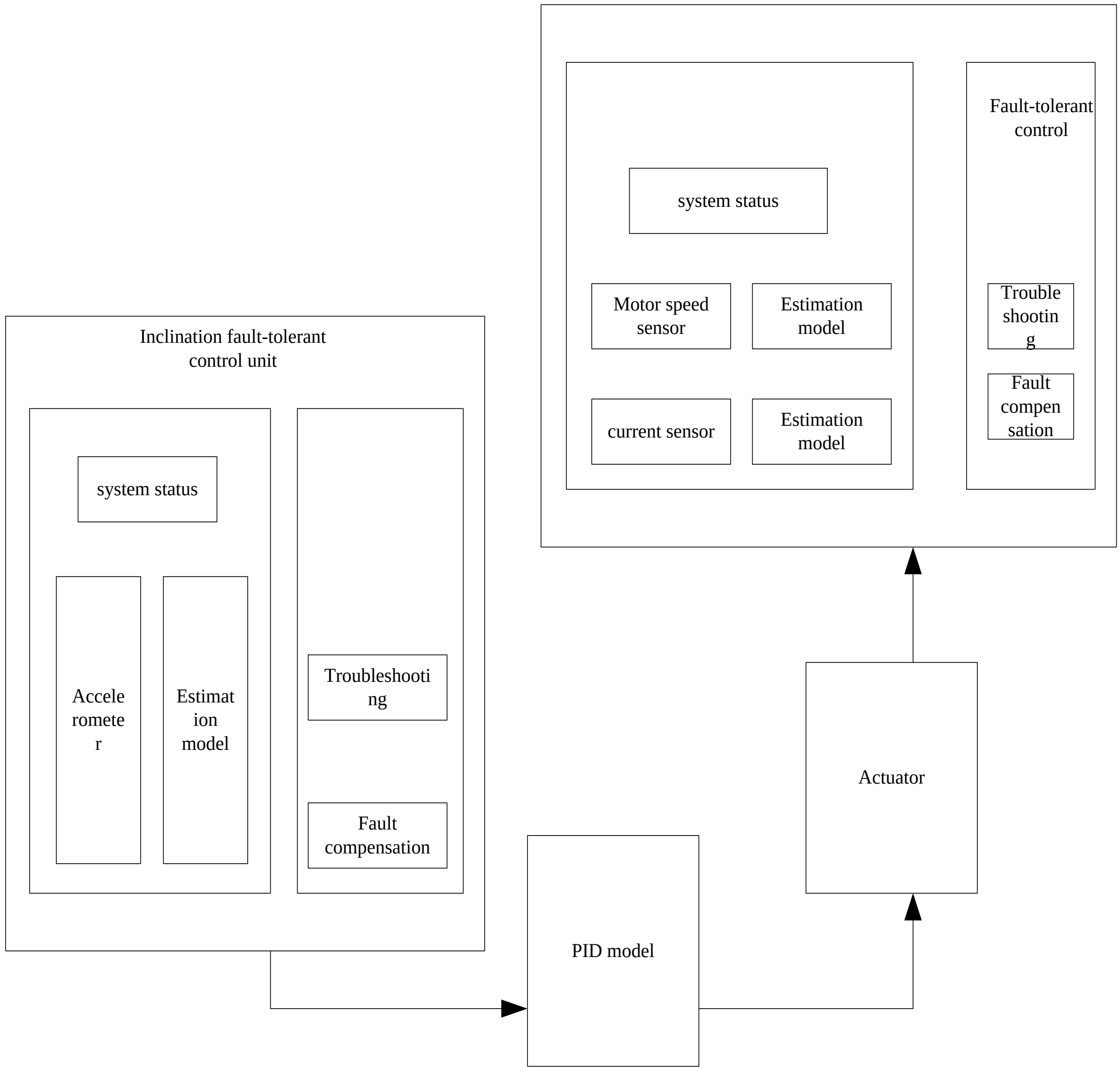

Figure 2. General framework of fault tolerant control method

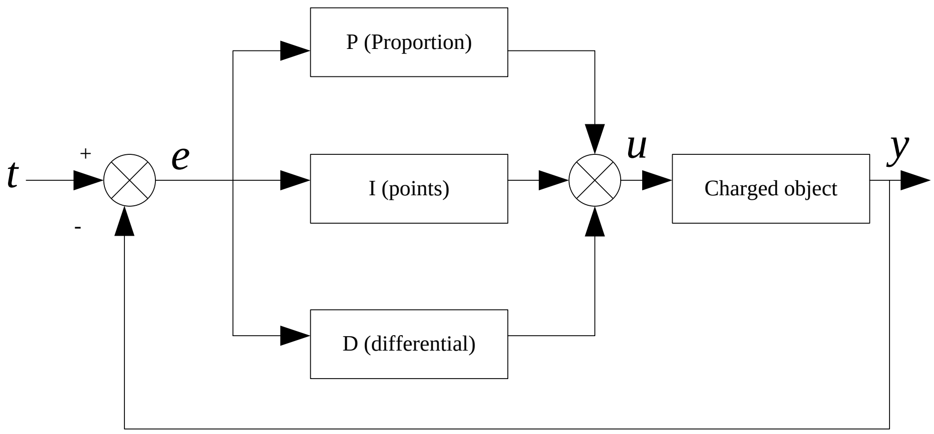

Figure 3. Schematic diagram of PID control system

It can be seen from the above figure that the PID control system compares the output value y of the controlled object with the ideal value t, and then inputs the deviation value g into the controller to generate a regulating factor to control the output of the controlled object. The mathematical model of the algorithm in the continuous time domain is as follows:

$$u = h\left(e + \frac{1}{T} + \frac{t}{g}\right) \tag{5}$$

In formula (5), u represents the output control quantity of the controller, h is the proportional gain coefficient of the controller, T is the integral time constant of the controller, t is the differential time constant of the controller, and g represents the relative deviation between the output value of the controlled object and the ideal value.

In the pro control algorithm, there are great differences in the debugging functions of proportion, integral and differential, which are described in detail as follows:

First, in the proportional control, the proportional gain coefficient makes the adjustment factor proportional to the relative deviation g, which can directly affect the control effect. Increasing the proportional gain coefficient can improve the response speed of the system and reduce the steady-state error of the system, but the excessive proportional gain coefficient will lead to system oscillation and destroy the stability of the system. Therefore, a single proportional link cannot meet the control requirements of complex system, so an integral link is needed.

Second, in the integral control link [26], the integral gain coefficient can be used to eliminate the steady-state error (or static error) of the system. In the control process, as long as the system deviation exists, the integral control will continue to operate until the steady-state error is eliminated, and the integral control will stop. The length of the controller integral time is related to the strength of the integral control function. The integral control function weakens with the increase of the integral time. The longer the time to eliminate the steady-state error is, the less the overshoot of the control system and improve its stability. On the contrary, the shorter the integral time is, the stronger the integral control function is. However, if the integral control function is too strong, the overshoot of the system will be caused, and its stability will be destroyed Qualitative.

Thirdly, in the differential control, the differential gain coefficient can be used to reflect the change rate of relative deviation. Differential control has the function of predicting the trend of deviation and makes corresponding advance adjustment to eliminate it before the deviation signal disappears, so as to reduce the adjustment time of the system, prevent the occurrence of system oscillation, and improve its dynamic characteristics. However, differential control is very sensitive to noise interference and has amplification effect on it, so if the differential control time is too long, the anti-interference ability of the system will be weakened.

Therefore, according to the PID control algorithm, this paper determines that the closed-loop control process of the mechanical electronic parking brake system is to input the expected value of power. The actual braking force is obtained by the servo motor, lead screw nut, cable and brake, and finally controlled by the PID controller.

According to the above process, the starting control of the tram power system ramp is based on personal experience to determine the time to release the handbrake as to achieve a smooth start. If the driver is inexperienced and the timing is improper, it is easy to cause the car to slip or the engine to be forced to fire. The simulation model of starting on ramp is designed to simulate the situation of the driver when starting on ramp. It includes the conversion model of engine torque transmission ratio and the control strategy model of auxiliary starting on ramp. When starting on the ramp, the driver will generally put the gear in first gear forward or reverse according to the site conditions, so the transmission ratio coefficient of the engine output torque through the final drive, transmission gear, etc. is converted into the driving force acting on the tire and the desired ideal braking force for comparison. Then the mathematical model of moment transfer of mechanical part can be obtained as follows:

$$r = i \otimes j \otimes \frac{a}{s} \tag{6}$$

In formula (6), r represents the output torque of automobile engine, i represents the maximum torque ratio of torque converter, j represents the gear transmission ratio, and s represents the reduction ratio of final drive.

The calculation formula of braking force required for parking is as follows:

$$L = \frac{m + C_g}{r \times u \times C_f} \tag{7}$$

In formula (7), L is the braking force required for parking, m is the slope angle of the tram, C_g is the mass of the tram, and C_f is the friction coefficient of the tram. According to the above calculation, the starting control strategy is designed as follows: the mechanical electric parking brake system detects the engine output torque in real time, and compares it with the required braking force converted from the mathematical model of ramp angle. Then, according to the difference between the force converted from the engine output torque and the required ideal braking force and the driver's intention, the servo motor is driven reversely at the right time Turn to release the parking brake tension, and ensure the smooth start of the vehicle to avoid the phenomenon of sudden rush and sliding.

Because most tram vehicles are powered by on-board battery [27], and DC motor has the advantages of strong aerodynamic performance, good speed regulation performance, easy control, etc. DC motor can convert DC electric energy into mechanical energy, so it is the main power of mechanical electric parking brake system. According to the electromagnetic characteristics of DC motor, the mathematical model can be obtained as follows:

$$v = r + l + \frac{w}{e} \tag{8}$$

In formula (8), v is the input voltage of servo motor, l is the armature current of servo motor, w is the back EMF of servo motor.

According to the torque equivalence of DC motor, the torque balance mathematical model of servo motor can be obtained as follows:

$$J = \frac{C}{V} + F \tag{9}$$

In formula (9), J represents the electromagnetic torque generated by the servo motor, V is the total moment of inertia of all rotating parts (including transmission mechanism, reducer and load machinery) driven by the servo motor, C is the rotation speed of the servo motor, F is the sum of all kinds of friction torque and load torque on the rotation axis of the servo motor.

On this basis, the voltage output calculated by PID controller is used as the control voltage input of servo motor, and the output of the whole servo motor is the rotation angle of servo motor. There is a saturation module in the servo motor, which is used to set the upper and lower limits of the output. The first saturation module is used to limit the upper and lower limits of the servo motor control voltage. The second saturation module is used to limit the upper and lower limits of the servo motor output rotation angle. The rotation angle of the servo motor output is used as the input of the following transmission mechanism model, so the limit value is to prevent the excessive output angle from affecting the operation of the screw nut mechanism, so as to avoid excessive wear of the mechanism. Then the model control of the transmission mechanism of the power system of the tram is carried out. In the mechanical electric parking brake system, the transmission mechanism is an important part of the executive module. The driving mechanism is mainly composed of lead screw nut and cable. The input of the lead screw nut mechanism is the rotation angle of the output of the previous servo motor, while the output of the lead screw nut mechanism is the feed of the lead screw nut mechanism. According to the previous experimental data, the relationship between the feed rate and the pull force of the screw nut meets the following empirical formula:

$$N = 6.817z^2 - 11z = 7.64 \tag{10}$$

In formula (10), z is the feed of the screw nut.

In the overall model of the lead screw nut mechanism, the servo motor overcomes the total moment of inertia, friction and load torque of the lead screw nut drive mechanism to drive the lead screw nut to rotate. In this process, through fixing the lead screw, it affects the nut to make a linear horizontal movement, and applies the braking force to the brake through the cable.

Because the observation value of the generalized observer to the system state is not affected by the sensor fault basically, this strategy directly uses the observation value of the tram power system to construct the robust state feedback controller to stabilize the system, and does not need to consider the similarity between the generalized fuzzy system and the common linear system, so the state observer and the controller of the system can be designed separately, so that the closed-loop The control system satisfies the sufficient condition of asymptotic stability. The state feedback controller of fuzzy system is established as follows:

$$M = X * I * Z(t) \tag{11}$$

In formula (11), M represents the observation value of the tram system state, X represents the generalized observation error, I represents the vehicle operation performance parameter, Z represents the observation noise, and t represents the observation time.

According to the above process, the fault-tolerant control of the tram power system based on PLC is completed.

5. Experiment

Build an experimental platform to verify the effectiveness of PLC based fault-tolerant control method of tram power system. For fault-tolerant control of tram power system, the rationality of gain coefficient in different control links determines the effect of fault-tolerant control, so the experiment verifies the rationality of gain coefficient in different control links.

5.1. Establishment of experimental platform

In this paper, the hardware of the mechanical electric parking brake system is built in the ring simulation by using the Autobox developed by DSpace company, and the power module circuit, sensor circuit, motor drive circuit, system input and output interface and system control strategy are designed respectively. The hardware structure used in the experiment is as follows.

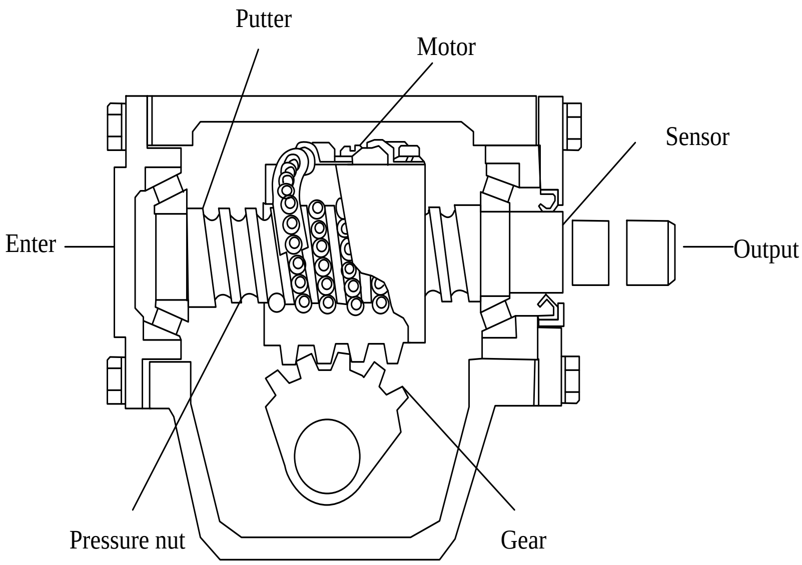

Figure 4. Experimental hardware structure

DSpace is a set of real-time simulation system, which consists of two parts: hardware system and software environment. Among them, the hardware system mainly includes processors with high-speed computing ability and various rich I / O interfaces, allowing users to combine according to their own needs; the software environment mainly includes RTI software, software for testing and debugging, such as software with the function of generating and downloading program code, software for testing and debugging, etc. The code in the hardware system is automatically generated by RTI software and downloaded to the control program to realize the real-time simulation experiment of the system, and then the variables are accessed by controldesk software to realize the experiment and debugging of the simulation system. The output table of the controller control signal applied in the experiment is as follows:

Table 3. Control signal output summary

Signal	Signal type	Signal connection
App indicator	Switch	Indicator hard wire
Mode indicator	Switch	Indicator hard wire
System fault indicator	Switch	Indicator hard wire
System failure warning tone	Switch	Buzzer hard wire

The input circuit needs to ensure that the analog and digital signals of each sensor can be collected by the control unit; the output circuit needs to ensure that the control signals output by the controlled unit can be accurately transmitted to the actuator and warning lights, etc., without interference from other external factors. The summary table of system controller signal acquisition is as follows:

Table 4. Summary of signal acquisition of experimental controller

Signal name	Signal form	Signal source connection
EPB operation button	Switch	Button hardwire
Operation button	Switch	Button hardwire
Engine speed	Digital quantity	Car electronic network
Engine torque	Digital quantity	Car electronic network
Accelerator	Digital quantity	Car electronic network
Speed	Frequency	Magnetoelectric sensor
Servo motor speed	Frequency	Motor speed sensor
Vehicle inclination	Analog	Tilt sensor
Gear information	Switch	Switch hard wire
Ignition key	Switch	Switch hard wire

At the same time, the hardware in the loop simulation uses the XP operating system installed in the notebook, on which the modeling and simulation software MATLAB r2007b and the test monitoring software control desk are installed. The main construction steps of the experimental platform are as follows:

Firstly, the simulation model block diagram of the mechanical electronic parking brake system is established in Matlab / Simulink software, and the experimental parameters are set according to the simulation results to ensure that the simulation system can output the correct simulation curve; secondly, the input and output interfaces in the simulation system are connected with the I / O interfaces provided by rt11005 module in DSpace to form a closed-loop control system; then the algorithm is defined The option is fixed step, the setting step time is 0.001 s, the build button in Matlab / Simulink of the motor converts the simulation model block diagram of the mechanical electric parking brake system into C language code; finally, the compiler code provided by DSpace is compiled and loaded into the ds2211 control board card in the Autobox, so as to realize the overall system simulation using the Autobox as the electronic control unit. At the same time, control desk is used to monitor the simulation process in real time. The overall structure of the experimental platform is as follows:

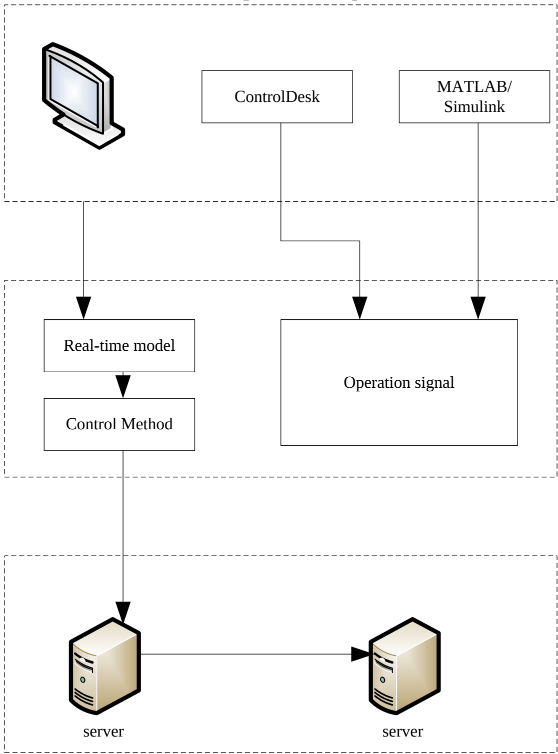

Figure 5. Experimental test platform

5.2. Rationality analysis of gain coefficient of proportional control link

In the proportional control, the proportional gain coefficient is determined by the adjustment factor and the relative deviation, which affects the strength of the fault-tolerant control. Among them, the regulation factor refers to the regulation parameter of the proportional control; the relative deviation value refers to the difference between the output value of the controlled object and the ideal value; a reasonable proportional gain coefficient can improve the response time of the fault-tolerant control, reduce the steady-state error of the power system, and ensure the safe operation of the power system of the tram. The initial value of the adjustment factor is set to 0.5, and the initial value of the relative deviation is set to 1.0. In each case, experiment 10 times, and take the average value. The results of the proportional gain coefficient are shown in the table below.

Table 5. Proportional gain coefficient

Regulatory factors	Relative deviation value	Proportional gain coefficient	Response time (ms)
0.5	1.0	20.13	12.03
1.0	1.1	21.16	11.10
1.5	1.2	22.62	10.00
2.0	1.3	23.94	9.99
2.5	1.4	24.16	9.12
3.0	1.5	30.00	10.03
...	...	...	...
5.0	1.9	35.46	11.23
5.5	2.0	39.56	12.56

As shown in Table 5, when the adjustment factor is 3.0 and the relative deviation value is 1.5, the response time of fault-tolerant control is the shortest, indicating that the rationality of proportional gain coefficient is the strongest at this time, which is 30.00.

5.3. Rationality analysis of gain coefficient of integral control link

Fault tolerant control in the integral control link, the integral gain coefficient is determined by the integral time and overshoot, and its function is to eliminate the steady-state error of the tram power system. Among them, integration time refers to the number of integrations; Overshoot refers to the maximum limit value of fault tolerance. A reasonable integral gain coefficient can eliminate the steady-state error of the power system and ensure the safe operation of the power system of the tram. The integration time is set to 1 time, and the overshoot is set to 0.5. In each case, experiment 10 times, and take the average value. The integral gain coefficient results are shown in the table below.

Table 6. Integral gain coefficient

Integral time (Times)	Overshoot	Integral gain coefficient	Steady-state error
1	0.5	12.03	+2.30
2	0.6	12.11	+2.20
3	0.7	12.23	+2.03
4	0.8	12.56	+1.92
5	0.9	12.48	+1.82
6	1.0	12.94	+1.24
...	...	...	...
19	2.4	14.26	+0.51
20	2.5	15.00	0

As shown in Table 6, when the integration time is 20 times and the overshoot is 2.5, the steady-state error of fault-tolerant control is 0, indicating that the integration gain coefficient is the most reasonable at this time, which is 15.00.

5.4. Rationality analysis of gain coefficient of differential control link

In the differential control, the differential gain coefficient is determined by noise and prediction deviation, which reflects the change rate of relative error. Among them, noise refers to the interference factors in the process of fault-tolerant control; prediction deviation refers to the difference between the output value and prediction value of the controlled object. Reasonable differential gain coefficient can improve the rate of fault-tolerant control and ensure the safe operation of the tram power system. The initial noise value is set to 30, and the initial prediction deviation value is set to 3.5. In each case, 10 experiments are conducted, and the average value is taken. The differential gain coefficient results are shown in the table below.

Table 7. Differential gain coefficient

Noise (dB)	Forecast deviation	Differential gain coefficient	Control rate (Number of faults / MS)
30	3.5	10.12	34.64
40	3.6	15.12	39.45
50	3.7	20.13	40.15
60	3.8	26.48	46.15
70	3.9	26.79	49.51
80	4.0	29.45	53.16
...	...	...	...
150	4.8	29.98	59.78
160	4.9	35.46	45.12

As shown in Table 7, when the noise is 150 and the prediction deviation is 4.8, the fault-tolerant control rate is the largest, indicating that the differential gain coefficient is the most reasonable at this time, which is 29.98.

6. Conclusion

In conclusion, in order to meet the fault-tolerant requirements of the tram power system, the PLC based fault-tolerant control method of the tram power system designed in this study can improve the rationality of the gain coefficient of the fault-tolerant control link, improve the fault-tolerant performance of the power system, and provide a more effective guarantee for the operation safety of the tram. At present, the research on fault-tolerant control of tram power system is still in its infancy, and further experimental research and demonstration are needed as an industrial product. Therefore, the following aspects need to be studied and tested:

1. First, there is no emergency braking control strategy in the fault-tolerant control simulation model, that is, when the service brake fails, the parking brake system can replace the service brake to apply the braking force to the driving vehicle, so that it can stop driving smoothly and reliably;
2. Second, although the fault-tolerant control strategy has been designed in this experiment, due to the time and cost problems, there is no specific single-chip microcomputer as the control unit, so only the dual core redundancy method is used to realize the possibility of fault compensation of electronic control system;

3. Third, because no suitable single-chip microcomputer is selected as the electronic control unit, no real vehicle test is carried out. It is hoped that there will be a chance to burn the fault-tolerant control program into the single-chip microcomputer and carry out real vehicle verification;
4. Fourthly, for the parameter uncertainty, this paper mainly considers the case that the unknown parameter enters the system state equation linearly, and there is not enough research on the adaptive control of the more general nonlinear parameter uncertainty system. In addition, this paper assumes that the unknown quantity is constant or slowly changing. How to further study the uncertain parameters of time-varying based on this paper is also an important problem.

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