ISSN: 2414-1895 DOI: 10.6919/ICJE.202608_12(8).0014

# Performance Optimization and Fault-tolerant Control Technology of Drive System

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## Abstract

**Amid the rapid development of the new energy vehicle sector, the drive system, a pivotal power component of electric vehicles, directly dictates the vehicle's performance, economic efficiency, safety, and operational reliability. Current pure electric vehicles are confronted with challenges such as limited driving range, uneven power performance and high failure risks in the drive system. Although rotor permanent magnet brushless motors are widely applied in electric vehicle (EV) drive systems due to their high efficiency and power density, they are prone to permanent magnet demagnetization and winding faults, which pose severe threats to vehicle operational safety. Therefore, performance optimization and fault-tolerant control technologies for drive systems have become critical breakthroughs to enhance the overall competitiveness of new energy vehicles. This paper systematically reviews the structural types, performance optimization methods and fault-tolerant control technologies of EV drive systems at home and abroad. It analyzes the advantages and disadvantages of different drive modes, core optimization approaches and key fault-tolerant control technologies, identifies the current research bottlenecks, and outlines the future development trends. The findings of this study serve as a useful reference for enhancing the performance and reliability of new energy vehicle drive systems, bolster the high-quality development of China's new energy vehicle sector, and contribute to realizing the goals of carbon peaking and carbon neutrality.This project focuses on the precise parameter matching of key components in the powertrain of pure electric vehicles, as well as innovative solutions to the existing problems of rotor permanent magnet brushless motors.**



## Keywords

**Permanent Magnet Synchronous Motor; Fault Diagnosis; Multi-motor Coupling Drive; Parameter Matching; Topology Optimization; Torque Ripple Suppression.**


## 1. Introduction

### 1.1 Research Background

Against the backdrop of the increasingly severe global energy crisis and environmental pollution, the automotive industry, as a core sector of energy consumption and pollutant emission, is facing enormous transformation pressure[1,2]. Traditional fuel vehicles rely on fossil energy, which not only consumes a large amount of non-renewable resources but also emits massive pollutants that exacerbate environmental problems. Consequently, nations across the globe have introduced a set of regulatory measures to foster the advancement of the new energy vehicle sector. Pure electric vehicles, with the advantages of zero emission and high energy efficiency, have become the core carrier of the transformation and upgrading of the automotive industry.

This drive system is the core power component of pure electric vehicles, and its performance directly affects key vehicle indicators such as acceleration, climbing capacity and driving range[3].While its reliability is closely related to the safe operation of the entire vehicle. At present, most drive systems of pure electric vehicles adopt rotor permanent magnet brushless motors. Even with their built-in benefits of high efficiency and exceptional power density, such motors are prone to problems including irreversible demagnetization of permanent magnets, winding faults and inverter faults under long-term high-load operation and extreme temperature environments. In the event of failing to handle these faults in a timely manner will give rise in complete failure of the drive system. Therefore, improving comprehensive performance of the drive system and developing efficient fault-tolerant control technologies have become research hotspots in the field of new energy vehicles.

### 1.2 Research Significance

This paper carries out a comprehensive and thorough survey of the performance optimization and fault-tolerant control technologies for new energy vehicle drive systems, which carries significant theoretical significance and practical engineering worth.

At the theoretical level, by systematically sorting out the latest domestic and international research status, analyzing the advantages, disadvantages and applicable scenarios of different technical routes, clarifying the current research bottlenecks and proposing future development trends, this paper improves the theoretical system related to new energy vehicle drive systems, provides clear research ideas and reliable reference basis for subsequent academic research, and further promotes technological and theoretical innovation in this field.

At the engineering level, the research results can provide strong technical support for new energy vehicle enterprises, help optimize the structural design of drive systems and improve their power performance, economic efficiency and operational reliability. It not only enhances the overall driving performance of vehicles through performance optimization, but also reduces the safety risks caused by faults through fault-tolerant control technologies. In the long run, the research can also advance technological upgrading of China's new energy vehicle industry, enhance the market competitiveness of domestic products, break the monopoly of foreign core technologies, improve energy utilization efficiency, reduce pollutant emissions, and contribute to alleviating energy and environmental pressure and achieving the national dual carbon targets.

## 2. Overview of Research Status at Home and Abroad

With the rapid advancement of the global new energy vehicle sector, the performance optimization and fault-tolerant control technologies of pure electric vehicle drive systems have become research hotspots for scholars and enterprises worldwide. Countries around the world have carried out extensive and in-depth research on the core directions including structural design, parameter matching, control strategy optimization, and fault diagnosis and fault-tolerant control of drive systems, forming rich theoretical research results and practical engineering application cases[4].

Overall, foreign research started early, and relying on a sound industrial foundation and advanced technical reserves, foreign academic institutions have formed systematic studies outcome in the field of performance optimization and malfunction-tolerant control, with strong engineering transformation capabilities. On the basis of learning from advanced foreign experience, domestic research has made remarkable progress in parameter matching optimization, dual-motor coupling drive, and fault-tolerant structural innovation in combination with the actual needs of the local industry, and some research achievements have reached the international leading level. However, there is still considerable room for improvement in the independent research and development of core technologies and the collaborative processing of multiple complex faults in China.

### 2.1 Foreign Research Status

Foreign research on pure electric vehicle drive systems started in the early stage, and relying on a complete industrial chain and cutting-edge technical reserves, systematic research results have been

ISSN: 2414-1895 DOI: 10.6919/ICJE.202608_12(8).0014

formed in the field of performance optimization, with strong engineering transformation and application capabilities. In terms of drive system performance optimization, foreign scholars took the lead in focusing on the application and upgrading of permanent magnet brushless motors. Chau K T et al. systematically sorted out the application status and development trends of PM brushless DC drive systems in electrified as well as hybrid electric vehicles, establishing a robust theoretical underpinning for the subsequent development of motor drive technologies[4].

With regard to transmission system upgrading, foreign research focuses on improving transmission efficiency of reducers and analyzing the dynamic performance under complex working conditions. SIDDHARTH B R et al. carried out dynamic performance analysis under different real-time working conditions for the front-wheel drive hybrid electric vehicle architecture, providing a reliable basis for the working condition adaptation and performance optimization of the drive system[5]. In terms of fault-tolerant control technologies, foreign research focuses on the accurate fault diagnosis and high-precision fault accommodation control of permanen-magnet synchronous motors. Teams such as Zhu X Y have carried out a great deal of in-depth research on motor topology optimization and fault suppression[6-8]. Through multi-mode optimization design, torque ripple coordinated suppression and other technical schemes, the operational reliability and fault-tolerant performance of motors have been significantly improved. At the same time, mature technical solutions have been formed in current sensor faults, composite fault diagnosis and other aspects, with leading diagnosis accuracy and real-time performance in the world.

Foreign research is also in-depth on the impact of vehicle emission regulations on the advancement of drive technologies. SADOI Y analyzed the driving effect of Euro IV automobile emission regulations on the development of automobile technical capabilities in the ASEAN region [2], providing a valuable policy-level reference for the technological upgrading and development of drive systems.

## 2.2 Domestic Research Status

With the rapid rise and vigorous development of China's new energy vehicle sector,research investment in the performance optimization and fault-tolerant control of pure electric vehicle drive systems has been continuously increased, forming distinctive research characteristics in line with the actual needs of the local industry, and some research achievements have been effectively applied in industrial applications.

In terms of parameter matching optimization, Yin Andong et al. carried out in-depth research on the coordinated matching optimization of pure electric vehicle powertrain systems based on the iSIGHT platform [3].Providing a practical and effective method for the rational design of key parameters of drive systems; Chen Feng et al. deeply analyzed the main influencing factors of the transmission efficiency of reducers for electric vehicles, providing solid theoretical support for the structural optimization and efficiency improvement of transmission systems[9]. In the field of multi-motor coordinated control and energy recovery, domestic research focuses on working condition adaptation and performance improvement. Xu Huachao et al. analyzed the impact of braking energy recovery on the braking stability of front-drive electric vehicles [10]. Providing an important basis for the optimization of energy recovery control strategies; Zhang Jiaqi compared and analyzed the steady-state turning performance of front-drive and rear-drive electric vehicles through ADAMS/Car simulation, providing a reliable reference for the scientific selection of drive system layout methods[11].

In the field of dual-motor coupling drive technology, domestic researchers have achieved important breakthrough developments. XUE Qicheng presented a new dynamic coordinated control strategy for power shifting of dual-motor electric vehicles, which effectively reduced shift jitter and significantly improved the driving experience; relevant research teams also carried out a comprehensive review research on the topology and control method of dual-motor coupled powertrain systems [12]. Systematically sorting out the development status and technical routes of domestic dual-motor coupling drive technologies. In terms of fault-tolerant control technologies, domestic research focuses

ISSN: 2414-1895 DOI: 10.6919/ICJE.202608_12(8).0014

on engineering application and technological innovation. Chen Simin carried out in-depth research on symmetric dual-redundancy permanent magnet motors for aerospace [13]. Providing an important reference for the redundancy fault-tolerant design of drive motors for electric vehicles; at the same time, domestic research has also formed characteristic achievements in the patent intelligence analysis and development route research of global electric vehicle energy management. Providing a clear direction for the independent investigation and advancement of drive system technologies. Scholars Ouyang Minggao and Wang Pin analyzed the development trends and countermeasures of new energy vehicles in China in combination with the current situation of the domestic industry [14, 15]. Providing macro guidance for the research and development and promotion of drive system technologies. Overall, domestic research has made important breakthroughs in many sub-fields, but there is still a certain gap with the international advanced level in the precision manufacturing of core components.

## 3. Structural Types and Characteristics of Electric Vehicle Drive Systems

Electric vehicle drive systems have a variety of structural types, which can be divided into multiple types according to drive modes, coupling modes and other factors. The working principles, advantages and disadvantages, and applicable scenarios of different types of drive systems are significantly different. This section mainly introduces several typical structural types of drive systems and analyzes their performance characteristics.

### 3.1 Single-motor Drive System

The single-motor drive system is the earliest drive structure applied to electric vehicles and is also one of the most widely used drive structures at present. Its core structure consists of a motor, a reducer and a differential. A single motor provides driving force, which is decelerated and torque-increased by the reducer and then transmitted to the driving wheels through the differential to drive the vehicle to run. According to the different installation positions of the motor, the single-motor drive system can be divided into three forms: front-wheel drive, rear-wheel drive and four-wheel drive. Among them, the front-wheel drive has a simple structure and low cost, and is widely used in small pure electric vehicles; the rear-wheel drive has better power performance and is suitable for medium and high-end pure electric vehicles; the four-wheel drive is mainly used in high-performance pure electric vehicles, which can improve the handling stability and off-road performance of the vehicle.

The advantages of the single-motor drive system mainly include: simple structure, small number of parts, low manufacturing cost and convenient maintenance; simple control logic, easy to achieve precise control; high operating efficiency under low-speed and light-load working conditions, which can meet the travel needs of ordinary users. Its disadvantages are mainly manifested in: the motor needs to take into account both low-speed heavy-load and high-speed light-load working conditions, resulting in large fluctuations in motor working efficiency and low energy efficiency under complex working conditions; limited power performance, difficult to meet the acceleration and climbing needs of high-performance electric vehicles; once the motor fails, the entire drive system will completely fail with poor fault-tolerant performance.

### 3.2 Single-motor with Transmission Drive System

To make up for the defects of insufficient power performance and energy efficiency of the single-motor drive system, scholars have proposed the single-motor with transmission drive system. On the basis of the single-motor drive system, this system adds a transmission, usually a 2-3 speed automatic transmission. Through the shift adjustment of the transmission, the working speed and torque of the motor are changed, so that the motor works in the high-efficiency range, thus enhancing the power performance and economy of powertrain system.

The advantages of the single-motor with transmission drive system mainly include: through transmission shifting, the high-performance working interval of the motor can be expanded, overall energy efficiency of the drive system can be improved, and the driving range of the vehicle can be

ISSN: 2414-1895 DOI: 10.6919/ICJE.202608_12(8).0014

expanded; it can enhance the vehicle driving performance, improve low-speed acceleration performance and high-speed driving capacity, taking into account both power performance and economy; the structure is relatively simple, and the manufacturing cost is lower than that of the multi-motor drive system. Its disadvantages are mainly manifested in: the addition of the transmission increases the structural complexity and manufacturing cost of the system, and also increases the maintenance difficulty; power interruption and jitter may occur during the shifting process, affecting the driving experience; the system’s fault-tolerance performance is still poor, and the failure motor or transmission will cause the failure of the drive system.

### 3.3 Dual-motor Coupling Drive System

The dual-motor coupling drive system is a drive structure that has developed rapidly in recent years. This system adopts two motors as power sources, and couples the power of the two motors through a coupling mechanism such as a planetary gear train and a gear set to realize the coordinated output of power, which can flexibly adapt to the needs of different working conditions and improve the power performance and economy of the drive system. According to different coupling modes, the dual-motor coupling drive system can be divided into three types: speed coupling, torque coupling and speed-torque coupling.

The speed coupling drive system superimposes the speeds of the two motors through the coupling mechanism while keeping the torque unchanged, which can realize high-speed and large-speed output and is suitable for high-speed driving conditions, but has low energy efficiency under low-speed heavy-load working conditions; the torque coupling drive system superimposes the torques of the two motors through the coupling mechanism while keeping the speed unchanged, which can realize low-speed and large-torque output and is suitable for low-speed heavy-load working conditions, but has poor energy efficiency under high-speed driving conditions; the speed-torque coupling drive system can realize the coupling of speed and torque, and can flexibly distribute the power and torque of the two motors according to the needs of different working conditions, so that the motor always works in the high-efficiency range with the best comprehensive performance, suitable for various complex driving conditions.

The advantages of the dual-motor coupling drive system mainly include: excellent power performance, which can take into account the needs of low-speed large torque and high-speed large speed, meeting the use needs of high-performance electric vehicles; high energy efficiency, through the flexible distribution of motor power, the motor always works in the high-efficiency range, extending the vehicle's driving range; improved fault-tolerant performance, when one motor fails, the other motor can be used to drive the vehicle alone to ensure the basic driving safety of the vehicle. Its disadvantages are mainly manifested in: complex system structure and high design difficulty of the coupling mechanism; complex control logic, requiring the design of efficient power distribution strategies; high manufacturing cost, a large number of parts and high maintenance difficulty.

### 3.4 Multi-motor Drive System

The multi-motor drive system usually has 3 or more motors and is developed on the basis of the dual-motor coupled powertrain system. Through coordinated work of multiple motors, it realizes the precise distribution and efficient output of power, and is mainly applied to high-performance pure electric vehicles, new energy buses and other models. The multi-motor drive system can be divided into two forms: centralized multi-motor coupling drive and distributed multi-motor drive. The centralized multi-motor coupling powertrain system centrally transmits the power of multiple motors to the driving wheels through a coupling mechanism with a relatively compact structure; the distributed multi-motor drive system installs motor directly on wheels (such as in-wheel motor and wheel-side motor) without a transmission mechanism, which can realize the independent control of wheel power.

Advantages of the multi-motor powertrain system mainly include: excellent power performance, the coordinated work of multiple motors can provide greater power and torque, meeting the use needs of high-performance and large-load vehicles; extremely high energy efficiency, the energy of each motor will be precisely distributed in accordance with the needs of different working conditions, so that all motors work in the high-efficiency range; excellent fault-tolerant performance, when some motors fail, the coordinated work of the remaining motors can guarantee the normal operation of the vehicle and even maintain high driving performance; the distributed multi-motor drive system can realize the independent control of wheels, improving the handling stability and off-road performance of the vehicle. Its disadvantages are mainly manifested in: extremely complex system structure and control logic, requiring the design of efficient coordinated control strategies; high manufacturing cost, a large number of parts and high maintenance difficulty; the motor of the distributed multi-motor drive system has a large volume, limited installation space, and increased wheel load, which affects the driving smoothness of the vehicle.

### 3.5 Performance Comparison of Different Drive Systems

To clearly compare the performance characteristics of different drive systems, this paper compares the above four typical drive systems in terms of structural complexity, power performance, energy efficiency, fault-tolerant performance, manufacturing cost and other aspects, as shown in Table 1.

**Table 1.** Performance Comparison of Different Types of Pure Electric Vehicle Drive Systems

| Drive System Type | Structural Complexity | Power Performance | Energy Efficiency | Fault-tolerant Performance | Manufacturing Cost | Applicable Scenarios |
|---|---|---|---|---|---|---|
| Single-motor drive system | Low | General | Poor under complex working conditions | Poor | Low | Small pure electric vehicles, household commuter vehicles |
| Single-motor with transmission drive system | Medium | Good | Good (expanded high-efficiency range) | Poor | Medium | Compact pure electric vehicles, mid-range household vehicles |
| Dual-motor coupling drive system | Medium-high | Excellent | Good (speed-torque coupling is optimal) | Good | Medium-high | Medium and high-end pure electric vehicles, high-performance sedans |
| Multi-motor drive system | High | Outstanding | Outstanding (precise power distribution) | Outstanding | High | High-performance pure electric vehicles, new energy buses |

It can be seen from Table1 that the single-motor drive system and the single-motor with transmission powerstrain system are suitable for mid-to-low-end household pure electric vehicles, with the advantages of low cost and convenient maintenance, but relatively poor power performance, energy efficiency and fault-tolerant performance; the dual-motor coupling drive system is suitable for medium, high-end pure electric vehicles, which can take into account power performance, energy efficiency and cost with good comprehensive performance; the multi-motor drive system is suitable for high-performance pure electric vehicles and new energy buses, with the best power performance,

ISSN: 2414-1895 DOI: 10.6919/ICJE.202608_12(8).0014

energy efficiency and fault-tolerant performance, but complex structure and high cost. Looking ahead, as technology continues to evolve, the multi-motor coupling drive system will become the main development direction of electric vehicle powerstrain systems, and gradually realize structural simplification and cost reduction to promote its popularization and application.

## 4. Fault-tolerant Control Technologies of Drive Systems

Fault-tolerant technology of drive systems is the key to ensuring the safe operation of electric vehicles. Its core is to realize the timely detection, isolation and processing of drive system faults through fault diagnosis, fault-tolerant structural design, fault-tolerant control strategies and other means, ensuring that the drive system can operate stably in the fault state and avoiding the expansion of faults leading to system failure. The faults of the drive system mainly include motor winding faults, permanent magnet demagnetization faults, inverter faults, etc., and the corresponding fault-tolerant control technologies are also mainly carried out around these faults. This section will elaborate on the research status of drive system fault types, fault diagnosis methods, fault-tolerant structural design and fault-tolerant control strategies.

### 4.1 Main Fault Types of Drive Systems

Faults of electric vehicle drive systems mainly occur in components such as the motor body, inverter and sensor, among which motor body faults and inverter faults are the most common fault types, which seriously affect the normal operation of the drive system.

#### 4.1.1 Motor Winding Faults

Motor winding faults are one of the most common fault types of rotor permanent magnet brushless motors, mainly including winding disconnection fault, and winding grounding. Winding open circuit faults are mainly caused by winding lead breakage, winding coil burnout and other reasons, which will lead to motor torque drop and speed fluctuation, and in severe cases, the motor cannot operate normally; winding short circuit faults are mainly caused by winding insulation damage, short circuit between coils and other reasons, which will lead to excessive motor current, serious heating and even motor burnout; winding grounding faults are mainly caused by winding insulation aging, damp and other reasons, which will lead to motor leakage, posing a serious threat to personal safety and the safety of the entire vehicle.

The occurrence of winding faults is mainly related to factors such as motor structural design, manufacturing process and operating conditions. Unreasonable winding structural design and poor quality of insulating materials will lead to easy damage of winding insulation; substandard manufacturing processes will lead to poor contact of winding coils and breakage of leads; long-term high-load operation and extreme temperature environments will lead to aging of winding insulation and burnout of coils.

#### 4.1.2 Permanent Magnet Demagnetization Faults

Permanent magnet demagnetization fault is a unique fault type of rotor permanent magnet brushless motors, which is mainly divided into reversible demagnetization and irreversible demagnetization. Reversible demagnetization refers to the temporary decrease of the magnetism of the permanent magnet under the influence of external magnetic field or temperature, and the magnetism can return to normal when the external influencing factors disappear; irreversible demagnetization refers to the permanent decrease of the magnetism of the permanent magnet under long-term high-load operation and extreme high-temperature environments, which cannot be restored to normal, leading to motor torque drop and efficiency reduction, and in severe cases, the motor cannot operate normally.

The occurrence of permanent magnet demagnetization faults is mainly related to factors such as permanent magnet materials, operating conditions and temperature environments. Poor performance of permanent magnet materials results in weak anti-demagnetization ability; long-term high-load operation leads to an increase in motor temperature exceeding the rated maximum operating temperature of the permanent magnet; extreme low-temperature environments will lead to a

ISSN: 2414-1895 DOI: 10.6919/ICJE.202608_12(8).0014

temporary reduction in the magnetism of the permanent-magnet, and long-term exposure to extreme low-temperature environments will accelerate the aging of the permanent magnet and lead to irreversible magnetization loss; during high-speed operation, the direct-axis demagnetizing armature current cannot weaken the permanent magnetic field.

#### 4.1.3 Inverter Faults

The inverter is the core control component of the drive system, which is mainly responsible for converting the direct current output by the battery into the alternating current required by the motor. Its faults mainly include power device faults, drive circuit faults, control circuit faults and so on. Power device faults (such as IGBT faults) are the most common inverter faults, mainly including power device open circuit and short circuit, drive circuit faults will lead to the failure of power devices to turn on and off normally, affecting the output of the inverter; control circuit faults will lead to abnormal control logic of the inverter and failure to achieve precise control of the motor.

The occurrence of inverter faults is mainly related to factors such as power device quality, heat dissipation design and control logic. Poor quality of power devices results in weak impact resistance; unreasonable heat dissipation design leads to excessive temperature of power devices, accelerating aging and even burnout; unreasonable control logic leads to abnormal on and off timing of power devices and triggers faults.

### 4.2 Fault Diagnosis Methods

Fault diagnosis is the premise of fault-tolerant control. Its core is to collect the operating parameters of drive system (such as current, voltage, speed, temperature, etc.), analyze the change rules of the parameters, detect the occurrence of faults in a timely manner, and determine the fault type and fault location, providing a basis for fault-tolerant control.

#### 4.2.1 Model-based Fault Diagnosis Methods

The model-based fault diagnosis method establishes a mathematical model of the drive system and judges whether a fault has occurred with a comparing of deviation between the model-predicted output and real-world measured output. The advantages of this method are high diagnosis accuracy and ability to realize early fault detection, while the disadvantages are high requirements for model accuracy. When the model has errors or parameter changes, the diagnosis accuracy will decrease, and the computational complexity is high with poor real-time performance.

Academics have undertaken great deal of investigation of model-based fault diagnosis methods and proposed a variety of improved methods to improve diagnosis accuracy and real-time performance. Relevant research has established a multi-mode optimization design model of flux-controllable stator permanent magnet memory motors, and realized early detection of motor faults by comparing the deviation between model predicted values and actual measured values; some scholars have improved the model-based fault diagnosis methods by adopting sliding mode observers, extended Kalman filtering and other methods, improving the anti-interference ability and diagnosis accuracy, and realizing precise diagnosis of permanent magnet demagnetization faults and winding faults.

#### 4.2.2 Signal Processing-based Fault Diagnosis Methods

The signal processing-based fault diagnosis method collects the operating signals of the drive system (such as current signals, voltage signals, vibration signals, etc.), analyzes and processes the signals (such as Fourier transform, wavelet transform, spectrum analysis, etc.), extracts fault features, and judges whether a fault has occurred. The advantages of this method are that it does not need to establish an accurate mathematical model, has strong anti-interference ability and good real-time performance, while the disadvantages are that fault feature extraction is difficult and the diagnosis accuracy is greatly affected by signal quality.

Some scholars adopted the wavelet transform method to analyze and process the motor current signal, extract the characteristic frequency of winding faults, and realize the precise diagnosis of winding open-circuit and short-circuit faults; some scholars adopted spectrum analysis method to investigate

Volume 12 Issue 8, 2026
DOI: 10.6919/ICJE.202608_12(8).0014

motor vibration signal, extract the characteristics of permanent magnet demagnetization faults, and realize the timely detection of permanent magnet demagnetization faults.

#### 4.2.3 Intelligent Algorithm-based Fault Diagnosis Methods

The intelligent algorithm-based fault diagnosis method combines intelligent algorithms, establishes a fault diagnosis model through training sample data, and realizes fault detection and identification. The advantages of this method are that it does not require establishment of an accurate dynamic mathematical model, can adapt to complex working conditions and parameter changes, has excellent anti-interference performance, and can realize the diagnosis of multiple faults, while the disadvantages are that a large amount of training sample data is needed, the training workflow is complex, diagnosis accuracy is significant influenced by the quality of sample data.

In the contemporary era, intelligent algorithm-based fault diagnosis approaches have emerged as a research hotspot, and scholars have proposed a variety of improved methods to improve diagnosis accuracy and real-time performance. Relevant research aimed at symmetric dual-redundancy permanent magnet motors for aerospace, adopted neural network algorithms to establish a fault diagnosis model and realize precise diagnosis of motor faults; some scholars combined fuzzy control and support vector machine to propose a hybrid intelligent fault diagnosis method, which realized the diagnosis of winding faults, permanent magnet demagnetization faults and inverter faults, with significantly improved diagnosis accuracy and real-time performance.

### 4.3 Fault-tolerant Structural Design

Fault-tolerant structural design is the core support of fault-tolerant control. Its core is to realize fault isolation and redundancy backup by improving the structural design of the drive system, ensuring that the drive system can continue to operate stably in the fault state. The fault-tolerant structural design of the drive system mainly includes motor body fault-tolerant structural design, inverter fault-tolerant structural design and multi-motor redundancy fault-tolerant structural design.

#### 4.3.1 Motor Body Fault-tolerant Structural Design

Motor body fault-tolerant structural design is mainly aimed at winding faults and permanent magnet demagnetization faults, and improves the fault tolerance capability of the motor by improving the motor structure.

For winding faults, interphase electromagnetic isolation technology is mainly adopted. Through structural designs such as fractional slot concentrated winding, modular stator and closed slot, interphase electromagnetic decoupling is realized, the influence of the fault phase is effectively suppressed, and the fault tolerance of the motor in case of winding open circuit or short circuit is greatly improved. Relevant research adopted fractional slot concentrated winding and modular stator structure to realize interphase electromagnetic decoupling, reduce the impact of winding faults on motor operation, and enhance the fault resilience performance of the motor; some scholars adopted closed slot and magnetic wedge filling methods to further improve the interphase electromagnetic isolation effect and enhance the motor's fault tolerance to winding faults.

For permanent magnet demagnetization faults, auxiliary excitation systems are mainly adopted, such as hybrid excitation topology and brushless harmonic excitation. After the permanent magnet is demagnetized, compensation electromagnetic field with the same size and polarity as the residual magnetism of the permanent magnet after demagnetization is excited to offset its impact on the motor output characteristics and realize fault tolerance of demagnetization faults. Some scholars proposed a hybrid excitation topology, taking a five-phase hybrid excitation motor as the main model carrier, carried out demagnetization tests by using the brushless harmonic excitation method, realized fault tolerance of demagnetization faults, and broke through the current limitations of permanent magnet motors in the demagnetized state; relevant research designed a novel flux-intensifying interior permanent magnet motor, which reduced the risk of irreversible demagnetization by setting magnetic barriers on the q-axis and improved the motor's fault tolerance to permanent magnet demagnetization faults.

#### 4.3.2 Inverter Fault-tolerant Structural Design

Inverter fault-tolerant structural design is mainly aimed at inverter power device faults, and realizes fault isolation and fault tolerance through topology reconstruction and redundancy backup. Inverter fault-tolerant structures mainly include three-phase four-switch topology, multi-bridge arm topology, redundant power device topology and so on.

The three-phase four-switch topology is a commonly used inverter fault-tolerant structure. The advantages of this structure are simple structure and low cost, while the disadvantages are limited fault-tolerant performance and decreased post-fault output performance of the inverter; the multi-bridge arm topology realizes redundancy backup of power devices by increasing the number of bridge arms, and when some bridge arms fail, the remaining bridge arms can continue to work with excellent fault-tolerant performance, but complex structure and high cost; the redundant power device topology parallels redundant devices on each power device, and when the main power device fails, the redundant devices are put into operation to realize rapid fault switching with good fault-tolerant performance, but high cost and large volume.

#### 4.3.3 Multi-motor Redundancy Fault-tolerant Structural Design

Multi-motor redundancy fault-tolerant structural design is mainly aimed at multi-motor drive systems, and realizes fault tolerance through redundancy backup of multiple motors. When one or more motors fail, the coordinated work of the remaining motors can ensure the stable operation of the propulsion system and even maintain high driving performance. In the twin-motor coupling powerstrain system, when one motor fails, the other motor can be used to drive the vehicle alone; in the multi-motor distributed drive system, when some wheel motors fail, the coordinated work of the remaining wheel motors can ensure the normal operation and handling stability of the vehicle.

The key of multi-motor redundancy fault-tolerant structural design is to reasonably design the installation position of motors and power distribution strategies to ensure that the remaining motors can respond quickly after a fault and realize the stable output of power. The novel type of twin-motor coupling electric powerstrain system designed by relevant research adopts redundancy fault-tolerant structural design. When one motor fails, the efficient drive of the other motor is realized through the adjustment of power distribution strategy to guarantee the normal operation of the vehicle.

### 4.4 Fault-tolerant Control Strategies

Its core is to realize fault processing by adjusting the control strategy on the basis of fault diagnosis, ensuring that the drive system can operate stably in the fault state and minimizing the impact of faults on the performance of the drive system. The fault-tolerant control strategies of drive systems primarily include winding fault-tolerant control, permanent magnet demagnetization fault fault-tolerant control and inverter fault fault-tolerant control. Different fault-tolerant control strategies are adopted for different fault types.

#### 4.4.1 Winding Fault Fault-tolerant Controld

The core of winding fault fault-tolerant control is to suppress the influence of the fault phase through current/voltage reconstruction, flux linkage optimization, control strategy adjustment and other means after the winding fails, ensuring that the motor can continue to operate stably. Winding fault fault-tolerant control strategies are mainly based on vector control, direct torque control and sensorless control architectures, and realize stable operation in the fault state by improving the control algorithm.

Some scholars proposed a winding fault fault-tolerant control strategy based on the vector control architecture, which transferred the fault phase current to the normal phase through current reconstruction, realized the stable control of motor torque and speed, and reduced the impact of faults on motor performance; some scholars integrated vector control, direct torque control and sensorless control frameworks to develop a multi-mode coordinated control strategy, improving the performance of the drive system in the winding fault state; relevant research adopted a system multi-level design

ISSN: 2414-1895 DOI: 10.6919/ICJE.202608_12(8).0014

and control scheme to realize the stable operation of the motor in the winding fault state and improve the fault-tolerant performance.

#### 4.4.2 Permanent Magnet Demagnetization Fault Fault-tolerant Control

The core of permanent magnet demagnetization fault fault-tolerant control is to make up for the impact caused by the decrease of permanent magnet magnetism through flux linkage compensation, control strategy adjustment and other means after the permanent magnet is demagnetized, ensuring that the motor can continue to operate stably. Permanent magnet demagnetization fault fault-tolerant control mainly adopts a combination of harmonic injection method and sliding mode observer to detect the degree of demagnetization, and dynamically compensates for demagnetization faults in combination with the MTPA (Maximum Torque per Ampere) control algorithm.

Some scholars adopted a flux linkage observer combined with sliding mode control theory to realize dynamic compensation and stable operation in the demagnetized state. By detecting the degree of permanent magnet demagnetization, the control parameters are dynamically adjusted to make up for the flux linkage loss and ensure the stable output of motor torque and speed; some scholars proposed a permanent magnet demagnetization fault fault-tolerant control strategy based on model predictive control, which dynamically adjusted the current command by predicting the change of motor flux linkage to realize flux linkage compensation and improve fault-tolerant performance; relevant research reduced the risk of permanent magnet demagnetization by optimizing the design of rotor magnetic barriers, and realized fault tolerance of demagnetization faults in combination with the flux linkage compensation control strategy.

#### 4.4.3 Inverter Fault Fault-tolerant Control

The core of inverter fault fault-tolerant control is to ensure that the inverter be able to continue to provide stable alternating current for the motor through topology reconstruction, control strategy adjustment and other means after the inverter fails, ensuring the stable functioning of drive structure. Inverter fault fault-tolerant regulation mainly adopts topology reconstruction methods (such as three-phase four-switch, multi-bridge arm, etc.), and can also adopt a selective fusing method to convert possible short-circuit faults into open-circuit faults, and then realize fault tolerance through control strategy adjustment.

Some scholars adopted the three-phase four-switch topology reconstruction method. When one power device of the inverter fails, the continuous operation of the inverter is realized through topology reconstruction and current reconstruction, and the control strategy is adjusted to reduce the effect of faults on motor performance; some scholars adopted the multi-bridge arm topology structure, realized fault tolerance of inverter faults through the input of redundant bridge arms, and ensured the reliable and stable operation of the drive system; some scholars proposed adaptive inverter fault fault-tolerant control strategy, which can automatically regulate the control strategy and topology structure according to the fault type and fault degree, minimizing the performance attenuation caused by faults.

## 5. Research Bottlenecks and Future Development Trends

### 5.1 Current Research Bottlenecks

In recent years, the performance optimization and fault-tolerant control technologies of drive systems have made significant progress, but there are still many bottlenecks in practical engineering application: first, the high complexity of multi-motor coupling control, with complex coordinated control logic and the need for efficient power distribution strategies. The existing strategies have problems adapt to complex working conditions, and the design of coupling mechanisms is difficult, with to-be-improved efficiency and reliability; second, the difficulty in balancing power density and fault-tolerant performance, fault-tolerant design will reduce power density, and the pursuit of high power density will reduce fault-tolerant performance; third, insufficient fault diagnosis accuracy and real-time performance, with various fault types, complex features, affected by many factors, difficult multi-fault collaborative diagnosis and the need to strengthen anti-interference ability; fourth, high

ISSN: 2414-1895 DOI: 10.6919/ICJE.202608_12(8).0014

cost and difficulty in popularization, multi-motor drive and fault-tolerant control systems have many parts and complex structures, and the high cost leads to high selling prices of electric vehicles, as well as high maintenance difficulty and cost; fifth, poor adaptability to extreme working conditions, the existing technologies are mostly designed based on conventional working conditions, with decreased energy efficiency and increased fault rate under extreme working conditions, and fault-tolerant strategies are difficult to respond quickly.

### 5.2 Future Development Trends

Combined with research bottlenecks, industrial needs and technological development trends, future research will focus on the following directions: first, the intellectualization and high efficiency of multi-motor coordinated control technology, developing adaptive control strategies relying on AI technologies and so on, optimizing design of coupling mechanisms, and constructing power distribution models combined with neural network algorithms; second, the coordinated improvement of power density and fault-tolerant performance, exploring new motor topologies and fault-tolerant design methods, optimizing motor structures to improve power density by adopting new materials, innovating fault-tolerant structural design to improve fault-tolerant performance, and developing new flux-intensifying fault-tolerant motors.

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