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Summary of Fault Diagnosis of Electric Vehicle Braking System

Lin Zheng, Hailin Zhu*, Mingkai Gao, Lei Tian, Yuankun Zhou
College of Electromechanical Engineering, Dalian Minzu University, Dalian Liaoning 116605, China

Abstract: Driven by the " double carbon " strategy, the reliability and safety of electric vehicle braking systems have become the focus of the industry. This paper systematically reviews the research progress of fault diagnosis technology for electric vehicle braking system, focusing on the fault types, causes and characteristics of the two core systems of hydraulic braking and regenerative braking, covering typical problems such as mechanical wear, hydraulic leakage, electrical short circuit and sensor failure. By comparing and analyzing the principles, application scenarios and limitations of traditional and intelligent diagnosis technologies such as fuzzy theory, fault tree, expert system, neural network and grey theory, the development trend of multi-method fusion, deep integration of artificial intelligence and real-time diagnosis is revealed. This paper further discusses the construction path of intelligent diagnosis system based on big data, edge computing and Internet of things, aiming to provide theoretical support for improving the accuracy, efficiency and real-time performance of fault diagnosis of electric vehicle braking system, and help the industry 's technological innovation and standardization process.

Keywords Electric vehicle; Hydraulic brake; Regenerative baking

INTRODUCTION

At the seventy-sixth session of the United Nations General Assembly, China clearly proposed to vigorously develop the green economy, comprehensively layout the green energy industry, and implement the two major goals of ' carbon peak ' and ' carbon neutrality ' to help solve global environmental problems (Yang, et. al.,2022). With its significant environmental advantages and efficient energy utilization efficiency, new energy electric vehicles have become a key force in promoting low-carbon transformation in the transportation sector, and play an irreplaceable role in achieving the " double carbon " goal. As one of the core subsystems of the vehicle, the electric vehicle braking system undertakes multiple key tasks of ensuring driving safety, optimizing energy recovery and improving handling performance. However, during the use of electric vehicle braking system, due to the long-term wear and aging of various components, vehicle braking failure will occur, which will affect the safety of vehicle driving. Therefore, it is of great practical significance to study the fault diagnosis technology of electric vehicle braking system in order to realize fast and accurate fault location and repair, which is of great practical significance to improve the reliability and safety of vehicles.

The braking system fault of electric vehicle is mainly divided into hydraulic braking system fault and regenerative braking system fault. The failure of hydraulic braking system is usually related to the wear of mechanical parts, the leakage of hydraulic pipeline or the deterioration of braking fluid, while the failure of regenerative braking system is mostly due to the failure of electronic control unit, the decrease of sensor accuracy or the decrease of energy recovery system efficiency. In this paper, the types and causes of electric vehicle braking faults are described in detail. Then, the research status and progress of electric vehicle braking fault diagnosis technology are reviewed. The challenges of current diagnosis technology are analyzed in depth, and the future research direction of electric vehicle braking fault diagnosis technology is prospected. This paper aims to provide a useful reference for future research work in order to promote further exploration and development in this field.

ELECTRIC VEHICLE BRAKE COMMON FAULTS

As a key component of the vehicle, the electric vehicle braking system plays a vital role in the reliability and safety of the vehicle. Due to the comprehensive influence of many factors, its fault types show complex and diverse characteristics. In-depth analysis of these fault types is of great significance for achieving accurate fault diagnosis. The hydraulic braking system and the regenerative braking system constitute the core part of the electric vehicle braking system, and are also the areas with high failure rates. In this section, the faults of hydraulic braking system and regenerative braking system in electric vehicle braking system will be analyzed and expounded in detail. As shown in Fig.1, the structure diagram of an electric vehicle braking system is shown.

Corresponding Author: Hailin Zhu, College of Electromechanical Engineering, Da1ian Minzu University, Da1ian Liaoning 116605, China.

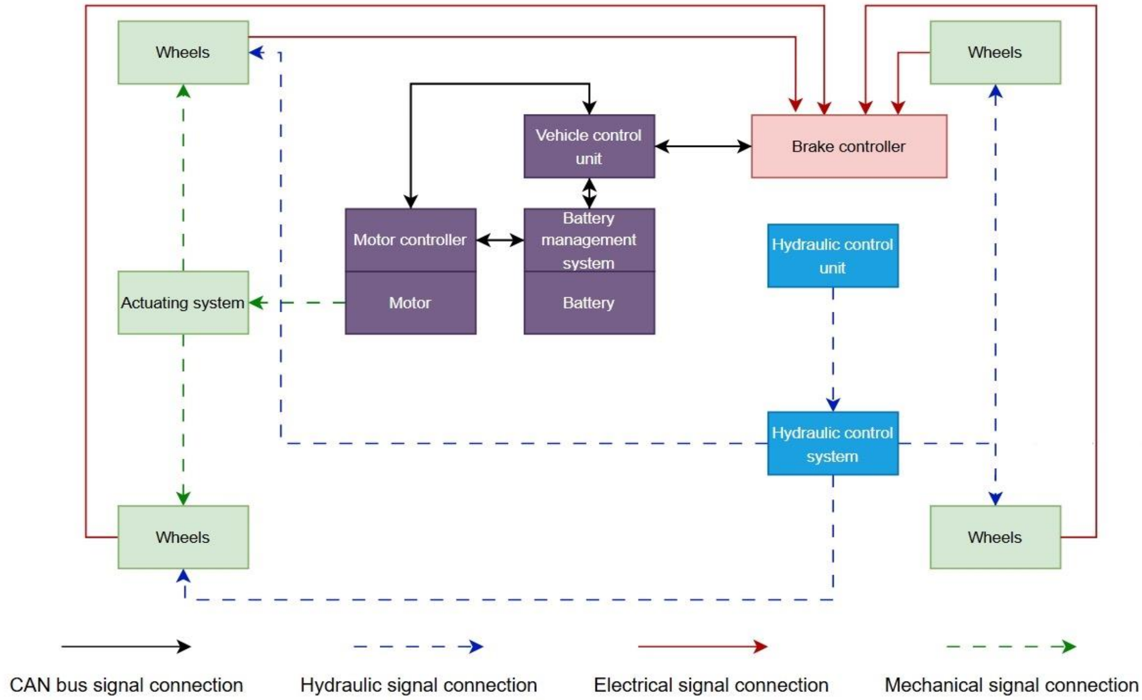

Figure 1. An Electric Vehicle Brake System Structure Diagram

Hydraulic Brake System

The hydraulic braking system, a fundamental component of electric vehicles, operates similarly to traditional vehicle hydraulic braking systems. It comprises a brake pedal, vacuum booster, master cylinder, force divider (or proportioning valve), brake shoes or calipers, and brake discs or drums (Wan, 2024). Common faults in this system include complete functional failure, inadequate braking performance, brake drag, and related issues (Qiao, 2023). The primary causes of these failures are outlined in Table 1.

Table 1. Hydraulic Brake System Failure

Fault Type	Underlying Causes	Possible Consequences
Basic function failure	Pipeline rupture, piston wear, connecting parts disconnect, etc.	Braking failure, vehicle no response.
Bad braking fault	Improper brake clearance, pipeline air, high temperature, return spring tension is too small, etc.	The braking force is insufficient and the braking distance increases.
Brake drag fault	The pedal reset spring is not sensitive, the piston is stuck, and the gap between the piston and the push rod is too small.	After braking, the wheels are still in the braking state, and the vehicle is difficult to start.

Regenerative Braking

Regenerative braking, also known as braking energy recovery, is the partial recovery of kinetic energy and potential energy during the deceleration and braking process of electric vehicles, which is converted into electrical energy through the motor and stored in an energy storage device for vehicle re-acceleration or starting (Guo, et. al., 2024). The fault of regenerative braking system mainly occurs in the motor, and the motor fault can be divided into electrical fault and mechanical fault (Yao, 2025). The main causes of the failure are shown in Table 2. The frequency of electrical faults is higher than that of mechanical faults. More than 70 % of electrical faults are caused by inter-phase and inter-turn short circuits. The occurrence of motor faults will lead to a decrease in torque, an increase in current, and a fire in severe cases (Choudhary A, et. al., 2022).

Table 2. Regenerative Braking System Failure

Fault Type	Possible Consequences	Underlying Causes
Electrical Failure	Inter-turn short circuit	Elevated stator winding temperature or inter-turn insulation damage
	Open circuit	Poor soldering joints in stator windings
	Overvoltage Undervoltage	Abnormal input voltage to the inverter
	Excessive temperature	Motor short circuit or locked rotor
Mechanical Failure	Bearing failure	Vibration or foreign object ingress into the bearings
	Bearing overheating	Insufficient lubrication
	Loosening of the stator core	Misalignment of the coupling or loosening of fasteners

TECHNIQUES FOR FAULT DIAGNOSIS OF BRAKING SYSTEMS

Braking is one of the most critical conditions in the operation of a vehicle. The effectiveness of braking performance and the condition of its operation can have a significant impact on many important vehicle performance aspects, such as safety and reliability. Currently, the common techniques for fault diagnosis of braking systems mainly include fuzzy theory, fault tree analysis, artificial neural networks, expert systems, and grey theory.

Fault Diagnosis Method for Braking Systems Based on Fuzzy Theory

The fundamental principle of fuzzy theory is to emulate human thinking logic by transforming natural language into fuzzy variables and human experiential knowledge into fuzzy rules. By integrating fuzzy inputs with fuzzy rules, the process of inference can be realized, yielding fuzzy output quantities (Zhan, et. al., 2023). In 1965, L.A. Zadeh published the paper "Fuzzy Sets," marking the official inception of fuzzy theory (Gong, 2024). Zhu, et. al. (2023) proposed an active fault diagnosis strategy based on fuzzy fault diagnosis. This strategy employs fuzzy control theory, utilizing the ratio of the actual motor torque signal to the expected output motor torque, as well as its rate of change, as input variables. Through fuzzy inference rules, the operating condition of the motor is assessed, and a fault factor is generated as the output. Wang (2024) proposed a fault diagnosis model that integrates Gaussian fuzzy theory with BP neural networks. This method transforms uncertain information into membership degrees through Gaussian fuzzification, thereby effectively enhancing the accuracy of fault diagnosis. The experimental validation of the fault diagnosis accuracy rate reached 85.71%, demonstrating the advantages of fuzzy theory in fault diagnosis. Si, et. al. (2017) proposed an intelligent fault diagnosis expert system based on fuzzy neural networks. This system integrates the advantages of fuzzy theory and neural networks, utilizing fuzzy reasoning to process uncertain information and extract fault features. Through adaptive learning, it achieves efficient fault identification. In engine fault diagnosis, the accuracy rate reached 94.5%, validating the effectiveness of fuzzy theory in the fault diagnosis of complex systems.

Fuzzy theory possesses significant advantages in fault diagnosis, such as its robust capability to handle uncertainties, the effective utilization of expert experience, strong adaptability, and ease of integration with other technologies. These characteristics enable it to perform exceptionally well in fault detection of complex systems. However, it also has certain limitations. For instance, the determination of membership functions can be challenging, the rule explosion problem may lead to increased system complexity, it lacks a rigorous mathematical foundation, and it often requires substantial human intervention. In practical applications, it is necessary to select and optimize the application of fuzzy theory according to specific scenarios, in order to fully leverage its strengths and overcome its weaknesses, thereby enhancing the accuracy and efficiency of fault detection.

Fault Diagnosis Method for Braking Systems Based on Fault Tree Analysis

A fault tree diagram is a logical causal relationship chart that utilizes the operational status of components to describe the operational status of the entire system, where the former is referred to as basic events and the latter as the top event(Song, 2024).Fault Tree Analysis (FTA) is a reliable method for both qualitative and quantitative analysis of typical system failures（Liang, et. al., 2020). Wang (2024) conducted an analysis of the faults in the 5T system equipment for railway passenger cars, based on Fault Tree Analysis (FTA) and the AMSAA model. An optimized maintenance strategy was proposed, which enhanced the system reliability. Improvement measures were also put forward to address issues such as data processing and information sharing, providing technical support for the safe operation of railway passenger cars. Luo (2024) proposed a fault diagnosis method for PEMFC (Proton Exchange Membrane Fuel Cell) stacks based on Fault Tree Analysis (FTA) and genetic algorithms to improve BP neural networks. Fault data were obtained through modeling and simulation, which enhanced the diagnostic accuracy rate. The fault detection rate reached over 93.5%, significantly improving the accuracy and efficiency of fault diagnosis. This method provides technical support for the reliable operation of hydrogen fuel cells. Dai (2025) proposed a fault diagnosis method based on the integration of T-S Fault Tree (TSFT) and Bayesian Network (BN). The method uses TSFT to analyze fault modes and employs T-S dynamic gates to describe the dynamic relationships between fault causes and modes. These relationships are then transformed into the Directed Acyclic Graph (DAG) of a Bayesian Network to achieve precise fault diagnosis.

Fault tree analysis (FTA) offers several advantages in fault diagnosis, including clear logic, comprehensiveness, intuitiveness, and the capability for quantitative analysis. It can clearly express the intrinsic relationships between system fault events, conduct a comprehensive analysis of fault factors, facilitate understanding and decision-making support, and quantitatively assess system reliability. However, it also has some drawbacks, such as the complexity of constructing the fault tree, difficulties in data collection, computational complexity, and limitations in logical expression. A deep understanding of the system is required, along with the collection of a large amount of data. Moreover, the computational workload is substantial for complex systems, and traditional logic gates may not be able to describe all complex fault relationships.

Fault Diagnosis Method for Braking Systems Based on Artificial Neural Networks

Artificial Neural Networks emulate the structure of the human brain's neural network and possess the capability for intelligent pattern recognition through learning from sample training. They are capable of classification, regression, and clustering, and can rapidly and accurately identify fault patterns from complex fault data (Meng, 2021). Artificial Neural Networks have been widely applied across numerous fields, and many scholars have not only utilized them but also optimized them during the application process. Hu, et. al. (2023) proposed a fault diagnosis algorithm optimized by the Firefly Algorithm for BP neural networks, which is applied to the fault diagnosis of clutches and brakes in high-speed presses. This algorithm achieves rapid and accurate fault diagnosis, outperforming traditional BP neural networks and BP neural networks optimized by genetic algorithms. Li, et. al. (2021) proposed a fault diagnosis method for inter-turn short circuit faults in the rotor windings of synchronous motors, based on Conditional Generative Adversarial Networks (CGAN) and Convolutional Neural Networks (CNN). This method utilizes CGAN to generate new samples to balance the dataset, addressing the issue of insufficient samples, and leverages the strong feature extraction capabilities of CNN to achieve high-precision fault classification, with an accuracy rate exceeding 99.5%. This research highlights the advantages of neural networks in fault diagnosis. Zhang, et. al. (2020) proposed a fault diagnosis method for typical faults in vehicle gearboxes based on Probabilistic Neural Networks (PNN). Vibration signals from the gearbox under different conditions were collected through experiments and then processed before being input into the PNN model. The results indicated that compared with BP neural networks, PNN can more accurately and rapidly identify gearbox faults, with higher diagnostic accuracy and faster diagnostic speed. In addition, other methods include BP neural networks optimized by genetic algorithms (Yang, et. al., 2021), Radial Basis Function (RBF) neural networks (Guo, 2024), and Self-Organizing Map (SOM) neural network methods (Liu, et. al., 2024), among others.

Artificial Neural Networks possess several advantages in fault diagnosis, such as their strong nonlinear mapping and adaptive learning capabilities. They can automatically identify complex fault features and provide high-precision diagnostic results, while also having a certain degree of generalization and parallel processing abilities. However, there are also some limitations, including the dependence on large amounts of high-quality data, the potentially substantial time and computational resources required for training, the tendency of traditional algorithms to fall into local optima, and the risk of overfitting for the models.

Fault Diagnosis Method for Braking Systems Based on Expert Systems

An expert system is essentially a computerized intelligent program system that possesses specialized knowledge and experience. Its core lies in the ability to simulate the decision-making processes of experts within a specific domain, utilizing the extensive experience and professional knowledge of experts in that field to conduct scientific reasoning (Peng, et. al., 2019). This type of system is capable of effectively resolving complex and challenging problems. It is essentially an intelligent software based on a knowledge base. Not only does it store a vast amount of knowledge from domain experts, but it also possesses the problem-solving thinking patterns of domain experts. It is able to provide solutions at the level of authoritative experts in the relevant field for application-oriented problems that require specialized knowledge. Fault diagnosis expert systems have played a significant role in improving detection efficiency, reducing troubleshooting time, and lowering maintenance costs (Fu, et. al., 2025). Madjid Tavana (2020) has carried out a systematic analysis of the theory, development and applications of expert systems, laying a solid theoretical foundation for future research and development in this field. Qin, et. al.(2022) proposed an expert system-based fault diagnosis method for electric vehicle drive systems. The knowledge base is built in rule-based form. The reasoning engine is designed using a database-based forward-chaining inference method. The system, developed with Visual Studio and SQL Server, can provide accurate diagnosis results and maintenance strategies, achieving a fault detection rate of 97%. Meng (2021) constructed a multi-level equipment fault tree for the electric vehicle charging process and integrated it with fuzzy mathematics and a BP neural network approach to develop an intelligent diagnostic expert system for faults. This system effectively enhances the accuracy and efficiency of fault diagnosis during electric vehicle charging.

Expert systems have multiple advantages in fault diagnosis, such as quick diagnosis, high stability, rich knowledge base, strong explanation ability, and knowledge sharing, which make them widely used in this field. However, they also have drawbacks, including high development costs, difficult knowledge updating and maintenance, limitations in inference processes, and a lack of creativity and flexibility.

Fault Diagnosis Method for Braking Systems Based on Grey Theory

In the field of fault diagnosis, grey theory provides an effective modeling approach for fault prediction and analysis by addressing uncertainties and incomplete information, making it particularly suitable for scenarios with limited data or incomplete information. Yao (2017) applied fuzzy grey relational analysis and fuzzy analytic hierarchy process (FAHP) from grey theory to comprehensively evaluate factors affecting the temperature rise of lithium-ion batteries. The study ranked the influence of ambient temperature, initial state of charge (SOC), and charging current on temperature rise, thereby providing a theoretical basis for battery thermal management. Wu, et. al. (2023) utilized grey relational analysis on real-world electric vehicle data to extract key features and combined local weighted linear regression (LWLR) with the XGBoost algorithm to develop a battery health state estimation model. This approach significantly enhanced the accuracy of predictions and offered a novel method for fault diagnosis based on grey theory. Pang, et. al. (2020) integrated grey theory with neural networks to construct an optimized grey neural network model using an improved fireworks algorithm. This model effectively managed small sample data and improved prediction accuracy, presenting a new perspective for fault diagnosis based on grey theory.

Grey theory, with its advantages in small-sample modeling, strong capability in handling uncertainties, and low computational cost, is particularly suitable for data-scarce scenarios in the field of fault diagnosis. It can quantify the causal relationships among multiple parameters through grey relational analysis. However, its accuracy is limited by nonlinear coupling faults and dynamic operating conditions, and it is sensitive to noise. To enhance its robustness, grey theory can be combined with neural networks, adaptive optimization, or signal denoising techniques. It is well-suited for low-cost real-time diagnosis of traditional braking systems, but in complex by-wire systems, it needs to be integrated with other models to overcome its limitations.

CONCLUSION AND OUTLOOK

The fault diagnosis of electric vehicle hydraulic and regenerative braking systems comes with its own specific types and causes. Current diagnostic techniques such as fuzzy theory, fault tree analysis, expert systems, artificial neural networks, and grey theory each have their own pros and cons. While they deliver multi-dimensional solutions for fault diagnosis, they also have limitations and need to be optimized for specific scenarios. In light of the problems with current braking system fault diagnosis methods, the following research outlooks are proposed for future fault diagnosis methods.

Multi-Method Fusion for Fault Diagnosis

Future fault diagnosis will focus more on the comprehensive use of multiple methods such as fuzzy theory, artificial neural networks, and fault tree analysis. Multi-method fusion in fault diagnosis integrates the advantages of different algorithms. It overcomes the limitations of single methods and greatly improves diagnostic accuracy, adaptability, and efficiency.

The Deep Application of Artificial Intelligence

By utilizing big data and machine learning technologies, we can establish a braking-system health-status model to achieve early-fault warning. Combined with edge-computing technology, in-vehicle systems can independently carry out real-time data processing and diagnostic decision-making. This process effectively reduces the risk of sudden failures and improves maintenance efficiency.

Real-time Fault Diagnosis

Future fault diagnosis of EV braking systems will greatly rely on real-time technological breakthroughs.

Presently, it mostly depends on offline historical data. As cloud computing and the Internet of Things develop, online fault-diagnosis systems can be built. These systems can collect and process data in real time, enabling real-time fault diagnosis.

In the future, EV braking-system fault-diagnosis technology will integrate intelligent techniques and multi-sensor data for more efficient and precise real-time diagnosis and prediction. This involves incorporating cutting-edge technologies like deep and reinforcement learning to boost system intelligence. It also includes developing intelligent maintenance systems and advancing technical standardization, which are crucial for enhancing the reliability and safety of EV braking systems and satisfying the industry's demand for high-performance diagnostic systems.

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