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A Review of Fault Diagnosis Techniques for Permanent Magnet Synchronous Motors in Electric Vehicles

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Abstract: Permanent magnet synchronous motors (PMSMs) are crucial components of electric vehicles, and their fault diagnosis is essential for ensuring vehicle safety. This paper introduces common faults in PMSMs used in electric vehicles, focusing on two diagnostic methods: signal processing-based techniques and intelligent diagnostic techniques. It provides a comprehensive review of the current research status in these areas. The paper summarizes the advantages and limitations of both diagnostic methods, analyzes the existing challenges in PMSM fault diagnosis technology, and discusses potential future research directions. The aim is to offer insights for future study and development in this field.

Keywords Electric vehicles; Permanent magnet synchronous motors; Fault Diagnosis

INTRODUCTION

The implementation of the "dual carbon" policy has intensified the demand for environmental protection and energy conservation, creating substantial opportunities for the new energy vehicle industry. Electric vehicles, as a key component of this industry, have attracted significant attention. Within these vehicles, permanent magnet synchronous motors (PMSMs) are crucial, as they convert electrical energy into mechanical energy through electromagnetic induction between permanent magnets and stator coils, thus providing driving power. Despite their widespread adoption, PMSM fault diagnosis presents considerable challenges due to the motor's intricate structure and the diversity of potential faults, including permanent magnet, circuit, rotor, and bearing faults. Traditional fault diagnosis methods, while effective in simple scenarios, struggle with complex conditions. The advent of artificial intelligence has introduced intelligent fault diagnosis techniques, which utilize big data and advanced algorithms to offer rapid and accurate diagnostics. This paper reviews the current state of PMSM fault diagnosis, identifies ongoing challenges, and discusses future research directions. Emphasis is placed on the need for further studies to enhance the accuracy and reliability of PMSM fault diagnosis, thereby ensuring the safe operation of electric vehicles.

OMMON FAULTS OF PMSMS IN ELECTRIC VEHICLES

During the operation of electric vehicles, high performance, high reliability, and safety are required. Most power system faults in electric vehicles originate from PMSM faults [Wang et al., 2016]. PMSMs are widely used in electric vehicles and other industrial fields due to their high energy conversion efficiency and high instantaneous power, becoming the mainstream choice for major automakers [Zhang, 2022]. As the core component of electric vehicles, common faults mainly include electrical faults, permanent magnet faults, and mechanical faults, which can also affect each other [Wu et al., 2021].

Electrical Faults

Electrical faults in PMSMs for electric vehicles include sensor faults, stator inter-turn short circuit faults, and stator phase-to-phase short circuit faults [Yu et al., 2022]. Sensor faults can cause the motor to lose the ability to perceive its current operating state, affecting the motor's performance and stability. In all motor drive systems, at least 14% of faults are caused by sensor faults [Qiao et al., 2023]. Stator inter-turn short circuit faults are common and usually caused by factors such as motor overheating, overload, insulation wear, or prolonged operation. When a stator inter-turn short circuit occurs, the current increases sharply, leading to a temperature rise, which may cause insulation damage to the wires, damaging the stator windings and even leading to stator phase-to-phase short circuit faults in severe cases [Liang et al., 2013].

Permanent Magnet Faults

Permanent magnet faults are unique to PMSMs, primarily manifesting as demagnetization of the permanent magnets. Permanent magnets may demagnetize due to overheating or damage during motor operation. During prolonged operation of electric vehicles, the reverse magnetic field generated by the stator current can interact with the permanent magnet's magnet-

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ic field, leading to gradual demagnetization of the permanent magnets. When demagnetization occurs, it can cause motor vibration, insufficient motor torque, and an increase in motor current to meet the required torque, which further raises the temperature, exacerbating the demagnetization fault [Abdelli et al., 2016].

Mechanical Faults

Mechanical faults in PMSMs for electric vehicles include rotor eccentricity faults and bearing faults. Rotor eccentricity faults are usually caused by improper rotor installation or external impacts, leading to motor imbalance and affecting motor efficiency. When rotor eccentricity faults occur, the motor vibrates continuously, producing noise, and in severe cases, it can affect the normal operation of the motor and the vehicle [Liu, 2018]. Bearing faults are usually caused by bearing wear, insufficient lubrication, or external vibrations. Among all mechanical faults in PMSMs, bearing faults account for 50% [Ye et al., 2000]. Bearing faults can cause unstable rotor rotation, increased friction and wear, and damage the motor's lifespan and performance.

RESEARCH STATUS OF TRADITIONAL FAULT DIAGNOSIS TECHNIQUES FOR PMSMS IN ELECTRIC VEHICLES

Traditional fault diagnosis techniques for PMSMs in electric vehicles encompass various methods, with the most common being signal processing-based fault diagnosis methods. These methods first utilize sensors to collect fault signals and then analyze the collected signals using techniques such as wavelet transform and fast Fourier transform (FFT). The analysis results are used to determine whether the motor has a fault and accurately identify the fault type.

Electrical Faults

For electrical faults in PMSMs, an improved wavelet transform method has been proposed for detecting stator winding inter-turn short circuit faults. This method analyzes both stator current and vibration signals using the improved wavelet transform, processing and analyzing two sets of experimental data from PMSMs in LabVIEW, demonstrating the feasibility of the method [Liang et al., 2018]. Another study proposed a new diagnosis method that extracts fault features of motor signals under different speeds using the FFT algorithm. Experimental results show that this method effectively screens fault features and achieves accurate fault diagnosis [Liu et al., 2024]. The most commonly analyzed signals in electrical faults are voltage and current signals. An analysis of partial short circuits in PMSMs using the FFT algorithm to detect voltage signals found that voltage changes significantly during short circuit faults, demonstrating the method's superiority in fault diagnosis regardless of stator winding configuration [Korkosz et al., 2021]. Furthermore, power analysis of PMSMs can be conducted based on measured voltage and current signals. For instance, a study on inter-turn short circuit faults in five-phase PMSMs proposed a diagnosis method based on the Hilbert transform. This method uses the Hilbert transform to obtain orthogonal delayed signals of current and voltage, calculates the generalized instantaneous reactive power for each phase, compares the differences in generalized instantaneous reactive power of each phase to identify the phase winding with an inter-turn short circuit fault, and experimentally verifies the method's effectiveness [Yang et al., 2021].

Permanent Magnet Faults

A study analyzed demagnetization fault signals in PMSMs, explaining that high temperatures or short circuits can cause irreversible demagnetization of permanent magnets, affecting motor performance and vehicle safety. Experiments on four types of demagnetization faults demonstrated the validity of this analysis method [Candelo-Zuluaga et al., 2020]. The wavelet transform method, besides being well-applied in electrical fault diagnosis of PMSMs, also shows good results in demagnetization fault diagnosis. A new diagnosis method based on signal and time-domain energy analysis was proposed for diagnosing demagnetization faults in permanent magnet linear motors. This method utilizes finite element analysis to obtain magnetic signals and introduces complex continuous wavelet transform (CCWT) for signal preprocessing, with experiments proving its effectiveness [Song et al., 2020]. Additionally, voltage difference signal analysis has been explored. A novel demagnetization fault diagnosis method uses fault characteristic harmonics amplitude in voltage difference signals for diagnosis, establishing a motor fault model to study the impact of different demagnetization distributions and severities on voltage difference signals, and verifying the diagnostic accuracy through experiments [Zhan, 2023].

Mechanical Faults

A study introduced an intelligent fault diagnosis method for rolling bearings based on wavelet time-frequency maps. This method applies continuous wavelet transform to bearing vibration signals to generate time-frequency maps, achieving fault type diagnosis and recognition, with experiments confirming the effectiveness of using time-frequency maps for feature extraction and bearing fault diagnosis [Yuan et al., 2017]. For rotor eccentricity fault diagnosis, besides vibration signals, other signal data from PMSMs should also be considered. One study explored the characteristic positions of rotor eccentricity faults in PMSMs, comparing various diagnostic methods for these faults. It indicated that vibration signals, stator current, and magnetic flux density are commonly used signal data for diagnosing rotor eccentricity faults in PMSMs [Li et al., 2019]. However, processing non-stationary signals remains challenging after obtaining common signal data. A new vibration feature extraction method using an improved wavelet packet decomposition algorithm was proposed for this purpose, with experiments verifying the feasibility of the feature extraction method [Tang et al., 2024]. Another study proposed a new diagnostic method for PMSM bearing and rotor eccentricity faults by analyzing the vibration characteristics of bearings and rotors, using the Vold-Kalman algorithm to extract fault characteristic components, and employing signal reconstruction technology to reduce the impact of motor speed variations, with diagnostic accuracy reaching 88% [Zhao et al., 2023].

RESEARCH STATUS OF INTELLIGENT FAULT DIAGNOSIS TECHNIQUES FOR PMSMS IN ELECTRIC VEHICLES

Intelligent diagnostic technology refers to the use of artificial intelligence methods to achieve intelligent, efficient, and accurate diagnosis of PMSM faults in electric vehicles. Unlike traditional rule- and experience-based methods, intelligent diagnostic technology detects and diagnoses faults based on a large amount of data. Machine learning, a crucial tool in artificial intelligence, can fit complex mapping relationships by constructing deep models that simulate the learning process of the human brain, capturing deep information in data and improving the accuracy of PMSM fault diagnosis. Intelligent fault diagnosis techniques based on machine learning theory are widely used.

Electrical Faults

A study applied the Deep-Q-Network (DQN) algorithm in deep reinforcement learning to diagnose inter-turn short circuit faults in PMSMs. By establishing a PMSM model, analyzing key features under different operating conditions, constructing a feature dataset, and conducting algorithm training and parameter adjustment, efficient diagnosis of PMSM inter-turn short circuit faults was achieved, with an accuracy rate of 99.61% [Li et al., 2021]. Another study proposed a diagnosis method for winding short circuit faults in PMSMs based on insulation loss caused by inter-turn short circuits, using the short-time Adaline algorithm to extract the necessary second harmonic components as fault indicators, and experimentally verified the method's effectiveness [Wei et al., 2022]. When diagnosing PMSM faults in electric vehicles using machine learning technology, the imbalance of sample data between normal and fault states is a common issue. To address the imbalance of inter-turn short circuit samples in motor rotors, a new method was proposed that generates balanced datasets using CGAN and CNN, achieving high-accuracy fault diagnosis with a Softmax classifier. Experiments demonstrated that the fault recognition accuracy reached over 99.5% with balanced datasets, effectively avoiding noise interference and significantly improving diagnostic accuracy [Li et al., 2021].

Permanent Magnet Faults

A study explored common demagnetization faults in PMSMs in electric vehicles, using motor temperature information as input to train and classify using the BP back-propagation neural network, achieving accurate diagnosis of PMSM demagnetization faults. The effectiveness of the method was verified through the establishment of a test platform and simulation model [Zhang et al., 2022]. Another study used a convolutional neural network (CNN) model to diagnose demagnetization faults in stationary PMSMs. By using motor current signals as input, a new CNN model was established, and experiments confirmed the model's effectiveness in diagnosing demagnetization faults, with a diagnostic accuracy of 99.92% [Eker et al., 2023]. In addition to using temperature and current signals as feature data for input training, a novel diagnostic method was proposed, combining spatial air-gap magnetic flux density feature extraction and the probabilistic neural network (PNN) algorithm. Using air-gap magnetic flux density values as feature quantities for input, a rich fault sample library was established. Experimental results showed that this method could efficiently and accurately identify PMSM demagnetization faults, with a recognition rate of 99.4% [Zhang et al., 2019].

Mechanical Faults

A study proposed a new method for diagnosing bearing faults in PMSMs using an improved CNN-SVM structure. The method improves the fully connected network layer of the CNN, effectively reducing training parameters. The introduction of a support vector machine (SVM) as a replacement for the Softmax classifier showed a diagnostic accuracy of 99.86% and good transferability [Gong et al., 2020]. Another study presented a method for processing motor bearing fault signals by converting vibration signals into two-dimensional time-frequency maps using short-time Fourier transform, which were then used as input for CNN training. Utilizing the self-learning capability of CNNs, this method could deeply learn the relationship between motor bearing fault types and fault characteristics. Simulation experiments demonstrated that this method could effectively identify mechanical faults and perform accurate classification [Wang et al., 2020]. Besides CNN models, long short-term memory (LSTM) networks have also been well-applied in PMSM mechanical fault diagnosis. A study proposed a classification method based on discrete wavelet transform and an LSTM neural network model for PMSM fault diagnosis, proving through experiments that the method could accurately detect motor mechanical fault types and perform well under different speed conditions [Li et al., 2018].

CONCLUSION AND ANALYSIS

Signal processing-based diagnostic methods analyze current, vibration, temperature, and other signals during motor operation, extracting frequency and time-domain features using Fourier transform, wavelet transform, and other techniques for fault diagnosis and classification. These methods offer high accuracy and real-time capabilities but are sensitive to noise and rely heavily on expert experience. In contrast, intelligent fault diagnosis technology leverages machine learning and deep learning techniques, constructing models through training on large amounts of historical fault data for diagnosis and classification [Zhai et al., 2021]. This approach has self-learning and adaptive capabilities, can handle complex fault patterns and multi-source data, and reduces reliance on expert experience. However, it requires a large quantity of high-quality data and involves long model training times. Overall, both methods have their advantages and should be chosen based on specific fault diagnosis needs to improve the efficiency and accuracy of PMSM fault diagnosis.

PROBLEMS AND PROSPECTS

Existing Problems

1) Difficulty in diagnosing mixed faults: PMSMs may experience multiple faults simultaneously during operation. While significant progress has been made in diagnosing single faults, diagnosing mixed faults remains challenging. Effective extraction and analysis of mixed fault characteristic signals need to be addressed.

2) Insufficient research on partial demagnetization faults in permanent magnets: Current research on demagnetization faults in PMSMs primarily focuses on complete demagnetization faults, with relatively few studies on partial demagnetization faults. Partial demagnetization causes uneven magnetic fields in permanent magnets, making motor output signal characteristics more complex and challenging to diagnose compared to complete demagnetization faults.

3) Diagnosis of PMSMs during the deterioration of inter-turn short circuit faults into phase-to-phase short circuit faults: Inter-turn short circuit faults in PMSMs for electric vehicles are common. If not addressed promptly, they can deteriorate into phase-to-phase short circuit faults, further affecting motor performance. Research on diagnosing PMSMs during the transition from inter-turn short circuit to phase-to-phase short circuit is currently lacking.

Future Prospects

1) Integration of multiple sensors: Utilizing multiple sensors simultaneously can enhance the diagnosis of mixed faults in PMSMs by providing comprehensive fault status information. Coupled with advanced diagnostic technologies like artificial intelligence and deep learning, this approach can efficiently identify mixed fault characteristics in electric vehicle PMSMs.

2) Development of advanced algorithms and neural network models: Optimizing existing algorithms and neural network models for specific PMSM fault states can significantly improve fault feature extraction and diagnosis accuracy. Developing targeted signal processing algorithms and deep learning models will enhance the efficiency of fault detection and classification.

3) Construction of real-time diagnostic platforms: Real-time diagnosis is essential for analyzing fault state transitions in PMSMs. Establishing real-time diagnostic platforms will enable continuous monitoring and analysis of fault data, addressing the limitations of traditional offline methods. Future research should focus on developing real-time online fault diagnosis systems, leveraging advancements in Internet technology to enhance the real-time accuracy of fault detection.

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