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An overview of the optimization of motor protection mechanisms

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ABSTRACT
As the core equipment in industrial production, the reliability of its protection system directly affects production safety and efficiency. In this paper, the research status and technology development in the field of motor protection are systematically sorted out, and a comprehensive analysis is carried out from traditional protection methods to intelligent protection strategies. The study firstly explains the principle and realization of basic protection technologies such as overload protection, short circuit protection and overheating protection, and then focuses on the progress of the application of artificial intelligence, Internet of Things and other emerging technologies in motor protection. By comparing the research results at home and abroad, this paper finds that intelligent algorithms have significant advantages in terms of fault prediction accuracy and system response speed, but at the same time there are practical problems such as strong data dependence and high implementation costs. The study further points out that the future motor protection system will develop in the direction of multi-technology integration, energy saving and environmental protection, and networked monitoring. The research results of this paper can provide theoretical basis and practical reference for the optimization and innovation of motor protection technology.

KEYWORDS
Motor protection; fault diagnosis; intelligent control; internet of things; technology integration

1 Overview of Motor Protection's Current Status Worldwide

As the core driving device in industrial production, motors are widely used in many fields such as manufacturing, transportation and energy industries. The performance of the motor directly affects the efficiency, stability and safety of the whole system. Therefore, the protection system of the motor is crucial. Motor failure, especially due to overloading, overheating, mechanical failure, etc., not only affects production efficiency, but may even lead to equipment damage or system shutdown, which brings huge economic losses to enterprises. Therefore, how to optimize the motor protection system so that it can protect the motor timely and effectively under complex working conditions has become a research focus in the field of mechanical engineering.

With the rapid development of artificial intelligence, big data, Internet of Things and other technologies, the motor protection system has also entered the intelligent era. By combining mechanical load analysis, sensor data acquisition and real-time monitoring, it is possible to realize a comprehensive understanding of the operating status of the motor and fault early warning, which in turn improves the response speed and accuracy of the motor protection system.

1.1 Status of Domestic Research

Domestic research focuses more on how to optimise motor protection strategies through motor load characteristics. Through load analysis, researchers have explored the operating characteristics of motors under different load conditions and designed corresponding fault protection strategies for overload, overheating, short circuit and so on. For example, the use of load sensors to monitor real-time load changes, combined with fuzzy logic control algorithms, to design motor protection systems for different load conditions.

Many domestic studies combine motor protection systems with fault diagnosis techniques for optimisation. By monitoring the vibration, temperature, current and other parameters of the motor, the failure mode of the motor is analysed, and artificial intelligence, machine learning and other technologies are used for fault prediction and early warning. For example, motor fault diagnosis technology based on current signal analysis is widely used in China and is combined with motor protection systems to achieve early detection of faults and timely protection.

1.2 Current Status of Foreign Research

In Europe and the United States, the research of intelligent motor protection systems is at a more mature stage. Motor protection systems based on big data and machine learning are able to collect and analyse a large amount of motor operation data, conduct real-time monitoring of the motor status, automatically identify potential fault risks, and implement protection measures. For example, machine learning-based fault diagnosis methods are used to predict

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possible motor failures and protect them in advance.

Foreign researchers generally agree that the protection strategy of the motor should take into account the real-time changes of the load. For example, research in the United States, Germany and other countries has proposed that the response speed and protection accuracy of the motor protection system can be significantly improved by real-time monitoring and analysing the motor load, combined with advanced control algorithms. In these studies, the motor load not only affects the development of protection strategies, but is also closely related to issues such as energy consumption and efficiency optimisation.

1.3 Comparison of Domestic and Foreign Research and Development Trend

Domestic research in the motor protection system, mostly based on traditional control methods, although some research has begun to apply artificial intelligence and other new technologies, but the overall level of intelligence lags behind compared with foreign countries. Foreign countries pay more attention to the integration of intelligent algorithms, Internet of Things technology, big data analysis and other modern technologies in the motor protection application.

Research at home and abroad is likely to focus more on intelligent, electrified, and integrated optimal design in the future. In particular, combined with technologies such as big data, cloud computing, and the Internet of Things, motor protection systems will tend to be more intelligent, automatic, and efficient. In addition, green energy saving and environmental protection requirements will also promote the optimised development of motor protection systems.

2 Specific Ways of Motor Protection

There are many different strategies for protecting motors, and they all work slightly differently. As a result, there are different application scenarios. The following section analyses and compares the different motor protection strategies.

2.1 Motor Overload Protection Method Based on Current Monitoring

The core of motor overload protection lies in real-time monitoring of the operating current and taking protective measures when the current exceeds the safety threshold. This section describes in detail the overload protection mechanism based on current monitoring, including thermal relay and electronic overload relays and their action results.

2.1.1 Current Monitoring and Overload Judgement

The overload condition of a motor usually manifests itself in the form of a running current exceeding the rated value. By monitoring the input current of the motor in real time, it is possible to determine whether the motor is in an overload condition. Monitoring methods mainly include direct current sampling and indirect current estimation. Direct sampling usually uses current transformers or Hall sensors to convert current signals into measurable voltage or digital signals; indirect estimation is based on the motor's voltage, speed and other parameters to deduce the current value. Once the current is detected to consistently exceed the rated value (usually set at 1.05 to 1.2 times the rated current), the protection device starts the overload protection procedure.

2.1.2 Working Principle of Thermal Relay

A thermal relay is a traditional overload protection device whose core component is a bimetal. The bimetal is made of two metals with different coefficients of thermal expansion. When the current passes through the heating element of the thermal relay, the bimetal is gradually bent by heat. If the current exceeds the set value, the bimetal's bending degree will increase with the accumulation of heat, and ultimately promote the mechanical contact action, cut off the control circuit or trigger the release mechanism, so as to disconnect the motor power supply. The action time of the thermal relay and the size of the overload current is an inverse time limit characteristic, that is, the higher the current, the shorter the action time. This characteristic can effectively simulate the heating process of the motor to avoid false operation.

2.1.3 Working Principle of Operation of Electronic Overload Relays

The electronic overload relay uses modern electronic technology to achieve more accurate overload protection. Its core module includes current sensor, signal conditioning circuit and microprocessor. The current sensor (e.g. Hall effect sensor or Roche coil) collects the motor current signal in real time and sends it to the microprocessor after filtering and amplification. The microprocessor calculates the cumulative value of the thermal effect of the current by means of an algorithm (e.g., I^2t integral method) and compares it with a preset overload threshold. When the accumulated heat exceeds the threshold, the microprocessor outputs a control signal to drive a relay or solid-state switch to cut off the power supply. Compared with thermal relays, electronic overload relays have the advantages of fast response speed, high precision, strong programmability, etc., and also support a variety of protection functions (such as phase loss protection, unbalance protection, etc.).

2.2 Short-circuit Protection Method for Motors Based on Current Monitoring

Short-circuit fault is one of the most serious electrical faults in the operation of the motor, which is characterised by a sharp rise in current to 5~10 times the rated value in a very short time, which may cause equipment damage or even fire. Therefore, fast and reliable short-circuit protection is essential to ensure motor safety. This section will introduce the detection principle and implementation method of short-circuit protection in detail, focusing on analysing the operating principle and action characteristics of fuses and circuit breakers.

2.2.1 Detection and Judgement of Short-Circuit Current

The realisation of short-circuit protection relies on the real-time monitoring of abnormally high currents. When a short circuit occurs in a motor or its supply line, the current can surge to 5 to 10 times the rated current in milliseconds time. Detection methods include:

Direct current sampling: the current signal is collected through a current transformer or Roche coil, compared with a preset threshold (usually more than 5 times the rated current) by a comparator, and judged as a short-circuit if the threshold is consistently exceeded.

Current rate of change detection: The rate of rise of short-circuit current (di/dt) is much higher than that of normal starting or overload current, and short-circuit identification can be further improved by monitoring the current rate of change.

2.2.2 Working Principle of Fuse

A fuse is a passive short-circuit protection device, the core component of which is a fuse (or fusible link). The fuse is made of a low melting point alloy material and its current rating is selected according to the characteristics of the motor being protected. When the short-circuit current passes through the fuse, the fuse warms up rapidly due to Joule heat and fuses, thus cutting off the fault circuit.

2.2.3 Working Principle of Circuit Breakers

Circuit breakers for short-circuit protection by means of an active breaking mechanism.

Using the strong magnetic field generated by the short-circuit current to drive the armature action, the mechanical linkage mechanism instantly breaks the contacts. The response time of electromagnetic disconnection is usually 10~50ms, which is suitable for traditional power distribution system.

2.3 Voltage Monitoring Based under/over Voltage Protection Method for Motors

The operation of motors under under-voltage or over-voltage conditions may lead to problems such as overheating of the windings, loss of efficiency, torque fluctuations and even insulation damage. Therefore, real-time monitoring of the supply voltage and taking protective measures when the voltage is abnormal are of great significance to ensure the safe and stable operation of the motor. This section will introduce in detail the detection principle and implementation method of undervoltage/overvoltage protection, focusing on analysing the working principle and action characteristics of voltage relays and intelligent controllers.

The realisation of undervoltage and overvoltage protection relies on real-time monitoring of the motor supply voltage. Normally, the rated working voltage of the motor is allowed to fluctuate within a range of ±10% (e.g., 342~418V for a 380V system). The protection device needs to continuously monitor the three-phase voltage and judge the abnormality by the following ways:

Undervoltage judgement: When the voltage is continuously lower than 85% of the rated value (such as 323V for 380V system) and exceeds the set delay time (usually 0.5~5s), it is judged as an undervoltage state, to avoid the instantaneous voltage drop leading to false action.

Over-voltage judgement: When the voltage is continuously higher than 110% of the rated value (such as 418V for 380V system) and exceeds the set delay time, it will be judged as over-voltage state.

Voltage sampling can be done by resistor voltage divider network or voltage transformer to convert high voltage into low voltage signal suitable for measurement.

2.4 Phase Sequence Protection

Normal operation of three-phase motors relies on correct phase sequence connections. If the phase sequence of the power supply does not match the designed phase sequence of the motor, it will cause the motor to rotate in the reverse direction, which may lead to mechanical damage to the equipment, load failure, or safety accidents. Phase sequence protection ensures that the motor starts and runs in the correct phase sequence by monitoring the phase relationship of the three phase voltages in real time. This section describes in detail the working principle, realisation method and protection action of phase sequence protection.

The core of phase sequence protection lies in determining whether the phase sequence of the three-phase voltages meets the motor operating requirements (usually positive sequence: A-B-C). The detection method is mainly based on the following two principles:

Voltage phase comparison method. By measuring the phase difference between the three-phase voltages (normally 120°), if the phase order is detected as A-C-B or other non-standard order, it will be judged as reverse phase sequence. The phase relationship can be accurately captured using an over-zero detection circuit or phase-locked loop (PLL) technology.

Rotating Magnetic Field Detection Method Using a small induction motor or a micro-motor inside the electronic phase sequence relay, determine whether the phase sequence is correct by its rotation direction. If the direction of rotation is opposite to the calibrated direction, the protection action is triggered.

2.5 Vibration Protection

Monitor the vibration signal of the motor to determine if it is abnormal. Use vibration sensors (e.g. accelerometers): The sensor converts the vibration signal into an electrical signal, and analyses the frequency spectrum or amplitude to determine whether there is a mechanical problem (e.g. bearing damage, unbalance, etc.).

Table 1 Comparison of various strategies

Method	Advantage	Disadvantage	Applicable Scenarios
Overload Protection	Simple, low cost	Slow responsive	Conventional industrial motors
Short-Circuit Protection	rapid responsive	Easily misjudgement	All motors
Under/Over-Voltage Protection	Preventing Voltage Abnormalities	Sensitive to voltage change	Motors with large voltage fluctuations
Phase Sequence Protection	Preventing phase sequence errors	Three-phase motors only	Three-phase motor
Vibration Protection	Monitoring of mechanical failures	High cost	Key motor (Fans, pumps e.g.)

3 Motor protection strategy based on intelligent technology

With the development of Industry 4.0, Artificial Intelligence (AI) technology has shown significant advantages in the field of motor protection. Traditional protection methods are usually based on threshold judgement, which is difficult to deal with early fault diagnosis under complex working conditions. AI-driven intelligent protection systems, on the other hand, are able to achieve fault prediction and accurate protection through multi-dimensional data analysis, significantly improving the reliability and operational efficiency of motors. This section will introduce the working principle, realisation process and technical advantages of motor intelligent protection based on AI algorithm in detail.

The AI-driven motor protection system has a layered architecture and contains the following core modules: Data Acquisition Layer: Through the current/voltage sensors, temperature probes, vibration accelerometers, etc., real-time acquisition of motor operation data, the sampling frequency needs to meet the Nyquist theorem (usually $\geqslant$ 10 times the highest fault characteristic frequency). Edge computing layer: Data preprocessing is done at local devices (e.g., embedded gateways) to reduce the cloud transmission load. AI Analytics Layer: Deploy trained machine learning models for fault classification and prediction. Decision Execution Layer: Trigger protection actions or maintenance recommendations based on diagnostic results.

3.1 Protection Action Strategy

Response is graded according to the severity of the fault: Early warning level (early anomaly): Push maintenance recommendations (e. g. "insufficient bearing lubrication, recommended to deal with it within 72 hours") through HMI interface or mobile APP. Reduced capacity operation (medium-term failure): Automatically limits motor output torque to 70% to avoid worsening faults. Emergency shutdown (severe faults): Trigger the safety relay to cut off the main circuit, and at the same time upload the fault map to the cloud platform.

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