Communication Power Terminal Head Defect Diagnosis Method based on TMR Technique and Flow Temperature Modeling

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Abstract: With the increasing requirements of communication system on the reliability and intelligence level of power supply, the defect identification of communication power supply terminal head has become an important topic to ensure the safe operation of the network. This paper proposes a defect diagnosis method of communication power supply terminal head based on tunnel magneto-resistance (TMR) technology and current-temperature coupling model. By utilizing the TMR sensor's highly sensitive monitoring capability of current change and combining the coupling relationship between current and temperature response, an intelligent diagnosis system suitable for embedded deployment is constructed. The system realizes early identification of defects, state assessment and remote warning, and is especially suitable for communication power supply scenarios with unattended, space-constrained and harsh environments. The performance comparison with traditional methods verifies the comprehensive advantages of this method in terms of response speed, accuracy and deployment convenience, and it has good engineering application prospects.

Keywords: Tunnel Magnetoresistive Sensor (TMR); Communication Power Terminal Head; Defect Diagnosis; Flow-temperature Coupling Model

1. Introduction

With the increasing requirements of modern communication network on the reliability and intelligence level of power supply, communication power supply terminal head as a key node connecting the power supply equipment and power load, the stability of its operation state is directly related to the continuity and safety of the whole communication system. However, under the joint action of high load, strong interference and multiple environmental factors, the terminal head is prone to problems such as poor contact, oxidized corrosion and overheating erosion, which leads to a decrease in the efficiency of power transmission, and even causes equipment failure and communication interruption [1]. Therefore, how to realize the early identification, rapid warning and online assessment of defects in communication power terminals has become the focus of research to ensure the quality of communication network operation.

Currently, the operational status monitoring of power supply terminal head mainly relies on thermal imaging technology, current transformer or fiber optic temperature sensing system [2,3]. Although these methods play a positive role in specific application scenarios, there are still many shortcomings: such as high cost of thermal imager equipment and poor spatial adaptability; complex fiber optic deployment and sensitivity to the environment; and traditional current transformers with lagging response, large size and susceptibility to electromagnetic interference [4]. Especially in harsh environments such as remote, unattended or high temperature, these methods are difficult to realize stable and accurate real-time monitoring.

In order to break through the above limitations, tunnel magnetoresistance (TMR, Tunnel Magnetoresistance) sensing technology, as a new type of high-sensitivity magnetic field detection means, has shown great potential in the field of power equipment condition sensing in recent years. TMR sensors have the advantages of high sensitivity, low power consumption, small size, strong anti-interference ability, etc., and are suitable to be deployed in the space-constrained or multi-disturbance scenarios for current change monitoring [5]. Under space-constrained or multi-disturbance scenarios for current change monitoring [5, 6]. By combining the real-time current monitoring capability of TMR sensors with the theory of Coupled Current-Temperature

Model based on power-thermal effect, a diagnostic framework reflecting the thermal stability of terminal head operation can be further constructed.

The current-temperature coupling model is based on the physical mechanisms of heat generation due to current changes and heat transfer through contact resistance and thermal resistance [7]. The model can identify the local abnormal heating characteristics triggered by structural problems such as contact aging and internal fracture through the joint analysis of current and temperature change data, so as to provide early warning of possible defects. This modeling approach theoretically has good universality and explanatory power, and is expected to realize the online intelligent assessment of communication power terminal status without the need for large-scale wiring or complex acquisition devices.

This paper intends to systematically discuss a theoretical method system for defect diagnosis of communication power terminals based on TMR technology and flow-temperature coupling model. The specific content is arranged as follows: Chapter 2 introduces the principle basis of TMR sensing and flow-temperature model, and summarizes the types and characteristics of communication terminal defects; Chapter 3 analyzes the theoretical construction idea and system composition logic of the diagnostic model; Chapter 4 reviews the applicability and comparative advantages of the method and discusses the direction of future optimization; Chapter 5 sums up the value of the research and looks forward to the prospect of engineering applications.

2. Research Basis and Key Technical Principles

2.1 Principles and Advantages of TMR Technology

The Tunnel Magnetoresistance (TMR) effect is a magneto-electric conversion phenomenon based on the quantum mechanical tunneling principle, which was firstly proposed by Julliere in 1975, and has gradually moved towards engineering applications with the development of spintronics. Its basic structure includes an insulating tunneling layer sandwiched between two ferromagnetic layers. When the magnetization direction of the two ferromagnetic layers is the same, the probability of electron tunneling is large; on the contrary, the probability of tunneling decreases, which produces different resistive states [8].TMR sensors make use of this effect to detect magnetic field changes with high sensitivity.

The advantages of TMR technology in current monitoring are mainly reflected in the following aspects: firstly, its output signal is strong and low noise, which can realize mA-level current sensing; secondly, the device structure is compact and highly integrated, which is suitable for embedded system applications; again, TMR sensors have a strong anti-electromagnetic interference capability, which is suitable for high-voltage, high-frequency and strong interference scenarios. Compared with the traditional Hall elements or current transformers, TMR has obvious advantages in sensitivity and frequency response characteristics, especially suitable for communication power systems to monitor the rapid response to small changes in abnormal current. In recent years, TMR technology has been widely used in non-contact current measurement in industrial motors, electric vehicles, data centers and other scenarios, and has gradually expanded into the field of miniature power sensors. For example, the miniaturized TMR sensing module proposed by Lee et al. has been able to be embedded in a standard PCB structure to achieve millimeter-level precision current detection, which provides feasible technical support for end-head monitoring.

2.2 Overview of the Principle of the Flow-temperature Coupling Model

The current flow process, due to the existence of contact resistance and conductor internal resistance, is bound to be accompanied by the continuous generation of Joule heat. If the current changes drastically, the contact surface aging or heat dissipation conditions are limited, it will lead to increased local temperature rise, which in turn triggers the connection terminal material aging or even ablation. **Current-Temperature Coupled Model (Current-Temperature Coupled Model) **It is based on the electro-thermal physical coupling mechanism, the dynamic relationship between the current input and the temperature response to theoretical modeling.

The core of the model is to build a description of the current (I), contact resistance (Rc), thermal resistance (Rt) and the relationship between the ambient temperature (Ta) mathematical expressions, as follows:

$$T(t)=T_a+\int_0^t \frac{I^2(t)\cdot R_c}{C_{th}}\cdot e^{-\frac{t}{R_t C_{th}}}dt \qquad (1)$$

where C_{th} denotes the heat capacity constant and Rt is the thermal diffusion impedance. This type of model can be used to analyze the process of heat accumulation and dissipation, and predict the trend of temperature rise due to current anomalies, which is especially suitable for the thermal stability assessment of micro-contact areas such as terminal heads [9]. Based on this model, not only can we analyze the hysteresis of the temperature response to power load changes, but also derive the critical temperature threshold judgment mechanism through the model, which can be used to construct the terminal overheating warning system. In addition, under the condition of known load characteristics and environmental thermal parameters, the resistance change of the aging contact point can also be inversely analyzed to provide a basis for fault location identification.

2.3 Failure Characteristics of Communication Power Supply Terminal Head

Communication power supply terminal head, as a connection node between the cable and the equipment, carries a high-current operating load for a long time, and its structure includes connecting bolts, crimped copper noses, terminals and insulating shells. Common forms of failure mainly include: 1) intermittent discharge caused by poor contact; 2) increased contact resistance caused by electrochemical corrosion; 3) carbonization or ablation of insulation produced by local overheating.

These defects are often not easy to detect in the early stages of operation, but will gradually be reflected as physical phenomena such as increased current signal fluctuations, lagging temperature response, and abnormal local high temperatures. For example, in the case of elevated contact resistance, even if the current is maintained at a constant level, areas of thermal inhomogeneity will appear at the terminal head due to a significant increase in Joule heat. Continuous tracking of micro-current changes is achieved by TMR sensors, [10] and combined with temperature monitoring models, early anomaly features can be effectively extracted to achieve passive visualization and trend prediction of defects.

In addition, the structural location of the terminal head is generally hidden, and the traditional manual infrared inspection has the problem of blind area. The embedded inspection system based on TMR+flow temperature model has low power consumption, remote deployment and edge processing capability, which is more adaptable to the current trend of intelligent and distributed development of communication system.

3. Defect Diagnosis Model and System Construction

3.1 Application of Flow Temperature Model in Terminal Head Defect Diagnosis

The core role of the current-temperature model in the system can be summarized in two aspects: firstly, real-time assessment of the operational trend relationship between current and temperature, and secondly, online early warning triggering through the construction of risk level criteria. The model itself does not require complex numerical calculations on the device side, but rather processes the monitoring data in sliding time windows with the help of calibrated experience curves and response templates. The processing logic is characterized by lightweight and fast response, which is suitable for deployment in edge processors with limited resources.

During system operation, the current signal collected through the TMR sensor and the temperature data fed back from the thermal element will be synchronized and fed into the flow-temperature model judgment module. The model analyzes the fitted residuals of the temperature-current inter-trend and combines it with the historical benchmark curve to determine whether it deviates from the normal operating trajectory. Compared with traditional univariate monitoring, the model has the ability to analyze bivariate coupling, which can identify potential defects earlier.

Figure 1 shows two typical temperature response curves under the application scenarios of the model in the system - the temperature rises smoothly with the current in the normal state, while in the defective state (e.g., a sudden increase in contact resistance), the temperature curve rises sharply in a nonlinear manner, and there is an obvious response hysteresis and out-of-control phenomenon:

In order to facilitate the rapid identification of abnormal patterns in the system, the output of the model not only includes the current risk level (e.g., whether it exceeds the warning threshold), but also generates a set of trend characteristics, such as: the value of the change in the slope of the temperature, the degree of offset of the historical data, and so on, and the characteristic values will become the basis of the inputs of the "diagnostic evidence module" for further combining environmental parameters and power loads for comprehensive risk assessment. Characteristic values will become the basis for the subsequent "Diagnostic Criteria Module", which will be used to further combine environmental parameters and power loads for comprehensive risk assessment.

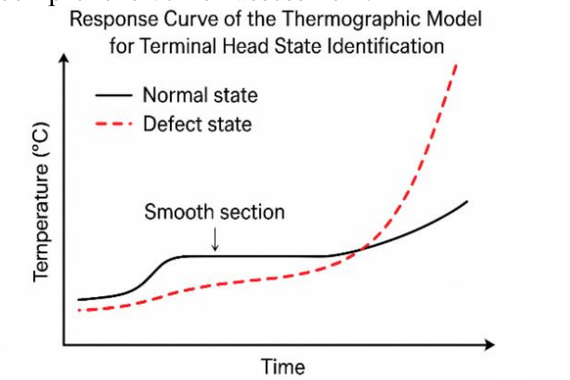

Figure 1. Schematic of the Response Curve of the Flow Temperature Model in Terminal Head State Identification

3.2 System Functional Module Design

According to the actual operational requirements and defect identification objectives of the communication power terminal head, the system is divided into five core functional modules, which are: data acquisition module, preprocessing module, defect identification module, status assessment module and warning push module.

Data Acquisition Module: Through the integration of TMR sensors, temperature/flow rate sensors and other components, the system realizes the multi-dimensional acquisition of the working environment and operating parameters of the terminal head. In order to avoid error interference, the system design adopts multi-point deployment mechanism to ensure the comprehensiveness and real-time data acquisition.

Data preprocessing module: clean, denoise, normalize and other operations on the original signal, and use the sliding window filtering algorithm to integrate the time series data, to provide a stable data base for the subsequent defect identification.

Defect recognition module: as the core processing unit of the system, it carries out feature extraction and matching comparison on the sensed data. Dynamically switch to static feature matching mode or dynamic trend recognition mode according to real-time status.

Status assessment and warning module: When the system identifies potential defects, the status assessment module will output risk level judgment according to the type of defects, which is divided into "normal", "mild warning", "moderate warning" and "heavy warning". It is categorized into "normal", "mild warning", "moderate warning" and "severe risk". According to the assessment level automatically triggered SMS or platform push mechanism to realize remote dynamic intervention and maintenance scheduling.

The following figure (Figure 2) shows the logical flow and data interaction process between the system functional modules:

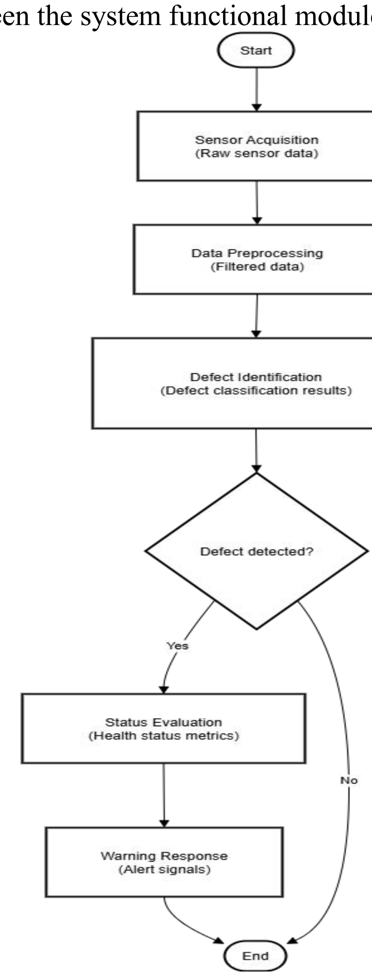

Figure 2. Logical Structure Diagram of the Functional Modules of the Communication Power Terminal Head Defect Diagnosis System

3.3 Analysis of the System's Applicable Environment and Boundary Conditions

The communication power terminal head defect diagnosis method based on the TMR technology and the flow temperature model is highly adaptable to a variety of typical communication power supply environments. However, before the actual deployment, the boundaries of the physical conditions and the data conditions need to be fully evaluated:

(1) Physical deployment conditions

The method This method relies on the TMR sensor's ability to monitor electromagnetic signals, temperature distribution and humidity changes with high sensitivity, so it is necessary to ensure that there is enough space for miniaturized sensors to be arranged inside the equipment, and at the same time to ensure that the sensors are far away from strong sources of interference (e.g., strong electromagnetic radiation, heavy metal heat sinks, etc.). In addition, the terminal head structure needs to allow the sensor and the equipment surface full contact to improve data quality.

(2) Data stability conditions

flow temperature model is extremely sensitive to real-time data fluctuations, requiring edge collection nodes with high sampling accuracy and frequency. If the communication power system in the long-term operation of large-scale data interruption or serious sampling offset, will directly affect the stability of the diagnostic model and judgment accuracy.

(3) Applicable Defect Type Boundary

The current method has good recognition ability for the following three types of typical faults: poor contact of terminal oxidation, micro-discharge phenomenon caused by loose wiring, and degradation of insulation performance caused by moisture. For non-thermally induced faults such as structural fracture and strong impact damage, the recognition ability is still limited.

4. Applicability Analysis and Application Prospects of Diagnostic Methods

4.1 Comparative Analysis with Traditional Defect Diagnosis Methods

In the field of defect identification of communication power supply terminal head, traditional monitoring and diagnosis methods mainly include thermal imaging technology, fiber optic temperature sensing and current transformer method. Each of these methods has a certain degree of technical maturity and engineering applicability, but some limitations are also exposed in practical application that cannot be ignored.

Thermal imaging technology relies on infrared thermograms for surface temperature distribution analysis, but the results are susceptible to environmental thermal perturbations, insensitive to small changes in contact resistance response, and high cost, not suitable for large-scale deployment. Fiber-optic temperature sensing, although with high sensitivity and anti-electromagnetic interference advantages, but its installation is complex, high maintenance costs, and usually relies on dedicated signal demodulation equipment, is not conducive to the implementation of a small space. The current transformer law focuses on the monitoring of load current changes, although the principle is simple, but it is difficult to realize the early identification of contact defects, there is a certain lag.

In contrast, the defect diagnosis method based on TMR (tunnel magnetoresistance) sensing technology and the flow-temperature coupling model shows significant advantages in terms of response speed, deployment convenience and diagnostic accuracy. The method realizes the sensitive capture of contact resistance micro-variation by real-time acquisition of magnetic field and temperature gradient information. Meanwhile, TMR sensors are small in size and low in power consumption, and can be flexibly deployed in high-density electronic environments, which is especially suitable for internal deployment in space-constrained communication equipment. Its model does not rely on external vision or fiber optic systems, effectively avoiding the interference problems caused by environmental occlusion and wiring complexity.

Table 1 lists the comparison of several mainstream defect diagnosis methods under the key performance indicators, which shows that the TMR + flow temperature modeling scheme has comprehensive advantages in a number of indicators.

4.2 Typical Application Scenarios

The diagnostic method based on TMR and flow-temperature coupling model is especially suitable for the following types of communication power system environments:

(1) Outdoor base station power supply system: such base stations are usually deployed in remote areas, facing large temperature fluctuations and electromagnetic interference risk, TMR sensors have good resistance to environmental interference, while the low power consumption characteristics are also suitable for long-term remote operation.

Table 1. Performance Comparison of Common Defect Diagnosis Methods

Method	Response speed	Deployment difficulty	Precision and stability	Cost	Environmental adaptability
Thermal imaging diagnosis	Medium	High	Medium	High	Poor
Optical fiber temperature sensing	High	High	High	High	Excellent
Current transformer method	Low	Low	Medium	Low	Average
TMR + flow temperature model	High	Low	High	Medium	Excellent

(2) Remote or unattended communication sites: such as mountainous communication relay stations, wireless base stations along railroads, etc., with high maintenance costs, manual inspection difficulties and other issues, there is an urgent need for on-line deployment, independent diagnosis of the program, TMR + flow temperature method can be embedded in the terminal head internal deployment, to achieve round-the-clock status monitoring.

(3) Miniaturized communication equipment (e.g. 5G micro base station) power supply system: space limitations lead to the difficulty of deploying traditional sensing solutions, while the TMR solution can realize miniaturized integration, greatly alleviating space constraints and guaranteeing reliable operation of equipment.

In addition, in industrial communication systems, power electronic control cabinets, military communication power supply and other occasions with high requirements for security and real-time, the method also shows strong potential for application.

5. Conclusion

In this paper, a defect diagnosis method integrating TMR sensing technology and current-temperature coupling model is proposed for the hidden problems such as poor contact and local overheating, which are prone to occur in the terminal head of communication power supply in the complex environment. The method realizes real-time correlation judgment of current and temperature trends through bivariate coupling modeling, which breaks through the limitations of traditional methods in terms of high deployment cost and diagnostic lag. The system structure is lightweight and easy to be embedded inside the communication equipment, which is suitable for a variety of remote or unattended scenarios. Future research can optimize the model adaptive capability, data fusion accuracy and high-frequency anomaly feature extraction, in order to further expand its application potential in other power electronic systems.

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