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Temperature Measurement Method and Simulation of Power Cable Based on Edge Computing and RFID

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ABSTRACT

Aimed at the problem of large errors in traditional power cable temperature measurement methods, a method based on edge computing and radio frequency identification (RFID) is proposed. Firstly, a RFID electronic label design scheme was constructed utilizing the radio frequency signal between alternating electromagnetic fields to achieve the communication and information identification between two devices. Then, the design of power cable edge intelligent terminal is analyzed from the aspects of hardware and software. On this basis, the early warning criterion formula of power cable temperature fault state is abstracted by using edge computing algorithm. Based on edge computing and RFID, the corresponding temperature measurement method is proposed. Finally, the proposed power cable temperature measurement method is compared with other three methods through simulation experiments. The results indicate that the temperature measurement error of the proposed method is the minimum under different currents and in cross-sectional areas. Compared to the other three methods, the maximum improvement is 5.15% and 7.92%, while the minimum improvement is 1.05% and 1.45%, which outperforms the comparable algorithms in terms of performance.

KEYWORDS

Edge computing, Edge intelligent terminal, Power cables, RFID, Temperature calculation

1 INTRODUCTION

The power industry plays an important role in a country's economic construction. With the progress of urban construction and industrial modernization, the demand for the power industry is increasing (BORECKI M., 2020; CHEN K, YUE Y, TANG Y J., 2021; CHENG Y C, ZHAO L, WU, X T, et al., 2020). In order to meet the growing demand for electricity, power cables, as the lifeline of cities, are constantly being added to the urban power grid. They not only play an important role as "blood vessels and nerves" in urban power transmission and distribution, but also are essentially

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basic products for the future informatization and electrification of cities (CZAPP S, SZULTKA S, TOMASZEWSKI A., 2020; ENESCU D, COLELLA P, RUSSO A., 2020; FU Chenzhao, LI Honglei., 2021). However, power cables are laid underground and operated in a concealed environment. Under high voltage and current conditions, these long-term continuous power cables are particularly prone to heating up. If undetected and improperly handled, a power cable fire may be caused, resulting in huge economic losses. Therefore, being able to timely and accurately understand the temperature of power cables during operation is very important for the operation and maintenance of the power system (GHONEIM S, AHMED M, SABIHA N A., 2021; HOLYK C, LIESS H D, GRONDEL S, et al., 2021; LI Huan, LI Jianying., 2020).

According to engineering experience and relevant theories, a power cable fire is not a sudden accident, but rather a continuous increase in temperature, aging insulation, and in leakage current during the operation of the power cable, ultimately causing the accident (LI J, XU Y, ZHANG M, et al., 2019; LI Shengtao., WANG Shihang., YANG Liuqing., et al., 2022; LIU D W, LIU Y, LI F, et al., 2020). Therefore, by continuously monitoring the temperature changes of power cables, it is possible to fully and accurately understand the working conditions and carry out timely fault maintenance according to the situation. In particular, when the temperature is too high (exceeding the preset value) or it changes too quickly, the insulation is relatively weak. At this point, an alarm mechanism will be triggered and staff will be reminded to take timely action to avoid accidents (MOHAMED A, GOUDA O., 2020; Phadkule, Saket Sanjay, Sarma, Shrutidhara., 2023; RMA V, LARA J., 2020).

In the process of power system maintenance, the conductor temperature of power cables, as one of the important monitoring indicators, cannot only reflect the operation status of high-voltage power cables, but also directly determine one of the key parameters of their carrying capacity (Shibu, Melvin, Kumar, Kukatlapalli Pradeep, Pillai, Vinay Jha, et al., 2023; WANG Haoyue, WANG Xiaowei., 2022; WANG Yulong., 2021). When the load current exceeds the current carrying capacity, the conductor temperature is higher than the rated value. Under the action of electricity, heat, and machinery, the insulation structure of the power cable is gradually damaged, and the internal leakage current increases, ultimately leading to the breakdown of the insulation structure of the power cable. When the estimated current carrying capacity is too low, the operating temperature of the conductor is also low, wasting the transmission capacity of high-voltage power cables (WEI Yanhui, ZHENG Yuanhao., 2022; WU J Z, LIN J J, GAO Z J, et al., 2020). During the long-distance power transmission, due to quality issues with accessories and the poor manufacturing technology, there is excessive contact resistance between the core conductor at the intermediate joint of the power cable and the metal connecting pipe (XIONG L, CHEN Y H, JIAO Y, et al., 2019), resulting in crimping defects at the joint. When the contact resistance increases, the partial discharge phenomenon and the leakage current increase, causing increased electromagnetic loss, which will also affect the operating temperature of power cables. Therefore, temperature monitoring of high-voltage power cable conductors is of great significance for evaluating the safety of power transmission systems and for ensuring the stable and efficient operation of power cables. Timely detection and replacement of faulty high-voltage power cable joints can effectively prevent accidents, such as fires and explosions, and are important means to ensure the safe operation of the power system (YANG B, WU K H, ZHENG Z J, et al., 2021; YANG L, HU Z, HAO Y P, et al., 2021). Therefore, monitoring the operating temperature of power cables is of great importance to ensure the safe operation of power cables.

VanDeursen, A, Wouters, P, Steennis, F. (2021) simulates the expected waveforms in the time-domain reflectometer testing by combining numerical thermal modeling and modal analysis based on the characteristics of different materials. On this basis, the consistent temperature correlation of power cable conductors during the fault period and the impact of rapid temperature rise of power cables on wave propagation were analyzed. However, this method lacks certain applicability for multi-loop concentrated power cable clusters. Li, ZM, Yang, H, Yang, F, et al. (2022) combined deep learning with state assessment in the process of power cable temperature measurement, designed down sampling and up sampling networks by introducing transfer learning and Deconvolution, and proposed a state assessment model of power cable infrared image based on deep learning. However, this method is greatly influenced by the number of power cable layers. Brakelmann, H, Anders, GJ. (2022) proposed a mathematical model for power cable current carrying capacity to allow non-iterative calculations of water temperature and the temperature related losses along power cables. Based on this, the heat absorbed and released by cooling pipes and the impact of water flow on the temperature of power cable conductors were evaluated. However, as the current increases, the calculation error of the model also increases. Xie, J, Sun, T, Zhang, JQ, et al. (2022) proposes a power cable defect recognition model based on the task requirements of power cable channel detection and the method of power cable temperature anomaly detection, wavelet transform image segmentation, and power cable temperature anomaly detection, which can identify power cable skin defects and overheating in complex environments. However, this method cannot achieve real-time dynamic monitoring. In Salas, FMA, Orlande, HRB, Domingues, LAMC, et al. (2021), aimed at the problem of power cable temperature rise caused by the physical structure and the uneven current distribution, the transient temperature distribution in the cross section of aluminum conductor power cable was evaluated based on the measurement of power cable surface temperature by infrared camera combined with Particle filter. And in this process, the evolutionary heat conduction model inside the power cable and the uncertainty of measuring temperature were considered. However, this method overly relies on the skin temperature of power cables. The study of You, F, Yang,, Liu H, et al. (2022) is aimed at the temperature measurement of shore power cables used for power supply of port ships. Through the analysis of special use conditions of shore power electric power transmission and shore power cables, a temperature field simulation model was established to study the influence of ambient temperature, wind speed and solar radiation on the temperature distribution of shore power cables. However, this method does not consider the influence of mutual heating effect and power cable layout on conductor temperature. Deng Z, Bao G (2021) attempted to solve the problem of power cable connector temperature measurement. Their research achieved the acquisition of power cable connector temperature by embedding a passive wireless temperature sensor in the power cable connector and transmitting energy to the temperature sensor through super high frequency electromagnetic waves. On this basis, it transmitted information to the server through the NB IoT network to achieve real-time temperature monitoring. However, this method is not suitable for dealing with problems with complex boundaries and irregular regions.

From the above analysis, it can be seen that traditional cable temperature detection algorithms are mainly based on the principle of temperature measurement, including infrared thermal imaging technology, temperature measurement optical fibers (laying temperature measurement optical fibers inside or outside the cable sheath to achieve online temperature monitoring), single bus distributed electronic temperature measurement (arranging temperature sensors at the cable joints and uploading them to the temperature collector through a bus to achieve online temperature measurement), etc. The cable temperature detection algorithm based on deep learning mainly utilizes deep learning models to predict and detect the temperature of cables. These models analyze and learn from historical temperature data and other related factors, to achieve prediction and anomaly detection of future cable temperatures. The advantage of this method is that it can automatically extract features, improve prediction accuracy and anomaly detection accuracy, while reducing manual intervention and errors.

Overall, traditional cable temperature detection algorithms are simple to implement and cost-effective, but require manual intervention and regular calibrations. Algorithms based on deep learning can automatically extract features, improve prediction accuracy and anomaly detection accuracy, but the prerequisite requires a large amount of historical data and high computational resources.

Aimed at the problem of large error in traditional power cable temperature measurement methods, a power cable temperature measurement method based on edge computing and RFID is proposed. The power cable temperature is continuously monitored by the RFID technology. The problems of low precision, complex construction and high cost in the existing monitoring system are solved by the two key technologies of passive temperature measurement and edge computing of RFID electronic tags, so that workers can read the temperature of each measuring point through the upper computer terminal. And it can handle accidents that may occur due to high temperatures at any time, providing a guarantee for the safe operation of the power cable system (ZHANG Y, CHEN X, ZHANG H, et al., 2020; ZHOU J, YAO K, HUANG X, et al., 2019).

The main structure of the paper is as follows:

(1) An analysis was conducted on the relevant content of RFID electronic tags for power cables, including the basic principles of RFID and the design scheme of RFID electronic tags.
(2) This paper introduces the proposed method for measuring power cable temperature, including the hardware and software architecture of the cable edge intelligent terminal, the proposed edge computing algorithm, and the RFID based temperature inversion calculation method. The flow chart of cable temperature measurement based on edge computing and RFID is given.
(3) The proposed method has been experimentally validated. This includes the verification of temperature measurement errors for power cables under different currents and for power cables with different cross-sections. A comparative verification with other methods is also carried out.
(4) A summary of the paper's main content is offered.

2 POWER CABLE RFID ELECTRONIC LABEL

2.1 RFID

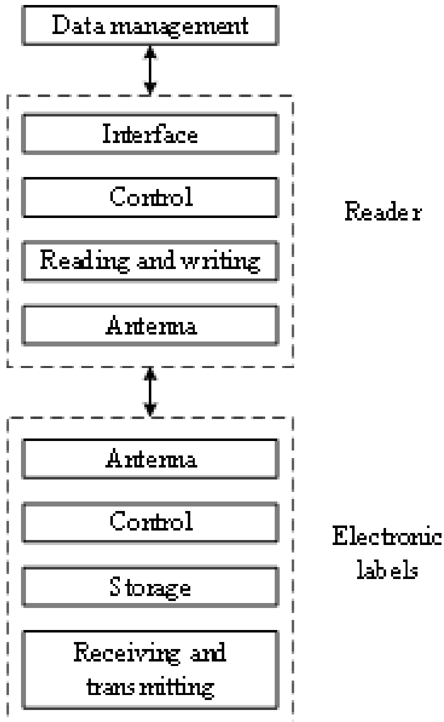
RFID is a short distance recognition communication technology that identifies specific targets, reads and writes target related data through wireless communication signals. It can achieve the non-contact automatic recognition and can read labels in harsh environments where barcodes cannot be used. RFID can penetrate objects for non-contact recognition because of its communication through wireless radio frequency. It cannot only penetrate snow, fog, ice, paint and dirt, but also has an extremely fast reading speed. Through the spatial coupling of radio frequency signals, the non-contact information transmission is achieved, and the recognition purpose is achieved through the transmitted information.

RFID is equivalent to numbering or naming specific objects and identifying them. It attaches an RFID electronic tag to the target object and uses a dedicated RFID reader to read and write the wireless frequency signal on the RFID electronic tag. The RFID electronic tag and the RFID reader utilize the radio frequency signal between alternating electromagnetic fields to achieve communication and recognition of information between two devices. RFID is divided into three categories: passive, active and semi active. The passive RFID feeds back the information stored in the chip to the reader/writer by sensing the RF signal emitted by the reader/writer. In the active RFID, tags will actively send signals of a specific frequency, and the reader/writer will read and decode the signals. The semi active RFID combines passive technology and active technology, utilizing the passive technology for a close range precise positioning and the active technology for long-distance recognition and data uploading. Compared with barcode technology, RFID has the advantages of faster recognition speed, more big data capacity and better security performance.

The RFID system consists of an application software system, a reader and a transponder. Each independent tag, as a transponder, is composed of a specialized chip and a professional antenna. As the electronic code written in it is unique and can be installed on the target object, it can achieve the function of automatically identifying the target object. The reader mainly accurately and quickly transmits the object identification information and other related information on the label to the host for processing. The application layer software further processes the collected data and provides it for users. The working principle of the RFID system is shown in Figure 1.

The reader uses an internal antenna to send a specified frequency of RF signal. When the tag enters the working area of the antenna, the internal antenna will generate an induced current and activate the tag. The tag accepts the reader's data or transmits its encoded information through the internal

Figure 1. Working principle of RFID system



antenna. The carrier signal sent from the tag is received by the system through the receiving antenna and is transmitted to the reader through an antenna regulator. The reader decodes and demodulates the received signal, and then transmits the data through a computer network. At the same time, the application layer software system determines whether the label is legal based on logical operations, and make corresponding judgments and quick reactions when different situations occur, and handle them in a timely manner. RFID tags can demodulate data that is partially demodulated from the received RF pulses and sent to the application layer software system. The application layer software system can complete the closed-loop and store related operations upon receiving instructions.

2.2 Design scheme of RFID electronic tags for power cables

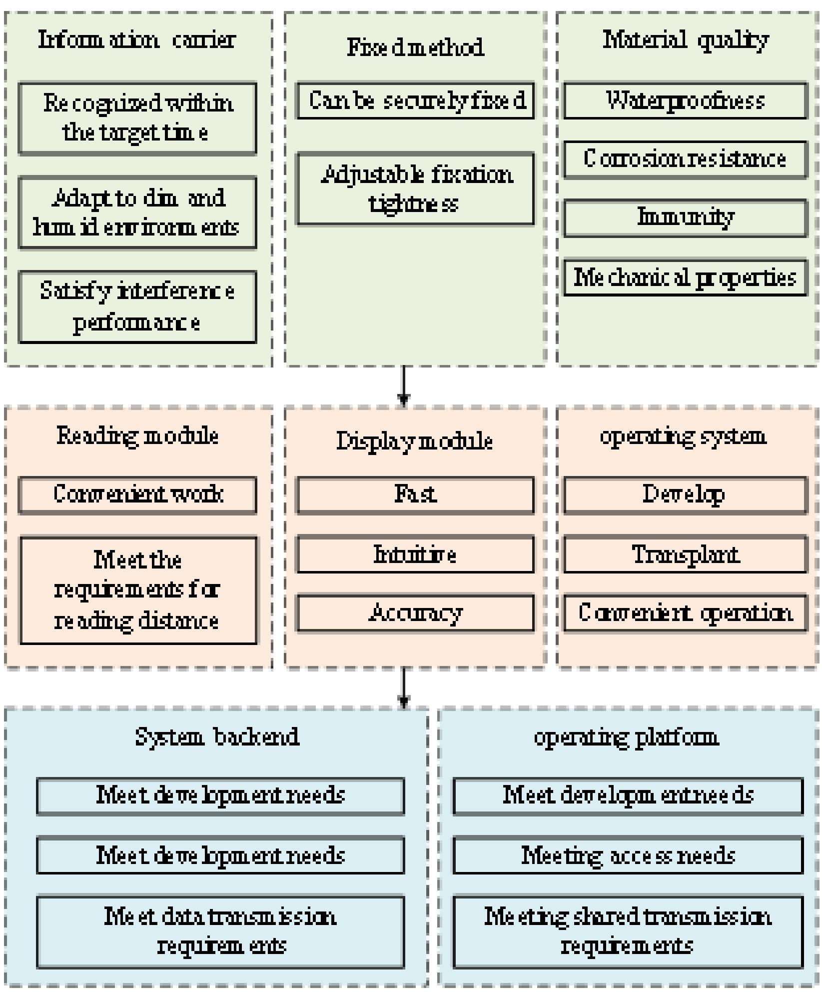
Currently, RFID is widely used in resource management systems, with main characteristics as follows: (1) It can be used in harsh environments, has anti magnetic performance, waterproof performance, high temperature resistance, and conflict prevention functions, and is not easily affected by environmental factors. Even in environments where the barcode technology cannot adapt, its recognition does not require visible light and does not require visual visibility. (2) It has long reading distance, fast data reading speed, and a convenient application. It can accurately read data by simply placing it in the electromagnetic field formed by the reader, achieving passive and contactless operation. To some extent, it eliminates the cost of error correction and management efficiency by manual intervention. It is capable of processing multiple labels simultaneously, repeatedly editing the data on the labels and reusing the labels. (3) Its label can adopt hierarchical confidentiality measures for data, making it only readable at designated nodes in the supply chain, with anti-counterfeiting characteristics.

By applying RFID to power cable identification, the power cable label can be installed on the power cable body, and a carrier for storing power cable information can be implanted inside. The appearance and material of the power cable label can be designed based on the usage method and the on-site environment. It can be identified through reading devices and combined with an electronic label management system to read and manage the information of power cables. The design concept of RFID electronic tags for power cables is shown in Figure 2.

According to the current power cable management requirements, electronic information label identification points can be divided into the following 6 types of content identification points:

(1) Power cable equipment terminals: ring network box terminals, etc.
(2) Power cable intermediate joint body: The location where two power cables are connected in an underground pipeline.
(3) Starting and ending points of power cable circuits: The starting point, ending point, and vertex position of the turning radius inside the underground cable well.
(4) Observation well power cable body.
(5) The power cable body at the junction position of the "T" type power cable trench.
(6) The power cable body is located at the opening of the power cable circuit: The cable crosses both ends of the road or can be the cable body at both ends of the cable protection pipeline.

Figure 2. Design concept for power cable RFID electronic tags



3 METHOD FOR CALCULATING THE TEMPERATURE OF POWER CABLES

3.1 Power cable edge intelligent terminal

The intelligent terminal at the edge of power cables is a key equipment in the construction of the Internet of Things for power cables. It plays a connecting role in the data transmission link and mainly achieves two functions: The first is to serve as the "hub" between local communication networks and remote communication networks, achieving unified access and control of monitoring data. The second is to serve as the core computing unit located at the edge, completing functions, such as resource scheduling, data storage, and data calculation. The power cable edge intelligent terminal can connect various mainstream brand cameras for power cable scenarios and achieve front-end calculation through front-end algorithms. After completing the fault identification analysis, it can be uploaded to the IoT management platform, effectively improving fault identification speed and reducing back-end calculation pressure. At the same time, the power cable edge intelligent terminal also integrates multi-band wireless transceiver units, utilizing local wireless and wired communication interfaces to connect various monitoring sensors, achieving the unified management of sensor data throughout the power cable gallery.

In terms of hardware design, the development of power cable edge intelligent terminal motherboard should use high-performance chips, have an edge AI computing ability, support the operation of no less than 12 containers and the 5G/4G/Ethernet northbound communication interface, as well as communicate with the IoT management platform through message queuing telemetry transport (MQTT). Its overall design is based on the lightweight edge computing framework, and uses the application container engine Docker as the operation mode of various sensor services, communication interfaces and other modules.

The hardware composition is shown in Figure 3.

In terms of software design, the software architecture mainly consists of the IoT communication layer, business container layer, and edge computing master layer, as shown in Figure 4 below.

The IoT communication layer is responsible for the unified communication between various sensor/terminal business containers and the IoT management platform, and performs overall information security protection operations. The remote message interface module is responsible for the unified interface of MQTT messages, achieving south and north data interaction with the IoT management platform.

Figure 3. Hardware architecture of cable edge intelligent terminal

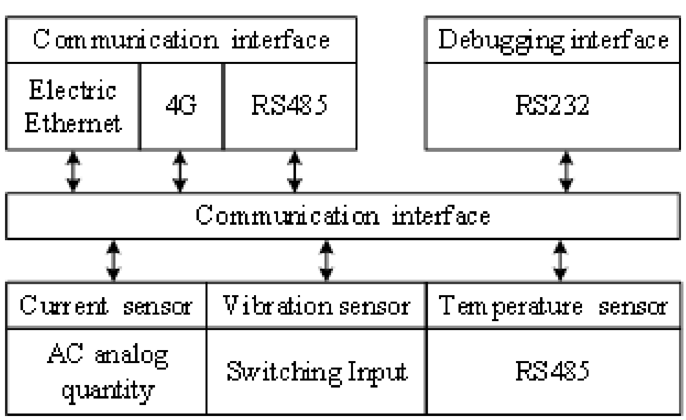
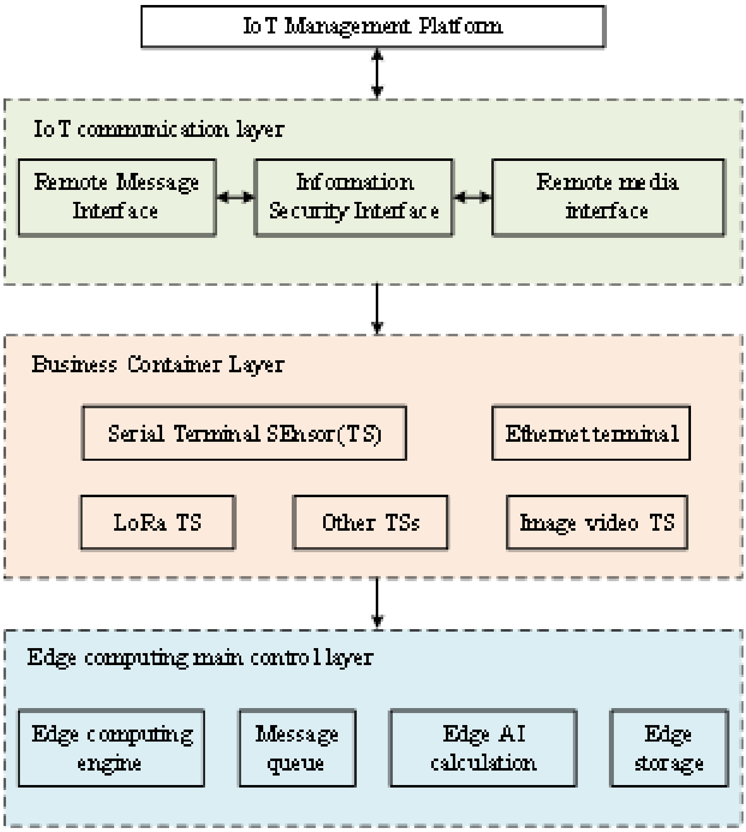


Figure 4. Software architecture of cable edge intelligent terminal



3.2 Edge computing algorithm

The realization of edge computing for power cable temperature analysis requires comprehensive analysis of multiple parameters. Before the edge computing, the data shall be preprocessed to remove possible interference points. Common data preprocessing algorithms include moving the average algorithm for identifying pulse interference, least square method and data processing algorithm based on probability statistics, etc. Based on the software and hardware resources of the terminal and the data situation of power cable monitoring, the sliding window median filtering method is used for data preprocessing. In the process of preprocessing the temperature data of power cables and the advantages of sliding window median filtering method over other algorithms are mainly manifested in the following aspects:

(1) Effectively removing outliers: The sliding window median filtering method divides the data into several sliding windows and sorts the data within each window; thereby, effectively removing outliers. Compared to other methods, the sliding window median filtering method is more robust in handling outliers.
(2) Able to maintain data stability: Owing to the fact that the sliding window median filtering method sorts the data within each window and selects the median as the output, it can maintain data stability. Compared to other methods, the sliding window median filtering method is smoother in data processing and avoids drastic fluctuations in the data.

(3) High computational efficiency: The sliding window median filtering method has relatively high computational efficiency. Compared to other methods, it has lower computational complexity; therefore, the better performance in processing large-scale data.
(4) Wide applicability: The sliding window median filtering method is suitable for various types of data processing scenarios, including time series data, image processing and signal processing, etc. Compared to other methods, it has a wider range of applications.

Therefore, the sliding window median filtering method was chosen to preprocess the temperature data of power cables. The processed data obtained by the sliding window median filter is used as the data source for subsequent edge computing. The analysis and processing of joint temperature after removing interference data in data preprocessing mainly includes the following three situations: The first is the joint temperature over limit alarm, which starts when the maximum or average measured joint temperature exceeds the alarm threshold. The second is the joint temperature sudden exceeding limit alarm, which is triggered when the difference between the maximum and average temperature values of any phase exceeds the alarm value. The third is the alarm for the temperature imbalance of the joint exceeding the limit, which is triggered when the temperature difference between any two phases of the measured joint temperature exceeds the alarm value.

For the above three situations, a formula for predicting the temperature fault status of power cables can be abstracted, as shown in Eq (1).

$$\begin{cases} T_x > T_{s1} \\ \left|\Delta T_x\right| > T_{s2} \\ \left|\Delta T_\alpha\right| > T_{s3} \end{cases} \tag{1}$$

In the formula, T_x is the real-time temperature at the monitoring point x of the power cable. ΔT_x is the temperature change within adjacent measurement cycles. ΔT_α is the temperature difference between adjacent phases of the power cable. T_{s1}, T_{s2} and T_{s3} are the set values for different temperatures of power cables. If any of the conditions in Eq (1) is met, it can be determined that the joint temperature has reached the "fault state" and the corresponding alarm is triggered.

3.3 RFID-Based Temperature Measurement Inversion Calculation Method

Based on the temperature field distribution characteristics of power cables, a typical thermal circuit model of a three-core power cable is established in Eq (2).

$$\begin{cases} T_c - T_s = R_1\left(\omega_c + 0.5\omega_d\right) \\ T_s - T_p = 3\left[\omega_d + \left(1+\beta_1\right)\omega_c\right]R_2 \\ T_p - T_k = 3\left[\omega_d + \left(1+\beta_1+\beta_2\right)\omega_c\right]R_3 \\ T_k - T_0 = 3\left[\omega_d + \left(1+\beta_1+\beta_2\right)\omega_c\right]R_4 \end{cases} \tag{2}$$

In Eq(2), β_1 is the loss factor of the metal shielding resistance. β_2 is the resistance loss factor of the armor layer. R_1 is the thermal resistance of the insulation layer. R_2 is the thermal resistance of the inner sheath. R_3 is the thermal resistance of the outer sheath. R_4 represents the thermal resistance of the surrounding medium. T_c is the temperature of the power cable conductor. T_s is the temperature of the metal shielding layer. T_p is the temperature of the metal armor layer. T_k is the surface temperature of the power cable. T_0 is the ambient temperature. ω_d represents the dielectric loss of the insulation layer. ω_c is the conductor loss, with $\omega_c = I^2 R$, and I is the current of the power cable. R is the AC resistance of the conductor.

According to the installation position of the RFID chip, the temperature T_p of the armor layer is equivalent to the actual measured temperature of the chip. When the shape parameters of the power cable and the environmental temperature T_0 are known, the value of the conductor temperature R can be obtained by an inverse calculation after obtaining the temperature T_p of the armor layer. After the calculation, it can be obtained that T_c and T_p meet the following Eq (3).

$$\begin{aligned} T_c = 2T_p - T_0 + R_1\left(\omega_c + 0.5\omega_d\right) + 3\left[\omega_d + \left(1+\beta_1\right)\omega_c\right]R_2 \\ - 3\left[\omega_d + \left(1+\beta_1+\beta_2\right)\omega_c\right]\left(R_3 + R_4\right) \end{aligned} \tag{3}$$

In practical situations, the thermal resistance coefficient and dielectric parameters of metal materials in power cables are significantly affected by temperature. Therefore, the relationship between the relevant physical parameters and T_c was considered, and further modifications were made to the inversion calculation method. The physical parameters of power cables affected by temperature include: AC resistance R per unit length of power cable conductor; Loss coefficient β_1 of metal shielding or metal sleeve; Loss coefficient β_2 of the armor layer; Air environment thermal resistance R_4.

The AC resistance of a unit length power cable conductor is shown in Eq (4).

$$R = R_0\left[1+\gamma\left(T_c - 20\right)\right]\left(1+\eta_1+\eta_2\right) \tag{4}$$

In Eq (4), R_0 is the DC resistance of the conductor at 20 ° C. γ is the temperature coefficient of the metal. η_1 and η_2 are skin effect factors and proximity effect factors. When the power cable model is determined, both R_0 and γ are known values.

The loss coefficient β_1 of metal shielding or metal sleeve is shown in Eequation (5).

$$\beta_1 = \frac{1.7R_s}{\left[1+\left(\frac{R_s}{X}\right)^2\right]R} \tag{5}$$

In Eq (5), R_s is the metal shielding resistance per unit length. X is the metal shielding reactance per unit length.

The loss coefficient β_2 of the armor layer is shown in Eq (6).

$$\beta_2 = \frac{s^2K^2 \times 10^{-7}}{RDh} + \frac{2.25s^2Kh \times 10^{-8}}{RD} \tag{6}$$

Where s is the distance between the conductor axes. h is the equivalent thickness of the armor. D is the diameter of the armor. μ is the relative permeability of the steel strip. If the power cable model is determined, the above parameters are all known values, and the intermediate coefficient K can be directly calculated.

The thermal resistance U of the air environment is shown in Eq (7).

$$R_4 = \frac{1}{\pi \cdot D_0 \cdot g \cdot \left(\Delta T_s\right)^{0.25}} \tag{7}$$

Where D_0 is the outer diameter of the power cable. g is the heat dissipation coefficient. ΔT_s is the temperature difference between the surface temperature of the power cable and the ambient temperature.

From the temperature relationships among different structural points, it can be obtained that:

$$\begin{aligned} \Delta T_s = T_k - T_0 = T_c - T_0 - R_1\left(\omega_c + 0.5\omega_d\right) \\ - 3\left[\omega_d + \left(1 + \beta_1\right)\omega_c\right]R_2 \\ - 3\left[\omega_d + \left(1 + \beta_1 + \beta_2\right)\omega_c\right]\left(R_3 + R_4\right) \end{aligned} \tag{8}$$

3.4 Power Cable Temperature Measurement Based on Edge Computing and RFID

In order to better calculate the temperature of power cables, we consider using modular and structured programming to write the main program. The main program of the system can achieve the serial communication through the upper computer, can receive data while also transmitting data, and then perform various operations on temperature labels.

The label operation program can complete the sending and receiving functions of label operation commands. A program containing a front-end temperature detection system for reading/writing temperature labels can execute relevant data sent by the upper PC computer. These data are sent in the form of serial ports, and the input data includes command codes, parameter lengths, and related content. At the same time, the upper PC also receives the relevant data sent by the program exit, achieving the reverse transmission of data. The output data includes the content and the length of the response to the command code and the status flag bits, etc.

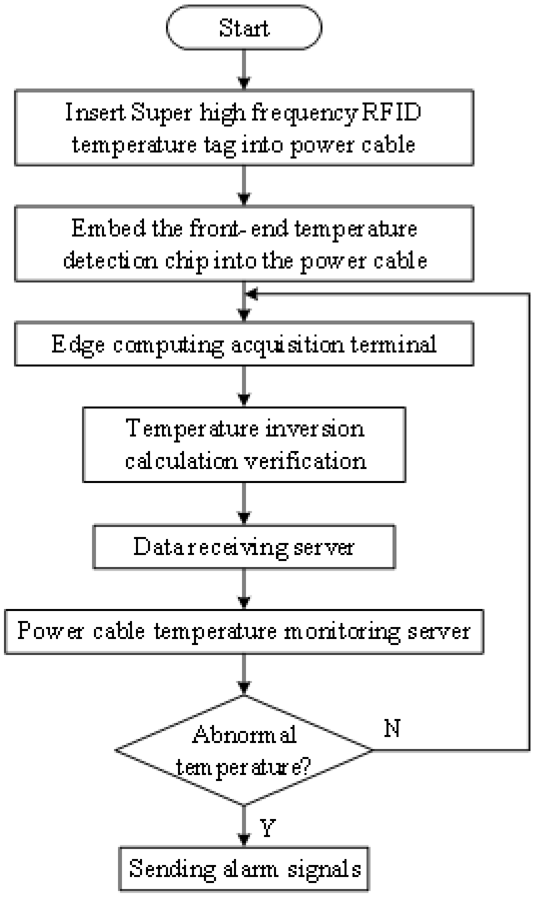
The reception of response commands is divided into two steps, namely receiving data information and receiving CRC verification information. The data information will be calculated after receiving the Check digit of CRC, and will be compared with the CRC Check digit receiving the response command at the same time. If the results are not equal, the error flag in the CRC Check digit will be returned. However, if the two results are equal, it is thus proved that the accepted instruction is false after receiving the instruction and the correct data will be returned.

Based on the above programming ideas, the power cable temperature measurement process based on edge computing and RFID tags is proposed in Figure 5 below.

Figure 5 mainly includes the following steps:

(1) Insert the super high frequency RFID temperature tag into the power cable for temperature monitoring, and install it between the armor layer and the outer sheath of the power cable.
(2) Insert the front-end temperature detection chip into the power cable and install it in the power cable connector.

Figure 5. Cable temperature measurement process based on edge computing and RFID



(3) Send the acquired real-time temperature of power cable to the edge computing acquisition terminal.
(4) Use relevant data and power cable structure to invert and calculate the real-time temperature of power cables.
(5) Send the collected real-time temperature of power cables and the inversion calculation results to the data receiving server and power cable temperature monitoring server for comparative analysis.
(6) If the temperature of the power cable is abnormal, an alarm signal will be sent.

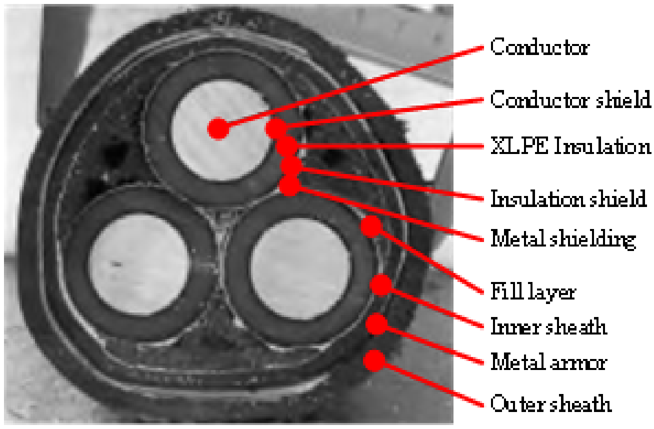
4 EXPERIMENTAL SIMULATION AND ANALYSIS

4.1 Sample Selection of Power Cables

When conducting temperature measurement experiments on power cables, YJV22 cross-linked polyethylene power cables were selected as the research object. Taking YJV22-8.7/15-3×400 mm^2 power cables as an example, the cross-sectional structure of the power cables is shown in Figure 6.

The conductor and metal shielding material of this type of power cable is copper, and the armor layer is steel strip armor. The main insulation layer includes the conductor shielding layer, XLPE insulation layer and insulation shielding layer.

Figure 6. Sample profile of power cables



The relevant parameter settings during the experiment are as follows.

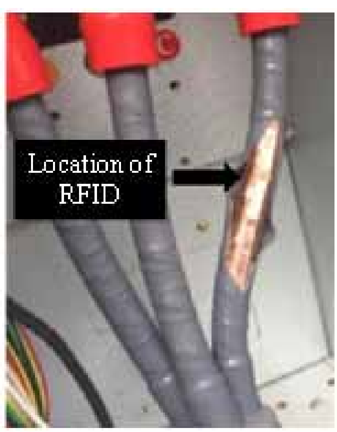
4.2 Simulation results of cable temperature

The installation position of RFID during the power cable calculation is shown in Figure 7.

Table 1. Parameters setting

Parameter	Value
Working frequency of RFID	860~960 MHz
Data transmission of RFID	5G mobile network
Tag capacity of RFID	1 M
Time delay of edge computing	3 ms
Number of concurrent connections	6

Figure 7. Installation location of RFID



The YJV22-8.7/15-3×400 mm^2 power cable is used for simulation testing based on MATLAB. When different currents are used, the temperature measurement results of the power cable are shown in Figure 8.

The temperature measurement errors using the YJV22-8.7/15-3×400 mm^2 power cable are shown in Table 2.

From the above experimental results, it can be seen that in the temperature measurement results obtained by using different currents, as the current continues to increase, the temperature of the power cable also increases, and the heating rate gradually slows down with the increase of current. Among the 10 sets of temperature measurement results obtained, the maximum error is 2.16% and the minimum is 0.93%.

The following is a temperature measurement experiment using a 100A current. In the case of using power cables with different sections, the temperature measurement results of power cables are shown in Figure 9.

Figure 8. Temperature measurement results of power cables under different currents

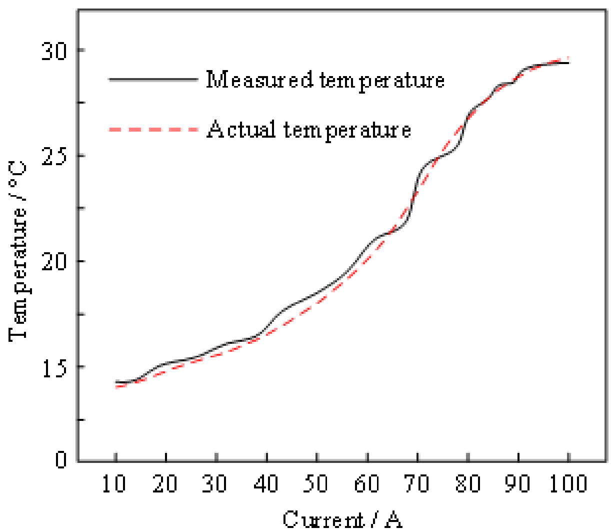


Table 2. Temperature measurement error of power cables under different currents

Current (A)	Actual temperature (°C)	Measured temperature (°C)	Error
10	18.1	18.5	2.16%
20	19.8	20.2	1.98%
30	20.4	20.8	1.92%
40	21.8	22.2	1.80%
50	25.6	26.1	1.92%
60	29.7	30.3	1.98%
70	35.4	36.1	1.94%
80	43.4	43.0	0.93%
90	45.6	46.5	1.94%
100	48.3	49.3	2.03%

The temperature measurement errors of power cables with different cross-sections during the experiment are shown in Table 3.

From the results obtained by using the same current to measure the temperature of power cables with different cross-sectional areas, it can be seen that the larger the cross-sectional area of the power cable is, the lower its temperature will be. Among the six sets of temperature measurement results obtained, the maximum error is 2.60% and the minimum is 0.89%.

4.3 Comparative analysis

In order to further verify the advantages of the proposed method for measuring power cable temperature based on edge computing and RFID, the following comparative experiments are carried out respectively between the proposed method and the Image Contour (Xie, J, Sun, T, Zhang, JQ, et al., 2022), the Infrared Particle filter (Salas, FMA, Orlande, HRB, Domingues, LAMC, et al., 2021) and the UHF RFID (Deng Zhifei, Bao Guanghai., 2021). The temperature measurement results and errors of different methods under different currents are shown in Figure 10 and Table 4.

The temperature measurement results and errors of different methods for different cross-section power cables are shown in Figure 11 and Table 5.

Figure 9. Temperature measurement results of power cables with different sectional areas

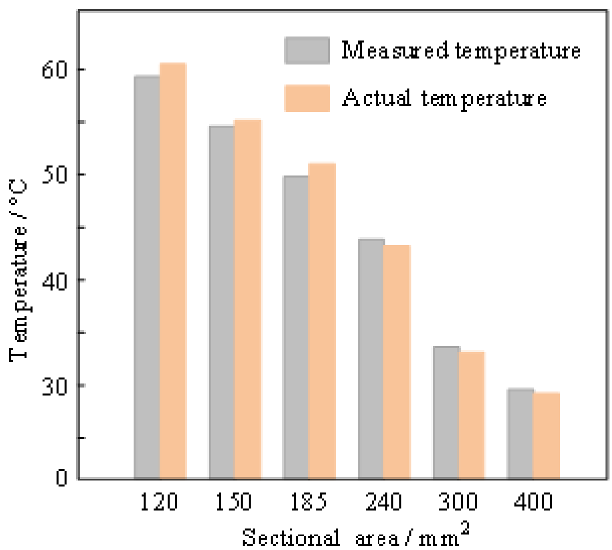


Table 3. Temperature measurement error of power cables with different sectional areas

Areas (mm^2)	Actual temperature (°C)	Measured temperature (°C)	Error
120	66.3	64.6	2.56%
150	64.4	62.8	2.48%
185	61.6	60.0	2.60%
240	56.3	56.8	0.89%
300	51.9	52.5	1.16%
400	48.6	49.3	1.44%

Figure 10. Temperature measurement results of power cables using different methods

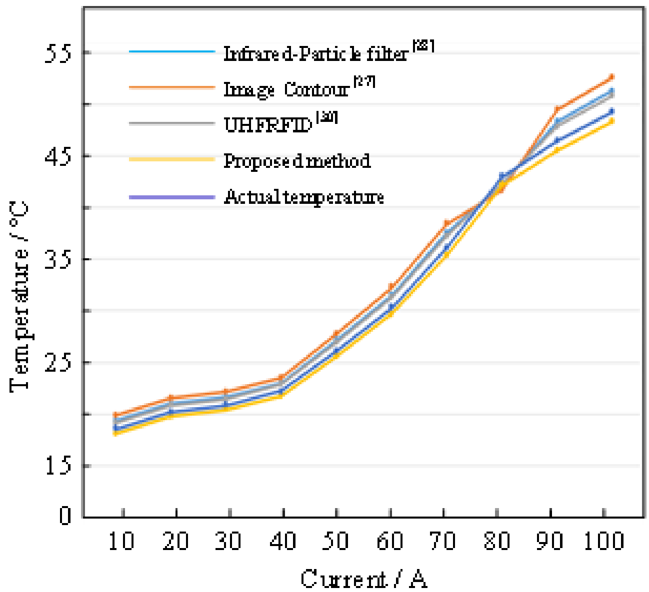


Table 4. Temperature measurement errors of different methods under different currents

Current (A)	Image Contour	Infrared-Particle filter	UHFRFID	Proposed method
10	7.15%	4.40%	3.42%	2.16%
20	6.55%	4.03%	3.13%	1.98%
30	6.36%	3.91%	3.04%	1.92%
40	5.96%	3.66%	2.85%	1.80%
50	6.33%	3.90%	3.03%	1.92%
60	6.55%	4.03%	3.13%	1.98%
70	6.41%	3.94%	3.06%	1.94%
80	6.08%	3.89%	3.47%	0.93%
90	6.40%	3.94%	3.06%	1.94%
100	6.71%	4.13%	3.20%	2.03%

Tables 4, 5 and Figures 10, 11 demonstrate the temperature measurement results of different methods under different experimental currents, as well as the temperature measurement results for power cables with different cross-sectional areas. It can be seen that the proposed method has the smallest temperature measurement error in the temperature measurement results obtained from experiments using power cables with different currents and cross-sectional areas.

4.4 Discussion

From the experimental analysis and comparison results, it can be seen that in 10 groups of experimental results obtained by using the power cable temperature measurement method based on edge computing and RFID, the maximum error is 2.16% and the minimum error is 0.93%. From the results obtained by

Figure 11. Temperature measurement results of power cables using different methods

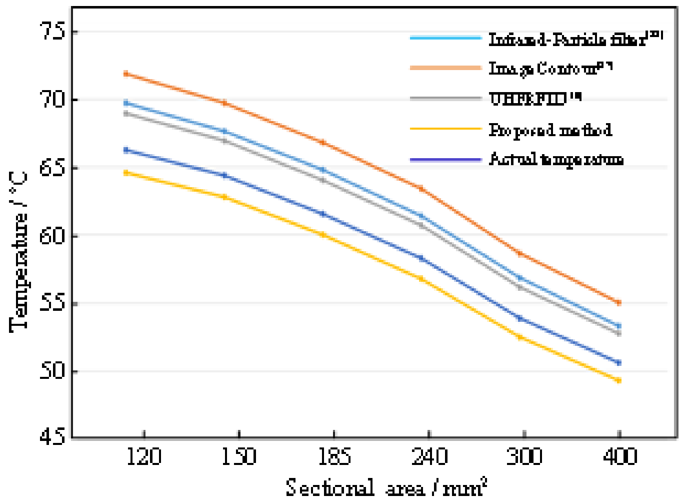


Table 5. Temperature measurement errors of different methods under different currents

Current (A)	Image Contour	Infrared-Particle filter	UHFRFID	Proposed method
120	8.48%	5.22%	4.05%	2.56%
150	8.21%	5.05%	3.93%	2.48%
185	8.59%	5.28%	4.10%	2.60%
240	8.81%	5.42%	4.21%	0.89%
300	8.92%	5.49%	4.26%	1.16%
400	8.84%	5.44%	4.23%	1.44%

using the same current to measure the temperature of power cables with different cross-sectional areas, it can be seen that the larger the cross-sectional area of the power cable is, the lower its temperature will be. Among the six sets of temperature measurement results obtained, the maximum error is 2.60% and the minimum error is 0.89%.

From the comparison, it can be seen that compared to the other three comparison methods, the maximum increase was 5.15% and 7.92%, while the minimum increase was 1.05% and 1.45%. This is because applying RFID to power cable identification can directly read temperature data by installing power cable labels on the power cable body, which is not easily affected by environmental factors in contactless operation and can improve the accuracy of temperature measurement results to a certain extent. In addition, by introducing the edge computing method of power cable temperature analysis integrating multiple parameters, and using the moving average algorithm with identified pulse interference to process the temperature data, the error of temperature measurement is greatly reduced.

The RFID tag used in the proposed method adopts a miniaturized sensor and a metal resistant design, suitable for completely enclosed cable operating environments. After implanting it inside the cable, it can achieve the intelligence, miniaturization, low cost, and low energy consumption without affecting the insulation performance of the cable. The shortcomings of traditional cable equipment temperature monitoring technology, such as non-contact, low accuracy, low integration, complex implementation, and high cost, are thus solved. At the same time, by monitoring the temperature of the cable, the real-time current carrying capacity of the cable can be calculated, which can timely and effectively prevent safety hazards during cable operation, providing technical support for the cable's safe operation.

However, in contrast to this advantage, the temperature measurement system implanted with cables needs to be placed at monitoring points, making it inconvenient to frequently replace the power module. In addition, in order to improve the working life of the system, we need to further reduce the power consumption of the system, including measures such as reducing the consumption of the front-end temperature detection system and increasing the efficiency of the rectifier circuit. In future, the in-depth research and the improvement in low power consumption and high efficiency are needed. The proposed method realizes the measurement of cable temperature based on RFID and edge computing, during which, the data collected by RFID tags need to be transmitted to the edge computing node for processing. This means that the accuracy of cable temperature calculation depends to some extent on the speed of communication, but there may be delays in data communication or slow data transmission rates, which may result in the inability to obtain real-time cable temperature data or delayed alarms.

5 CONCLUSION

Aimedat the problem of large error in traditional power cable temperature measurement methods, a power cable temperature measurement method based on edge computing and RFID is proposed. The proposed method has a minimum temperature measurement error of 0.93% for cables with the same cross-sectional area flowed through different currents. For cables with different cross-sectional areas flowed through the same current, the minimum temperature measurement error is as low as 0.89%. The experimental verification results indicate that building RFID electronic tags for power cables can utilize RF signals to achieve high-precision information data communication and recognition between devices. The use of modular and structured main programs can facilitate various operations on temperature RFID tags. Using edge computing algorithm to calculate the power cable temperature can effectively reduce the temperature measurement error. The focus of our work will be on the current carrying margin, the operating status and the impact of the laying method of power cable trenches on the temperature measurement of power cables. On this basis, we are committed to building a real-time monitoring and warning system that can be applicable to different cable working environments, achieving real-time prediction of cable temperature and improving the accuracy and timeliness of its warning.

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