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Investigation of AI-based Image Recognition Technology Combined with Sensor Technology for Power Grid Quality and Safety

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The power grid (PG) has the important task of transmitting, distributing, and supplying electricity, and is an indispensable infrastructure in modern society. Its quality and safety are directly related to productivity, economic development, and people's everyday lives. The current traditional power grid quality and safety monitoring rely mainly on manual inspection, which has the problems of poor efficiency and high labor costs. In order to enhance the quality and safety of the power grid, improve the efficiency of power grid monitoring, and reduce energy consumption, this study combines image recognition technology with sensor technology based on artificial intelligence (AI) to conduct in-depth research on the quality and safety of the power grid. This study uses images 1 and 2 of the sample PG route as infrared technology data, and performs noise reduction and feature extraction on the images, analyzing the role of sensor technology in PG job safety detection. To calculate the PG quality safety IR test results, this study sets the parameters to a total of 500 rounds every 50 times. The experimental results show that the node energy L of neural networks, genetic algorithms, and decision tree algorithms is totally consumed by the 600th iteration, while simulated annealing is completely consumed by the 550th iteration. This indicates that the combination of image recognition technology with sensor technology can efficiently monitor in real-time the quality and safety of the power grid, which helps to provide effective support for the safe and stable operation of the power grid.

Keywords: Image recognition technology, artificial intelligence, power grid system, sensor technology, power grid quality safety

1. INTRODUCTION

With the advancement of the global energy Internet strategy, China's communication and direct-current PG network construction is developing rapidly. The utilization of new technologies such as Image Recognition (IR) to improve power transmission inspection services has been an important issue faced by PG enterprises in recent years. Currently, traditional recognition technologies can no longer meet the development needs associated with PG quality safety. Defects and dangers hidden in complex environments cannot be accurately identified. Therefore, there is an urgent need for AI technology with self-learning ability that can identify and analyze the defects of overhead transmission lines and equipment, and abnormal and risk conditions in the channel environment.

The safety hazards of PG operation are associated with any abnormalities or undetected incidents that may occur during the use of equipment, which may lead to power supply system failures. When PG equipment malfunctions, due to various inherent defects, it not only poses a threat to people; it also reduces the service life and reliability of PG

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equipment. Many PG companies have begun to use various image acquisition devices such as drones, inspection robots, fixed cameras, and panoramic cameras to collect images of PG equipment. The traditional fault diagnosis method based on manual experience is influenced by factors such as the knowledge level and work experience of the fault diagnosis personnel. Also, the efficiency of fault diagnosis is closely related to the number of personnel and the number of hours that they have been required to work. Long-term manual identification work not only causes engineering personnel to experience psychological fatigue; it also reduces the accuracy and efficiency of fault identification, and is likely to harm engineering personnel.

With the mature development of artificial intelligence and the Internet of Things theory, image processing technology and sensor technology have made considerable progress. In the field of power grid quality and safety, image recognition technology can analyze and identify image data of power grid equipment, and sensor technology can achieve real-time monitoring of key parameters of the power grid. The combination of image recognition technology and sensor technology has important practical value and significance in terms of achieving comprehensive management of power grid quality and safety, timely discovering problems and taking corresponding measures, and ensuring the safe operation of the power grid.

This article combined the field of PG quality safety with sensor technology as the core and, based on AI IR technology, conducted in-depth research on the hidden danger detection and fault location technology of transmission line equipment and channel inspection objects, and combined it with prior knowledge. On the basis of application pattern research, the results of intelligent IR in testing the safety of PG quality were analyzed, and it was found that it could achieve rapid and accurate analysis of fault locations and defect types, thus enabling timely, effective, and targeted elimination of risks and hazards.

2. RELATED WORK

Sensor technology plays a vital role in power communication networks, especially given today's vigorous promotion of smart grid technology. Shuiqing Xu proposed a simultaneous diagnosis method for power switch open circuit faults and current sensor faults in grid connected three-level neutral point clamped inverters [1]. M. Vergin Raja Sarobin believed that the low-cost, low-power and collaborative features of wireless sensor networks were becoming a popular communication technology in smart grids [2]. The focus of Meysam Gheisarnejad's research was on developing future wireless sensors as communication for network physical microgrids under uncertain switching topologies [3]. Rajan Vinodray Vamja used an adaptive modified second-order generalized integrator-based estimator to derive the reactive components of the grid voltage angle and load current in the implementation of voltage-oriented control, thus greatly reducing the requirements of sensors [4]. Jie Wang found that the self-powered sensor could effectively convert the resistance change caused by the stretching or compression of hydrogel into the change of voltage output signal without an external power supply [5]. These studies have achieved good results, but communication cost is the main factor affecting the energy loss of sensors with limited resources.

Data shows that a power distribution network online monitoring based on image difference recognition has been studied and implemented. Bilal Al-Hayani believed that when wireless sensor networks uploaded high-quality images during PG operations, the challenging task was to achieve higher throughput and minimum bit error rate without affecting image quality [6]. Swalpa Kumar Roy found that hyperspectral image classification was widely used for the analysis of remote sensing images of PG operations. Hyperspectral images include images from different bands, and convolutional neural networks are one of the most commonly-used visual data processing methods based on deep learning [7]. Juan Mario Haut's recent research showed significant potential for generating high performance in hyperspectral image classification. However, a sufficient number of labeled samples were required to perform correctly and promote effectively. The high-dimensional nature of hyperspectral data makes it difficult to design classifiers based on PG [8]. Zhuangli Hu proposed a method for fast feature embedding using convolutional neural network convolutional architecture based on fast regions, and performed deep learning on massive transmission tower images [9]. Mou-Fa Guo found that after a power system fault, the current and voltage signals collected by the substation were identified using a convolutional neural network using a time-frequency energy matrix as the pixel matrix to achieve image similarity discrimination [10]. Hence, previous research indicates the continuous development and evolution of IR technology, and the combination of sensor technology and PG quality has become a hot research topic nowadays.

3. PROCESS EVALUATION OF AI IN IR TECHNOLOGY

3.1 General Steps of IR Technology

3.1.1 Image Preprocessing

AI IR technology obtains relevant information mainly through image preprocessing in practical applications, so it directly affects the recognition results and is a very important part of the entire process. Efficient image preprocessing can help the operation of IR systems, and ensure the accuracy of relevant images.

To comprehensively improve recognition efficiency during preprocessing work, methods such as adding noise, reducing noise, and removing fog can be used [11]. By preprocessing the image, the restoration of the image is achieved, ensuring the quality and clarity of the image restoration. In the field of PG quality and safety, it is necessary to use AI IR technology during the inspection of overhead transmission lines. By collecting images through one-click processing, the relevant image data can be obtained with the best solution. Sample 1 of the inspection image of overhead transmission lines is denoised, as shown in Figure 1.

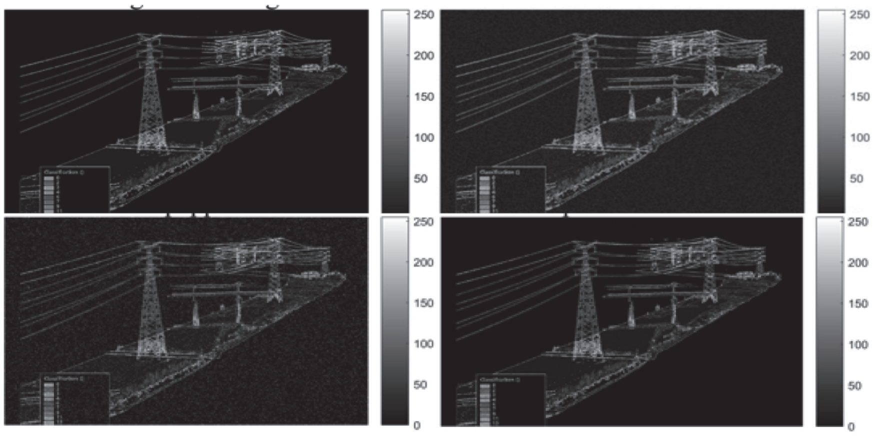

Figure 1 Image denoising process.

Table 1 Comparison of mean, standard deviation, and residual energy.

	Mean value	Standard deviation	Residual energy(%)
Original signal	0.382	15.4	99
Signal 1	0.386	17.2	95
Signal 2	0.376	15.7	92
Signal 3	0.374	13.2	85
Signal 4	0.379	12.9	87

Due to the granular nature of the image, there can be a decrease in contrast and masking of the image details. Therefore, it can be attributed to Poisson noise, as shown in Figure 1. The denoised image has a strong sense of granularity. Based on the above image, the original signal is extracted and compared with the mean, standard deviation, and residual energy of the four signals, as shown in Table 1.

Table 1 shows that the mean and error of signal 1 exceeded those of other signals, while the residual energy of denoised signal 1 was quite close to the original signal. It can be seen that signal 1 denoising was suitable for denoising stationary noise. The mean value of signal 2 after denoising decreased by 0.006 compared to the original signal, although the standard deviation improved. This was because signal 2 denoising filtered out too many non-stationary components including useful ones, which could reduce the fluctuation degree of the signal while basically retaining useful components, thus improving stability to some extent. Compared to the remaining energy of the original signal, signal 2 retained 92% after denoising, while signals 3 and 4 had significantly lower residual energy after denoising compared to the original signal.

The relationship between the noisy image and the original image satisfies the following formula:

$$g(n,m) = h(n,m) * f(n,m) + l(n,m) \tag{1}$$

In Formula (1), $h(n,m)$ is a point spread function, h is a system, and * is a convolution operation. Both sides of Formula (1) are simultaneously subjected to Fourier transform, resulting in the following formula:

$$G(n,m) = H(n,m) * F(n,m) + L(n,m) \tag{2}$$

Assuming there is no noise, the following can be obtained from Formula (2):

$$F(n,m) = \frac{G(n,m)}{H(n,m)} \tag{3}$$

In the formula, $H(n,m)$ represents an inverse filter and then performs an inverse Fourier transform on it. However, everything encountered in reality is noisy, so the resulting $F(n,m)$ can only be an estimate.

3.1.2 Image Feature Extraction

The image feature extraction work is analyzed, which requires two steps: extraction and filtering. The corresponding object image can contain multiple feature points, and each feature point corresponds to its corresponding feature subset [12]. Therefore, it is necessary to scientifically and reasonably select feature points in order to effectively and accurately recognize images. Color features are the first feature points to be captured. However, when capturing local feature points, the texture feature is the first captured feature point, as shown in Figure 2.

Figure 2 shows the results of FAST (Feature from Accelerated Segment Test) feature extraction, SURF (Speeded-Up Robust Features) feature extraction, and Harris corner detection for PG operation images. The Harris algorithm is used to extract point like features within the local small window of the image. If a point moves slightly in any direction, it can cause a significant change in the grayscale. The number of grayscale changes is defined as follows:

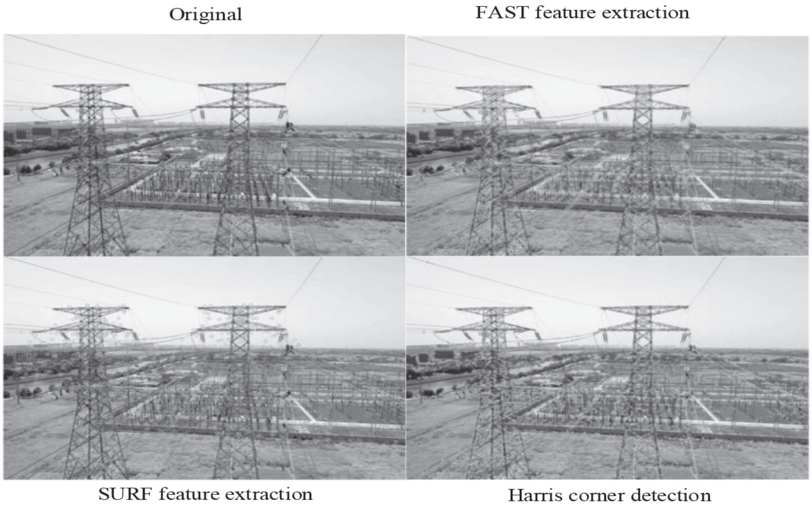

Figure 2 Image feature extraction process.

$$E(\Delta n, \Delta m) = \sum_{n,m} [I(n + \Delta n, m + \Delta m) - I(n, m)]^2 \quad (4)$$

Among them, $I(n, m)$ is the gray value of the pixel, and I_n and I_m are the partial derivative of image $I(n, m)$. Δn is the lateral displacement, and Δm is the longitudinal displacement.

$$E(\Delta n, \Delta m) = \sum_{n,m} [I(n, m) + \Delta n \cdot I_n + \Delta_m \cdot I_m - I(n, m)]^2 \quad (5)$$

It is assumed that the window function is as follows:

$$M = \sum_{n,m} w(n, m) \begin{pmatrix} I_m^2, I_m I_m \\ I_n I_m, I_m^2 \end{pmatrix} \quad (6)$$

The corner response function is as follows:

$$R = \det(M) - k \cdot trace^2(M) \quad (7)$$

where det (M) is a determinant of matrix M, and $trace^2(M)$ is the direct trace of matrix M. If R is greater than a threshold, there is only one corner.

3.1.3 Image Matching Classification

Image matching classification can organically combine the processing results of each step with the processing results, achieving efficient feature analysis of the same image. Regarding the PG, the use of AI IR technology can accurately match and classify the images according to the actual situation seen in the photos. This article will analyze the infrared test results of PG quality and safety in the last section.

3.2 Application Content of AI IR Technology

3.2.1 Online Video Monitoring

To better prevent unexpected events, cameras need to collect data efficiently and conduct online monitoring of the power system, providing accurate data about abnormal alarm conditions. In this way, staff can timely identify the causes of abnormal phenomena and take appropriate preventative measures. Although conventional cameras can monitor the occurrence of accidents, the accuracy of the cameras is not consistent, which can affect the accuracy of recognition. In addition, infrared cameras can also be used to capture a person's infrared profile. Specifically, such cameras need to combine the profile with contours and use AI IR technology to preprocess the obtained data, extract crowd features, and achieve online monitoring to determine the identity and actions of the crowd.

3.2.2 Automatic Image Detector

Firstly, to detect and calibrate the identified content, traditional instrument calibration methods rely mainly on manual completion, which has the problems of poor efficiency and cumbersome operation. The use of automatic image detectors for image area calibration can set specific area categories to improve the efficiency of manual calibration. Secondly, the indicator status is identified, and a general indicator status identification algorithm is studied to enable it to clearly distinguish non-standard indicator status from different manufacturers and technical indicators, and to read the results. Finally, the identification of alarm states is addressed by adopting an expandable alarm state identification algorithm that can flexibly add or remove alarm states in future development.

3.2.3 Video Compression

Video compression can reduce data storage. Specifically, in order to meet different data retrieval needs, it is necessary to synchronously store data and images, and take corresponding time point data snapshots to provide a basis for manual analysis. Firstly, the recordings must be classified in chronological order. Secondly, it is necessary to synchronize the data with the snapshot system. For abnormal alarms, when a certain identification value is inconsistent with the set alarm value, it is necessary to analyze different related data within the same identification value at the same time,

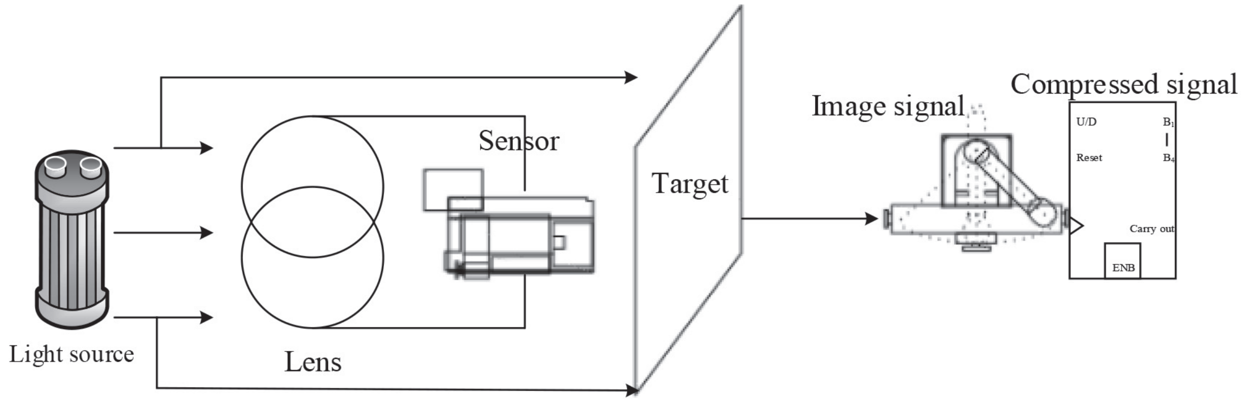

Figure 3 Simulation process of sensor technology.

Table 2 FOS under conditional classification.

Serial Number	Light wave parameters	Tested object
1	Phase modulation	Current
2	Intensity modulation	Density
3	Wavelength modulation	Displacement
4	Polarization modulation	Temperature
5	Frequency modulation	Volume

and synchronously display the abnormal conditions after the alarm value.

4. ROLE OF SENSOR TECHNOLOGY IN SAFETY DETECTION OF PG QUALITY

The safety information related to PG quality is obtained by various sensors, including various physical quantities, chemical quantities, and biomass [13]. The performance of the perceptron directly affects the quantity and quality of information obtained by the perception system, which is the basis for building a high-quality perception technology system. Among them, information processing mainly involves preprocessing the signal, post-processing the signal, and extracting and selecting features. The primary task of IR is to recognize and classify existing information. Therefore, perception technology must follow the information theory and system theory, which include many technologies and are adopted by many industries. Here, the Fiber Optic Sensor (FOS) technology and simulation process diagram are introduced, as shown in Figure 3.

4.1 Fiber Optic Sensing Technology

The light emitted by the light source is transmitted to the photosensitive unit via a photoconductive fiber, and the light generated by the external field strength in the photosensitive unit is then transmitted to the sensor through a light modulation mechanism [14–15]. The measured parameters of the sensor are converted into information such as amplitude, phase, and polarization, and finally processed by a microprocessor to obtain the measured parameters.

Sensors are the core of perception technology and can be divided into three different types according to their functions:

Sensing type: The sensor uses optical fibers as sensing elements to detect and modulate the light transmitted in the fibers. This type of sensor is obtained by demodulating the signal. Fiber optic not only plays a role in light conduction, but also acts as a sensitive component.

Light sensing: The sensor uses a light source as the transmission medium and senses changes in the measured parameters through a sensing method. In such a sensing system, the light source is only a guide. The light source is illuminated from a fiber optic sensing element, so the fiber optic sensing element would be adjusted by the measured object.

Pickup type fiber sensing: This uses optical fibers as probes to receive light emitted by the measured object or reflected and scattered by it. The most representative ones are fiber laser Doppler velocimeters and radiation type fiber optic thermometers. Table 2 shows the FOS under conditional classification.

According to the different parameters of the modulated light wave, it can be divided into phase modulated FOS, intensity modulated FOS, wavelength modulated FOS, polarization modulated FOS, and frequency modulated FOS. According to the properties of the tested object, the current, density, displacement, temperature, and volume of the fiber like structure can be classified. Extensive online research reveals that there are two types of FOS: interferometric and non-interferometric. Also, different physical quantities can be measured through phase, frequency, intensity, and polarization modulation methods [16]. Table 3 shows the specific data.

Table 3 Classification and measurement of FOS.

Sensor		Optical phenomenon	Tested	Optical fiber	Classification
Interference type	Phase	Magnetostriction	Current, Magnetic field	Single mode, multi-mode	a
Non-interference type	Frequency	Doppler effect	Light blocking board blocks the light path	Single mode	c
	Strength	Light blocking board blocks the light path	Temperature, Vibration pressure, Acceleration, Displacement	Multimode	b
	Polarization	Faraday effect	Current, Magnetic field	Single mode	a, b

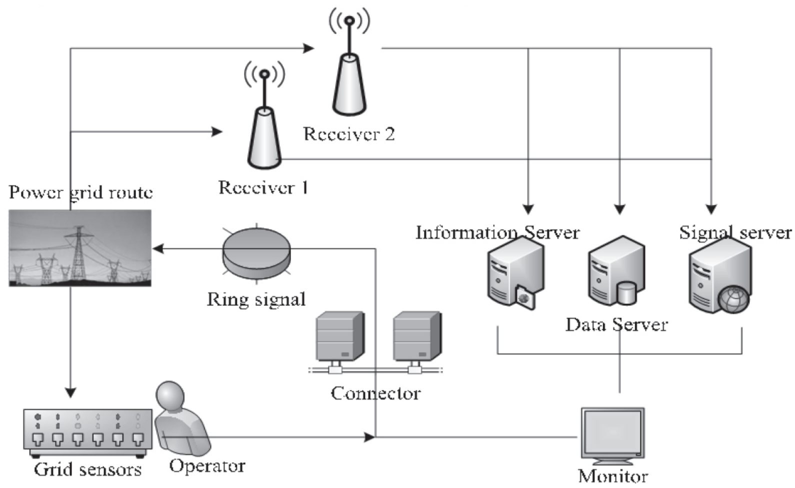

Figure 4 Structure of sensor technology in smart grid.

4.2 Application of Sensors

In the safety risk control system of PG quality engineering, the sensor transmits the sensed data to the server, and transmits other data such as the time and times of entering the safety risk source to the detector server via the signal source. It then transmits the captured images and other data to the image server, and then transmits the security information in the photos to the computer. Finally, IR technology is integrated into the platform. Figure 4 simulates the structural diagram of sensor technology in the smart grid.

At present, most security systems monitoring PG quality are based mainly on video surveillance, and are regularly inspected by security personnel. However, due to the limitations of the camera's exposure range and the inherent defects of manual inspection, not all safety hazards can be detected and eliminated. By noting phase changes in the spectrum and signal transformation, intrusion events can be detected and the location of the intrusion can be obtained. A mathematical model is constructed to reduce the false alarm rate of fiber optic line environmental characteristic parameters and alarm monitoring values. Distributed optical fiber vibration sensing technology is commonly used in unattended substations, transmission towers, fossil-fuel power station, fans and other key areas, which improves the monitoring from simple physical isolation to intelligent mode, thus achieving the early warning and monitoring of illegal intrusion, and improving the effectiveness of perimeter intrusion prevention. At the same time, it can also monitor the vibration of the upper section of the high-voltage cable and display alarm information based on the monitored data, thereby locating the fault point to improve the management's ability to handle emergency situations.

The transmission line is the lifeline of the entire PG system. Disturbance by external factors could lead to large-scale power outages and even the collapse of the entire power system. Human vandalism, environmental pollution, and natural disasters have become challenges that affect the safety of PG systems, such as the inability to passively locate wires over long distances. By laying a single core fiber optic cable along the transmission line, real-time monitoring of disturbances to contact cables, junction boxes, and optical cores on the transmission line can be carried out, and these incidents can be collected and analyzed to determine the location, type, and strength of the disturbances, thereby helping line maintenance personnel to timely detect any damage to the transmission line. This effectively solves the problem of early warning and monitoring of line damage, providing warning, intelligent analysis, and auxiliary decision-making support for safety personnel.

Most electrical equipment such as cables, switchgear, and transformers in the PG are located in environments with strong magnetic fields, high voltages, and high currents [17–18]. Conventional electron temperature sensors cannot work in strong magnetic fields and are not appropriate for flammable, explosive and corrosive environments. The measurement of temperature distribution using point type temperature sensor also faces difficulties in terms of installation, wiring

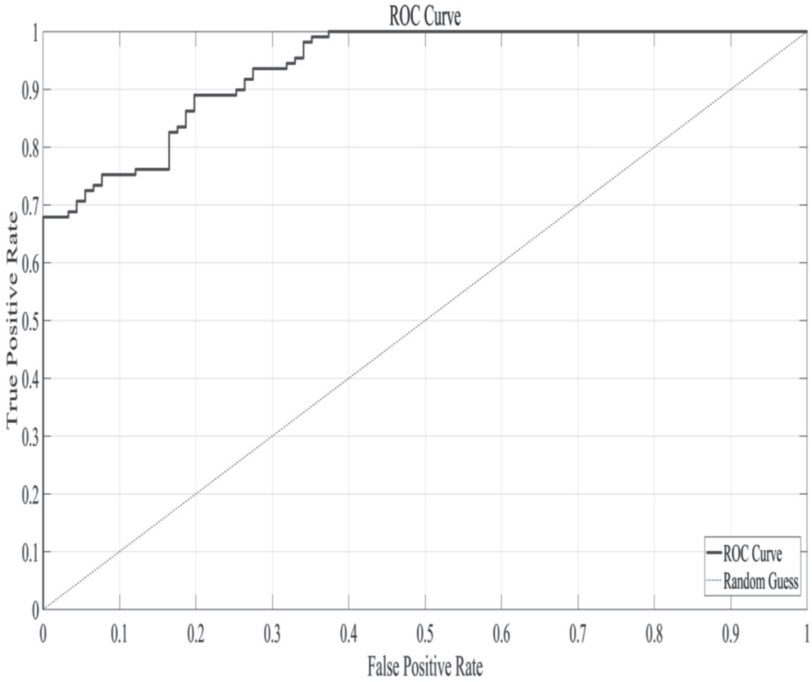

Figure 5 ROC curve.

and maintenance. Distributed fiber optic temperature-sensing technology can achieve distributed measurement of temperature fields continuously distributed along the fiber optic, and can achieve high accuracy, high spatial resolution, and low error. It can be used in a variety of different environments to solve the measurement problem that other sensors cannot achieve in certain environments.

5. EVALUATION OF THE RESULTS OF IR TESTING FOR PG QUALITY SAFETY

5.1 Judgment Criteria for IR

Accurately removing all sample sizes from the detection time is currently a commonly used method to determine the overall accuracy of the model. However, due to the limited amount of information available, this method cannot fully indicate the overall performance of the model. Hence, a fuzzy matrix based on fuzzy set theory is used, where the diagonal represents the consistency between the predicted values of the model and the theoretical values. Therefore, the correct result can be obtained by dividing the number of test images by the diagonal. The larger the value on the diagonal, the darker the color of the chaotic implicit matrix, indicating that the model has better prediction performance in this regard; the other dimension is the error, where the smaller the value and the lighter the color, the greater is the accuracy of the model.

Accuracy A refers to the proportion of TP (True Positives) in the recognized image, which is the same as the proportion in the recognized image.

$$A = \frac{TP + TN}{TP + FP + FN + TN} \tag{8}$$

where TP refers to the correct recognition of positive samples as positive samples; TN (True Negatives) means that negative samples are correctly identified as negative samples; FP (False Positives) means that negative samples are incorrectly identified as positive samples; FN (False Negatives) means that positive samples are mistakenly identified as negative samples; N represents the number of samples in the test set [19], and Figure 5 shows the receiver operating characteristic curve (ROC) curve:

According to Figure 5, AUC (Area Under Curve) represents the area below the ROC curve. The closer the AUC value is to 1, the higher is the AUC value. The AUC value is a probability value. A positive sample and a negative sample are randomly selected. The current classification algorithm is based on the calculated value, and the probability of placing this positive sample before the negative sample is the AUC value. The larger the AUC value, the easier it is to prioritize positive samples over negative samples, which means better classification of positive samples. AUC is calculated according to the following formula:

$$AUC = \frac{1}{2}\sum_{i=1}^{m-1}(x_{i+1} - x_i) \cdot (y_i + y_{i+1}) \tag{9}$$

The horizontal axis of ROC is the false positive rate. FPR (False Positive Rate)=FP/(FP+TN) represents the probability of being incorrectly predicted as a positive sample in all negative samples, which is the false alarm rate. The vertical axis of ROC is the TPR (True Positive Rate)=TP/(TP+FN), which represents the probability of correct prediction in all positive samples. The diagonal coordinates of the accuracy ROC curve correspond to real-time estimation.

5.2 Smart Grid Sensor Routing Evaluation

Because of the large number of sensor nodes, limited network resources, and complex routing problems between the PG

Table 4 Performance analysis of various algorithms.

Algorithm	Energy-saving	Real-time	Accuracy	Mobility
Neural network	5	8	6	2
Genetic algorithm	4	4	8	5
Decision tree	3	4	8	9
Simulated annealing	6	5	4	7

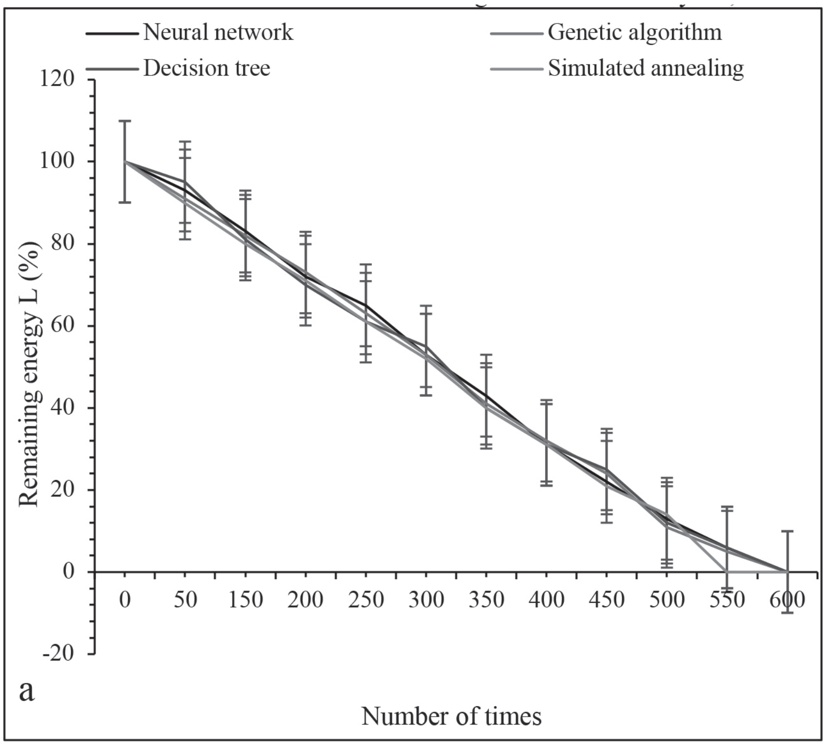

Figure 6 Value of residual energy L of the sensor.

route system and routing devices, the networking technology of PG quality monitoring network based on routing devices was studied and applied to PG quality monitoring [20]. In the networking process, the optimal route refers to a data transmission route that meets specific requirements. In wireless sensor networks, nodes are often limited by energy, quantity and information acquisition. The networking protocols in wireless sensor networks can generally be divided into two categories: One is plane routing; the other is cluster routing. Their scalability is poor, and the dynamic maintenance of routing needs complex control. In the clustering routing protocol, node positions are not equal, and this divides the entire network into multiple different clusters, each with a cluster head. The cluster head summarizes, processes, and forwards the collected data, and adopts clustering routing algorithms to effectively reduce the communication load of the network, thereby effectively reducing the overall energy consumption of the network. Here, the commonly-used neural networks, genetic algorithms, decision trees, and simulated annealing in AI algorithms are used for sensor network analysis. The performance range of the algorithm is 1–10. The higher the value, the better is the performance of the algorithm, as shown in Table 4.

As shown in Table 4, the real-time performance of neural networks in sensor networks was the best of the four algorithms, but their mobility was the worst; the accuracy of the genetic algorithm in sensor networks was excellent, but its real-time performance was poor; the mobility of decision trees in sensor networks, but their energy efficiency was poor; simulated annealing had the best energy-saving performance in sensor networks, but its accuracy was poor. It is not difficult to see that various network algorithms have their own advantages and characteristics, so no optimal algorithm can be applied to every situation. In addition, some of the current algorithms carried out only theoretical simulation and did not align very well with the actual situation. Moreover, the energy consumption, efficiency and reliability of nodes in the PG patrol wireless sensor network should be given priority; hence, the existing networking protocols could not be applied to the PG patrol wireless sensor network.

The value of residual energy L of the sensor was determined by the average density of nodes in the entire sensing monitoring area. Among them, every 50 times was a round, with a total of 500 times being the limit. Based on the deployment of sensor nodes in the intelligent sensor inspection system of the PG operating system, the residual energy L values of sensors under four AI related algorithms were analyzed, as shown in Figure 6.

Figure 6 shows the curve of the average energy consumption of nodes for four AI-related algorithms as a function of the number of network runs. The node energy L of neural networks, genetic algorithms, and decision tree algorithms was consumed to 0 at the 600th time, while simulated annealing was consumed completely at the 550th time. The remaining energy L showed a downward trend. At the 200th time, the remaining energy L of simulated annealing appeared higher than other algorithms for the first time. At the 500th time, the remaining energy L appeared higher than other algorithms for the second time. The trend of curve changes indicates that the nodes in the simulation algorithm consumed more energy than other algorithms. It could be speculated that if the energy consumption of a certain node suddenly decreased, its energy would quickly deplete and eventually the node would malfunction, and may even cause the entire network to collapse.

6. CONCLUSIONS

IR technology is a hot topic in the field of image research. The smart grid provides users with stable, reliable, safe, flexible, and high-quality electricity. To ensure the safety and reliability of the smart grid, power information security technology is necessary. By examining the IR process, this study reviewed image feature extraction methods and IR algorithms, and summarized the research direction of IR. In the smart grid, the application of sensor technology is becoming increasingly widespread. The PG business is also constantly expanding, and information security is becoming increasingly important. This study analyzed the outcome of combining sensors and PG quality safety, studied the trend of ROC curve changes using IR criteria, and discussed the variation of average energy consumption by node sensors during network operation times using four algorithms as examples.

DECLARATION OF CONFLICTING INTERESTS

The authors declare that there is no conflict of interest regarding the publication of this work.

DATA AVAILABILITY STATEMENT

The data used in this paper can be obtained by emailing the authors.

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