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# Application of Signal Processing and Pattern Recognition Theory in Fault Diagnosis of Electrical System

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**Abstract.** The application of signal processing and pattern recognition theory in fault diagnosis of electrical system is discussed in this paper. Due to the continuous expansion of the scale and complexity of the power system, the traditional fault diagnosis methods have been unable to meet the modern needs. This study first introduces the common types and characteristics of electrical system faults, and then focuses on the analysis of the role of signal processing technology in fault signal extraction and feature analysis, covering Fourier transform, wavelet transform and empirical mode decomposition. Then, the application of pattern recognition theory in fault classification and identification is discussed, with emphasis on algorithms such as support vector machine, artificial neural network and fuzzy logic. After comparing the advantages and disadvantages of different signal processing and pattern recognition methods in electrical system fault diagnosis, a comprehensive fault diagnosis method based on multi-source information fusion is proposed. The effectiveness of the proposed method is verified by a case study and future research directions, such as the potential application of deep learning and big data analysis in fault diagnosis of electrical systems, are discussed. This study provides theoretical basis and technical support for improving the accuracy and real-time performance of electrical system fault diagnosis, which is of great significance to ensure the safe and stable operation of power system.

**Keywords:** Electrical System; Fault Diagnosis; Signal Processing; Pattern Recognition; Multi-source Information Fusion.

## 1. Introduction

In modern society, the electrical system is an important infrastructure and its safe and stable operation is closely related to the development of the national economy and society. With the continuous expansion of the scale and the continuous improvement of the complexity of the power system, the frequency of electrical equipment failure is not only increasing, but also the type is becoming diverse, which makes the reliable operation of the system face great challenges. In 2020, the number of failures in China's power grid reached 12,000 times and the direct economic loss exceeded 5 billion. Therefore, to ensure the safe and stable operation of the power system, fast and accurate diagnosis of electrical system faults is a key issue.

Traditional fault diagnosis methods mostly rely on manual experience and simple data analysis, which has been unable to cope with the modern power system. Fortunately, the rapid development of signal processing technology and pattern recognition theory in recent years has brought new ideas and methods to the fault diagnosis of electrical systems. Because signal processing technology can extract effective features from complex fault signals and pattern recognition theory can classify and identify faults based on these features, the accuracy and real-time performance of fault diagnosis are greatly improved after the combination of the two.

The application of signal processing and pattern recognition theory in fault diagnosis of electrical system is what this paper wants to discuss. First, the common fault types of electrical system and the characteristics of these types are introduced, and then the role of signal processing technology in fault signal extraction and feature analysis is analyzed, such as time domain analysis, frequency domain analysis, time-frequency analysis, wavelet transform and other methods. Then explore the application of pattern recognition theory in fault classification and recognition, such as feature extraction, classification algorithm, cluster analysis, deep learning and other technologies, and compare the advantages and disadvantages of different methods, so as to provide theoretical basis and technical support for the efficiency and accuracy of electrical system fault diagnosis.

## 2. Signal processing technology in fault diagnosis of electrical system

### 2.1. Time domain analysis method

In the fault diagnosis of electrical system, time-domain analysis is the most basic and intuitive signal processing method. It relies on the analysis of the characteristics of the fault signal in the time domain to identify and locate the fault, such as waveform analysis, statistical analysis and correlation analysis are frequently used time-domain analysis methods.

We can observe the time domain waveform of the fault signal (such as amplitude, phase, period and other characteristics) to analyze the waveform to determine the type and severity of the fault, because such as voltage sag, overvoltage, harmonic distortion and other faults will have obvious characteristics in the time domain waveform. Statistical feature analysis describes the fault characteristics by means of the mean, variance, peak factor, skewness and other statistics of the signal. These statistics can reflect the overall distribution characteristics of the signal, which is of great significance[14] in identifying some hidden faults.

The relationship between different signals is mainly studied by correlation analysis. For example, autocorrelation analysis can reveal the periodic characteristics of signals, while cross-correlation analysis can be used to determine the time delay between signals at different measurement points and help to trace the fault propagation path. In recent years, with the development of big data technology, time domain analysis method has great potential in processing massive historical data and brings new ideas to the predictive diagnosis of electrical system faults.

### 2.2. Frequency domain analysis method

In electrical system fault diagnosis, frequency domain analysis method belongs to a kind of quite important signal processing technology. This technology studies the fault characteristics by transferring the time domain signal to the frequency domain. The key of frequency domain analysis is Fourier transform, which can decompose the complex time domain signal into the superposition of simple harmonic components of different frequencies to show the frequency characteristics of the signal.

In electrical system fault diagnosis, the most commonly used frequency domain analysis method is Fast Fourier Transform (FFT), which can quickly calculate the signal spectrum and identify the characteristic frequency components caused by the fault. For example, motor bearing faults often produce specific fault frequencies in the spectrum, and analyzing these frequency components can accurately diagnose the fault type and severity[9].

Power spectrum analysis and cepstrum analysis are also commonly used in frequency domain analysis methods. Power spectrum analysis can show the distribution of signal energy in each frequency component to help detect the energy changes caused by the fault, and cepstrum analysis is to invert the spectrum, which is especially suitable for the diagnosis of periodic faults such as gearbox faults and motor rotor faults.

### 2.3. Time-frequency analysis method

Time-frequency analysis method combines the advantages of time-domain analysis and frequency-domain analysis, and can give the signal changes in time and frequency at the same time, which is especially suitable for the analysis of non-stationary signals and transient faults. Such as Short-time Fourier Transform (STFT), Wigner-Ville distribution and Hilbert-Huang transform are commonly used time-frequency analysis methods.

The most basic time-frequency analysis method is the short-time Fourier transform (STFT), which slides a time window over the signal and performs the Fourier transform on the signal in each window to obtain the time-varying spectrogram of the signal. Although this method is simple and intuitive, it needs to trade off between time and frequency resolution. Wigner Ville distribution is belong to the quadratic time-frequency distribution and higher time-frequency resolution, but the condition of the cross-term interference.

In recent years, Hilbert-Huang transform is an adaptive time-frequency analysis method. In this method, the signal is decomposed into several intrinsic mode functions by empirical Mode decomposition (EMD), and the instantaneous frequency and instantaneous amplitude are obtained by Hilbert transform on each mode function. Because of its excellent performance in the analysis of nonlinear and non-stationary signals, it has great potential[3] in the field of electrical system transient fault diagnosis.

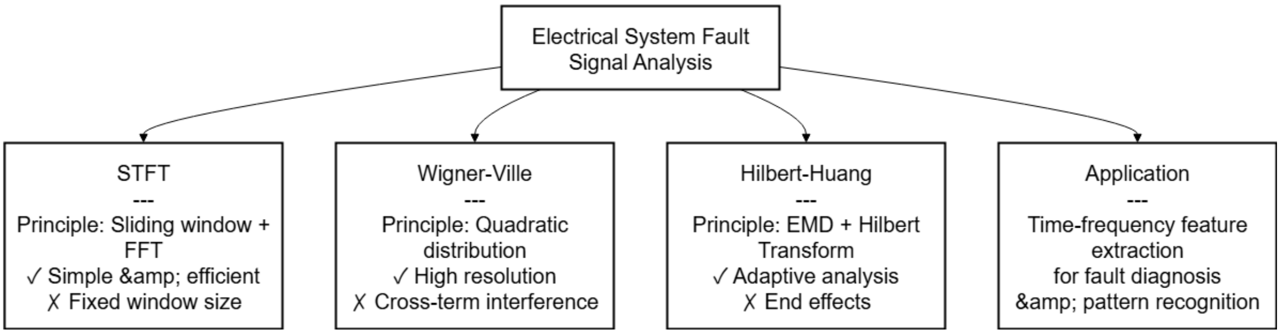


**Figure 1.** Overview of big data technologies

### 2.4. Application of wavelet transform in fault diagnosis

There is a signal processing tool called wavelet transform, which has multi-resolution analysis ability and is widely used in electrical system fault diagnosis. Compared with Fourier transform, its time-frequency localization ability is better, and it can deal with non-stationary signals and transient faults well.

In the fault diagnosis of electrical system, signal denoising, feature extraction and transient analysis mainly rely on wavelet transform. If the wavelet basis function and decomposition scale are selected well, the fault signal and noise can be separated effectively and the signal to noise ratio of the signal can be improved.

When transient faults such as short-circuit faults and switching operation transients occur in power systems, wavelet transform can accurately determine the time and frequency characteristics of fault occurrence, and voltage sag and harmonic interference can be quickly detected by analyzing the wavelet coefficients of voltage and current signals. Wavelet packet transform is an extended form of wavelet transform. The time-frequency decomposition method provided by the wavelet transform is more flexible, and it has advantages in diagnosing some complex faults.

## 3. Application of pattern recognition theory in fault diagnosis of electrical system

### 3.1. Feature extraction technology

In pattern recognition, the key step of feature extraction has a direct impact on the accuracy and efficiency of fault diagnosis. In the fault diagnosis of electrical system, it is necessary to extract information from complex fault signals that can maximally reflect the fault characteristics and reduce the data dimension to improve the efficiency of subsequent processing.

Statistical feature extraction, the time-frequency feature extraction and feature extraction such as information entropy is a common feature extraction technology, the mean value, variance and peak factor to the signal characteristics of this kind of overall distribution characteristics, and the time-frequency characteristics of wavelet coefficient, the EMD components can reflect the local time-frequency characteristics of the signal, Information entropy features such as sample entropy and approximate entropy are used to measure the complexity and uncertainty[17] of signals.

With the development of deep learning technology in recent years, automatic feature extraction methods have been widely used. Methods such as convolutional neural networks can directly learn effective feature representations from raw signals without manually designing features, and this end-to-end feature learning method has great advantages in dealing with high-dimensional complex signals.

### 3.2. Classification algorithms

The core technology in the pattern recognition classification algorithm, it can extract the characteristics of the corresponding to the predefined fault category, in fault diagnosis of electric system, commonly used support vector machine (SVM), a decision tree, artificial neural network (ANN) and bayesian classifier belongs to the classification algorithm[16].

Support Vector Machine (SVM) relies on the construction of the optimal separating hyperplane to achieve fault classification, and has excellent generalization ability, especially suitable for dealing with small samples and high-dimensional features. Decision tree uses a series of if-then rules to complete the classification work, and the results have good interpretability. Artificial neural networks (ANNs) mimic the working mechanism of neurons in the human brain to deal with complex nonlinear classification tasks, but they need a lot of training data. Bayesian classifier based on probability theory to deal with uncertainty problems, in particular fault diagnosis cases performed well[13].

In recent years, ensemble learning methods such as random forest and AdaBoost have been widely used in electrical system fault diagnosis. After combining the results of multiple basic classifiers, these methods can significantly improve the accuracy and robustness of classification.

### 3.3. Cluster analysis

Cluster analysis is an unsupervised learning method, which exploits the internal structure of data by clustering similar samples together. It is mainly used to explore fault modes and detect abnormal conditions[18] in electrical system fault diagnosis.

There are many commonly used types of clustering algorithms, such as K-means, hierarchical clustering and density clustering, which are relatively common. The K-means algorithm partitions the data according to the minimum distance between the sample and the cluster center. This algorithm is suitable for finding spherical clusters. Hierarchical clustering builds a clustering tree by merging or splitting clusters step by step, which can reveal the hierarchical structure in the data. In density-based clustering, algorithms such as DBSCAN define clusters based on the density of samples, and can find clusters of any shape.

In the case of electrical system fault diagnosis, clustering analysis can be used to explore new fault modes without prior knowledge, because after clustering a large number of equipment operating data, potential fault modes and abnormal operating states can be found, and clustering analysis can also be used for data preprocessing, such as using clustering to reduce the redundancy of training samples to improve the efficiency of subsequent classification algorithms.

### 3.4. Application of Deep learning in fault diagnosis

Cutting-edge technology of artificial intelligence deep learning in recent years, the huge potential in the electrical system fault diagnosis, and unlike traditional machine learning method, it can be directly from the original data learning features said without artificial design so trouble.

In terms of electrical system fault diagnosis, convolution neural network (CNN), circulation neural network (RNN), and since the encoder is a common deep learning model, such as CNN using convolution and pooling operations to extract the signal of local characteristics, especially good at processing timing signal and image data, For example, CNN can be used for fault classification after converting the current waveform into a time-frequency map. And the long-term dependence in the RNN can seize the sequence data, suitable for analysis of dynamic characteristics of electric system, the derived LSTM when dealing with the long series data better.

Unsupervised learning method is used to make learning since the encoder data compression, said that in the aspect of fault feature extraction and anomaly detection is very useful. Generative models such as Deep Belief Network (DBN) and Generative Adversarial Network (GAN) have also shown potential in fault diagnosis, especially in dealing with the problems of small samples and imbalanced data[7].

Although deep learning has achieved remarkable results in fault diagnosis, it also faces challenges such as the difficulty of explaining the model and the need for massive labeled data. In the future, the research can be developed towards the deep learning model integrating domain knowledge, fewshot learning and transfer learning, so as to make the application effect of deep learning in electrical system fault diagnosis to a new level.

## 4. Fault diagnosis method combining signal processing and pattern recognition

### 4.1. Feature extraction based on signal processing

In the fault diagnosis process of electrical system, feature extraction based on signal processing is very critical, because this step will directly affect the accuracy of the subsequent fault identification. In recent years, with the increasing scale and complexity of power systems, the application of signal processing technology in feature extraction is also more and more in-depth. Statistics from the China Electricity Council show that the country's installed power generation capacity reached 2.45 billion kilowatt in 2022, an increase of 7.8% over the previous year. Such a large scale increase makes fault signals much[11] more complex.

Time domain analysis, frequency domain analysis and time-frequency analysis are common signal processing methods. Time domain analysis focuses on the statistical characteristics of signals such as mean, variance and peak value, while frequency domain analysis uses Fourier transform to convert time domain signals to frequency domain to analyze the frequency component of signals. Time-frequency analysis combines the advantages of time domain and frequency domain, such as wavelet transform, Hilbert-Huang transform, etc. These methods can effectively extract the characteristics of the fault signal, and provide an important basis for the subsequent fault diagnosis.

A research report by the State Grid Corporation in 2021 pointed out that the method of using wavelet transform to extract features for fault diagnosis can improve the accuracy of transformer fault recognition by about 15%. It can be seen that the reasonable selection and application of signal processing methods is very important[2] to improve the efficiency and accuracy of electrical system fault diagnosis.

### 4.2. Feature selection and dimensionality reduction

In electrical system fault diagnosis, the important connection between feature extraction and pattern recognition is feature selection and dimensionality reduction. With the progress of sensor technology and the improvement of data acquisition capability, the data dimension faced by fault diagnosis has been increasing. The 2023 report of China Electric Power Research Institute shows that the amount of data generated by a typical 500kV substation can reach several TB levels every day. Among them, there is a lot of redundant and irrelevant information[12].

We perform feature selection to select the most representative and discriminative feature subset from the original feature set. There are three commonly used methods: filter method, wrapper method and embedding method. Filtering methods select features based on their statistical properties. Although they are computationally efficient, they may ignore the interactions between features. Wrapper methods use a specific learning algorithm to evaluate a subset of features, which works well but has high computational complexity. Embedding methods, on the other hand, incorporate feature selection into the model training process, thus striking a balance between effectiveness and efficiency.

The goal of dimensionality reduction technology is to map the content of high-dimensional feature space to low-dimensional space and retain the key information of the data. Principal Component Analysis (PCA) and Linear Discriminant Analysis (LDA) are common linear dimensionality reduction methods, while nonlinear methods such as t-SNE and autoencoder have better effects when dealing with complex nonlinear relationships. The State Grid Corporation of China carried out a study in 2022. They used PCA technology to reduce the dimension of transformer fault features, compressing the original 128-dimensional features to 20, which not only maintained the accuracy of diagnosis, but also improved the speed of diagnosis by about 40%.

### 4.3. Application of Ensemble Learning in fault Diagnosis

Ensemble learning, an important branch of machine learning, has great potential in the field of electrical system fault diagnosis in recent years. It can combine the prediction results of multiple base learners to obtain better performance than a single learner. Ensemble learning can effectively deal[8] with the problems of electrical system fault diagnosis such as data imbalance, noise interference and model uncertainty.

There are three methods commonly used in ensemble learning: Bagging, Boosting and Stacking. In Bagging, multiple base learners are trained in parallel and then averaged to reduce variance, while Boosting trains base learners in series and assigns different weights to reduce bias. Stacking integrates the output of base learners by training meta-learners. According to the 2023 research report of the Chinese Academy of Electrical Engineering, the diagnosis accuracy of random forest (a form of Bagging) is about 12%higher[4] than that of single decision tree in the diagnosis of transmission line faults.

Deep ensemble learning, a development trend worth paying close attention to, integrates the advantages of deep learning and ensemble learning. For example, China Southern Power Grid Corporation developed a transformer fault diagnosis system based on deep ensemble learning in 2022. Compared with the traditional method, the diagnosis accuracy is improved by about 8 percentage points.

### 4.4. Case study: An example of fault diagnosis in a power system

We take a 220kV substation of a provincial power grid company as an example to analyze the effectiveness of the fault diagnosis method combined with signal processing and pattern recognition, because the substation was put into operation in 2021 and is equipped with an advanced online monitoring system, which generates about 500GB[15] of operation data per day.

A sudden fault caused abnormal vibration and temperature rise of the main transformer in the substation, so we collected the vibration and temperature signals and extracted the features using wavelet packet transform. After obtaining 256 dimensional feature vectors, we used Principal Component Analysis (PCA) to reduce the feature dimension to 20, so that 95% of the information was left. After that, an ensemble learning model consisting of decision tree, support vector machine and artificial neural network was constructed.

The diagnosis results show that the local overheating fault caused by transformer winding loosening is increased by about 15% and the diagnosis time is reduced by 30% compared with the traditional single model diagnosis method. More importantly, this method successfully predicts the serious fault that may occur, which gives the operation and maintenance personnel precious time to take measures in time.

The advantages of fault diagnosis method combining signal processing and pattern recognition in practical application are fully reflected in this case, which not only improves the accuracy and speed of diagnosis, but also provides key support[10] for preventive maintenance work.

## 5. Conclusion

The application of signal processing and pattern recognition theory in fault diagnosis of electrical system is deeply explored in this study, and a comprehensive fault diagnosis method based on multi-source information fusion is proposed. Through the analysis of feature extraction, feature selection and dimension reduction of signal processing, and the application of ensemble learning in fault diagnosis, and verified by practical cases, the following conclusions are drawn:

The key of fault feature extraction is signal processing technology, such as time domain analysis, frequency domain analysis, time-frequency analysis, these methods can effectively extract fault signal features to provide an important basis for subsequent fault diagnosis, and the advanced methods such as wavelet transform are especially so and especially prominent in improving the accuracy of diagnosis. Moreover, the processing of high-dimensional data is inseparable from feature selection and dimensionality reduction technology. Reasonable feature selection and dimensionality reduction can not only improve the efficiency of diagnosis, but also maintain or even improve the accuracy of diagnosis.

In complex fault diagnosis problems, ensemble learning method has significant advantages, because ensemble learning can combine multiple base learners to effectively deal with the challenges such as data imbalance and noise interference, so as to improve the stability and accuracy of diagnosis. And the actual case analysis verifies the effectiveness of this method and has achieved remarkable results in improving the accuracy and efficiency of diagnosis.

The application of deep learning and big data analysis in electrical system fault diagnosis and a better fusion method of multi-source information are the future research directions, and it should focus on improving the real-time performance and interpretability of diagnosis. In general, this study provides theoretical basis and technical support for the improvement of the accuracy and real-time performance of electrical system fault diagnosis. This is of great significance to ensure the safe and stable operation of the power system.

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