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An overview of machine learning applications in elastic power systems

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Abstract. With the development of economy and the access of renewable energy, the power system is facing new challenges. Machine learning provides a new way for the intelligent management of power system through big data analysis, pattern recognition and predictive modeling. This paper reviews the application of machine learning technology in elastic power system, including load forecasting, transient stability assessment, intelligent scheduling and fault diagnosis. Machine learning will better improve the stability, reliability and economic benefit of the system. Future research will focus on algorithm optimization, model adaptability improvement and integration with traditional power system knowledge to promote the development of power system to a higher level of intelligence and automation.

Keywords: Machine learning, elastic power system, load forecasting, transient stability evaluation.

1. Introduction

With the rapid development of economy, the demand for electricity continues to rise, which puts forward higher requirements for the power supply capacity, stability and reliability of the power system. The transformation of the global energy structure, especially the large-scale access of renewable energy, makes the operation of the power system complex and changeable, and it is particularly important to establish a flexible power system that can adapt to load fluctuations, resist external interference and quickly restore power supply. The elastic power system can not only ensure the continuity and stability of power supply, but also respond quickly and resume normal operation in emergencies such as natural disasters and cyber attacks, so as to ensure the normal operation of social economy and the basic needs of people's lives.

With the rapid development of artificial intelligence technology, machine learning has shown great application potential in various fields. Especially in the field of power system, machine learning has begun to change the traditional way of electricity production, transmission and distribution. Through techniques such as big data analysis, pattern recognition and predictive modeling, machine learning can help power systems achieve more refined and intelligent management. The application of machine learning in power systems has broad prospects, but the current research at home and abroad still has a long way to go. In foreign countries, some developed countries have begun to apply machine learning technology in the management and optimization of power systems. For example, in 2014, IBM of the United States carried out Watt-Sun photovoltaic prediction project based on machine learning model, which greatly improved the accuracy of photovoltaic prediction [1]. Due to the complexity and particularity of the power system, the application of machine learning technology in the power system still faces many challenges, such as the quality and quantity of data, the generalization ability and interpretation of the model, real-time and computing resources. In China, with the development of smart grid construction and energy Internet, some universities and research institutions have begun to carry out related research work. The team of Xu Yinliang from Shenzhen International Graduate School of Tsinghua University combined machine learning and optimization theory to propose a semi-end-to-end power system operation control theory and model, effectively improving the economy and security of power system operation [2]. However, there are shortcomings in domestic research, such as scattered research fields and strong data dependence. For example, although a variety of load forecasting models such as LSTM have been proposed, the discussion on generalization ability and practical application effect is insufficient.

In this paper, machine learning is discussed in four aspects: load forecasting of elastic power system, transient stability assessment of power system, intelligent power scheduling, fault diagnosis of power system and relay protection.

2. Load forecasting of power system

As the world's exploitable energy resources are decreasing, it is critical to rationally plan the use and distribution of electric energy to minimize unnecessary energy waste. Accurate and timely power load forecasting can effectively supply the generated electricity to the end industrial and commercial users at the lowest cost. However, due to the difficulty of storing electricity in large quantities, a high degree of balance must be maintained between generation and consumption. If there is a large deviation between the predicted result of power load and the actual situation, it may lead to the occurrence of adverse situations such as emergency power outage or power surplus. Accurate medium and long term power load forecasting results play a significant role in improving the stability and economic benefits of the power system. Meanwhile, timely and effective short-term power load forecasting can effectively avoid the occurrence of emergencies such as emergency power outage and emergency power supply, thus significantly reducing unnecessary waste of resources.

In the past two decades, the wide application of global smart grid technology has accumulated a large amount of power industry data. Traditional load forecasting methods are usually based on statistical principles, such as time series analysis, regression analysis, etc. These methods have certain limitations when dealing with nonlinear data and a large number of variables, and cannot fully utilize these rich data and the powerful computing power of modern computers. Machine learning and deep learning technology began to emerge gradually in the field of power load forecasting, and showed excellent performance and performance. Figure 1 shows a typical approach that has emerged over the course of a long-term study of electrical loads [3].

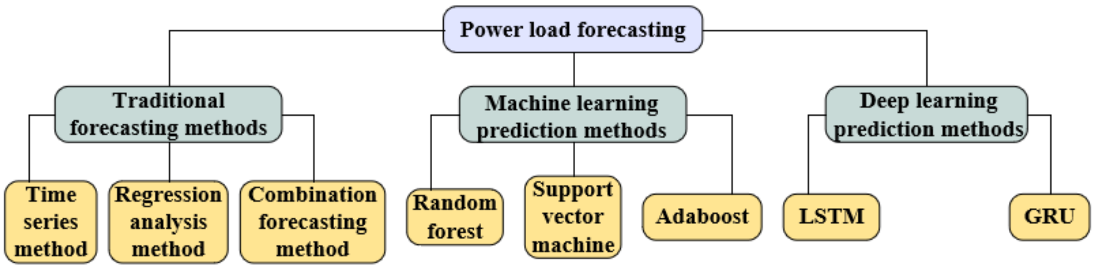

Figure 1. Power load forecasting method

2.1. Medium and long term power load forecasting

Medium - and long-term power load forecasting is mostly to forecast the electricity consumption of a certain area over a period of time. Figure 2 lists several innovative research methods for medium and long term power load forecasting [4-7] .

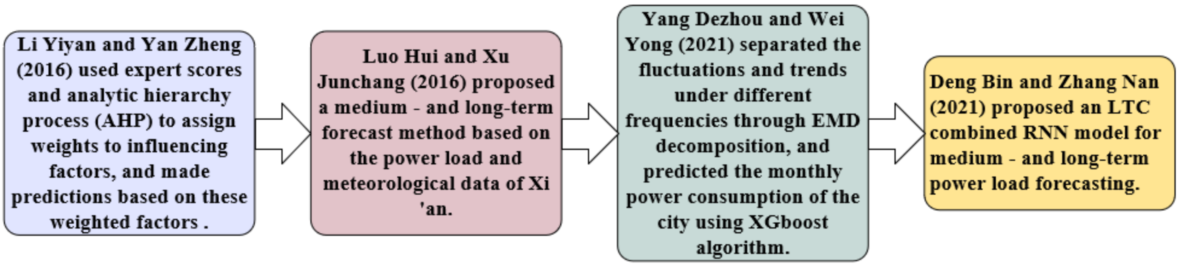

Figure 2. Several innovative medium and long term power load forecasting models

Urban electricity consumption is affected by many factors such as social and economic development, climate change and policies, especially in the context of climate change, the impact of meteorological conditions on urban electricity consumption is increasingly significant. Existing research methods on urban electricity consumption forecast include multiple regression model, conventional mathematical model, neural network model, econometric model and so on. Luo Hui and Xu Junchang built a model based on the principle of econometrics, aiming to explore how meteorological factors affect urban electricity consumption in Xi 'an, as shown in Figure 3 [5].

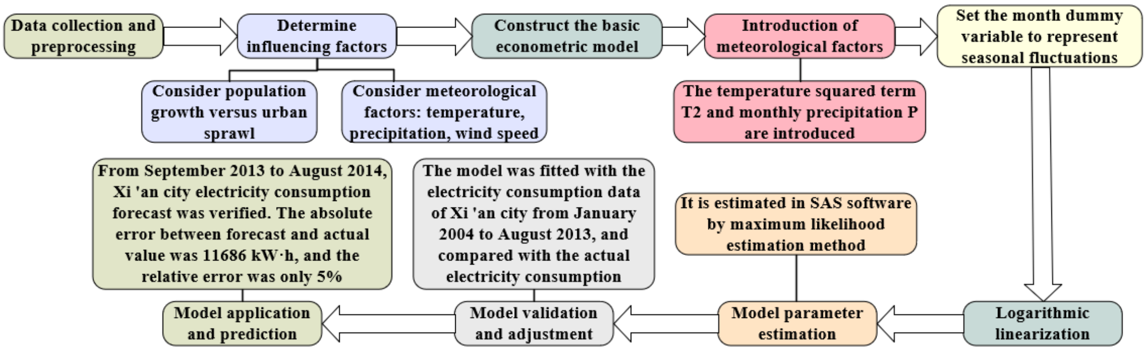

Figure 3. Medium and long term load forecasting model combined with meteorological factors

Enhance the generalization ability of the model to different power grids and environments; Improve overall forecasting performance by integrating multiple models; Developing models that are updated in real time and dynamically adjusted in response to market changes; Using genetic algorithm, particle swarm optimization and other optimization model parameters to improve forecasting efficiency. Through the continuous research and practice in these directions, the accuracy and efficiency of medium and long-term load forecasting will be improved, and strong support will be provided for the stable operation and optimal management of the power system.

2.2. Short-term power load forecasting

Timely and accurate short-term power load forecasting is helpful for power plants to make generation plans, decide the start and stop time of generator sets, and ensure the safe and reliable operation of power systems. Figure 4 lists several authoritative short-term forecasting methods [8-10].

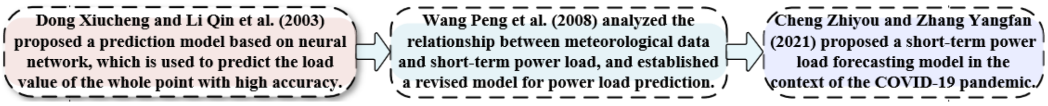

Figure 4. Short-term power load forecasting model

The power load fluctuations caused by the COVID-19 pandemic in 2021 pose a huge challenge to short-term load forecasting (STLF). Zhiyou Cheng and Yangfan Zhang proposed a Fear index (FI) based short-term power load forecasting method under the influence of COVID-19 [10]. The generalized regression neural network (GRNN) was used as the prediction model, and the smoothness factor σ of GRNN was optimized by the Fruit Fly Optimization Algorithm (FOA) to improve the prediction accuracy and stability, as shown in Figure 5. The empirical analysis used load data from Germany from 2019 to 2020, and the results showed that the prediction method with the introduction of FI could effectively improve the prediction accuracy during the pandemic period[10]. However, support vector machine (SVM), random forest (RF) or other deep learning models can be considered to form a multivariate model fusion to further improve the robustness and accuracy of the prediction.

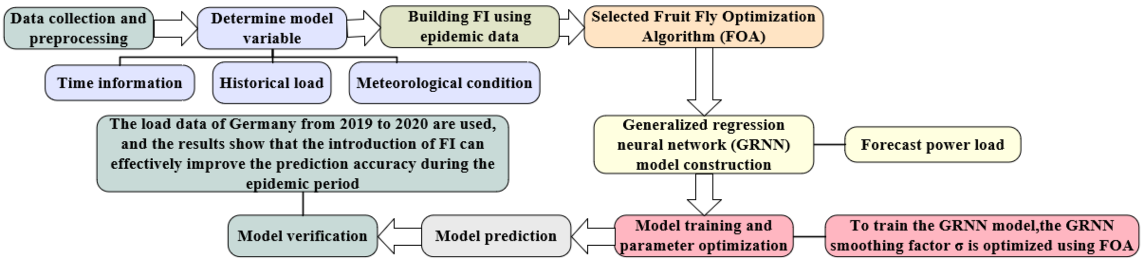

Figure 5. Short-term power load forecasting method under the influence of epidemic situation based on Fear Index (FI)

The improvement direction of short-term load forecasting model will focus on improving accuracy, efficiency and adaptability. For example, advanced algorithms such as convolutional neural network (CNN) and recurrent neural network (RNN) in deep learning, especially long short-term memory network (LSTM), will be integrated to better capture complex patterns in time series data, and knowledge in power system engineering, data science, artificial intelligence and other fields will be integrated to promote the development of short-term load forecasting technology.

3. Transient stability assessment of power systems

The dynamic characteristics of the power system are complex and difficult to predict. Once a major disturbance or failure is encountered, the normal operation of the power grid may be disrupted, and even the collapse of the power system and large-scale power outage will have a profound impact on the society. Therefore, it is particularly important to evaluate the transient stability of the power system. The key task of analyzing the transient stability of power system is to judge whether the system can restore or return to the original equilibrium point after a large disturbance. Figure 6 shows the various methods for evaluating the transient stability of power systems.

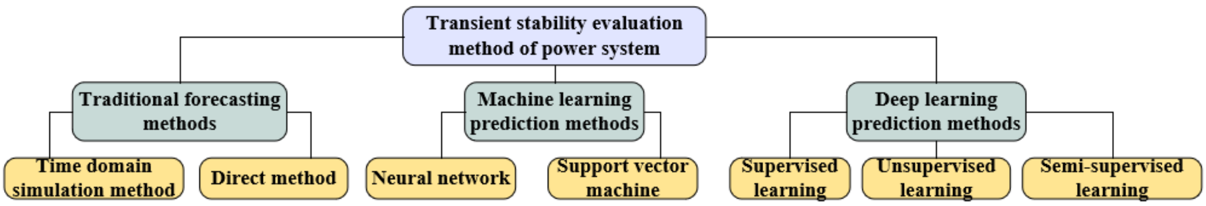

Figure 6. Transient stability evaluation methods of power system

In the transient stability analysis of power system, the traditional methods include the time domain simulation method and the direct method, which are usually carried out under the preset disturbance conditions, to analyze the load state when the disturbance occurs, the power network structure and the possible fault situation, and formulate the corresponding solutions. However, the accuracy of the time-domain simulation method depends on the initial conditions and the accuracy of the model, and its calculation amount and response speed may not meet the needs of large-scale power grid stability control; Direct law requires more in-depth study of energy function under complex system model. With the continuous development and scale expansion of power system, relying on these traditional methods can no longer meet the actual needs of modern power system operation.

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3.1. Application of machine learning

The rapid development of artificial intelligence provides a new solution for transient stability evaluation of power system. By correlating transient stability and electricity volume, machine learning method analyzes and extracts the potential functional relationship between them, which makes it possible to judge the transient stability of power system effectively under new operating conditions. Neural network is one of the earliest and most widely used machine learning algorithms. Table 7 shows several key steps in the development of neural networks in transient stability analysis, starting with basic neural network applications and gradually introducing other algorithms and techniques to solve specific problems [11-13]. However, the model based on neural network has some problems, such as weak adaptability to the change of power network topology, local minimization, overfitting of training data, which leads to a decline in model generalization ability.

Table 7. Several key development steps of neural networks in transient stability analysis

Improved development of neural network algorithms	Features
Introduction of genetic algorithm	Solve slow speed and local minimum problems
Rough set and information entropy theory	Improved algorithm performance
Combination of PNN and RBF	Enhance transient stability judgment ability

The emergence of support vector machine (SVM) algorithm can effectively solve the problems existing in neural networks, and it is quickly used in the field of transient stability evaluation. Table 8 briefly summarizes the methods or techniques adopted by SVM algorithm in different research stages in the field of transient stability assessment [14-16].

Table 8. The key development nodes of SVM algorithm in the field of transient stability assessment

Development of SVM algorithm	Features
SVM algorithm introduction	Solve the problems of neural network overfitting
SVM model was applied for the first time	Transient stability analysis of large-scale power grid
Information fusion combined with SVM	Improve the accuracy of classifier
Response trajectories are combined with CVM	Fault screening
SVM approximate security domain intersection	The transient stability evaluation under security domain
The strategy of "extended boundary" is proposed	Improve the coverage rate of instability fault determination

When the data conforms to some unknown but fixed distribution characteristics, the error between the actual output of the classifier and the expected ideal output is minimized through optimization algorithm, so as to ensure the accuracy and stability of the classifier. This algorithm is supported vector machine. The traditional support vector machine is mainly based on Euclidean distance to measure the similarity between samples. However, in the field of machine learning, there are many distance measurement methods, including Mahalanobis distance. Integrating Mahalanobis distance into SVM model helps to improve the model's performance in classification tasks. Figure 9 shows a power system transient stability evaluation model based on Mahalanobis distance support vector machine [17].

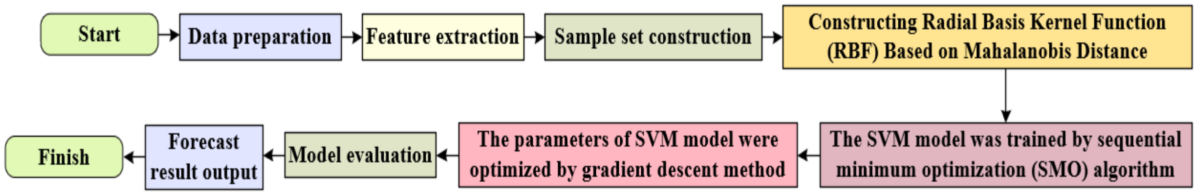

Figure 9. Transient stability evaluation model of power system based on support vector machine based on Mahalanobis distance

In recent years, optimization methods for shallow network architecture have approached their development limits, and in the actual power grid system application scenarios, the massive data from real operation far exceeds the amount of data generated by the simulation model. As a result, the application of traditional machine learning methods in the transient stability analysis of power system has encountered a bottleneck. The emergence of deep learning algorithms has brought new breakthroughs and possibilities to this field.

3.2. Application of deep learning

As a subfield of machine learning, the core of deep learning is to use large-scale training data and multi-layer neural network structure to discover deep features in data, so as to improve the accuracy of classification and evaluation. Automatic extraction of key features through deep learning enhances the accuracy of prediction and evaluation, which plays an important role in the transient stability evaluation of power systems. Table 10 shows the classification and representative algorithms of deep learning.

Table 10. Classification and representation algorithms of deep learning

Classification of Deep Learning	Representative algorithms
Supervised learning	Deep Perceptron (Deep MLP), Convolutional Neural Network (CNN)
Unsupervised learning	Deep Belief Networks (DBN), Stacked Autoencoders (SAE)
Semi-supervised learning	Self-training model, mean teacher model, etc

The deep belief network DBN model is used to study the influence of large-scale wind power on the transient stability of power system. In a transmission grid system containing a wind farm, the influence of wind power capacity changes on system stability is analyzed through simulation. Figure 11 shows the DBN model used to predict the change trend of generator rotor Angle after fault removal. The results show that DBN can accurately predict rotor Angle changes and effectively evaluate the transient stability of the power system [18].

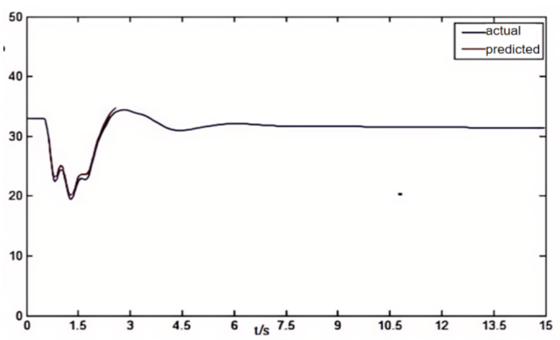

Figure 11. Comparison diagram of rotor Angle DBN model prediction

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In the future, non-traditional data sources can be used to enhance the predictive power of the model; Use ensemble learning methods to improve the accuracy and robustness of the overall assessment; And combine machine learning and deep learning techniques with advanced applications of smart grids to achieve a more comprehensive assessment and management of power system stability.

4. Smart power scheduling

The power dispatching of smart grid is the real-time monitoring, optimization control and intelligent management of all aspects of power generation, transmission, transformation, distribution and electricity consumption, so as to improve the operational efficiency, reliability and flexibility of the power grid, while reducing operating costs, and promoting the extensive access and efficient use of renewable energy. If the power grid dispatching system has abnormal business, it will have a great impact on the stable operation of the power grid, and even lead to the power grid paralysis. Therefore, the anomaly detection of service data is very important. Anomaly detection refers to finding problems in the data that do not conform to expected patterns. The traditional power dispatching anomaly detection methods mainly rely on expert experience and judge the anomaly by setting static threshold. However, when the service changes or the data distribution characteristics change, the static threshold method is easy to produce false alarm or missing alarm.

The machine learning model can process and analyze a large amount of historical and real-time data, improve the accuracy of the prediction of the power grid operation state through continuous learning and optimization, and provide more flexible and accurate solutions for scheduling decisions. In addition, machine learning technology is particularly prominent in anomaly detection, which can effectively identify local anomalies and global anomalies in the power grid, timely warning, and reduce potential failure risks. Compared with traditional rule-based scheduling methods, machine learning not only improves the scheduling efficiency, but also enhances the stability and reliability of the system, laying a solid foundation for realizing the long-term goal of smart grid.

The power dispatching data anomaly detection method uses the unsupervised mode. Table 12 shows several existing unsupervised anomaly detection methods[19].

Table 12. Several unsupervised outlier detection methods

Methods of unsupervised outlier detection	Features
Integration-based approach	High computational efficiency, but limited ability to detect local anomalies
A distribution-based approach	Unusually sensitive to global distribution, but may not perform well when dealing with local anomalies
A clustering based approach	Intuitive and easy to understand, but may not be sensitive enough to noise and anomalies in non-spherical distributions
A distance-based approach	Can handle multi-dimensional data, but the calculation cost of high-dimensional data is higher.
Outlier detection based on relative density	The calculation cost is very high, and it is difficult to apply to the anomaly detection of large-scale streaming data
Outlier detection based on isolation	It has linear time complexity and low memory requirements, but is insensitive to local exceptions

In a streaming data environment, data flows continuously and rapidly, and its statistical properties may change unpredictably over time, a phenomenon known as conceptual drift. Traditional machine learning relies on generalizations of historical data, which may not be relevant to new data due to conceptual drift. Therefore, the introduction of concept drift detection technology in pattern recognition and data flow mining has greatly improved the traditional machine learning research. Table 13 shows various concept drift detection algorithms[20].

Table 13. Concept drift detection algorithms

Concept drift detector classification	Representation Algorithms
Method based on sequential analysis	Page-Hinkley Test, Geometric Moving Average (GMA)
Statistics-based approach	Drift Detection Method (DDM), Early Drift Detection Method (EDDM)
Method based on sliding window	Adaptive Sliding Window (ADWIN), drift detection methods HDDM_A and HDDM_W based on Hofding boundary

Wang Feng designed an adaptive time-weighted window concept drift detector (ADHDDM_W) based on Hofding inequality[19], aiming at the dynamic change of service data distribution in power dispatching automation system over time. The model is shown in Figure 14. The effectiveness of the algorithm in improving detection accuracy[19], solving lag and "empty window" problem is demonstrated by testing the public data set and the actual power dispatching data.

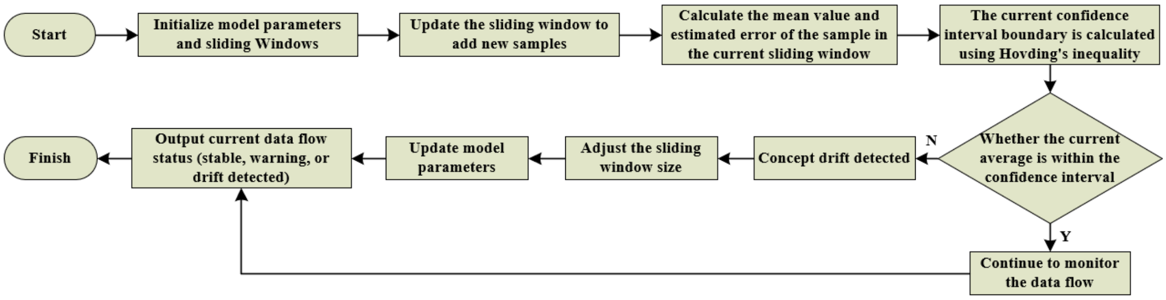

Figure 14. An adaptive time-weighted window concept drift detector based on Hovding inequality

5. Power system fault diagnosis and relay protection

Traditional fault identification and relaying methods are usually based on frequency domain analysis, which rely on discrete Fourier transform (DFT) or fast Fourier transform (FFT) to extract frequency domain features from the time domain signal of the power system. Fault feature extraction relies on heuristic rules, requiring industry experts to presuppose protection setting values and logical criteria based on prior knowledge of electrical equipment faults. These methods have limitations in terms of the diversity of fault type criteria and the coordination between protection setting values.

Machine learning technology, especially deep learning, provides new solutions for power system fault identification and relay protection because of its powerful data processing and automatic feature extraction capabilities. Machine learning models are able to learn fault characteristics from a large amount of historical data and automatically identify and classify different types of faults without manually setting thresholds and complex rules. This approach can significantly improve the accuracy and speed of fault identification, and reduce the possibility of misactions and missed judgments. In recent years, for different types of power systems and various components and equipment, scholars have carried out extensive research and made progress based on the principle of machine learning. Table 15 shows the research status of machine learning technology in power system fault identification and relay protection [21-24].

Table 15. Research methods of machine learning in power system fault identification and relay protection

Type of system or component device	Research methods
Microgrid systems	Recurrent neural networks, decision trees
Flexible DC systems	Stacked Autoencoder (SAE)
Transmission lines, transformers	Support vector machine, wavelet transform, deep learning

In UHV DC transmission lines, it is a method that uses multi-resolution singular spectrum entropy and support vector machine to identify faults inside and outside the region. The flow chart is shown in Figure 16. This method is applied to the simulation model established according to the actual parameters of Yunguang-± 800kV UHVDC transmission system. It can distinguish the faults outside the rectifier side, inside the area and outside the inverter side at the same time[22].

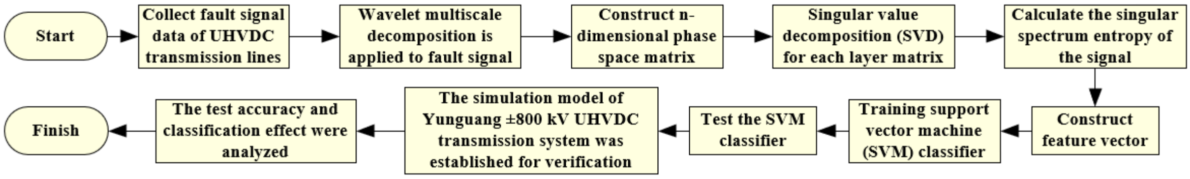

Figure 16. A machine learning-based fault identification model for UHVDC transmission lines

Machine learning technology has a broad application prospect in the field of power system fault diagnosis and relay protection. With the development of smart grid technology and the arrival of the era of big data, machine learning can provide more accurate and efficient fault analysis and decision support with its powerful data processing capability and pattern recognition advantages. The future improvement direction should focus on the optimization of the algorithm to improve the adaptability and robustness of the model to the complex power grid environment. In addition, real-time performance is the key to fault diagnosis and relay protection, and research on faster data processing and decision making algorithms will be the focus in the future. Combining power system expertise and fusing traditional protection principles with machine learning models to achieve a more comprehensive and efficient fault handling mechanism will be an important way to push forward progress in the field. Through continued research and innovation in these directions, machine learning will play a more critical role in power system fault diagnosis and relay protection.

6. Conclusion and Prospect

The application of machine learning technology in the field of elastic power system has brought innovative solutions for load forecasting, stability evaluation, intelligent scheduling and fault diagnosis. In power load forecasting, machine learning technology can accurately predict short and medium term power demand by analyzing historical data, effectively avoiding resource waste and emergency power outage events. In the field of transient stability assessment, the machine learning model extracts the potential function relationship by associating the transient stability and electricity volume of the system to improve the accuracy and efficiency of the assessment. In the field of intelligent power dispatching, machine learning technology significantly improves the efficiency and reliability of power grid operation through real-time monitoring and optimal control. In addition, the field of fault diagnosis and relay protection has also realized the rapid and accurate identification of faults through machine learning technology, improving the stability and security of the power system. However, there are still the following problems and challenges:

1. The training of machine learning models requires a large amount of high-quality data, and the collection and processing of data may face difficulties in practical applications.
2. The generalization ability and interpretation of the model need to be improved, especially in the complex and changeable power system, where the model needs to be able to adapt to different operating conditions and new failure modes.
3. Real-time performance and computing resources are also key factors to be considered in the application of machine learning in power systems. Future research needs to focus on the optimization of algorithms, improving the adaptability and robustness of models, while developing lightweight machine learning models to meet the requirements of real-time.
4. Privacy protection and data security are also issues that cannot be ignored in smart grid, and more secure data utilization and model update mechanisms need to be developed.

Looking forward to the future, the application of machine learning in power systems has a broad prospect. With the development of smart grid technology and the arrival of the era of big data, machine learning will provide more accurate and efficient decision support with its strong data processing capabilities and pattern recognition advantages. Future research will focus on further optimization of algorithms to improve the model's adaptability to complex power grid environments. The combination of ensemble learning and deep learning technologies will further improve the prediction accuracy and decision-making efficiency of power systems. In addition, combining machine learning technology with traditional power system expertise to achieve a more comprehensive and efficient fault handling mechanism will be an important way to promote progress in the field, which will push the power system toward a higher level of intelligence and automation.

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