Review on Applications of Artificial Intelligence in Relay Protection

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Abstract. With the continuous development of power grid sources, networks and loads, the emergence of distributed power sources and new types of loads has brought new challenges to the traditional power system relay protection. Combining artificial intelligence technologies, relay protection technology has made great developments. In this paper, the development of power grid from three aspects are firstly introduced: sources, networks and loads. Then impacts of power grid development on relay protection are discussed. Finally, the application of artificial intelligence technologies in relay protection is introduced in details.

Keywords: Relay protection · Artificial intelligence

1 Introduction

With rapid developments in different areas, there emerges new status of power grid, for example, the AC-DC hybrid networks appear; the grid-connected capacity of clean energy continues to grow; and more and more power electronic apparatus are adopted. For the power generation, the application of distributed energy on the power side has effectively alleviated the energy crisis. Voltage source converters (VSC)-HVDC can realize the independent control of active and reactive power, transmit power to the passive network, and connect the electric energy generated by small and scattered renewable energy sources more economically. For the power transmission, large grids are interconnected. DC grids and active distribution networks are widely used. For the power loads, a series of new loads such as DC loads and controllable loads appear. With the development of sources, networks and loads, the random and nonlinear characteristics of power system are enhanced, and the fault features become more complicate, which brings new problems to relay protection. For example, the interconnection of distributed energy reduces the accuracy of setting calculation; the wide application of DC links in large power grid interconnections produce setting methods that are different from those of AC systems; and the huge data information increases the difficulty of fault diagnosis.

Artificial intelligence (AI) technology has many advantages in feature extraction, identification, big data processing and so on. It can make outstanding performance in

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modern power system relay protection with abundant information, chaotic fault features and high performance requirements. It can be used for online protection value settings, fault detections, disturbance and fault identification, fault diagnosis, and fault location, etc.

This paper firstly discusses the new form of power grid development, then analyzes some problems of relay protection under the new form of power grid, and finally focuses on the application of AI in relay protection.

2 Development of Power Grids

2.1 The Developments at Source Side

Distributed generation (DG) has a variety of classification methods according to different classification methods. According to the installed capacity of the power supply, distributed power supply can be divided into three categories: small ones (less than 100 KW), medium ones (between 100 KW and 1 MW) and large ones (greater than 1 MW). According to the interconnecting forms, DGs can be divided into: AC-DC-AC connected distributed DGs and DC-AC connected DGs. In accordance with the energy type, DGs can be divided into wind power, solar power, tidal power generation, fuel cell power generation, small hydro power generation, the micro gas turbine power generation, biomass power generation [1]. The advantages of DGs are less investment and short construction time. Chinese government prefers to interconnect DGs into the power grids, and thus more and more distributed power generation will be connected. Wind power farm DC grid-connection is a hot research topic in recent years. Through DC grid-connection, wind power farm can improve the power factor, and then transport electric energy with the highest efficiency. It has low coupling with the power grid and can realize independent control of active power and reactive power [2, 3].

2.2 The Developments at Network Side

As the key to build global energy interconnection, power grid interconnection helps to optimize the allocation of all kinds of energy resources in a wide range of the world more conveniently. China has basically built a smart power grid with ultra-high voltage network as the backbone network and multi-level grid coordination. At the same time, China is also actively carrying out power grid interconnection and power exchange with Russia, Kazakhstan, Laos and other countries.

China has elevated the development of renewable energy to an important position, and gradually realized the strategic adjustment of the energy structure. The construction of a nationwide DC transmission network will not only make more effective use of renewable energy, but also actively promote the construction of a stronger smart grid. The South Australia HVDC Demonstration Project which was constructed by China Southern Power Grid Corporation was successfully put into operation in December 2013. It is the first flexible MTDC project based on VSC-HVDC in the world [4]. Subsequently, the State Grid Corporation of China built a five-terminal flexible DC demonstration project in Zhoushan with a voltage grade of ±200 kV and put it into operation. In February

2018, the construction of Zhangbei Flexible DC Project started, and the voltage level of VSC reached ±500 kV, which is the highest voltage level of flexible DC project in the world.

Active distribution network is a development mode of smart distribution network in the future. It has active management of distributed power supply, energy storage equipment and customer bi-directional load model. It is a distribution system with flexible topology [5, 6]. From 2010 to 2014, the European Union has also successively carried out many demonstration projects, including the ADINE demonstration project, DISPOWER project and DER LAB project. The EU Fifth Framework Project, the EU Sixth Framework Project and the EU Seventh Framework Project also contain many demonstration projects related to active distribution network technologies.

2.3 The Developments at Load Side

In recent years, more and more new kinds of loads begin to appear, such as electric vehicles. In contrast to AC loads, DC loads appear. DC load is the general term of the power load supplied by DC, such as electric vehicles, variable frequency air conditioners and mobile phones, etc. Also, the controllable load is proposed under the circumstance of smart grid. Controllable load, also known as flexible load, is a kind of power load with interrupting ability or translation ability, such as washing machines, air conditioners, dishwashers, etc. There is also industrial power adjustable equipment and electric vehicles using charging piles for charging, etc. DC load and controllable load are not completely separated. For example, electric vehicles belong to both DC load and controllable load [7, 8].

3 Relay Protection Problems Due to the Developments of Power Grid

Relay protection device is an integral part of power system. When a fault or disturbance occurs in a part of the power system due to natural, man-made or equipment failure, relay protection devices should quickly isolate the fault part to ensure the stability of the power system, to maximize the non-fault part of the power grid, and to continue reliable power supply.

When more and more large power grids are interconnected via DC links, the fault features of hybrid DC networks will appear. The setting calculation of protection will change, which is different from that of AC networks. The power flow calculation changes when the distributed power supply is connected to the power grid. First of all, the calculation model is changed. There are several different interface forms and calculation models when distributed power is connected to the grid. Among them, the calculation method of power flow in distribution network based on sensitivity compensation has become the basic model to study many grid-connection problems of distributed power supply. It can be divided into synchronous generator interface, asynchronous generator interface and power electronic converter interface, as shown in Table 1. Secondly, the applicable calculation method is changed. The research on power flow calculation of distribution network with distributed power supply mainly focuses on establishing more accurate distributed power generation model and improving the existing power flow calculation method [9].

Table 1. Distributed power supply capacity and its interface to the power grid

Power generation forms	Typical capacity range/W	Common interface with power grid
Solar photovoltaic	1.0–1.0 × 105	The DC/AC converter
Wind	1.0–1.0 × 10^5	Asynchronous generator
Micro-gas turbine	1.0 × 10^4–1.0 × 10^5	AC/AC converter
A fuel cell	1.0 × 104–1.0 × 10^6	The DC/AC converter

The connection of DC system changes the network topology and power supply structure. The failure analysis method and the electric parameters is different from the traditional power grid, and is more likely to produce chain fault. The fault characteristics change from linear distribution to nonlinear distribution in the time space domain. Rapid control of DC system changed the failure characteristics of AC devices, and the fault characteristics of traditional LCC-based DC networks and flexible VSC-based DC networks are quite different. The hybrid grid fault characteristic changes impact the composition of the relay protection [10].

After the relay protection equipment is put into operation, a large amount of data is generated, including equipment factory data, test data, production and maintenance data, online real-time data, operation data, etc. Massive data provides a more comprehensive basis for online checking of setting, online monitoring and analysis, setting calculation, fault diagnosis, etc. At the same time, it puts forward higher requirements to obtain effective information and extract features from multi-source heterogeneous data.

4 Application of AI in Relay Protection

4.1 Relay Protection Setting and Online Checking

(1) Setting Value

The coordination of power system relay protection setting values should comprehensively consider the working range and performance of protection components, the voltage level of the system, the sensitivity and selectivity of protection actions, and the cooperation between different protection components. And the setting plan will change with system operations. This makes the setting calculation more complicated, and the workload of repeated calculation is very large and takes a long time. The optimal scheme may not be obtained.

In Literature [11], the expert experience, logical reasoning and object-oriented method in the AI expert system are combined with the numerical calculation function in the traditional setting calculation. AI reasoning programs are limited to construct forward, backward, and bidirectional reasoning from a static knowledge base. Object-oriented technology can well compensate for the low efficiency and flexibility of reasoning caused by this problem. The application of expert system and object oriented method can help to realize the concrete model of relay protection setting calculation.

Literature [12] gives a detailed description of the scheme of realizing the whole process automation of setting calculation, including the system structure, functional division, data platform. ActiveX Scripting technology is used to realize the realization of custom setting calculation in the secondary development of prefectural and county integrated setting calculation. Based on the technology, various models of protective device templates, setting calculation principle and setting calculation can be modified by the custom. This method is flexible, quick and easy to extend and maintain. An example of grid setting in LiShui district of ZheJiang province is given, which shows that this scheme can improve the efficiency of setting calculation and the level of intelligent equipment, and reduce the workload of setting personnel and the possibility of manual mistakes.

In Literature [13], the fuzzy theory is introduced to deal with the uncertainty of some coefficients in the value setting. In the setting calculation, there are quite a few coefficients (such as reliability coefficient) with uncertainty, and there are also quite a few stipulations about the value of setting parameters with fuzzy concept. The fuzzy theory is introduced to optimize part of the coefficients in the setting. An algorithm model is proposed to deal with the uncertainty of the setting coefficients, which avoids the arbitrariness of determining the parameter values only by experts' experience. This method enlarges the setting calculation ability of the expert system and improves the accuracy, reliability and practicability of the setting results.

(2) Online Checking

Online checking for the relay protection setting system is used to verify the performance of the relay protection setting value during operation. To determine whether the protection value meets the requirements of selectivity and sensitivity under the current operating state, it is necessary to consider the topology structure, operating state factors. Due to the complex and changeable structure of power grid, the fixed off-line setting mode leads to large amount of data, difficult analysis and time-consuming calculation for online checking.

Literature [14] applied the genetic algorithm to the relay protection setting calculation process, and verified it by an example. The protection fixed value and time fixed value of the distance protection section are calculated at the same time, and the set values which could meet the requirements were obtained. It can be seen that the genetic algorithm can adjust the fitness function to get the protection values of different requirements, while the conventional protection cannot get the protection values of different requirements.

In Literature [15], an optimal power grid partition strategy based on GN splitting algorithm is proposed. This strategy effectively uses the "maximum number of edge interfaces" to realize the initial partition of the complex grid. The optimal number of partitions is determined by calculating the comparative weighted modularity. Then, the quantitative measurement standard of checking computation time is defined, which is used as the optimal objective function to carry out boundary node migration and achieve the optimal partition. It effectively overcomes the defects of the traditional methods, for example, the difficulty in measuring the rationality of the partition results and the inability to determine the optimal partition results. This method ensures that the partition results have higher parallel checking efficiency and acceleration ratio.

A hybrid parallel strategy for online checking of setting values based on multi-core cluster is also proposed in literature [15]. Through parallelism analysis, reasonable division of computing tasks and parallel algorithm design, this strategy realizes the parallelism of online checking process level and thread level.

4.2 New Principle of Protection

(1) Disturbance Identification

HVDC system has long transmission distance and wide distribution of lines, which is easily affected by climate conditions. The lightning damage becomes the most important interference. The non-fault lightning strike impact contains a great high frequency interference easy to introduce mistakes of the protection devices. Traditional relay protection methods need to select appropriate features according to the expression ability of features, for example, distinguish disturbance from fault by threshold method. But, due to the difficulty of feature extraction and high identification error, the reliability of disturbance identification is low.

The artificial neural network has the ability of self-learning. The neural network is trained by using the simulation data, and the fault features can be extracted objectively and reliably by unsupervised learning. Literature [16] deeply discusses the model characteristics of BP neural network and LVQ neural network and their learning and training process. Neural network can simulate the state and parameters of the power line when fault occurs, and then give corresponding responses. In the actual operation, if similar mistakes occur in the training, a correct response can be made in time. For unknown signals, it can also make the optimal response according to the existing knowledge, which is less dependent on the actual error signals and has a strong expansibility.

When the system is disturbed, the electromagnetic torque will change, and then the balance is destroyed, resulting in a change of the generator speed. The system frequency changes and oscillates. Literature [17] establishes a suitable oscillation model according to the actual situation, and studies the protection action in the oscillation process. The improved current mutation is selected as one of the input characteristic parameters of the oscillatory discriminant subnetwork of neural network. After calculation, the threshold to distinguish oscillations from faults is obtained. This value is not calculated manually, but given by a neural network to achieve the maximum accurate transient disturbance identification. A large sample of BP network training and border fitting classification are needed for training this neural network.

(2) Adaptive Protection

Adaptive protection is the protection which can adjust the protection characteristics or setting values according to the change of power system operation mode and fault state. When the power system is connected to the distribution network or the photovoltaic power station is connected to the grid, the setting of the adaptive distance protection will be affected. Adaptive distance protection is a method based on mathematical model, which can protect the power grid by calculating the relevant parameters. The concrete method is to define the inclination angle α, obtain the short-circuit impedance Z_d by vector graph, and then determine the setting value of the protection impedance according to the adaptive distance protection action criterion. The protection principle is shown in Formula (1).

$$|Z_m - \Delta Z_m| = |Z_d| \leq |Z_{set}| \tag{1}$$

Literature [18] studied how to use SVM to realize real-time and accurate adaptive protection. A neural network is used to help identify faults by taking all kinds of measurable electrical quantities in the fault circuit. The error caused by one or two discriminant parameters of distance protection action can be effectively avoided. Reliability and selectivity of the range protection action are greatly improved.

Literature on [19] studied an adaptive strategy of setting value of transmission line current protection based on online fault identification. The action mechanism of three-stage current protection is discussed. The PV system output active power and the effect of transition resistance are considered. The calculation formula of current protection adaptive setting value is constructed and the corresponding current protection adaptive criterion is established. It is used to solve the misoperation problems of transmission line current protection which may be caused by PV system connecting to distribution network.

In Literature [20], the influence of photovoltaic power station access on adaptive protection is analyzed based on the establishment of the grid fault analysis method including photovoltaic power station. Based on the analysis of the relationship between the positive sequence voltage and the positive sequence current at the protection site when the fault occurs, an adaptive setting formula suitable for photovoltaic output under random conditions is proposed. An adaptive protection scheme is proposed to reflect the fault by the positive sequence measurement value of the protection and operation to remove the fault in time.

4.3 Fault Location and Diagnosis

(1) Line fault location

Traveling wave-based fault location is the main method for transmission lines. Travelling wave detection technology is a combination of new mathematical analysis method, data acquisition device and digital signal processing method to realize fault location. The methods include mathematical morphological method, wavelet transform method and fault analysis method based on distribution parameters of transmission lines.

The improvement direction based on AI mainly includes three aspects. The first one is based on BP neural network. Some internal feedback channels are added to increase the learning ability of neural network. The second one is to use algorithms to optimize the location algorithms, such as particle swarm optimization, cloud genetic algorithm, L-M algorithm, quasi Newton algorithm, etc. The third one is to improve the initial weight and initial threshold of BP neural network.

In Literature [21], a multi-sensor fault detection for photovoltaic array is put forward based on the improved BP neural network. Based on the BP neural network, the internal feedback channel and deviation unit are added to improve the structure of the neural network, as well as the input and output.

An improved BP neural network algorithm based on particle swarm optimization is proposed in literature [22]. PSO algorithm and BP neural network are combined to form PSO-BP algorithm, which can not only use PSO algorithm to adjust the global characteristic network parameters, but also use BP algorithm to adjust and optimize the local characteristic parameters.

Literature [23] took BP neural network as a tool to study the regular relationship between eigenvalue and distance. Firstly, a single amplitude-distance BP neural network is established, and the acquired data is used as the sample data to train the BP neural network. As only one kind of features cannot describe the whole input in details, the actual output error of the trained network is very large. Then, a BP neural network with four eigenvalues as four inputs and distance value as one output is established. Through repeated training with small errors, the BP network achieves the effect of distance identification to a certain extent.

(2) Fault diagnosis

After the failure of the power network, the system can measure the changes of the voltage, branch current, power and other electrical quantities of each node of the power network. The action signal of the protection device, and the action information of the relevant circuit breaker started by the protection device can be got. At present, the fault diagnosis systems studied at home and abroad are based on protection information and switch action information. Most of the developed intelligent diagnostic systems rely on SCADA of the power grid dispatching center to provide complete switching and protection information.

Transmission network fault diagnosis mainly uses the logic relation of fault equipment, switch, relay protection action and operator's experience to infer the possible fault type. This process is difficult to be described by traditional mathematical model. AI technology is widely used in this field because it is good at simulating the process of human dealing with problems, easy to take into account human experience and has certain learning ability.

In Literatures [24, 25], Bayesian network method is used in fault diagnosis. A Bayesian network fault diagnosis methods integrates with a priori information and posterior information. It can effectively avoid the subjective bias that comes from using only a priori information and the blind searching and calculation in the absence of sample information. Also, it can avoid the effects of noise from using only posterior information. The problem of fault diagnosis is transformed into a decision problem with uncertain information, and the problem of uncertainty of fault information is solved better. A distributed diagnosis model is established by combining with the characteristics of power system.

Literature [26] proposed a fault diagnosis method based on RBF neural network. According to the simulation model of a VSC-HVDC system, the currents from the rectifier side and AC side of the converter station are collected. The root mean square value of each current was used to establish the fault dictionary, and the fuzzy numbering data was determined. Combined with a RBF neural network, the feasibility of the fault diagnosis method was verified.

Literature [27] put forward a fault diagnosis model of transmission network based on DS evidence theory. This method has a good ability of information fusion and can synthesize the fault information from all directions to get the final judgment. Also, the fault diagnosis model of transmission network based on mutual information network is proposed. Mutual information network is an effective feature selection and data classification method. It can select the input attributes associated with the target attributes, eliminate the redundant features, control the structure of the network, improve the processing speed of the algorithm, and use the connection rules between the end node and the target node to extract the knowledge, which can be used for future classification decisions and pattern recognition.

5 Conclusions and Prospects

AI technology is based on unsupervised learning algorithms. Those algorithms have good ability to fit complex functions and strong feature expression ability. It is suitable for solving big data, strong uncertainty and other complex problems, so that it has a better and better performance in data-driven research and application fields.

Under the new situation, the model of power grid system is changeable, the fault mechanism is complex, and the fault features are difficult to be extracted. AI technology can solve the dilemma faced by traditional relay protection. With the improvement of the sampling accuracy of relay protection, the function of fault analysis based on transient signal is applied. At the same time, with the improvement of CPU processing performance, complex machine learning can also be applied in relay protection. The development of technology will better promote the research and application process of the new generation of AI in the field of relay protection.

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