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TRANSFORMER FAULT DIAGNOSIS AND LOCATION METHOD BASED ON FAULT TREE ANALYSIS

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Abstract. Fiber optical current transformer (FOCT) is widely used in power systems for fault diagnosis and analysis, which can improve its operational reliability. Construct fault modes and fault trees based on fault data of all fiber current transformers, and construct a fault feature space. Constructing a fault diagnosis expert system using fault trees and fault feature space clustering centers to achieve accurate diagnosis of fault types, patterns, and components. The proposed method was validated using fault data and case studies of all fiber current transformers in a regional power grid, and the results showed that: The on-site fault case is closest to the cluster center of drift deviation fault, so it belongs to drift deviation fault. Further extract the on-site maintenance report, which indicates that the operating temperature of the all fiber current transformer is relatively high. The diagnostic results of the fault diagnosis expert system for the faulty all fiber current transformer are consistent with the actual results on site, verifying the accuracy and reliability of this method.

Key words: All fiber current transformer, Fault Mode and Effects Analysis Method, Fault tree, Expert system, fault diagnosis

1. Introduction. Transformer is a very important electrical equipment in the power system, whose main responsibility is to measure and transmit current and voltage information to ensure the safe operation of the power system. However, due to various reasons, transformers may malfunction, such as insulation damage, inter turn short circuits, open circuits, etc. These faults may lead to measurement errors, equipment damage, and even power system accidents.

Firstly, insulation damage is a common occurrence of transformer faults [1]. The insulation layer of the transformer plays a role in protecting the coil and magnetic core. Once the insulation layer is damaged, current may directly enter the coil of the transformer through the insulation layer, causing measurement errors and even equipment damage. Insulation damage may be caused by aging due to prolonged operation, or it may be due to harsh external conditions such as high temperature, humidity, etc. Therefore, it is very important to regularly inspect and maintain the insulation layer of the transformer to ensure its normal operation. Secondly, inter turn short circuit is also a common problem of transformer faults [2]. The coil of a transformer consists of many turns, and when a short circuit occurs between some of these turns, the current will bypass these turns, causing measurement errors. Short circuit between turns may be caused by damaged coil insulation, insufficient insulation distance between coils, and other reasons. In order to avoid inter turn short circuits, it is necessary to ensure that the coil insulation of the transformer is intact and that there is sufficient insulation distance between the coils during installation. In addition, the open circuit of the transformer is also a common fault situation. When the coil of the transformer is interrupted or poorly connected, it will result in the inability of current to flow through the coil and make accurate measurements. An open circuit may be caused by coil damage, loose wiring terminals, and other reasons. In order to avoid open circuit faults, it is necessary to regularly check whether the coils of the transformer are intact and ensure that the connection terminals are firmly and reliably connected [3]. The above mentioned fault situations are only a part of the possible occurrence of transformers, and the actual situation may be more complex. In order to ensure the safe operation of the power system, in addition to regular inspection and maintenance of transformers, other measures should also be

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taken, such as setting up overcurrent protection devices, installing backup transformers, etc., in order to cope with possible fault situations. In addition, with the development of the power system and the application of intelligent technology, the methods for detecting and preventing transformer faults are also constantly improving [4]. For example, using an infrared thermal imager can detect temperature anomalies in transformers, thereby detecting potential faults in advance. In addition, the emergence of intelligent transformers can achieve real-time monitoring and fault diagnosis of transformers, further improving the reliability and safety of transformers.

In short, as an important electrical equipment in the power system, the failure of transformers may have serious impacts on the power system. Therefore, we need to pay attention to the inspection and maintenance of transformers, timely detect and eliminate transformer faults, in order to ensure the safe operation of the power system. The author's purpose is to study the fault diagnosis and localization method for transformers based on fault tree analysis. By establishing a fault tree model for transformers, analyzing the mechanism and possible fault paths of transformer faults, and determining the probability and importance of faults occurring. Based on the results of fault tree analysis, the author proposes corresponding fault diagnosis and positioning strategies, providing technical support for the rapid diagnosis and accurate positioning of transformer faults. Through this study, the aim is to improve the efficiency and accuracy of transformer fault handling, ensuring the safe operation of the power system.

2. Principle and Fault Mode Analysis of All Fiber Optic Current Transformer.

2.1. Principle of all fiber optic current transformers . When linearly polarized light passes through certain optical materials in a direction parallel to the magnetic field, due to the influence of the magnetic field, the front side rotates. The formula for calculating the rotation angle θ of polarized light is

$$\theta = \mu\nu \int_{L_1}^{L_2} H(L)dL \tag{2.1}$$

In the formula, μ is the magnetic permeability of the material; V is the Verdet parameter of the optical material; L is the distance traveled by light in the material; H (L) is the function of the spatially distributed magnetic field with respect to L[5]. If fiber optic or magneto optic block glass is used to close the optical path around the conductive conductor, then

$$\theta = \mu\nu N \oint H(L)dL = \mu\nu Ni \tag{2.2}$$

In the formula, N is the number of turns of the optical path and current intersection; I is the current flowing through the conductor. Therefore, the current can be calculated by detecting θ.

2.2. Fault mode analysis of all fiber optic current transformers . The process of inferring the form, location, and cause of a fault based on fault knowledge and a certain strategy is called the fault diagnosis process. In the diagnosis process, corresponding fault knowledge should be used as the basis, such as fault symptoms, fault detection methods, degree of fault harm, and maintenance measures. The external manifestation of faults is the fault mode, which can be observed through human senses or measuring instruments and meters [6]. When diagnosing equipment faults, it is necessary to first determine the fault mode through factual data, and then determine its impact on the system through the determined fault mode, and propose targeted maintenance measures and solutions. The Fault Mode and Effect Analysis (FMEA) method is used in multiple fields such as nuclear and aviation industries to eliminate equipment failure hazards. FMEA can provide a comprehensive qualitative analysis of system or equipment failure modes. In the design process of a system or equipment, the FMEA method analyzes the potential failure modes of its constituent units and their impact on the system or equipment, and classifies each potential failure mode according to its severity, proposing possible design, prevention, and improvement measures [7]. Before analyzing the all fiber current transformer using FMEA method, it is necessary to subdivide its various components to establish a reliability diagram of the all fiber current transformer. Existing research indicates that the main factors affecting the reliability of current transformers are as follows.

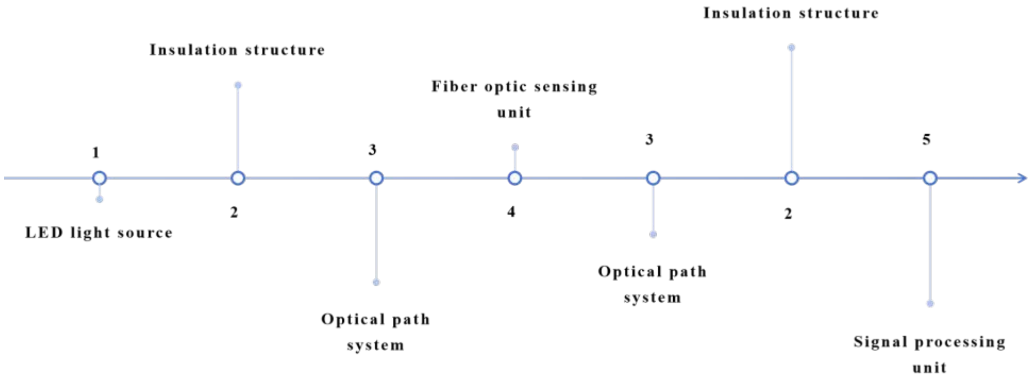

Fig. 2.1: Reliability Block Diagram of Full Fiber Current Transformer

(1) The influence of sensor head structure. The optical material of the sensor head undergoes changes in its optical properties under the influence of external electric fields, temperature fields, and stress fields, resulting in various effects that affect the stability of the transformer system.
(2) The impact of optical system. Due to the difference in surface smoothness and parallelism of optical components, as well as the inevitable small displacement during the bonding process, there will be deviation angles in the optical path system, which will affect the stability of the transformer.
(3) The impact of signal processing circuits. The differences in component performance in signal processing circuits lead to certain deviations, such as low-pass filters and the dispersion of component parameters, which will affect the amplitude frequency response and cause errors in signal processing [8].
(4) The influence of insulation structure. The insulation structure not only affects the linear range of system measurement, but also the selection of insulation materials affects the analysis of electric fields. The thermal expansion and contraction of materials cause changes in the distance between electrodes, thereby affecting the stability of transformers.
(5) The impact of LED characteristics. The output of the sensor is a function of wavelength, and the characteristics of LED determine the stability of the wavelength. With the change of temperature, the wavelength of LED will change, thereby affecting the stability of the transformer. Analyze the various parts of the all fiber current sensor and establish its reliability diagram, as shown in Figure 2.1.

Figure 2.1 is based on a commonly used and effective total reflection fiber optic current transformer. Therefore, the insulation structure and optical path system through which the incident and reflected light pass are the same. Therefore, this reliability block diagram only contains 5 different parts. The above parts will individually or comprehensively affect the stability of the all fiber current transformer, and this impact on stability will be manifested through the output of the transformer [9]. Therefore, based on the abnormal situation of the output of the transformer and the influence of specific parts of the transformer, the following 5 different types of current transformer faults can be determined.
(1) Fixed deviation fault. A fixed deviation fault occurs when there is always a fixed deviation between the measured value and the true value.
(2) Drift deviation fault. The sensor head of an all fiber current transformer is easily affected by temperature, leading to a decrease in the performance of optical or electronic components, resulting in drift of measurement values over time. This drift is known as drift deviation fault.
(3) Variable ratio deviation fault. The ratio of a transformer represents the proportional relationship between the true value and the measured value. In practical applications, sudden changes in the ratio may occur due to changes in the operating environment and an increase in operating time, resulting in distortion of the transformer output signal. This situation is called ratio deviation fault.

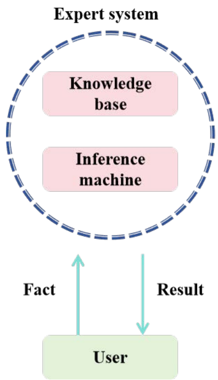

Fig. 3.1: Basic Principles of Expert Systems

(4) Accuracy distortion fault. The failure of the signal processing module and transmission unit of the all fiber current transformer can cause distortion in the accuracy of the measured values. When accuracy distortion occurs, the average measurement value remains unchanged and the measurement variance changes [10].
(5) Complete failure failure. Due to hardware circuit faults and optical component failures, the measured value of an all fiber current transformer does not change with the true value and always maintains a certain value (zero or maximum range value). This type of fault is called a complete failure fault.

3. Expert System for Fault Diagnosis of All Fiber Current Transformers . Expert system ES (Expert System) enables computer software systems to apply knowledge, facts, and reasoning mechanisms to solve complex problems that typically require human experts to solve. The expert system mainly consists of two parts: An expert knowledge base and an inference machine. Based on the facts provided by the user, the system uses certain inference methods to make inferences and judgments based on the knowledge base, and finally outputs the results [11]. The basic principle is shown in Figure 3.1.

3.1. Knowledge Base. The knowledge base is the fault knowledge base of all fiber current transformers, which is used to store domain expert knowledge and is a key factor in determining the performance of expert systems. The author's knowledge base consists of the following three parts:

1) FMEA Table. Using the FMEA table as expert knowledge, there is a certain connection between the component names, fault modes, fault consequences, and fault types in the table. By analyzing the output data of the transformer, the fault type and most of the fault consequence information can be obtained. Combined with a simple analysis of the transformer structure, the fault location can be determined, thus achieving fault diagnosis and providing corresponding response measures [12].

2) Fault clustering center. The fault situation of the all fiber current transformer can be reflected through the data obtained from its monitoring. For any all fiber current transformer, obtain the time-domain characteristics of its monitoring data, including rise time, fall time, pulse width, and duration; Frequency domain features refer to spectral peaks in the frequency domain; Shape parameters, namely skewness and kurtosis; And 11 feature quantities, including time center of gravity, equivalent duration, frequency center of gravity, and equivalent frequency width, are used to construct its feature vector for time-frequency joint features. Construct feature vectors for each fault case and classify them according to the fault type to form a feature space for that fault type. Finally, calculate the clustering center of this feature space and use it as a knowledge base.

3) Fault Tree. Using the fault tree as a knowledge base, after inferring the fault type of the tested current transformer, the FMEA table and fault tree can be combined to diagnose the fault of the tested current transformer, providing the fault location, fault consequences, and response measures.

3.2. Inference Machine. The inference machine provides results based on user input data, utilizing knowledge from the knowledge base and following certain inference rules. Rules are generally expressed as

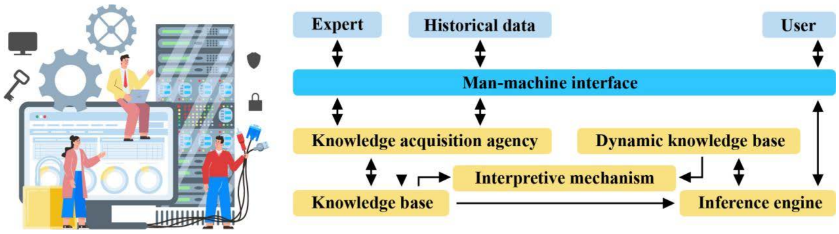

Fig. 3.2: Functional Structure of Expert System

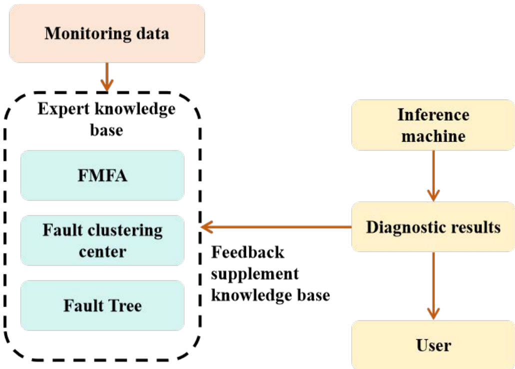

Fig. 3.3: Diagnosis process of expert system

IF-THEN, where IF is the premise and THE is the inference. When diagnosing faults in all fiber current transformers, the real-time monitoring values of the all fiber current transformer are taken as input, and then feature vectors are extracted to calculate the distance between this feature vector and each fault cluster center. The fault type with the smallest distance corresponds to the fault type of the all fiber current transformer [13]. Match the operating conditions (including operating conditions and environmental conditions) of existing all fiber current transformers with the basic events of the fault tree, and provide the final fault diagnosis result in combination with FMEA.

The functional structure and diagnostic process of the fault tree based all fiber current transformer fault diagnosis expert system based on fault mode and impact analysis method are shown in Figure 3.2 and Figure 3.3, respectively.

4. Fault diagnosis examples. Based on simulation data of mathematical models for various fault types and existing fault data of all fiber current transformers, a total of 5569 pieces of data were extracted. From these data, 11 quantities were extracted, including rise time, fall time, pulse width, duration, frequency domain spectral peak, skewness, kurtosis, time center of gravity, equivalent duration, frequency center of gravity, and equivalent frequency width, to construct feature vectors. Normalize the maximum and minimum values for each feature quantity to obtain the clustering centers of each fault type, as shown in Figure 4.1.

Extract the rise time, fall time, pulse width, duration, frequency-domain spectral peak, skewness, kurtosis, time center of gravity, equivalent duration, frequency center of gravity, and equivalent frequency width of all fiber current transformer fault cases obtained on site, and normalize them to obtain their corresponding feature vectors, as shown in Figure 4.2.

Calculate the Euclidean distance between the feature vectors of the fault cases in Figure 4.2 and the clustering centers in Figure 4.1, as shown in Table 4.1.

According to the calculation results in Table 4.1, it can be seen that the on-site fault case is closest to the cluster center of the drift deviation fault, so it belongs to the drift deviation fault. Further extract the

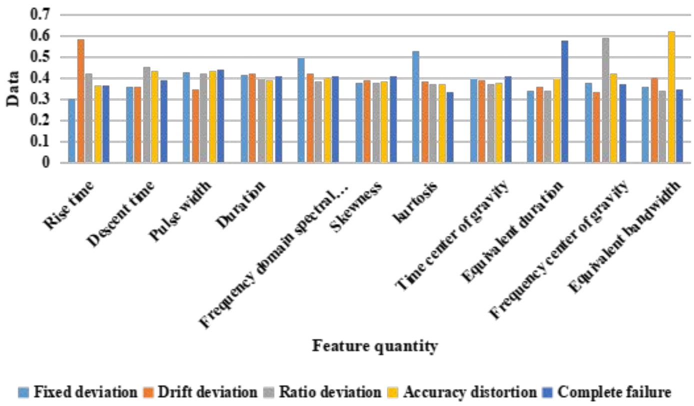

Fig. 4.1: Clustering center for each fault type

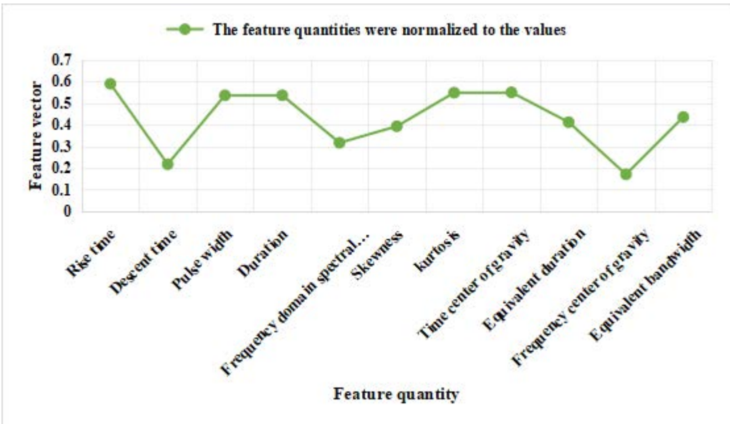

Fig. 4.2: Characteristic vector of the fault case

Table 4.1: Euclidean distance between the feature vectors of the fault cases and the cluster center of each fault type

Fixed deviation	Drift deviation	Change ratio deviation	Accuracy distortion	Complete failure
0.4914	0.4041	0.6112	0.5408	0.5042

on-site maintenance report, which indicates that the operating temperature of the all fiber current transformer is relatively high[14,15,16,17]. Therefore, a fault diagnosis conclusion can be drawn: The drift deviation fault of the all fiber current transformer may be caused by a decrease in fiber temperature performance or a decrease in sensor unit temperature performance. It is recommended to replace the fiber or conduct performance testing on the sensor unit[18,19,20]. This conclusion is consistent with the conclusion given in the on-site report of the all fiber current transformer that high temperatures lead to a decrease in the performance of the optical transmission system.

5. Conclusion. The author analyzed the impact of each part of the full fiber current transformer on overall stability, provided a reliability diagram of the full fiber current transformer, and analyzed the types of faults from the perspective of monitoring data, constructing a fault mode and impact analysis Table. A fault tree for all fiber optic current transformers was constructed based on the fault mode and impact analysis table for qualitative analysis of faulty current transformers. A fault diagnosis expert system for all fiber current transformers is proposed, which uses the clustering center, FMEA table, and fault tree of the faulty current transformer as the knowledge base of the expert system. Based on the corresponding inference rules, any all fiber current transformer is diagnosed, and the fault type, fault mode, fault component, and corresponding response measures are provided. The on-site fault case verified the usability of the method proposed by the author.

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