Design of Fast Fault Diagnosis System for Transformer Equipment based on CBR and RBR

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Abstract. After studying the common defects and faults of transformers, we design and propose a fast fault diagnosis system for transformer equipment based on CBR(Case-Based Reasoning) and RBR(Rule-Based Reasoning). In the system, test cases are firstly matched with the cases. If there are similar cases, CBR is used to obtain the diagnosis conclusion. If there are no similar cases, the rule reasoning module based on FTA (Fault Tree Analysis) is launched. This module subdivides transformer fault modes into winding, core, bushing, on-load tap changer, cooling system, non-electric protection and other fault modes, and forms rules. Based on this situation, a transformer equipment fault tree is established to serve the rapid diagnosis system. The structural characteristics and fault modes of transformer windings, iron cores, bushings, on-load tap changers, cooling systems, non-electrical protection and other equipment are subdivided. And then, a fast fault diagnosis model and system for transformer equipment are established. Finally, the case study proved that the system can diagnose and analyse the equipment faults based on the comprehensive multi-source data of transformers, and the diagnosis conclusion is reliable and practical, which has provided support for realizing the state maintenance of transformers.

1. Introduction
Transformer is one of the most important devices in the power grid. Its operation state is related to the stability of the whole power system. However, because of the diversity and uncertainty of transformer fault, the fault diagnosis of transformer has always faced a lot of challenges in the power industry. At present, the common methods of transformer fault diagnosis include dissolved gas in oil analysis (DGA), improved three ratio method and David triangle analysis method. However, these methods have some problems, such as fuzzy diagnosis conclusion, difficulty in accurate fault location, etc., which cannot meet the needs of on-site operation and maintenance [1].

In recent years, the use of artificial intelligence technology for fault diagnosis has become a research hotspot, such as the use of artificial neural networks, support vector machines, genetic algorithms and other fault data training modelling to get a prediction model for fault prediction. For example, in reference [2], the ratio of dissolved gases in oil is taken as the eigenvector, and use the method of combining particle swarm optimization algorithm and multi-classification vector machine algorithm to train the model for fault diagnosis. In reference [3-4], a bi-directional fault diagnosis method is proposed by combining convolutional neural network with answer set program. However, this kind of algorithm needs big data to train the model, and there will be insufficient data in practical
application, which makes the trained model have low accuracy, and the degree of diagnosis refinement is not enough.

In recent years, the diagnosis method based on rough set theory, Bayesian theory and decision theory has become a popular method of fault diagnosis and analysis. This kind of method attempts to integrate the information of chemical test data, electrical analysis data and patrol inspection data of transformer, and establish a relationship network to calculate the potential fault of transformer, such as reference [5-7]. However, the causal relationship between transformer fault and characteristic factors is not clear, which needs a lot of expert experience to support, and the reliability of fault model is low.

In conclusion, this paper proposes and designs a transformer fault fast diagnosis system based on case-based reasoning (CBR) and rule-based reasoning (RBR). The system makes full use of historical experience to establish case base and rule base based on fault tree analysis (FTA). Through CBR and RBR, comparative analysis of cases with diagnosis and historical cases to obtain fault conclusions, save time and cost. Through the way of adding new cases, the case base is constantly evolving, effectively improving the reliability of the system.

2. Framework of fast fault diagnosis system

The basic idea of the transformer fault fast diagnosis system is to use the transformer account data, operation data, fault data and historical case information as the system input, and then use the diagnosis model to evaluate the operation state of the transformer and diagnose the latent fault, and get the fault diagnosis results and solutions. In this paper, a transformer fault fast diagnosis system based on CBR and RBR is designed and established. The system framework is shown in Figure 1, which includes user layer, fault diagnosis layer, case base layer and rule layer.

![Figure 1. Framework of fast fault diagnosis system](image)

2.1. User layer

The user layer is the top layer of the system, including four modules: input fault data module, fault pre-processing module, fault handling module and result feedback module. The user in this system...
refers to the power grid operation and maintenance personnel, who is mainly responsible for recording and pre-processing the fault phenomenon, then inputting the standardized record to the fault diagnosis layer, and putting forward the fault query requirements. After getting the diagnosis result, the maintenance personnel need to find out the cause of the fault and solve the fault. If the rule already exists in the case base, the next operation is not needed; if the rule is different from the case base or a new rule, the rule is fed back to the fault construction layer in time to update the case base, so as to improve the service quality.

2.2. Fault diagnosis layer
The fault diagnosis layer is responsible for fault diagnosis according to the fault phenomenon input by the user layer and feedback the diagnosis results to the user. It is the core of the diagnosis system, including two main modules: the fault diagnosis module based on CBR and RBR and the fault type and solution output module. The former can be divided into two sub modules: case matching module and rule reasoning module. The core of the fault diagnosis module based on CBR and RBR is to use CBR and RBR serial reasoning to diagnose the fault and output the diagnosis result. The output module of fault types and solutions is mainly responsible for outputting fault diagnosis results, including fault causes, fault solutions and other information to users, which belongs to the interactive interface between fault diagnosis layer and users.

2.3. Case base layer
The case base layer is the bottom knowledge base of the system, which is responsible for collecting and archiving the fault phenomena, fault causes, fault types and fault solutions of transformer fault cases, as well as updating the case base, so it includes two modules: phenomenon case mapping module and case base updating module. According to the historical fault diagnosis experience, the case mapping module collects the cases, including the mapping relationship among the fault phenomenon, cause, type and the practical solutions. When new fault diagnosis is carried out in the future, similar cases can be provided for the fault diagnosis layer, if any, experience can be used for reference, so as to avoid repeated reasoning. The case update module is responsible for collecting and storing new cases, updating and evolving the case base in time.

2.4. Regular layer
The rule layer is also the bottom rule base of the system, which is responsible for the generation and management of rules. Its core is the rule generation module. This paper adopts the rule generation model based on FTA. The rules generated by this module serve the rule reasoning module of the fault diagnosis layer.

3. Fault diagnosis model

3.1. Fault diagnosis model based on CBR and RBR
The idea of this paper is to use the method of case matching and rule-based reasoning to search case base and similar cases according to input fault phenomenon. If there is similarity, diagnosis results and corresponding maintenance strategies can be obtained quickly. If there is no suitable similar case, rule-based reasoning will be started, and finally the result of reasoning will be output as the diagnosis result.

Step 1: fault data input. The user inputs the description information of the characteristic attributes of the transformer fault data and puts forward the query requirements.

Step 2: data pre-processing. Before fault diagnosis, due to the inconsistent attribute description of fault phenomenon, it is necessary to pre-process the description information of fault phenomenon to obtain the unified and standardized characteristic value of fault phenomenon.

Step 3: case base matching. According to the characteristics of fault phenomenon, we retrieve the fault case database, use the matching algorithm to match the cases, and call the cases similar to the cases to be diagnosed in the case database for fault diagnosis. If there are similar cases, the case with
the largest similarity is used as a template to call the case for diagnosis results output. If there is no similar case, we start the fourth stage of rule-based reasoning algorithm based on FTA.

The process of case retrieval and matching can be divided into four steps: case feature recognition, case index, initial matching, case selection. We are responsible for sorting according to similarity from multiple similar cases, preferentially selecting the most similar cases for diagnosis, and finally outputting matching results to prepare for the next step of outputting diagnosis results.

Step 4: rule reasoning based on FTA. In this step, the rule-based reasoning model based on FTA is adopted, and the rule conclusion generated by reasoning is taken as the diagnosis result of the case to be detected. The core idea of the model is: according to the previous experience of experts, all cases are induced to generate rules by using fault tree, and then the inference method based on rule engine is used to match the fault phenomenon, data and rule base to infer the diagnosis conclusion.

Step 5: output the diagnosis result. This stage is responsible for generating fault diagnosis results according to the previous methods (matching to the most similar cases, or using rule-based reasoning model), and then outputting the relevant result information, such as fault diagnosis results, possible fault causes and solutions, to guide the next operation.

Step 6: update the case base. According to the new fault information diagnosed by the system, we update and maintain the case database.

Step 7: diagnosis result feedback. The final fault diagnosis result information is fed back to the system user.

3.2. Rule generation model based on FTA
Fault tree is established as a framework application structure. Each fault node is unique in the fault tree, and its input, attribute, algorithm and output can be configured as required. The diagnosis process is to judge the fault tree node first, and then to judge the fault node comprehensively. The transformer fault can be divided into winding fault, core fault, casing fault, etc [8,9].

3.2.1. Winding failure
The fault modes of transformer winding can be divided into short circuit, open circuit, looseness, deformation, displacement and burning loss. Among them, winding short circuit can be divided into layer short circuit, turn short circuit, cake short circuit and strand short circuit. Most of the winding faults are caused by the unreasonable structure and insulation of the winding itself. The short circuit of the winding has the highest probability, which not only involves the winding itself, but also has a great impact on the core, lead wire, insulation screen, etc. When the winding is short circuited, there will be partial high temperature or high energy discharge in the transformer.

3.2.2. Core failure
During the normal operation of power transformer, the core must be grounded reliably, otherwise the suspended voltage of core to ground will cause intermittent discharge of core. When the core is grounded at two or more points, circulation will be formed in the core, resulting in local overheating or even burning loss of the core. The main causes of the core failure are the multi-point grounding caused by the foreign matters and damp in the box; the partial short circuit of the core caused by the insulation damage between the laminations; the grounding strip fusing, the suspension discharge caused by the poor grounding, etc.

3.2.3. Casing failure
The casing is affected by electric field, wind and rain, pollution, etc. for a long time, and it is also the place where transformer faults occur frequently. The failure modes of casing mainly include oil leakage, porcelain bushing flashover, insulation damp, casing heating caused by poor contact of guide rod, suspension discharge caused by poor grounding of casing end shield, resulting in partial insulation carbonization.
4. Case analysis and results

Since a 110kV transformer was put into operation in 2010, it has been impacted by external short circuit of medium voltage and low voltage side for many times. Especially from April 2018 to August 2019, there were 22 trips of high-voltage circuit breaker caused by external short-circuit of medium voltage and low-voltage side of transformer, and the short-circuit impact was very serious. The analysis results of oil chromatogram of transformer over the years are shown in Table 1, and acetylene gas appears in the oil. In 2019, the preventive test found that the winding capacitance as shown in Table 2 respectively.

Table 1. Oil chromatogram analysis result (unit: µL/L)

| Date       | Hydrogen | Acetylene | Total hydrocarbon | Carbon monoxide |
|------------|----------|-----------|-------------------|-----------------|
| 2010.6.6   | 0        | 0         | 1.5               | 18              |
| 2019.4.22  | 1.4      | 0.4       | 5.6               | 365             |
| 2018.10.6  | 15.3     | 1.1       | 50.3              | 110.3           |
| 2019.9.13  | 43       | 3.4       | 75.3              | 1344            |

Table 2. Test value of winding capacitance (unit: PF)

| Test winding                      | Tested in March 2014 | Tested in October 2019 | Capacitance increased in 2019 |
|----------------------------------|----------------------|------------------------|------------------------------|
| High voltage - medium, low voltage and ground | 8743                 | 8234                   | −5.8%                        |
| Medium voltage - high, low voltage and ground | 15043                | 17723                  | +17.8%                       |
| Low voltage - high voltage, medium voltage and ground | 15437                | 18097                  | +17.2%                       |

According to the test results of winding capacitance in Table 2, the capacitance of high voltage to medium and low voltage and ground decreases, the capacitance of medium voltage to high and low voltage and ground rises, the capacitance of low voltage to medium and high voltage and ground rises, and the capacitance between windings is inversely proportional to its geometric distance, so the inward shrinkage deformation of medium voltage winding can be judged.

After the above state information is input into the system, the output result of the fault diagnosis model shows that the transformer may have deformation.

The disassembly inspection of the transformer confirmed that the three-phase medium voltage and low-voltage windings had obvious deformation, especially the medium voltage c-phase winding, which verified the effectiveness of this method, as shown in Figure 2.

5. Conclusions

In this paper, we study the common defects and failure modes of transformer, expert diagnosis experience, classic diagnosis algorithm, and design a series transformer equipment fault fast diagnosis
system based on CBR and RBR. Through the case study, this method and system can guide the diagnosis of transformer fault and provide guidance for equipment maintenance decisions.

Acknowledgments
This work was supported by 2018 intelligent manufacturing special project of ministry of industry and information technology of the people's Republic of China "research and test verification of remote operation and maintenance standard for power transmission and transformation equipment"(524625180050).

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