Exploration of Transformer Operation and Maintenance Technology and Realization of Transformer Condition Monitoring System

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Abstract. With the increasing complexity of the power grid, the transformer has become a key component of the power system and plays an irreplaceable role in the reliable and safe operation of the power system. The working environment of the power system is very harsh in the process of power supply and distribution tasks, which makes many transformers in the power system face the problem of frequent failures. This situation affects the normal operation of the transformers in the system. Therefore, the power company needs to focus on the condition monitoring and fault diagnosis of transformers. In view of this, analyzing the condition monitoring and fault diagnosis technology in the use of large-scale transformers is beneficial to deal with various problems of the transformer in time, and accurately grasp the operating status of the transformer. Therefore, it can improve the operational reliability of the transformer. It is of great significance to reduce the failure of the power system.

Keywords: Transformer · Condition Monitoring · Fault Diagnosis

1 Introduction

With the increasing power demand and the complex grid structure, more and more power equipments and facilities are involved in the power grid in order to meet the power demand. The main transformer has multiple functions such as power transmission, power distribution and voltage conversion in the power grid. If a fault occurs, it will affect the normal power supply and distribution, and bring extremely adverse effects on people's production and life. Therefore, in order to ensure the normal operation of main transformers in the power grid and improve their reliability, the modern technology should be used to monitor the status of transformers and diagnose their faults, so as to deal with abnormal conditions of transformers quickly and make them to return to normal at the first time.

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2 The Reasons of Transformer Fault

2.1 Equipment Aging

Aging of transformer components is one of the causes of transformer fault. During the use of the transformer, if the transformer is not replaced for a long time, its normal operation will be affected due to the aging of the components. According to the survey, the insulation facilities in the transformer are the most prone to aging, resulting in poor insulation of the transformer. So it can not play its real role in the power grid, and even may lead to a series of electricity safety accidents. Therefore, during the use of the transformer, professional staff should pay attention to the working condition of the transformer, strictly prohibit overload operation, and replace the aging facilities in time.

2.2 Influence of Weather

Affected by the function and volume of the transformer in the power grid, most transformers are generally arranged in the outdoor environment, so that the transformer is often disturbed by the weather factors during operation. In extreme weather, transformers will not be able to maintain normal operation and break down frequently. For example, in thunderstorms, the frequency of transformer failures is very high than usual.

2.3 Management and Maintenance

Routine management and maintenance can effectively eliminate various faults in the operation and use of the transformer, and it can ensure the normal operation of the transformer. However, some power companies neglect the management and maintenance of transformers in their daily work, and just arrange for professional maintenance after the fault occurs, but that can not achieve the goal of preventive management and maintenance, which can easily cause various problems in the operation of transformers.

3 Development Status of Transformer Condition Monitoring Technology

Effective condition detection technology can analyze and monitor every running component by comprehensive and accurate data, and then find out the potential problems in the operation process of the main transformer in time. The equipment maintenance personnel can repair and adjust the equipment in time to avoid failure impact on the entire power system before the fault occurs. The main transformer maintenance work is mainly in operation by the online monitoring and analysis technology to realize the goal of monitoring the operation process. In general, the most common related techniques are as follows:

3.1 Online Monitoring and Analysis Technology for Oil and Gas

The principle of the online monitoring technology is that in case of main transformer fault, the released gas is different when the causes of the fault are different. The common gases include C2H2, C2H4, Co, CH4, H2, and C2H6, etc. This method uses oil chromatogram sampling and analysis technology to analyze the type and content of the released gas, then the cause of the fault shall be analyzed accordingly. At present, the oil and gas analysis technology has realized online real-time monitoring, and the real-time sampling and separation of the gas released from the transformer can be realized in the operation room, which greatly improves the detection efficiency and accuracy of the main transformer, and the probability of failure is controlled in a very low range.

When detecting the state of the main transformer, the single detection technology still has some limitations. Therefore, a variety of detection technologies should be comprehensively applied according to the actual situation of the substation, so as to have a comprehensive and accurate analysis of the operation state of the main transformer (Table 1).

Table 1. Gas components generated by different fault types

Fault type	Main gas composition	Secondary gas composition
Oil overheating	CH_4, C_2H_4	H_2, C_2H_6
Local discharge in oil paper insulation	H_2, CH_4, C_2H_2, CO	C_2H_6, CO
There are air bubbles in the oil or the water is damp	H_2	
Arcing in oil	H_2, C_2H_2	CH_4, C_2H_4, C_2H_6
Spark discharge in oil	CH_4, C_3H_4, CO, CO_2	H_2, C_2H_6
Oil and paper overheating	CH_4, C_3H_2, CO, CO_2	CH_4, C_2H_4, C_2H_6

3.2 Online Partial Discharge Monitoring Technology

During the operation of the main transformer, partial discharge may occur sometime. This means that a certain part of the main transformer has failed. Because the energy consumption of the transformer is relatively large, and local problems are difficult to be found in time. If the fault is not solved in time, it may lead to more serious failure of the power system. The current partial discharge online detection system often detect transformer fault with optical, acoustic and electrical means. Where acoustics sensor with its good sensitivity, it is widely used in the main transformer during the device status detection. This detection technology mainly captures the change of sound wave during partial discharge, then converts it into partial discharge signal, and finally analyzes the signal by the information receiving system, so as to realize the detection of partial discharge.

3.3 Online Temperature Monitoring Technology

During the operation of the main transformer, different parts will emit certain heat, and the heat released by the main transformer during normal operation shall be maintained at a relatively constant level. When a part of the main transformer voltage is not normal during operation, the released temperature will change accordingly. The temperature online inspection technology makes use of this characteristic to install the temperature sensor in the main transformer, and the real-time detection is carried out for different positions of the device. During the detection, the temperature sensor will present its perception of temperature as different optical transmission characteristics. After that, it will be converted into laser signal through the detection device to realize the temperature detection for different positions. This detection method can detect different positions of the main transformer at the same time and the effectiveness of detection is improved greatly.

3.4 Infrared Technology

With the continuous progress of science and technology, infrared technology has been widely used. With the support of the principle of infrared technology, a variety of equipments have been developed, such as thermometers and night vision devices. Infrared technology is very effective in fault diagnosis of main transformers. When detecting the internal structure temperature of the transformer, professionals can directly complete the detection through infrared ray, which not only shortens the detection time, but also ensures the accuracy of the temperature measurement results. After the detection, the fault can be analyzed and determined by comparing the obtained temperature parameters with the standard temperature parameters. Generally, infrared technology has outstanding advantages in transformer thermal fault diagnosis and identification. The types of thermal faults include internal thermal faults and external thermal faults. When using infrared technology to analyze external thermal faults, the process of fault identification is to scan and image first, and then analyze the imaging results. When diagnosing an internal thermal fault, the approximate location of the fault can be determined through thermal imaging analysis, and then accurate analysis, positioning and related processing can be carried out.

3.5 Vibration Analysis Technology

During the operation of transformer, the hysteresis expansion of silicon steel sheet affects the operation of transformer, which will cause certain vibration at the core of transformer. At the same time, due to the electric field of load current, the winding will also make certain vibration. With the continuous operation of the transformer, these two kinds of vibrations will be transmitted to the oil storage tank, causing the tank vibration. For such faults, vibration analysis technology can be used to complete the fault analysis process. Professionals can monitor the vibration signal in the oil tank in real time for reverse fault analysis, so as to quickly find out the problems that may be encountered by the main parts of the transformer. When using vibration analysis technology in transformer fault diagnosis, it is necessary to install the vibration sensors on the oil tank wall to collect and analyze the vibration signal, so as to improve the detection accuracy.

4 Multi-source Information Fusion Technology

Information fusion, also known as data fusion, is an information processing theory based on multi-sensor system problems. The general definition of information fusion is as follows, ordinate, optimize and comprehensively process the information from multiple sensors or sources, generate new valuable information, and draw more accurate and credible conclusions based on this. It can be seen that multi-sensor is the basis of information fusion, multidimensional information is the object of information fusion, and coordinated optimization and comprehensive processing are the core of information fusion. The process of information fusion can usually be divided into three levels: data fusion, feature fusion and decision fusion. These three levels represent the degree of mining the original data information.

1) Data fusion
   Data fusion is the fusion of raw data that has not been preprocessed and has just been collected. It belongs to the lowest level of information fusion. The fusion of data level can retain the original data information to the greatest extent, and its data information is richer than the feature fusion and decision fusion. However, due to the retention of a large amount of original data information, the amount of redundant data is also very large, which requires a long processing time. It can make high processing cost, and has poor real-time tracking ability.
2) Feature Fusion
   Feature fusion is the fusion of the extracted feature information after the collected original data is extracted by a certain preprocessing method. It belongs to the middle level of information fusion. The feature fusion is equivalent to compressing the original data, eliminating the non decisive information, mining the most important feature information, and taking this as the basis to provide the basis for decision-making analysis to the greatest extent. Compared with data fusion, its flexibility is enhanced and the processing cost is reduced.
3) Decision Fusion
   Decision fusion is the highest level of information fusion, the highest level of abstraction, and the most widely used. It is to fuse the perceptual information from completely different types of sensors or from different environmental regions into the final global decision. The decision fusion requires the data fusion and feature level to provide support, and the resulting results directly determine the level of decision-making. Its advantage is that it has strong fault tolerance. Even if there are errors or contradictions in the relevant information, the correct results can be obtained by selecting the appropriate fusion method.

Compared with traditional single source data, multi-source information fusion technology enhances the credibility of system information, improves the accuracy of data, and makes the system have better situational awareness and reasoning ability, and faster response time. From the perspective of cognition, multi-source information fusion is a process of gradual transformation from the energy of real physical space to the data (Fig. 1).

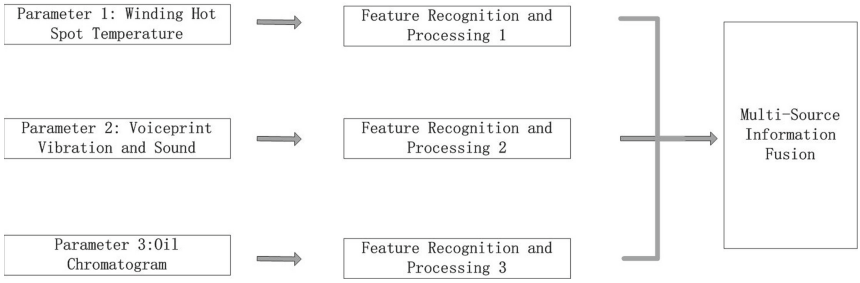

Fig. 1. Multi-Source Information Fusion

5 Development of Transformer Condition Monitoring System

The transformer condition monitoring system adopts a transformer state evaluation method based on multi-source information, including the following steps.

At first, it acquires transformer operating status information which includes the transformer winding hot spot temperature, voiceprint vibration, sound and oil chromatography information of the transformer. Then it uses fuzzy sets to evaluate the operating state information to obtain performance evaluation results of each state of the transformer. The D-S evidence theory is used to fuse the performance evaluation results of each state of the transformer to obtain multi-source fusion information. Then it calculates the life loss of the transformer based on the winding hot spot temperature of the transformer. Based on the multi-source fusion information and the life loss of the transformer, a state of health of the transformer is predicted. At last, the multi-source fusion information and the life loss of the transformer are transmitted as the input of the mathematical model of the transformer health state, and the result of the dependent variable is obtained. According to the result of the dependent variable, the health state of the transformer is determined.

The transformer condition monitoring system can accurately judge transformer operation status by integrating multi-source information such as transformer winding hot spot temperature, transformer voiceprint vibration, sound, and transformer oil chromatography, and combine transformer operation status and transformer life loss to generate and correct transformer operation assistance decision-making basis, providing the power grid operation and maintenance personnel with the decision-making basis for the safe and economical operation of transformer, and it can accurately predict the operating state of the transformer.

In order to obtain the operation status information of the transformer, it should collect the top oil temperature of the transformer, the ambient temperature of the substation and the load current of the transformer, and calculate the winding hot spot temperature of the transformer by using the GB standard differential equation solution.

It can collect the sound information when the transformer is running, and determine the transformer's voiceprint characteristics according to the sound information to obtain the voiceprint vibration and sound of the transformer.

It also should extract transformer oil and separate oil and gas, to analyze the content of fault characteristic gas dissolved in the oil, and obtain the oil chromatogram of the transformer.

At last, the D-S evidence theory is used to fuse the state performance evaluation results of the transformer to obtain multi-source fusion information, which is specifically realized by the following formula:

$$\mathrm{M}(\Phi) = 0$$

$$M(A) = \sum\nolimits_{A_1 \cap A_2 \cap \ldots \cap A_n = A} m_1(A_1).m_2(A_2)\ldots m_n(A_n) + \frac{k\varepsilon}{n} \sum\nolimits_{i=1}^{n} m_i(A)$$

$$\mathrm{m}(H) = \sum\nolimits_{A_1 \cap A_2 \ldots \cap A_n = H} m_1(A_1).m_2(A_2)\ldots m_n(A_n) + k(1-\varepsilon)$$

$$\mathrm{k} = \sum\nolimits_{A_1 \cap A_2 \cap \ldots \cap A_n = \Phi} \mathrm{m}_1(\mathrm{A}_1).m_2(A_2)\ldots m_n(A_n)$$

where, the finite set **H** represents the identification framework, that is all possible results, **A** is the subset of **H**, $\mathbf{m_n}$ **(A_n)** is the basic probability number of **A**, which represents the trust degree that the evidence supports the occurrence of proposition **A. M** is the basic probability assignment function, **k** is the conflict coefficient between evidences, **ε** is the reliability, **n** is all possible results, $\Phi = \mathrm{A}_1 \cap \mathrm{A}_2 \cap \ldots \cap \mathrm{A}_n$.

Based on the winding hot spot temperature of the transformer, the life loss of the transformer is calculated by the following formula:

$$L = \int_{t_1}^{t_2} V dt$$

where, **V** represents the relative aging rate of transformer thermal modified paper, and the calculation formula is:

$$V = \mathrm{e}^{\left(\frac{15000}{110+273} - \frac{15000}{\theta_h+273}\right)}$$

where, $\boldsymbol{\theta_h}$ refers to the hot spot temperature of transformer, $\mathbf{t_1}$ refers to the moment before the transformer operates and $\mathbf{t_2}$ refers to the moment after the transformer operates.

A transformer state evaluation device based on multi-source information is adopted. It includes an acquisition module for acquiring the operation state information of the transformer, which includes the winding hot spot temperature, voiceprint vibration, sound and oil chromatogram of the transformer. The evaluation module is used to evaluate the operation state information by using fuzzy set, and obtain the performance evaluation results of each state of the transformer. The fusion module is used to fuse the performance evaluation results of each state of the transformer by using D-S evidence theory to obtain multi-dimensional fusion information. A life loss calculation module is for calculating the life loss of the transformer based on the winding hot spot temperature of the transformer. And a prediction module for predicting the health state of the transformer based on the multi-source fusion information and the life loss of the transformer (Figs. 2 and 3).

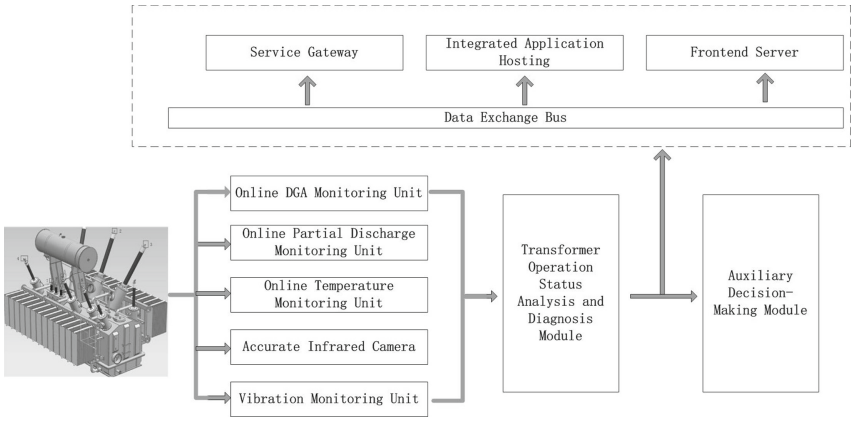

Fig. 2. System Schematic Diagram

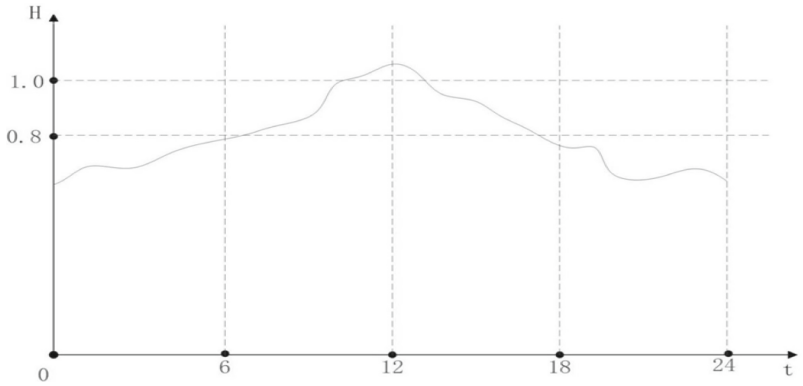

Fig. 3. Real Time Health Status of Transformer

The advantages of this system is that the operation state of the transformer can be accurately judged by integrating multi-source information such as transformer winding hot spot temperature, transformer voiceprint vibration and sound, and transformer oil chromatogram. Combined with the operation state of the transformer and the life loss of the transformer, the auxiliary decision-making basis for transformer operation can be generated and corrected, which provides the decision-making basis for safe and economic operation of transformer equipment for power grid operation and maintenance personnel, and the operation state of the transformer can be accurately predicted (Fig. 4).

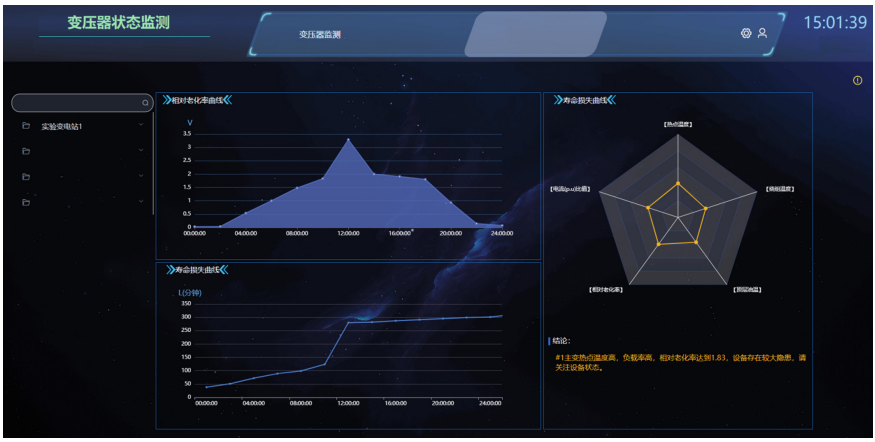

Fig. 4. Main Interface of Transformer Condition Monitoring System

6 Conclusion

This paper discusses the advanced condition monitoring and fault diagnosis technology and the fusion of multi-source data. With the transformer condition monitoring system, the people can discover the abnormal transformer operation in time, so as to improve the operation reliability of large transformers and reduce the huge losses caused by transformer faults. In the process of technology integration, according to the needs of actual work, a variety of advanced technologies can be comprehensively applied to achieve the monitoring and control of transformer. The development trend of intelligent technology will become an important development direction of transformer operation and maintenance technology in the future.

References

1. Liu, H., Mei, G.: Large transformer condition monitoring fault diagnosis technology. Mod. Manuf. Technol. Equip. **57**(08), 181–182 (2021)
2. Shen, Y., et al.: Application of data fusion technique in status assessment of transformers. Electr. Autom. **39**(04), 84–87 (2017)
3. Xia, Y., Guo, C., Chen, Y., Yang, Y., Liu, H.: Evaluation model of transformer overload capacity considering multi-factors. J. Mech. Electr. Eng. **34**(05), 509–514 (2017)
4. Xu, Q.: Transformer State Assessment and Fault Diagnosis Based on Information Fusion. Shang Hai Dian Ji University (2019)
5. Yong, M., et al.: Research on condition evaluation algorithm of oil-immersed transformer based on Naive Bayes. J. Phys. Conf. Ser. **2196**(1) (2022)
6. Yang, B., Lei, Y., Jia, F., Xing, S.: An intelligent fault diagnosis approach based on transfer learning from laboratory bearings to locomotive bearings. Mech. Syst. Signal Process. (2019)
7. Gan, T., Zheng, J., Zhang, Y., Zhang, C., Huang, M., Li, Z.: Transformer condition identification based on domain adaptation. Smart Power **50**(02), 82–88 (2022)
8. Han, T., Liu, C., Yang, W., Jiang, D.: Deep transfer network with joint distribution adaptation: a new intelligent fault diagnosis framework for industry application. ISA Trans. **97**(C) (2020)

9. Dai, J., Song, H., Yang, Y., Sheng, G., Jiang, X.: Dissolved gas analysis of insulating oil for power transformer fault diagnosis based on re LU-DBN. Power Syst. Technol. **42**(02), 658–664 (2018)
10. Yang, T., Zhang, H., Huang, L., et al.: Incipient fault diagnosis based on improved principal component analysis for power transformer. Electr. Power Autom. Equip. **35**(6), 149–153, 165 (2015)
11. Wu, Y., Sun, X., Zhang, Y., Zhong, X., Cheng, L.: A transformer fault diagnosis based on improved squirrel search algorithm and support vector machine. J. Phys. Conf. Ser. **2203**(1) (2022)
12. Zhou, Y., Tao, L., Yang, X., Yang, L.: Novel probabilistic neural network models combined with dissolved gas analysis for fault diagnosis of oil-immersed power transformers. ACS Omega **7**(1) (2022)
13. Zhu, Y., et al.: Analysis of 220kV oil immersed inverted current transformer fault and precautions during operation. In: Proceedings of 2017 2nd International Conference on Automation, Mechanical Control and Computational Engineering (AMCCE 2017), pp. 776–779 (2017)