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DGA and Weibull Distribution Model-based Transformer Fault Early Warning

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DGA and Weibull Distribution Model-based Transformer Fault Early Warning

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Abstract：As an important power transmission and transformation equipment, transformer fault has a great impact on the safe and stable operation of smart grid and probably incurs serious consequences. Therefore, how to detect and warn the fault of transformers as early as possible becomes particularly critical. In this paper, a fault early warning method based on DGA and Weibull distribution model is proposed for a large number of transformers in smart grid and the calculation formulas of the attention value and warning value of transformer fault are given. First, the defect rate and fault rate of transformers can be obtained by analysing the transformer maintenance data. Then, the attention value and warning value of transformer fault are calculated with the Weibull distribution model according to the gases volume distribution of oil chromatographic data, which provides an effective method for the transformer fault early warning. The actual case study shows that the proposed method can effectively achieve the transformer fault early warning.

1. Introduction

The operation reliability of transformer is directly related to the safe and stable operation of power system, and the power outage accident caused by transformer fault will bring about huge economic losses. At present, the on-line monitoring technology of transformer based on dissolved gas analysis (DGA) has attracted extensive attention of scholars all over the world. By real-time monitoring the volume fraction and production rate of dissolved gases in transformer oil, the on-line monitoring system can achieve the early warning of transformer fault. To improve the early warning accuracy of transformer, the attention value and warning value of transformer fault should be determined more accurately. This paper proposes an early warning method of transformer fault based on DGA and Weibull distribution model by processing the transformer oil chromatographic data, analysing the defect rate and fault rate of various transformers, fitting the data distribution of transformer oil chromatographic data and calculating the attention value and warning value of transformer fault, and verifies the effectiveness of the proposed method by a case study with actual transformer operation data. The case study indicates that the attention value and warning value calculated by the proposed method can reduce the false alarm and missed alarm and improve the accuracy of transformer fault early warning.

The rest of this paper is organized as follows. This paper begins with the related works in Section 2 and introduces the DGA and Weibull distribution model-based transformer fault early warning method in Section 3. In Section 4, we conduct a case study to compare the calculation result of the proposed

method with the actual situation of operating transformers in a regional substation. Finally, the conclusion is drawn with discussion in Section 5.

2. Related Works

At present, several common methods of DGA in transformer oil are linear regression, grey theory, machine learning and combination analysis. Zhao and Wang respectively use the methods of one-time fitting and linear interpolation to transform the dissolved gas sequences within unequal time interval into the dissolved gas sequences within equal time interval, and achieve good prediction of transformer faults by exponential smoothing and background value modification [1,2]. Xiao et al. use a grey system to analyze the correlation between other dissolved gases and the dissolved gases to be predicted, and select the dissolved gases that have higher correlation with the dissolved gases to be predicted as the input of the grey system to improve the prediction accuracy [3]. Mao uses a weighted Markov model to improve the prediction accuracy of the grey multivariable model [4]. BP algorithm, genetic algorithm and Kalman filter algorithm are used to establish the prediction model of DGA in transformer oil, and three prediction algorithms are often weighted and combined to optimize the prediction accuracy [5,6]. Mortada et al. use quantum genetic algorithm to obtain high quality initial values, and then use Levenberg-Marquart algorithm to optimize the threshold and weight of multi-layer feedforward neural network [7]. Zhu et al. combine the advantages of grey system and least squares support vector machine to accumulate the original sequence of dissolved gases in oil into a sequence with certain regularity [8].

3. The Early Warning of Transformer Fault based on DGA and Weibull Distribution Model

As shown in Figure 1, to calculate the attention value and warning value, we should first differentiate and classify the large number of transformer oil chromatographic data according to the transformer voltage level, and then use the curve fitting method to construct the distribution model of the transformer oil chromatographic data. Finally, the cumulative probability is correlated with the defect rate and fault rate of transformer, and the inverse cumulative distribution function is used to. The corresponding threshold is calculated as the attention value and warning value to achieve the fault early warning of transformer in operation.
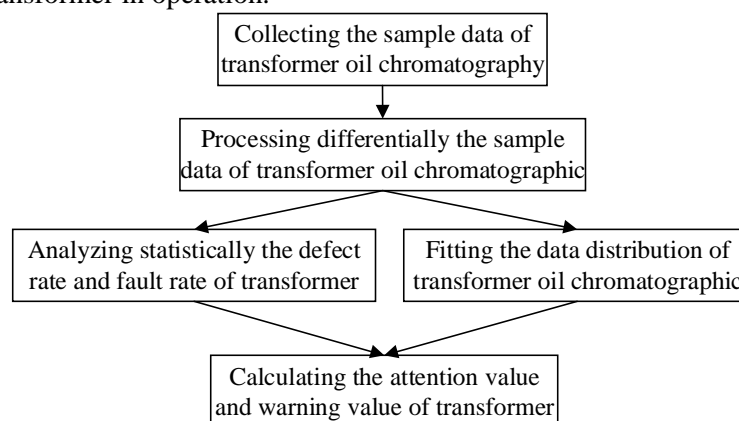

Figure 1. The early warning of transformer fault based on DGA and Weibull distribution model

3.1. Processing Differentially the Sample Data

The sample data collected by various transformer sensors and stored in an on-line monitoring system mainly include *account information*, *fault records* and *oil chromatographic data*. The account information inlcude substation name that transformer belongs to, transformer types, voltage level, pollution level, transformer manufacturers and transformer oil manufacturers, etc. The fault records includes substation name that transformer belongs to, installation location and number, operation time, connection mode and specific defect descriptions, etc. The oil chromatographic data include the type and number of oil chromatographic sensors, data acquisition time, dissolved gases volume and total

hydrocarbon volume. Considering that voltage level is one of the most basic characteristic attributes of transformer, the oil chromatogram data integrated with account information and fault records is taken as the characteristic data and classified according to the voltage level of transformer.

3.2. Analyzing Statistically the Defect Rate and Fault Rate
After pre-processing the sample data, it is indispensable to statistically analyse the defect rate and fault rate of transformers under each voltage level. Defect rate and fault rate are two important indicators to describe the potential risks of transformers. Herein, the defect and fault refer respectively to the defect and fault types of transformers related to the oil chromatography data. Besides the admission acceptance report data of transformers, the actual operation data and daily overhaul data of transformer should be synthetically considered so as to analyse the defect rate and fault rate of transformer as accurately as possible.

3.3. Fitting the Data Distribution of Oil Chromatographic
Histogram can reflect the frequency distribution law of the sample data, which is called frequency distribution histogram or frequency histogram. The distribution of oil chromatographic data is easily fitted with frequency distribution histogram. Given a set of sample data with n values $X_1, X_2, ..., X_n$ and assumed that it obeys the probability distribution D, the probability density function or probability aggregation function f_D of the probability distribution D is shown as follows:

$$P=(x_1, x_2, ..., x_n)=f_D(x_1, x_2, ..., x_n|\theta) \tag{1}$$

In formula (1), θ is the distribution parameter of f_D. In order to determine the probability distribution that the sample data obeys, the maximum likelihood of θ should be estimated by finding a value among all values of θ to maximize the probability function f_D. If the maximum likelihood estimation of oil chromatogram data conforms to the Weibull distribution, the attention value and warning value of transformer fault can be calculated.

The Weibull distribution is the theoretical basis of reliability analysis and life prediction proposed by *Waloddi Weibull*. The probability density function of the Weibull distribution is shown as follows:

$$f(x) = \frac{\beta}{\eta}\left(\frac{x}{\eta}\right)^{\beta-1} e^{-(x/\eta)^{\beta}} \tag{2}$$

The corresponding cumulative probability distribution function (also called fault distribution function) is shown as follows:

$$F(x) = 1 - e^{-(x/\eta)^{\beta}} \tag{3}$$

In formula (3), β denotes the Weibull slope, also known as the shape parameter. η denotes the feature value, also known as the scale parameter. When these two parameters are determined, the Weibull distribution model is only determined. The shape and scale parameters can be estimated by the maximum likelihood estimation. For the Weibull distribution in this paper, assumed that $X=(x_1, x_2, ..., x_n)$ is the sample data, θ represents the model parameters (β, η) to be estimated, the logarithmic likelihood function is shown as follows:

$$ln\,L\,(\theta|x) = ln\prod_{i=1}^{n}\frac{\beta}{\eta}\left(\frac{x_i}{\eta}\right)^{\beta-1} e^{-(x_i/\eta)^{\beta}} = \sum_{i=1}^{n}(ln(\beta) + (\beta-1)\,ln(x_i) - \beta\,ln\,\eta - (x_i/\eta)^{\beta}) \tag{4}$$

The likelihood equations are shown as follows:

$$\begin{cases} \frac{\partial\,ln\,L(\theta|x)}{\partial\beta} = 0 \\ \frac{\partial\,ln\,L(\theta|x)}{\partial\eta} = 0 \end{cases} \tag{5}$$

By substituting (3) into (4), the estimate values of β and η can be obtained. Therefore, the parameters of the Weibull distribution can be estimated based on the sample data of the oil chromatographic, and the distribution of dissolved gases in transformer oil can be established.

3.4. Calculating the Attention Value and Warning Value

In different early warning scenes, the attention value and warning value of oil chromatographic data represent different meanings respectively. When the volume fraction of a dissolved gas is detected to exceed the attention value, the on-line monitoring system will give a notification of "attention", which means that the transformer may malfunction. When the volume fraction of a dissolved gas is detected to exceed the warning value, the on-line monitoring system will give a notification of "warning", which means that the transformer has malfunctioned. In addition, the attention value and warning value are closely related to the defect rate and fault rate.

For a specific type of transformers, assuming that the proportion of transformers in normal state is a%, the proportion of transformers in defective state is b%, and the proportion of transformers in fault state is c%. The proportion relationship of each state and the probability density function curve are shown in Figure 2.
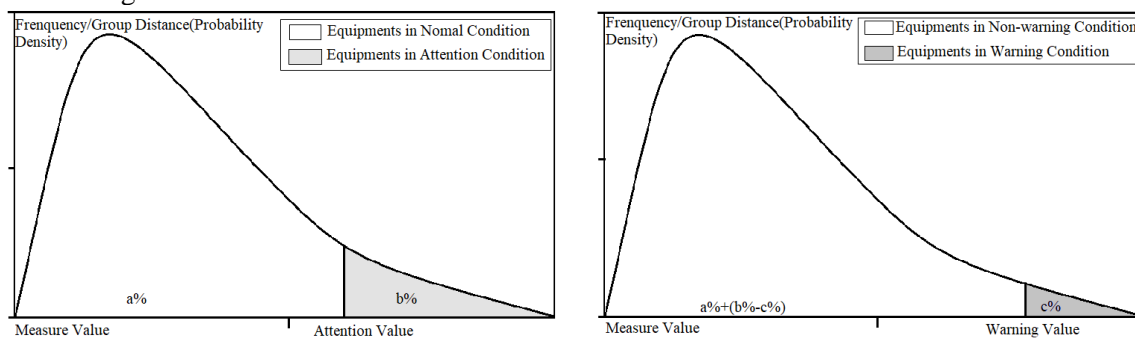

Figure 2. The relation between the proportion of each state and the curve of probability density function

For any probability distribution, once the value associated with a specific cumulative probability is given, the response value associated with a specific probability can be determined by using the inverse cumulative distribution function. The inverse cumulative distribution function of the Weibull distribution function is shown as follows:

$$q = F^{-1}(p|\eta, \beta) = -\eta[ln(1-p)]^{1/\beta}, p \in [0,1] \tag{6}$$

where p represents the cumulative probability and q represents the corresponding value when the cumulative probability is p. The cumulative probability of the Weibull distribution is correlated with the defect rate and fault rate. When the cumulative probability is set to 1-defect rate, the attention value related to the defect rate can be obtained. When the cumulative probability is set to 1-fault rate, the warning value related to the fault rate can be obtained.

4. The Case Study

4.1. Analyzing the Oil Chromatography Sample Data

We collected one year's transformer operation and maintenance data in a regional substation, including account information, fault records and oil chromatogram data. The fault records contain 1573 pieces. The oil chromatographic data contain 114326 pieces of information such as the volume fraction of dissolved gases (including H_2, CO, CO_2, CH_4, C_2H_6, C_2H_4, C_2H_2 and), which mainly come from the transformers with three voltage levels of 110kV, 220kV and 500kV. Therefore, we took three voltage levels as the quota of classifying the oil chromatographic sample data as shown in Table 1.

Table 1. The classification results according to three voltage levels

voltage level/kV	quantity of transformer	record set/item
110	8	1844
220	173	51236
500	220	61246
total	401	114326

According to the defect analysis report of transformer provided by the regional substation, the defect rate and fault rate of transformers under three voltage levels is shown in Table 2.

Table 2. The defect rate and fault rate corresponding to three voltage levels

voltage level/kV	defect rate/%	failure rate/%
110	2.82	0.05
220	4.54	0.18
500	1.79	0.9

4.2. Calculating the Attention Value and Warning Value

Taking the volume fraction of H_2 dissolved in transformer oil as an example, there are 153210 pieces of data, the minimum value is 1.91uL/L and the maximum value is 264.37uL/L. All the data are divided into 100 groups and analysed with the method described in section 3.3 to draw its frequency distribution histogram. The frequency histograms of H_2 volume fraction dissolved in a 220kV transformer oil and total hydrocarbon volume fraction dissolved in a 500kV transformer oil are drawn, as shown in Figure 3. From the frequency histograms, it can be seen that the volume fraction distribution of H_2 and total hydrocarbon dissolved in oil are in accords with the Weibull distribution.
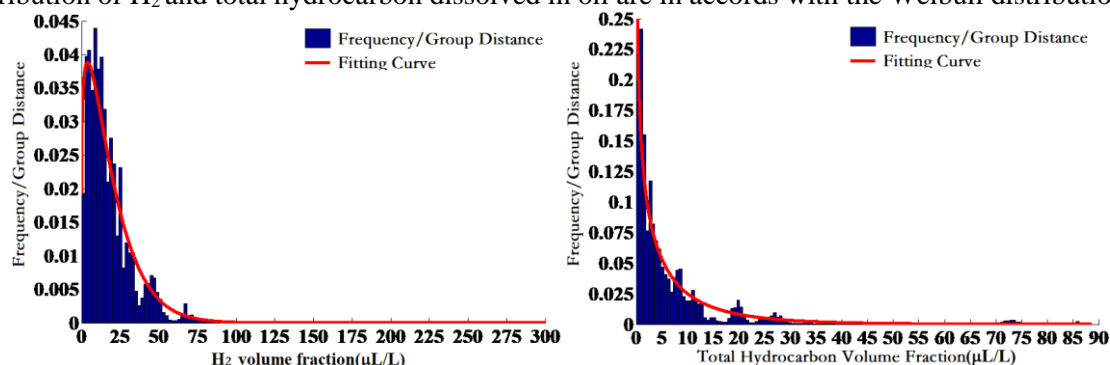

Figure 3. The frequency histograms of H2 and total hydrocarbon dissolved in transformer oil

The attention value and warning value of gas volume fraction dissolved in transformer oil under three voltage levels are calculated as shown in Table 3.

Table 3. The attention values and warning values of gas volume fraction(μL/L) under three voltage levels

gas type	110kV		220kV		500kV	
	attention value	warning value	attention value	warning value	attention value	warning value
H2	106.58	160.24	45.15	76.94	30.27	35.16
CO	998.8	1350.1	1302.2	2212.6	854.72	967.67
CO2	1864.8	1884.6	6846.2	10910	3745.8	4242.5
CH4	21.28	31.81	41.06	79.93	16.27	18.44
C2H6	4.23	5.64	32.46	93.21	13.85	16.66
C2H4	1.34	1.45	32.46	63.65	5.083	6.14
C2H2	3.78	3.86	1.41	2.27	1.51	1.55
total hydrocarbon	25.15	30	88.31	109.89	27.21	31.62

4.3. Comparing the Result with Actual Circumstances of Operating Equipment

Based on the on-line monitoring data of a 220kV transformer from February 22 to June 15, 2014 provided by the regional substation, the attention values and warning values calculated in this paper are verified as shown in Figure 4.

We can find that the volume fraction of total hydrocarbon exceeds the attention value from March 20 to May 2 and exceeds the warning value on June 4, and the on-line monitoring system has given the

corresponding alarm respectively. According to the actual maintenance report of the transformer, there is an interruption maintenance record on June 4 and the fault type is high temperature overheating.
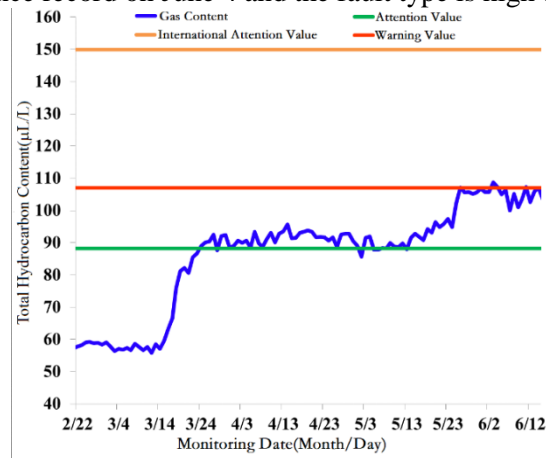

Figure 4. The variation trend of the volume fraction of dissolved gases in transformer oil

5. Conclusion and Future Work

DGA with various data analysis models has an important role in the early warning of transformer fault. By analysing the defect rate and fault rate of various transformers and characterizing the sample data distribution of transformer oil chromatographic, the attention value and warning value of transformer fault can be calculated with some common probability distribution models such as the Weibull distribution, which is very helpful for the early warning of transformer fault. This paper proposes a feasible and effective transformer fault early warning method based on DGA and the Weibull distribution model. In the future, we will improve the proposed method by taking the gas production rate into account.

Acknowledgments

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