Study on Transformer Insulation Condition Evaluation Method Based on Equipment Operation Load

Dai Jianzhuo, Dong Ming, Wang Li, Ren Ming

***Abstract*—The insulation condition of power transformer is bound up with the safety and reliability of power grid operation. The change of transformer load will lead to equipment insulation status change. In this paper, a condition pre-warning method of power transformer based on load time series model was proposed. With the method, the dynamic change of original time series could be remained. The condition sudden change due to abnormal load change may be quantified, and two kinds of load change modes could be checked out, such as continual increase and step increase. Results show that the proposed load time series model could be applied to equipment operating status trend analysis which can make up for the inadequacy of on-line monitoring and provides a new idea for power transformer insulation pre-warning.**

***Keywords*—power transformer; insulation condition; pre-warming; load time series; condition monitoring**

I. INTRODUCTION

The power transformer is the key equipment in power system, whose insulating condition is directly related to the whole system's operating reliability and safety [1]. With the Chinese power grid rapid construction and progress, system voltage level and equipment capacity gradually increase and the power equipment has been increasingly important than before. Therefore, how to guarantee equipment normal operating become the primary task for operation and management department [2]. Recently, various test methods rush into power grid and get different applications, which play a certain role in guaranteeing power equipment's normal operation [3][4]. But due to some multiple reasons, i.e., the poor quality of monitoring system or device [5], the lack of management regulation [6] and low level of data analysis, the on-line monitoring still could not meet the needs of practical application. So it will be hard for the on line monitoring to play the role of pre-warming before equipment defect or fault taking place.

During power equipment in service, its operating pattern change may cause its insulating condition altering, i.e., power transformer load, switchgear acting, the operating pattern changing at equipment rated permission range is generally regarded as normal working condition. But in recent years, the on-site operating experience shows that several inner defects are exposed and even lead to faults when the equipment's load is promoted from long time low level to higher level. Although on-line monitoring data contain lots of equipment's condition information, it cannot monitor and assess this kind of insulating condition variation [7]. So the equipment running information can be obtained indirectly by equipment state monitoring and analysis, and the influence of some external factors can be eliminated based on the information data preprocessing. But due to the large amount of information data of the equipment operation, the character information is difficult to directly display, so the operation condition still cannot be estimated with the simple criteria.

Comparing with the on-line monitoring data, equipment's operating information has some characteristics, i.e., large scale, real time and short period. Reference [8] presented a smart grid condition monitoring platform based on cloud computing which can store mass data. Reference [9] put forward the idea of the combination of big data analysis and equipment condition assessment to improve the level of data comprehensive utilization in power system. Reference [10] provided the operating trend analysis method in preventative maintenance. With regard to abnormal value in continuous data, reference [11] proposed an outliers extraction method which was based on big data analysis. In order to enhance data quality, reference [12] raised a data reduction method based on rough set entropy, but this may cause data loss in the process of data cleaning, so as to influence data mining in subsequent condition assessment.

In this paper, an analysis method was proposed for power transformer load operation data based on time series. In Guangdong province, after the load testing data of more than twenty power transformers were analyzed, a condition assessment model was established based on equipment's load change, and the transformer operating status could be identified by time series method. With the proposed method, the dynamic change of original time series could be remained. The condition sudden change due to abnormal load change may be quantified, and two kinds of load change modes could be checked out, such as continual increase and step increase, which meet the electric transmission and transformation equipment's characteristic.

II. BASIC THEORY OF TIME SERIES ANALYSIS METHOD

Time series analysis method is kind of data mining method, which is a sequence of data points, typically consisting of successive measurements made over a time interval. It could be represented as $\{X_t, t=1, 2, \ldots, N\}$. Time series analysis comprises methods for analyzing time series data in order to extract meaningful statistics and other characteristics of the data. Time series forecasting is the use of a model to predict future values based on previously observed values.

G. U. Yule first proposed AR (Auto Regressive) model, and G. Walker used it for market economic forecasting. Since then, different mathematic models have been come up with

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[13], i.e., ARMA (Auto Regressive Moving Average), Multi-dimensional ARMA, non-stable time series model, and nonlinear time series model. Recently, the application range of time series has been enlarged day by day.

One of typical properties of time series is dynamic random change. In order to establish proper accuracy model, time series should be checked whether it meets the requirements of stationarity and zero mean value [14].

A. *Stationarity Test*

Stationary series have two features:

- Mean value μ_X and square deviation σ_X^2 are constant;;
- Autocovariance function R_k is only related with time interval k, not the time t.

There are many stationarity test methods, such as parametric test (i.e., segmented test) and non-parametric test (i.e., inverted sequence test and R_k test).

B. *Zero Mean Value Test*

The time series $\{X_t\}$ has a limited length N, and its mean value is determined by $\hat{\mu}_X=(\sum_{t=1}^{N} X_t)\Big/N$. $\hat{\mu}_X$ is the estimated value of $\mu_X=E[X_t]$ and it is the unbiased estimation of true value μ_X. Zero mean value test is to test whether the true value of $\{X_t\}$ is 0 or not. Only when the true value is not equal to 0, $\{X_t\}$is processed by $\mu_X=\hat{\mu}_X$,then the time series $\{y_t\}$ with zero mean value could be calculated by Equation (1).

$$y_t = x_t - \hat{\mu}_X \quad (1)$$

Where, t =1, 2, …, N.

In theory, when $\{x_t\}$ is normal distribution with confidence level of 97%, if Equation (2) exists, $\{x_t\}$ is time sires with zero mean value, otherwise $\{x_t\}$ should be transferred by Equation (1).

$$|\hat{\mu}_x|^2 \le 9\sigma^2(\hat{\mu}_x) \quad (2)$$

Where, $\sigma^2(\hat{\mu}_x)$ is the variance of $\hat{\mu}_x$

C. *ARIMA Model*

ARIMA (Auto Regressive Integrated Moving Average Model) model is most basic and the most popular time series model. ARIMA(p, d, q) is called difference auto-regressive moving-average model. p is auto regressive item, q is moving average item, and d is the number of difference when the time series are stationary. ARIMA model could be defined by following definition [15]:

Difference operator:

$$\begin{aligned} &\Delta x_t = x_t - x_{t-1} = x_t - Lx_t = (1-\mathrm{L})x_t \\ &\Delta^2 x_t = \Delta x_t - \Delta x_{t-1} = (1-\mathrm{L})x_t - (1-\mathrm{L})x_{t-1} = (1-\mathrm{L})^2 x_t \\ &\Delta^d x_t = (1-\mathrm{L})^d x_t \end{aligned} \quad (3)$$

For a stationary time series with zero mean value,$\{X_t, t = 1, 2, …, N\}$, it could be depicted by stochastic difference equation (4):

$$\begin{aligned} x_t - \phi_1 x_{t-1} - \phi_2 x_{t-2} - \cdots - \phi_p x_{t-p} = a_t - \theta_1 a_{t-1} - \theta_2 a_{t-2} - \cdots - \theta_m a_{t-q} \\ \Phi(\mathrm{L})\Delta^d x_t = \Theta(\mathrm{L}) a_t \end{aligned} \quad (4)$$

Where,

x_t is the value of $\{X_t\}$ at time of t;

ϕ_i (i = 1, 2, …, p) is auto-regressive parameters;

θ_j (j = 1, 2, …, q) is parameters of moving average model;

α_t is residual error.

The time series modeling is to determine the suitable ARIMA(p, d, q) model to fit the measured stationary time series.

III. Power Transformer Operating condition Model Analysis

According to the statistic of the load characteristic data of power transformer in Guangdong Province in 2014, the tendency mode of transformer's operating condition could be classified into two kinds of modes: sustained growth mode and stepping growth mode.

A. *Sustained growth mode*

With the increase of power load, power transformer's load rate increases continuously. In practical devices, its load level is a kind of sustained growth, as shown in Figure 1.

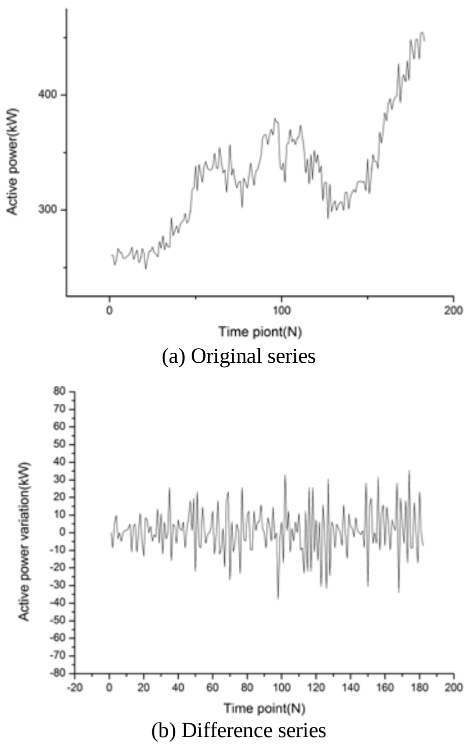
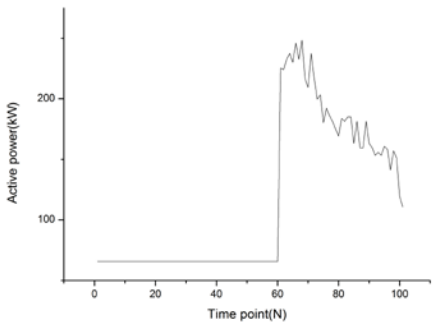


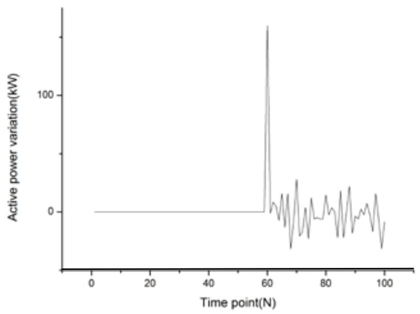
Figure 1. Typical sustained growth in load

B. *Stepping growth mode*

When load peak arises, in practical device, its load level is a kind of steeping growth, as shown in Figure 2.



(a) Original series



(b) Difference series

Figure 2. Typical stepping growth in load

C. *The characteristic analysis of transformer load growth tendency*

When the power transformer is in service, its load fluctuation is often large. In short time interval, abnormal load variation may induce some inner defects outbreaking, even leading to the fault taking place. Based on the load data analysis of power transformer, a flowchart for symptom extraction and decision for power transformer load is established in this paper, as shown in Figure 3.

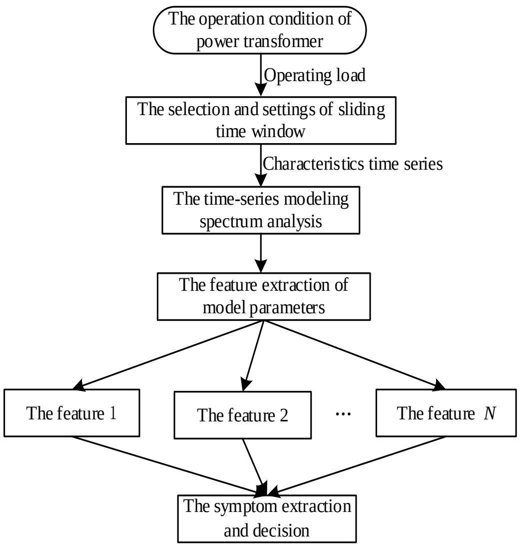


Figure 3. Flowchart for symptom extraction and decision

IV. TRANSFORMER LOAD CHARACTERISTIC AND CONDITION SYMPTOM EXTRACTION METHOD

A. *Feature determination*

The main parameters of operating device are voltage, current, power, frequency, etc.. Due to real time load variation, the condition of power equipment will change, so one or a few operating parameters could be chosen as the pre-warning feature of condition. In this paper, the equipment's power is treated as a condition feature. The load data is transformed into stationery time series by pretreatment. If the transformer's operation pattern alter, the mean value of load data time series will change. So it could be regard as one condition pre-warning feature. At the same time, in order to avoid pretreatment method influencing the load random variation characteristic, the residual error between detected time series and ARIMA model is also treated as the other condition pre-warning feature, among which the detected time series could be obtained by sliding time window for load data.

B. *Trend symptom extraction*

There are two stages for trend symptom extraction, one is self-study stage, and the other is symptom extraction.

- Self-study stage

ARIMA model is set up by using load data in normal condition and the self-study process is shown as solid line in Figure. 4. Firstly, statistical analysis is performed for load data of more than one transformer in 2014, the whole year. We find the transformer load data conforms to normal distribution. There is a big load fluctuation in January, June, July and August, while in other months, the load is stationary.

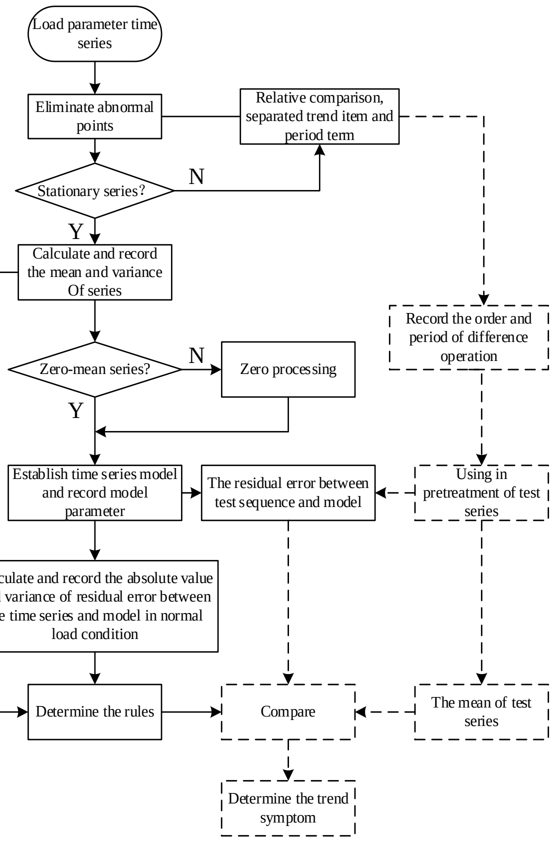


Figure 4. Flowchart of feature symptom extraction

Relatively stationary load fluctuation in load parameter sequence characteristics is analyzed. We use the load data in March as the feature and the slide time window is used to acquire 288 load data in one day. Using one day load data in normal condition to train ARIMA, the model could be described by Equation (5), and the result is shown in Figure. 5.

$$y_t + 0.695 y_{t-1} = \varepsilon_t \tag{5}$$

Using the other 30 days load data in one month as testing sample, the residual error ($\overline{\sigma}_a^2$) between measured value and calculated value could be obtained. Under normal condition, the residual error is within the range of $\overline{\sigma}_a^2 \pm 10\sigma$, where σ is the square deviation of residual error. Assuming μ and σ are mean value and square deviation respectively, and x is the characteristic parameter, the rule could be expressed as following: if $x < \mu - k_{\min}\sigma$, x exceed lower threshold; if $x > \mu + k_{\max}\sigma$, x exceed upper threshold, in which $k_{\max}$ and $k_{\min}$ are coefficients. If $\{x_t\}$ is the time series of characteristic parameter x of one power transformer in normal condition, besides, $x_{\max}$ and $x_{\min}$ is maximum and minimum value of the series respectively, $k_{\max} = k\,x_{\max}/\sigma$ and $k_{\min} = k\,x_{\min}/\sigma$, normally k is 1.5~3.

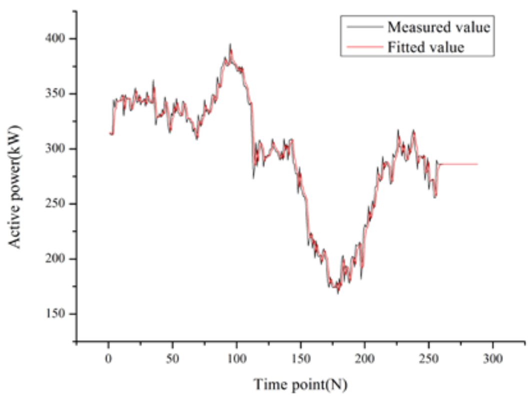


Figure 5. Model fitting outcomes of the whole day load series for one transformer

- Symptom extraction stage

For the condition evaluation and analysis of the equipment, the information of the equipment operating is increasing continuously.

The length of subsequence can be determined by monitoring cycle. For example, the transformer load information can be obtained by SCADA system every 5min [16]. In this paper, the length of subsequence is set as day or month. In other words, the data in the whole day or one month make a test sequence. The time series are pretreated by using the extracted parameter and the corresponding characteristic parameters are calculated, the symptom set could be gotten by comparing characteristic parameters with rules, as shown in Figure 4.

V. CASE STUDIES

One power transformer is chosen as object by random selection. Its load data in May are chosen as study sample and the load data in January, June, July or August are chosen as test sequence.

A. The establishment of Time Series model

The transformer load data in May is analyzed as shown in Figure 6. The fluctuation of load difference sequence is much smaller than that of the load sequence.

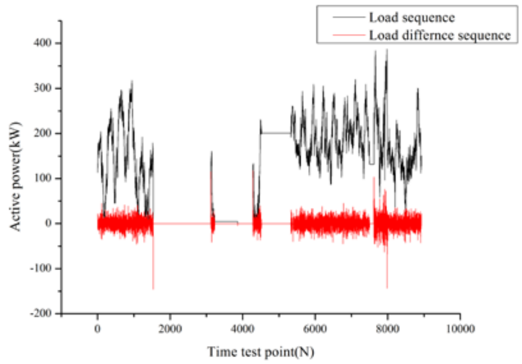


Figure 6. The load sequence and difference sequence in May

After pretreatment of load data in May, the ARIMA(1,0,3) is obtained and the results of load difference time series, model fitted and model residual are shown in Figure 7.

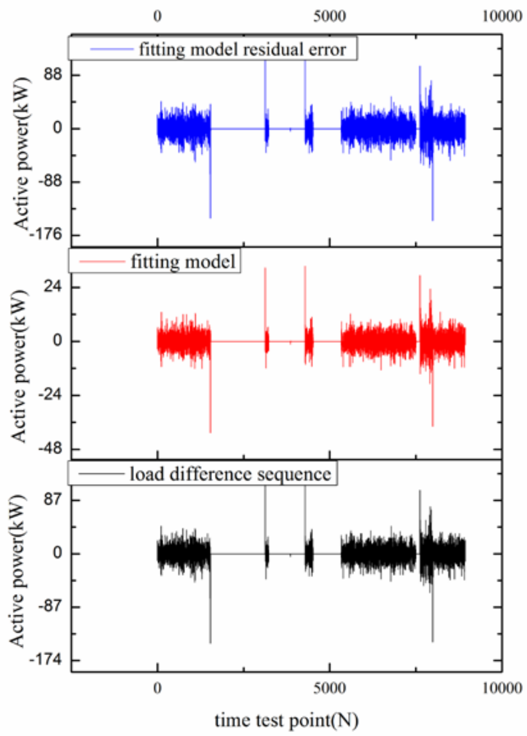


Figure 7. The load difference sequence, time series fitting model and model residual comparison diagram in May

It is clear that fitting time series model not only has good amplitude consistency with the load difference sequence but also hold the trend feature of the load difference sequence. Because the load difference sequence is of normal distribution, zero mean value and stationary, assuming the transformer running state belongs to the normal range. So the value of load difference series is in the range of (-150, 150). Comparing with the load difference sequence, fitting model residual sequence is also of normal distribution, zero mean value and stationary. So the value of load difference sequence fitting model residual is in the range of (-160, 120).

So we could conclude that this equipment is in good condition if its load characteristics meet the following requirements:

- The value of load difference sequence is in the range of (-150, +150);
- The value of load difference sequence fitting model residual is in the range of (-160, +120).

B. Condition evaluation and analysis

The load data difference series of the transformer in June are chosen as the test sample and the test data are applied into the prediction model ARIMA(1,0,3), which has been trained by the sample data. The results are shown in Figure 8.

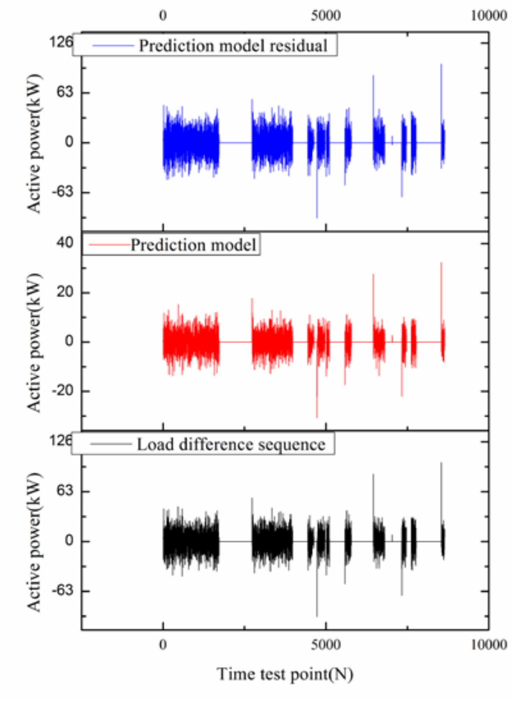


Figure 8. The load difference sequence, time series fitting model and model residual comparison diagram in June

According to the proposed rules, this equipment is judged to be in good condition.

VI. DISCUSSION AND CONCLUSION

Although the power transformer can run continuously according to the rated capacity at specified ambient temperature with a normal life expectancy (20~30 years), in the actual operation, the transformer has a great fluctuation in load, which can induce defects developing inside the equipment and lead to equipment failure.

According to the two different load change mode mentioned above, extracting characteristic parameters based on the load data, if only judging by the absolute value of monitoring parameter, which may apply for step growth mode not for sustained growth mode。Because under the normal condition, random fluctuation value sometimes even exceed that of the abnormal condition, the change of the sequence residual also should be considered when extracting the symptom. On the basis of the analysis method mentioned in this paper, transformer operation condition evaluation method will be built up gradually in terms of load fluctuation characteristics.

More than one power transformers' load characteristic in running are investigated in this paper and the condition change caused by load fluctuation can be evaluated by using time series analysis, and the following conclusions are drawn:

- The pattern of load fluctuation are classified into step growth and sustained growth mode by analyzing transformer load characteristic statistically;
- After counting and analyzing the load characteristic parameters of transformers under the normal operating conditions., the load time series model is established which could fit well on the load characteristic;
- The residual error between the test sample and time series model is used as the feature for condition evaluation, which could determine the load fluctuation range and diagnosis characteristics.

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