



Study of Algorithms of Oil Immersed Transformer Temperature Measurement Technology

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Abstract: *In the paper presented the temperature of an oil-immersed transformer was measured, based on the principles of the fluorescence afterglow life. Three methods were used to calculate the fluorescence afterglow life τ by using the least squares method, the integral area ratio method and Prony algorithm. The least-square method, the integral area ratio method and the program of Prony algorithm are written using Matlab and C++. The Least-square fitting is susceptible to the influence of the DC component. When the DC location is different, the fluorescence afterglow life τ values vary widely. The integral area ratio method is not influenced by DC component, but it has low sensitivity. Prony algorithm is not affected by DC, it has high sensitivity. So Prony algorithm is selected as a way to obtain the fluorescence afterglow lifetime value τ .*

Keywords: *Temperature, the least squares, integral area ratio, Prony algorithm, fluorescence afterglow life.*

1. Introduction

With the rapid development of our society, there appears a higher demand for the corresponding device security [1, 2]. The reliability of the power system needs to be assured. The transformer is the main equipment in the power transmission and transformation system, which is a kind of electrical equipment to realize AC power conversion. Insulation ability is one of the important factors to the life of the

transformer. The main factor that affects the ability of the transformer insulation is the temperature of the transformer winding. So the monitoring technology of transformer winding is the focus of the related research on the transformer. In the present transformer the oil temperature and the temperature of the transformer winding are the most widely used measurements, but due to measuring the values of average temperature, to reflect the transformer operation has certain limitations in accuracy in real time [3, 4]. Now there are two detection methods of oil-immersed transformer winding temperature. They are the direct measurement and the indirect measurement method. The indirect measurement method is an estimating simulation method. The simulation results are a little different from the real situation. The direct measuring method can put the sensors in the interior of the transformer, do real-time measurements and the measurement results are accurate. So the direct measurement method which is used to monitor the performance of the transformer is the important trend in future. Precise temperature measurement is very important.

2. Introduction of the fluorescence afterglow signal

Since the fluorescence lifetime and temperature is the essence, that has nothing to do with light intensity, so the formulation of the fluorescence decay curve is

$$(1) \quad I(t) = I_0 e^{-\frac{t}{\tau}} + I_d + I_n,$$

where τ is the intensity of the fluorescence afterglow, I_n is the random noise, I_d is the DC component of the system [5].

The fluorescence afterglow signal is collected continuously by the data acquisition card. According to previous experience, the collected signal voltage must be the close index curve. The decay time is calculated through the index curve. The attenuation time of the signal has a certain corresponding relationship with temperature. Thus the measured temperature is obtained by using the fluorescence afterglow lifetime [6-8]. There are three kinds of common methods to calculate the fluorescence afterglow lifetime, namely the least squares fitting, integral area ratio method, Prony algorithm.

3. The least squares fitting method

The method of the Least-squares fitting is a common method which is used to calculate the fluorescence lifetime. Its eliminating the DC component mathematical model is an exponential function aimed to find the exponential curve which has the least squares error with the measurement data of the measured afterglow through the method of Least-squares fitting. The exponential curve is used to calculate the fluorescence lifetime. The method focuses on the overall law of the signal and has a good effect on suppressing the partial disturbances of the measured signal and random noise.

For ease of fitting the processed signal which is a single exponential is given in

$$(2) \quad I(t) = I_0 \exp\left(-\frac{t}{\tau}\right).$$

Making variable substitutions into the linear equation, like the natural logarithm which is used in (2), it is obtained:

$$(3) \quad \ln I(t) = \ln\left[I_0 \exp\left(-\frac{t}{\tau}\right)\right] = \ln I_0 - \frac{t}{\tau}.$$

If $\ln I_0 = a$, $-\frac{1}{\tau} = b$, $\ln I(t) = y(t)$, (3) can be written as

$$(4) \quad y(t) = a + bt.$$

This is a linear equation. It can calculate the data requirements of the afterglow of the closest line by using the method of the least-squares linear fitting. The algorithm is as follows:

By measuring the data $(t_i, I_{(t_i)})$, $i = 1, 2, \dots, n$, calculate $y_{(t_i)} = \ln(I_{(t_i)})$, and then according to the definition of the least-squares method, the following is obtained:

$$(5) \quad S_0 = \sum_{i=1}^n t_i^0, \quad S_1 = \sum_{i=1}^n t_i^1, \quad S_2 = \sum_{i=1}^n t_i^2,$$

$$T_0 = \sum_{i=1}^n y(t_i)t_i^0, \quad T_1 = \sum_{i=1}^n y(t_i)t_i^1.$$

The normal equations are:

$$(6) \quad \begin{cases} S_0 a + S_1 b = T_0, \\ S_1 a + S_2 b = T_1. \end{cases}$$

Solving (6), a , b is given by

$$(7) \quad a = \frac{T_1 S_1 - T_0 S_2}{S_1^2 - S_2 S_0}, \quad b = \frac{T_0 S_1 - T_1 S_0}{S_1^2 - S_2 S_0}.$$

If (7) substitutes (6) a fitting straight line equation is given by

$$(8) \quad y(t) = \frac{T_1 S_1 - T_0 S_2}{S_1^2 - S_2 S_0} + \frac{T_0 S_1 - T_1 S_0}{S_1^2 - S_2 S_0} t.$$

Taking the index e on both sides in (8), the form of the fitting exponential curve can be resumed:

$$(9) \quad \exp[y(t)] = I(t) = \exp\left(\frac{T_1 S_1 - T_0 S_2}{S_1^2 - S_2 S_0}\right) \cdot \exp\left(\frac{T_0 S_1 - T_1 S_0}{S_1^2 - S_2 S_0} t\right).$$

Now the following equation can be obtained:

$$(10) \quad y = -Ax + B.$$

The advantage of the least squares fitting is a better fitting effect. By using the method, the unknown data is calculated. The sum of the squares errors is the smallest between the actual data and the calculated data. So the fitting effect of the best approximation can be achieved.

4. Integral area ratio methods

The integration method is the method which is earlier proposed. Equation (1) is the processing model, it can improve the signal strength and smooth noise, which is sensitive to the DC. In the paper, the integral ratio method is proposed as a mathematical model of the practical application of (1). It maintains the original advantages and avoids the influence of the DC component. Its processing time is shorter than the fluorescence time [10].

The principle of the integral area ratio method: A part of the exponential curve is divided into three parts at an equal time interval. Each part is integral respectively, as shown in Fig. 1.

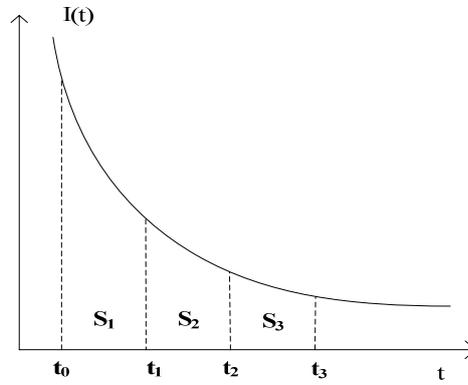


Fig. 1. Principle of integral area ratio method

The results of the fluorescence curves are integrated three times:

$$\begin{aligned}
 S_1 &= \int_{t_0}^{t_1} [I_0 \exp(-\frac{t}{\tau}) + I_d + I_n] dt = -I_0 \tau [\exp(-\frac{t_2}{\tau}) - \exp(-\frac{t_1}{\tau})] + I_d (t_2 - t_1), \\
 S_2 &= \int_{t_2}^{t_3} [I_0 \exp(-\frac{t}{\tau}) + I_d + I_n] dt = -I_0 \tau [\exp(-\frac{t_3}{\tau}) - \exp(-\frac{t_2}{\tau})] + I_d (t_3 - t_2), \\
 S_3 &= \int_{t_3}^{t_4} [I_0 \exp(-\frac{t}{\tau}) + I_d + I_n] dt = -I_0 \tau [\exp(-\frac{t_4}{\tau}) - \exp(-\frac{t_3}{\tau})] + I_d (t_4 - t_3).
 \end{aligned}
 \tag{11}$$

The average effect of the integral makes random noise which is reduced greatly by the type, so it is rounded and does not count.

Each time the interval is

$$t_3 - t_2 = t_2 - t_1 = t_1 - t_0 = \Delta T,
 \tag{12}$$

ΔT is the integral width of each integration. The following ratio can be obtained:

$$\frac{S_1 - S_2}{S_2 - S_3} = \frac{e^{-\frac{t_0}{\tau}} [1 + e^{-\frac{2\Delta T}{\tau}} - 2e^{-\frac{\Delta T}{\tau}}]}{e^{-\frac{t_1}{\tau}} [1 + e^{-\frac{2\Delta T}{\tau}} - 2e^{-\frac{\Delta T}{\tau}}]} = e^{\frac{\Delta T}{\tau}}.
 \tag{13}$$

For $\frac{S_1 - S_2}{S_2 - S_3} = B$, so that (13) is also written as

$$(14) \quad B = e^{\frac{\Delta T}{\tau}}; \tau = \Delta T / \ln B.$$

The integral ratio method has two advantages:

1) The method is simple. It is easy to implement it on a computer. It requires less computer memory and less time.

2) It is not needed to calculate DC component I_d singly, it only takes about 2 to 3 times of the measurement time of the fluorescence lifetime. It can shorten the processing cycle and save the measurement time greatly. It also quickens the speed of measurement and real-time. There are more advantages in the system which require a fast speed of response.

5. Prony algorithm

Prony algorithm is used to fit the sample data by using a linear combination of the exponential function [11-14]. The extended Prony algorithm uses the mathematical model with an exponential function of p arbitrary parameters – amplitude, phase, frequency and attenuation factor. The function form of the discrete time is

$$(15) \quad \hat{x}(n) = \sum_{i=1}^p b_i z_i^n, \quad n = 0, 1, \dots, N-1,$$

$\hat{x}(n)$ is used as an approximation of $x(n)$, assuming that b_i and z_i are plural in (15).

$$(16) \quad \begin{aligned} b_i &= A_i e^{j\theta_i}, \\ z_i &= A_i e^{[(\alpha_i + j2\pi f_i)\Delta t]j\theta_i}, \end{aligned}$$

where A_i is the amplitude, θ_i is the phase (its unit is radians), α_i is the attenuation factor (fluorescence lifetime), f_i is the oscillation frequency, Δt is the sampling interval,

$$(17) \quad \varepsilon = \sum_{n=0}^{N-1} |x(n) - \hat{x}(n)|^2.$$

The derived differential equation is

$$(18) \quad x(n) = -\sum_{i=1}^p \alpha_i x(n-i), \quad n = 0, 1, \dots, N-1.$$

In order to establish Prony fitting method, the linear matrix equation has been estimated using the least squares method. It is shown in

$$(19) \quad \begin{pmatrix} x(p) & \dots & x(0) \\ \vdots & \ddots & \vdots \\ x(N-1) & \dots & x(N-p-1) \end{pmatrix} \begin{pmatrix} 1 \\ \vdots \\ \alpha_p \end{pmatrix} = \begin{pmatrix} \varepsilon(0) \\ \vdots \\ \varepsilon(N-1) \end{pmatrix},$$

$$\gamma(i, j) = \sum_{n=p}^{N-1} x(n-j)x^*(n-i), \quad i, j = 0, 1, \dots, P.$$

The fitting equation of Prony method can be obtained

$$(20) \quad \begin{pmatrix} \gamma(0, 0) & \dots & \gamma(0, p) \\ \vdots & \ddots & \vdots \\ \gamma(p, 0) & \dots & \gamma(p, p) \end{pmatrix} \begin{pmatrix} 1 \\ \vdots \\ \alpha_p \end{pmatrix} = \begin{pmatrix} \varepsilon(p) \\ \vdots \\ 0 \end{pmatrix}.$$

The coefficients $\alpha_1, \dots, \alpha_p$ estimation can be obtained by calculating the equation. When α_1, α_p are obtained, the characteristic polynomial can also be obtained:

$$(21) \quad 1 + \alpha_1 z^{-1} + \dots + \alpha_p z^{-p} = 0.$$

Z_i are Prony poles. Then the index model of (15) is simplified to a linear equation of the unknown parameters b_i :

$$(22) \quad \begin{pmatrix} 1 & \dots & 1 \\ \vdots & \ddots & \vdots \\ Z_1^{n-1} & \dots & Z_p^{n-1} \end{pmatrix} \begin{pmatrix} b_1 \\ \vdots \\ b_p \end{pmatrix} = \begin{pmatrix} \hat{x}(1) \\ \vdots \\ \hat{x}(p) \end{pmatrix}.$$

The least-square solutions can be obtained by solving this equation:

$$(23) \quad b = (Z^H Z)^{-1} Z^H \hat{x}.$$

Its four parameter values are:

$$(24) \quad \begin{aligned} A_i &= |b_i|, \\ \theta_i &= \arctan[\text{Im}(b_i)/\text{Re}(b_i)]/(2\pi\Delta t), \\ \alpha_i &= \ln |Z_i| / \Delta t, \\ f_i &= \arctan[\text{Im}(Z_i)/\text{Re}(Z_i)]/(2\pi\Delta t). \end{aligned}$$

Prony algorithm has the following advantages:

1) Prony algorithm has its own advantages. The value of the four parameters – amplitude, phase, damping ratio (the fluorescence lifetime) and frequency can be directly calculated from the time domain signal, which makes the amount of calculation largely reduced.

2) Prony algorithm does not need to solve the complex characteristic equation and estimate the sample autocorrelation. It only needs to solve the linear equation and several polynomial equations. The signal information can be concluded. It can reduce the amount of calculation and improve the system accuracy. It is a nonlinear multidimensional filter method.

6. Selection of the algorithm

The mathematical model of the Least-squares fitting, eliminating the DC component is an exponential function that finds the exponential curve which has the least squares error with the measurement data of the measured afterglow by representing the afterglow measurement data through the method of Least-squares fitting [15]. The exponential curve is used to calculate the fluorescence lifetime. The method focuses on the overall law of the signal and has a good effect on suppressing the partial disturbances of the measured signal and random noise [16]. Calculating the DC principle of the Least-squares fitting method is shown in Fig. 2.

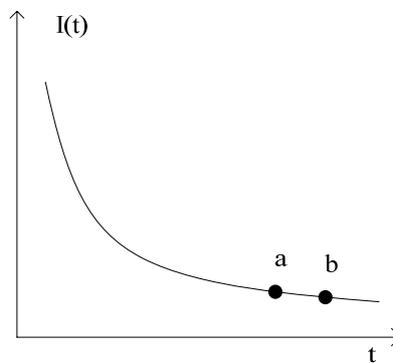


Fig. 2. Calculating DC principle of the Least-squares fitting method

In the figure the curve is the exponential decay curve of the fluorescence afterglow. In the interval of excitation the light pulse of the fluorescence cannot decay to zero. So the approximation of the direct current is calculated by the last paragraph of the fluorescent afterglow data values obtained. In the figure the fluorescence data between *a* and *b* were used to get the average *I*. Therefore, *I* is regarded as direct current and must be removed before fitting.

In Table 1 the least squares method is largely influenced by the impact of the DC component. When DC is taken in different positions, the error of results can reach 13.52%. The error is very large. That is why the Least-squares fitting method cannot be used to calculate the fluorescence lifetime τ .

Table 1. Fluorescence lifetime τ of different DC positions

Position of DC (count)	τ after being removed DC (μs)
390-410	569.2
800-820	550.2
195-205	501.4

The integral area ratio method is used to calculate the Fluorescent afterglow lifetime μs value. The measured temperature is 20-45 °C. The τ value is shown in Table 2.

Table 2. Fluorescence lifetime at different temperatures

Measured temperature (°C)	The fluorescence lifetime τ (μ s)
20	862.61
25	860.93
30	858.15
35	856.13
40	852.81
45	850.46

We can see that the change of the fluorescence lifetime τ is 11.95 μ s, when the measured temperature varied from 20 °C to 45 °C, when the temperature varied by 1 °C; the fluorescence lifetime τ varied to 0.48 μ s. The change is too small, so that the accuracy of the system becomes low.

For the same data Prony algorithm is used to calculate the fluorescence lifetime τ . The measured temperature is 20-45 °C. The τ value is shown in Table 3.

Table 3. Fluorescence lifetime at different temperatures

Measured temperature (°C)	The fluorescence lifetime τ (μ s)
20	683.84
25	678.00
30	663.26
35	643.21
40	630.48
45	625.59

The relationship between the temperature and the fluorescent lifetime is shown in Fig. 3.

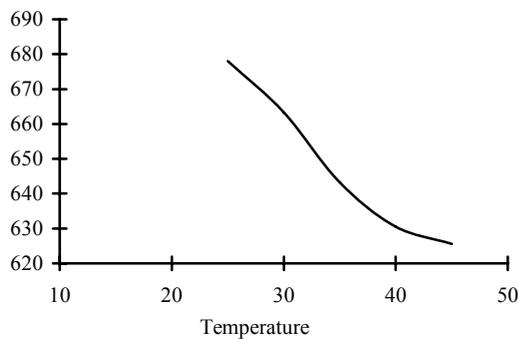


Fig. 3. The relationship between the temperature (°C) and the fluorescence lifetime (μ s)

We can see that the change of the fluorescence lifetime τ is 58.25 μ s, when the measured temperature varied from 20 to 45 °C. When the temperature varied by 1 °C, the fluorescence lifetime τ varied to 2.33 μ s. Thus the accuracy of the system is improved about 4 times. The change is very large compared to the integral area ratio method, that is why the accuracy of the system will improve largely. In the paper the processing method of calculating the fluorescent lifetime is used as Prony algorithm.

7. Conclusion

Three data processing algorithms were introduced in the paper, namely the least squares method, the integral area ratio method and Prony algorithm. The basic principle is introduced. Least-square fitting is susceptible to the influence of the DC component. The experiments prove that DC location is different, the maximum of the measured temperature error is 13.52%. Though the integral area ratio method is not affected by DC component, the fluorescent afterglow lifetime τ value changed to 11.95 μs , when the temperature changed to 25 °C. Prony algorithm is used to calculate the fluorescence lifetime τ . We can see that the change of the fluorescence lifetime τ is 58.25 μs . The accuracy of the system is improved approximately 4 times. That is why we use Prony algorithm to calculate the fluorescence lifetime τ .

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