The accurate determination of the winding's temperature rise

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Abstract. The resistance method to determine the temperature rise of the winding is discussed in this paper. The factors affecting the uncertainty are analyzed here. The uncertainty comes from the resistances and the environment temperatures at the beginning and at the end of the testing which are composed of type A and type B. The influence of different fitted curves to the value of the temperature rise is analyzed here also.

1. Introduction
Temperature rise test is the important safety testing item of the household electrical appliances, transformer, electric tools, electrical and electronic products and so on. This item determines if the difference between the temperature of the electrical products or their parts and the environment temperature under the specified conditions meets the corresponding standard’s requirements [1]. The item can evaluate the quality of the components of the product and the insulation materials. The test can effectively prevent fire spreading and ensure overall electrical safety. Transformers are widely used in electronic devices, and their usage rapidly increases. The end of the transformer's service life is the lost of its insulating ability. The main factor affecting the insulation capacity of the transformer is its winding’s temperature. If the transformer’s running temperature is too low, the capacity of the transformer is not fully utilized and the economic benefits are reduced. If it is too high, it will not only affect the life of the transformer but also poses a threat to the safety of the products. Therefore, it is important to analyze and calculate the temperature of the transformer’s winding.

The winding is the important part of the transformer to realize the voltage transformation. There are many methods[2-3] used to measure temperature or temperature rise, such as the infrared thermometers, thermocouple temperature measurement, on-line winding temperature rise tester, resistance method etc. However, the thermocouple method and infrared method are limited to the determination of the surface temperature of the sample. At the same time, because of the randomness selecting when doing the temperature measurement, these method can't really reflect the internal temperature of the sample. For its high accuracy, the resistance method can be widely applied by calculating the temperature inside the coils.

2. Requirements of the temperature rise of the winding
According to IEC 61558-1 “Safety of power transformers, power supplies, reactors and similar products-Part 1; General requirements and tests”, transformers and their supports shall not attain excessive temperature in normal use. The value of maximum temperatures in normal use of the winding is in table 1[4].
Table 1. The value of maximum temperatures in normal use of the winding

| Parts | temperature °C |
|-------|----------------|
| Windings, if the insulation system (i.e. bobbins and any other insulating material that are in contact with the windings) is: | |
| of class A | 100 |
| of class E | 115 |
| of class B | 120 |
| of class F | 140 |
| of class H | 165 |
| of other classes | - |

If other materials are used, they shall not be exposed to temperatures in excess of those which have been proved permissible for these materials. The classification is in accordance with IEC 60085 and IEC 60216. If other insulating materials than those covered by IEC 60085 and IEC 60216 are used, the insulation system shall withstand the accelerated ageing test.

3. Testing method

The resistance method is used to determine the temperature rise of the winding. It is important to note that the measured temperature is the mean temperature of the winding. However, the limited values in Table 1 have been adjusted to take into account the fact that, in these tests, the temperatures are mean and not hot-spot values[5].

The test is made in a draught-free location having dimensions such that the test results are not influenced. If the transformer has a $t_a$ rating, the test is conducted at $t_a \pm 5^\circ C$. Carry out the temperature rise testing according to the measurement method in chapter 14 of GB/T 19212.1-2016 "safety of power transformers, power supplies, reactors and similar products-Part 1: General requirements and tests"[4]. Before the start of the test, place the winding in the ambient temperature for 24h to make the winding’s temperature consistent with the ambient temperature. Measure the resistance of the winding with the digital multimeter and the ambient temperature with the thermocouple at the start of the testing. Carry out the heating testing, then measure the resistance of the winding after the winding’s temperature is stable. And the ambient temperature is also measured by the thermocouple. The temperature rise of the winding is calculated from the formula:

$$\Delta t = \frac{R_2 - R_1}{R_1}(x + t_1) - (t_2 - t_1) \quad (1)$$

Where, $\Delta T$ — the temperature rise, K (°C);

$R_2$ — the resistance at the end of the test, when steady conditions have been established, Ω;

$R_1$ — the resistance at the beginning of the test, Ω;

$t_2$ — the ambient temperature at the end of the test, °C;

$t_1$ — the ambient temperature at the beginning of the test. °C.

The key point of this test is the determination of the steady conditions[6-7]. The temperature is usually determined by the thermocouple method. The thermocouples are arranged in the windings.
Use the data collection meter to test the temperature of the setting points. The temperature can be considered as stable when the temperature curve flattens out, as shown in figure 1.

4. Evaluation of the testing uncertainty

The uncertainty evaluation of the temperature rise testing of the winding has always been a research hot spot. The uncertainty calculation formula is:

\[ u^2_c(y) = \sum_{i=1}^{N} \left( \frac{\partial f}{\partial x_i} \right)^2 u^2(x_i), \]  

(2)

According to formula (1), the uncertainty of the winding’s temperature rise is:

\[ u^2_c = u^2_c(\Delta T) = \sum_{i=1}^{4} c_i^2 u^2_i, \]  

(3)

Where \( c_1 = \frac{\partial \Delta T}{\partial R_1}, c_2 = \frac{\partial \Delta T}{\partial R_2}, c_3 = \frac{\partial \Delta T}{\partial t_1}, c_4 = \frac{\partial \Delta T}{\partial t_2}, \)

\( u_1, u_2, u_3 \) and \( u_4 \) is the uncertainty component given by \( R_1, R_2, t_1 \) and \( t_2 \) respectively.

- uncertainty component given by \( R_1, R_2 \):

The uncertainty component of the resistance is divided into type A and type B.

Type A: The four-terminal method is used to measure the resistance of the windings. The measuring instrument is digital multimeter. Repeat the measurement \( n \) times, and \( n \geq 6 \). Use Bessel formula to calculate the uncertainty of type A, see formula (4):

\[ u_i = \sqrt{\frac{N}{n-1} \sum_{j=1}^{N} (x_i - \bar{x})^2}, \]  

(4)

The measured value of the resistance after the power off and the related test time can be curve fitted by the least squares method. The zero - second value of the resistance is determined by the fitting curve. The uncertainty of the fitting curve can also be evaluated by type A.
Type B uncertainty comes from the digital multimeter and stopwatch. The calculation is based on their calibration certificates.

- uncertainty component given by $t_1, t_2$:

The uncertainty of ambient temperature is also divided into type A and type B. Using the data acquisition instrument to measure the ambient temperature. Similar to the uncertainty of the resistance, use Bessel formula to calculate the uncertainty of type A. The type B uncertainty is determined according to the calibration certificate of the data acquisition instrument.

5. The impact of the fitting curve to the test

The accurate determination of the zero-second resistance is a key factor in the winding’s temperature rise test. It is directly related to the accuracy of the temperature rise test. Because the zero-second resistance cannot be measured directly with the instrument, the scientific method is using the fitting curve method. The linear, exponential and polynomial fitting curves cause smaller error.

After the power off, 10 sets of data were collected and each set of data contained resistance and corresponding test time. Take x axis as the time values and y axis as the resistance values. Plot the curve. Use the fitting curve method to determine the zero-second resistance. The effect of the different curve fitting to the zero-second resistance is analyzed here.

| Table 2. Resistance values on different time after power off |
|------------------------------------------------------------|
| X-time (s) | Y- resistance (Ω) |
| 5          | 774.97           |
| 10         | 772.31           |
| 15         | 769.98           |
| 20         | 768.14           |
| 25         | 766.14           |
| 30         | 764.57           |
| 35         | 762.95           |
| 40         | 761.31           |
| 45         | 759.89           |
| 50         | 758.55           |
| 55         | 757.29           |
| 60         | 756.09           |

Using the different fitting methods, such as exponential, linear and polynomial, to obtain the zero-second resistance. The fitting curve diagram is shown in figure 2.
It can be conclude from the above fitting curve that the error of polynomial fitting is smaller than the exponential fitting and linear fitting. The r-squared value of polynomial fitting can reach to 0.999. Using polynomial fitting of different series, the difference is very small. The error value between the binomial and trinomial is about 0.07%. The error of exponential fitting and linear fitting to the polynomial fitting is about 0.2%. It can be seen that different fitting curves have certain influence on the determination of zero-second resistance.

6. Conclusion
The resistance method to determine the temperature rise of the winding is discussed in this paper. Also, the factors affecting the uncertainty are analyzed here. The uncertainty comes from the resistances and the environment temperatures at the beginning and at the end of the testing. The influence of different fitted curves to the value of the temperature rise is analyzed here also. The error of polynomial fitting is smaller than the exponential fitting and linear fitting.

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