

Study on the Detection of Transformer Oil Temperature

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Abstract. Based on the influence of the ambient temperature, wind speed and other factors on the transformer monitoring system, the hot spot temperature model of the transformer outer wall is established by using thermoelectric analogy theory and lumped parameter model. Through the analysis of experimental data, mathematical model of influence of ambient temperature and wind speed on temperature of transformer is built, and the correction values on the temperature of the transformer are obtained under the different ambient temperature and wind speed. The correction values make the transformer hot-spot temperature more objective and more authentic, which has significant influence on the running of the transformer safely and efficiently.

1 Introduction

As the demand for electrical energy increasing, the security of corresponding devices has a higher demand. In the power system, the transformer is one of the most important and most expensive equipment, which is the key point whether the grid operate safely, efficiently and economically. Due to the nature of the transformer and long-term continuous operation in the power grid, the transformer inevitably occurs a variety of malfunctions and accidents. Therefore, when the power system is developing to EHV, power grid, high-capacity and automated direction, the reliability of the transformer to the safe operation of power system is also increasing [1].

Because the internal structure of the transformer is complex and the transformer hot spots are usually in the position of the high potential, it is difficult for the transformer to monitor constantly by sensor and we need to use temperature calculation method to estimate the temperature distribution within the transformer and forecast the maximum temperature. And it is inaccurate to restrict the load value of the transformer by the temperature rise of the transformer, because it is limited by the ambient temperature. By experience, the maximum temperature of the transformer will be different in different season. In the summer, because the temperature rises and the user load increases, the transformer increase the heat but the cooling conditions deteriorate, causing a marked increase in the internal temperature of the transformer. And after repeated experiments, we found that, under the same temperature, the faster wind speed is, the lower wall temperature of the transformer is. If not considering the impact of wind speed and using the previous formula, the estimated value is smaller than the actual value, which is not good for real-time monitoring of transformer normal operation. Therefore, in this paper,

with the ambient temperature and wind speed as the input variable, the hot spot temperature model was established based on the transformer wall temperature.

2 Transformer surface temperature thermal model equivalent thermal circuit theory

When the oil-immersed power transformer runs, it has no-load loss and load loss, which transform the heat. Some of the heat increase the temperature of the transformer winding, the core and structure. The winding and the core dissipate the heat to the transformer oil, causing the temperature of the transformer oil rise, and the transformer oil dissipate the heat to the air by cooling device. When the temperature difference of each part achieve the balance between the heat generated and the heat dissipated, the parts reach a stable state and the temperature of the parts are no longer changed [3].

National standard GB1094.2-1996 stipulates that the transformer oil tank and structural surface temperature rising limit is 80K. If we want to discover the abnormal temperature of the transformer before all parts of the transformer temperature rising arrive the limit, we must be able to predict the normal temperature of transformer operation. In the literature [2] model, the transformer hot spot temperature model is modeling to the heat transfer process within the transformer wall, without considering the influence of the air and the transformer oil tank wall (outer) surface heat transfer resistance. However, in general, the transformer tank wall temperature is affected by the environmental temperature and wind speed. And if you ignore the impact, it will cause the calculated heat value becomes small, which is not good for real-time monitoring the operation condition of the transformer.

Therefore, the transformer tank wall temperature model in the paper considers the environmental factors.

According to heat transfer theory, the actual cooling structure of the transformer is refined, thinking that total thermal resistance is composed of four resistance in series. They are respectively thermal resistance R_1 of transformer oil, heat transfer resistance R_2 of the transformer oil and the tank wall (inside) surface, thermal resistance R_3 of the transformer tank wall and heat transfer resistance R_4 of air and transformer tank wall (outer) surface.

Temperature measuring point is located between R_3 and R_4 , and the ratio of the temperature difference between measuring point temperature θ_{meas} and ambient temperature θ_{amb} to the temperature difference between top oil temperature θ_{oil} and ambient temperature θ_{amb} is similar to the relationship of the partial pressure in the circuit. And compared with the transformer oil heat capacity, the transformer tank wall heat capacity, the thermal boundary layer heat capacity between transformer oil and the tank wall (inside) and the thermal boundary layer heat capacity between air and the transformer tank wall (outer) are very small, so the three heat capacities are ignored. Heat of transformer is from core loss q_{Fe} and winding copper loss q_{Cu} and C_{oil} represents the transformer oil heat capacity. So, the transformer surface temperature model equivalent circuit is shown in Figure 1.

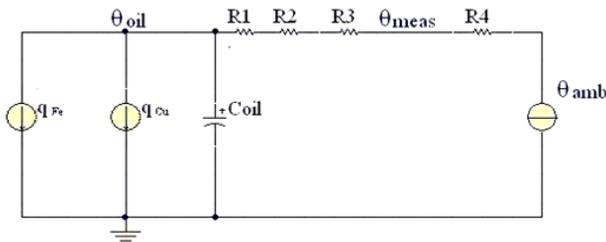


Figure 1. The transformer surface temperature model equivalent circuit

$$q_{Fe} + q_{Cu} = (1 + \beta)C_{oil} \frac{d\theta_{meas}}{dt} - \beta C_{oil} \frac{d\theta_{amb}}{dt} + \frac{1}{R} [(1 + \beta)(\theta_{meas} - \theta_{amb})]^n \quad (1)$$

wherein, θ_{meas} is transformer surface temperature measurements; R is the total resistance, $R = R_1 + R_2 + R_3 + R_4$. proportionality coefficient $\beta = (R_1 + R_2 + R_3) / R_4$.

Generally, the value of n is between 0.8 and 1.0. To derive conveniently, n is 1 in the paper.

Transformer core loss is proportional to the square of the voltage and taking into account the basically constant voltage in the operation of transformer, the core loss is constant, so $q_{Fe} = K_{Fe}$. Transformer winding copper loss is proportional to the square of the current, so $q_{Cu} = K_{Cu} I^2$.

Therefore, the transformer surface temperature prediction model is:

$$\theta_{meas}^{[k]} = \frac{T_0}{T_0 + \Delta t} \theta_{meas}^{[k-1]} + \frac{\Delta t + \beta(T_0 + \Delta t)}{(1 + \beta)(T_0 + \Delta t)} \theta_{amb}^{[k]} - \frac{\beta T_0}{(1 + \beta)(T_0 + \Delta t)} \theta_{amb}^{[k-1]} + \frac{\Delta t R K_{Cu}}{(1 + \beta)(T_0 + \Delta t)} I^2[k] + \frac{\Delta t R K_{Fe}}{(1 + \beta)(T_0 + \Delta t)} \quad (2)$$

wherein, T_0 is the time constant of the transformer top oil temperature ($T_0 = R C_{oil}$), Δt is the sampling interval, $\theta_{meas}^{[k]}$

is the tank wall surface temperature of the k -th sampling point. $\theta_{amb}^{[k]}$ is the environment temperature of the k -th sampling point. $I^{[k]}$ is the primary current RMS of k -th sampling point [4].

3 Experimental analysis and modeling of the inner and outer wall temperature of the transformer

To further study the correlation of the inner wall surface temperature and ambient temperature and wind speed, the paper carried out the following experiment.

When the ambient temperature is 23°C, 25°C or 29°C, we respectively measure the relationship between inner wall temperature and outer wall temperature in the no wind, first-class wind, second-class wind and third-class wind. Part of experimental data is shown in Table 1.

Table 1. Experimental data (part).

| wind speed | ambient temperature(°C) | hot spot temperature(°C) | 99 | 95 | 90 | 85 | 80 | 75 | 70 | 65 | 60 | 55 | 50 |
|------------|-------------------------|--------------------------|----|----|----|----|----|----|----|----|----|----|----|
| 0 | 29°C | IT | 99 | 95 | 90 | 85 | 80 | 75 | 70 | 65 | 60 | 55 | 50 |
| | | OT | 94 | 90 | 85 | 81 | 76 | 72 | 67 | 62 | 58 | 53 | 49 |
| | 25°C | IT | 97 | 93 | 88 | 84 | 78 | 73 | 68 | 63 | 58 | 53 | 49 |
| | | OT | 87 | 83 | 79 | 75 | 71 | 68 | 63 | 58 | 54 | 49 | 46 |
| | 23°C | IT | 96 | 93 | 88 | 83 | 77 | 74 | 67 | 62 | 58 | 53 | 48 |
| | | OT | 85 | 81 | 77 | 73 | 70 | 66 | 61 | 57 | 53 | 48 | 45 |
| 1 | 29°C | IT | 99 | 94 | 89 | 84 | 78 | 73 | 68 | 63 | 59 | 53 | 48 |
| | | OT | 78 | 75 | 73 | 70 | 65 | 61 | 58 | 54 | 51 | 48 | 47 |
| | 25°C | IT | 95 | 90 | 86 | 81 | 76 | 72 | 67 | 62 | 57 | 52 | 47 |
| | | OT | 72 | 69 | 66 | 62 | 59 | 55 | 52 | 49 | 46 | 44 | 43 |
| | 23°C | IT | 96 | 93 | 89 | 84 | 79 | 74 | 69 | 64 | 58 | 54 | 48 |
| | | OT | 72 | 68 | 65 | 61 | 58 | 54 | 51 | 47 | 44 | 42 | 41 |
| 2 | 29°C | IT | 96 | 92 | 87 | 83 | 78 | 73 | 67 | 63 | 57 | 53 | 47 |
| | | OT | 80 | 77 | 74 | 71 | 67 | 64 | 60 | 56 | 53 | 49 | 48 |
| | 25°C | IT | 96 | 92 | 87 | 83 | 78 | 73 | 67 | 63 | 57 | 53 | 47 |
| | | OT | 70 | 68 | 64 | 62 | 57 | 55 | 51 | 49 | 45 | 44 | 43 |
| | 23°C | IT | 98 | 94 | 89 | 85 | 80 | 74 | 69 | 65 | 60 | 54 | 49 |
| | | OT | 69 | 65 | 61 | 57 | 54 | 50 | 47 | 45 | 43 | 41 | 40 |
| 3 | 29°C | IT | 99 | 95 | 89 | 84 | 79 | 73 | 69 | 62 | 55 | 50 | 46 |
| | | OT | 80 | 76 | 72 | 68 | 64 | 59 | 56 | 53 | 50 | 47 | 46 |
| | 25°C | IT | 95 | 91 | 85 | 81 | 77 | 71 | 66 | 62 | 57 | 52 | 47 |
| | | OT | 70 | 67 | 64 | 61 | 57 | 53 | 50 | 47 | 46 | 44 | 42 |
| | 23°C | IT | 98 | 94 | 88 | 84 | 79 | 74 | 70 | 64 | 58 | 54 | 49 |
| | | OT | 69 | 65 | 61 | 58 | 55 | 51 | 47 | 44 | 42 | 41 | 40 |

Notes IT: Inside temperature(°C), OT: Outside temperature(°C)

After the experimental data for proper treatment, we do curves fitting by Matlab in different ambient temperatures θ_{amb} and wind speeds v . When the ambient temperature is 25°C, relationship between the inner and outer walls temperature of the transformer in different wind speed is shown in Figure 2.

In Figure 2, the fitting functions are:

Wind speed is 0:

$$y = 1.18153x - 5.64184$$

Wind speed is 1:

$$y = 1.5384x - 14.9263$$

Wind speed is 2:

$$y = 1.6691x - 19.8906$$

Wind speed is 3:

$$y = 1.62x - 17.2363$$

According to Figure 2 and the fitting functions, when the ambient temperature and the inner temperature of the transformer are constant values, different wind speed has different influence on the outer wall temperature of the transformer. The faster wind speed is, the greater the slope of the curve is. Therefore, it is better to estimate winding hot spot temperature when the heat transfer

resistance R_4 of air and transformer tank wall (outer) surface are considered.

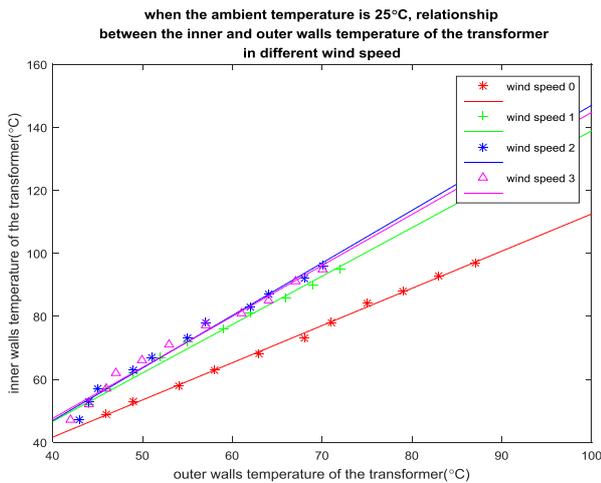


Figure 2. When the ambient temperature is 25°C, relationship between the inner and outer walls temperature of the transformer in different wind speed

When the ambient temperature is 29°C, relationship between the inner and outer walls temperature of the transformer in different wind speed is shown in Figure 3.

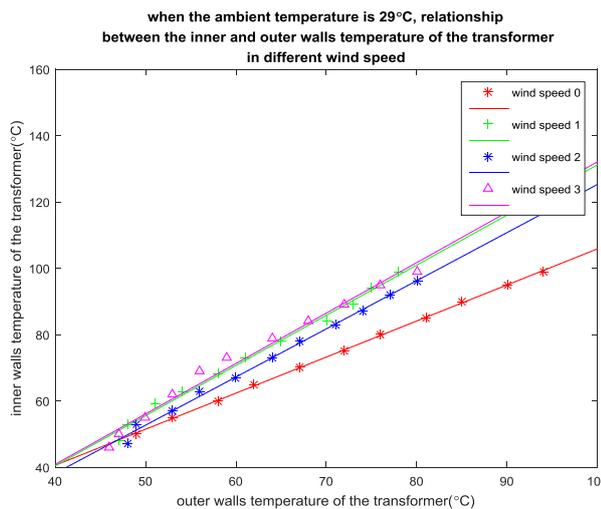


Figure 3. When the ambient temperature is 29°C, relationship between the inner and outer walls temperature of the transformer in different wind speed

In Figure 3, the fitting functions are:
 Wind speed is 0:
 $y=1.08753x-2.89908$
 Wind speed is 1:
 $y=1.5123x-20.0422$
 Wind speed is 2:
 $y=1.4515x-19.8711$
 Wind speed is 3:
 $y=1.52x-19.9018$

Compared with 25°C, when the ambient temperature is 29°C, the temperature difference values between inner wall and outer wall become smaller. So, when the inner wall temperature of the transformer is constant value, the higher ambient temperature is, the higher outer wall

temperature of the transformer is. What's more, the wind has small influence on heat dissipation.

When the ambient temperature is 23°C, relationship between the inner and outer walls temperature of the transformer in different wind speed is shown in figure 4.

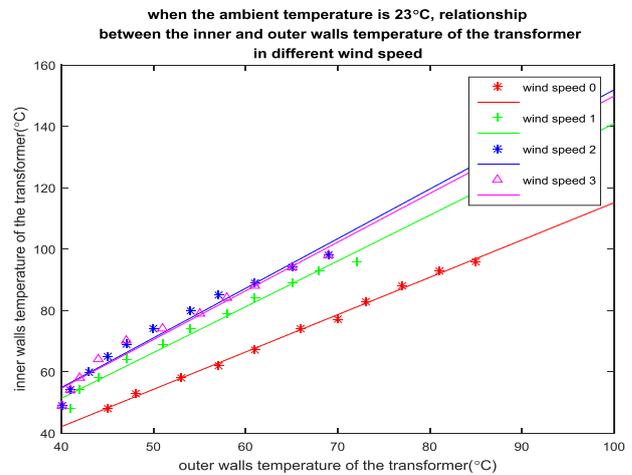


Figure 4. when the ambient temperature is 23°C , relationship between the inner and outer walls temperature of the transformer in different wind speed

In Figure 4, the fitting functions are:
 Wind speed is 0:
 $y=1.21657x-6.55123$
 Wind speed is 1:
 $y=1.49184x-8.32535$
 Wind speed is 2:
 $y=1.61694x-9.80792$
 Wind speed is 3:
 $y=1.58742x-8.87181$

The overall situation of 23°C is similar with 25°C, but when the wind speed is faster, the effect on heat dissipation is better in the situation.

4 Improved transformer hot spot temperature model

According to the experimental data, when the wind speed is constant value, if ambient temperatures are different, the inner and outer wall temperature difference will be different. It can tell us the change of ambient temperature has a great influence on the change of outer walls temperature. Similarly, wind speed also has obvious influence on the outer wall temperature. Therefore, based on the original model of literature [2], we need add the correction value of the influence on ambient temperature and wind speed, which is the temperature difference between the inner and outer wall.

When there is no wind, for example, according to the experimental data, the different temperatures of inner and outer wall are obtained in the different ambient temperatures, which is shown in Table 2.

According to Table 2, under condition of no wind, the fitting functions of the outer wall temperature and correction value are:(outer wall temperature: x , correction value: ΔT)

Ambient temperature is 29°C:

$$\Delta T_1 = 0.08753x - 2.89908$$

Ambient temperature is 25°C:

$$\Delta T_2 = 0.18153x - 5.64184$$

Ambient temperature is 23°C:

$$\Delta T_3 = 0.21657x - 6.55123$$

Table 2. The different temperatures of inner and outer wall in the different ambient temperatures

| wind speed | ambient temperature | hot spot temperature (°C) | 99 | 95 | 90 | 85 | 80 | 75 | 70 | 65 | 60 | 55 | 50 |
|------------|---------------------|-----------------------------|----|----|----|----|----|----|----|----|----|----|----|
| 0 | 29°C | Inside temperature (°C) | 99 | 95 | 90 | 85 | 80 | 75 | 70 | 65 | 60 | 55 | 50 |
| | | Outside temperature (°C) | 94 | 90 | 85 | 81 | 76 | 72 | 67 | 62 | 58 | 53 | 49 |
| | | temperature difference (°C) | 5 | 5 | 5 | 4 | 4 | 3 | 3 | 3 | 2 | 2 | 1 |
| | 25°C | Inside temperature (°C) | 97 | 93 | 88 | 84 | 78 | 73 | 68 | 63 | 58 | 53 | 49 |
| | | Outside temperature (°C) | 87 | 83 | 79 | 75 | 71 | 68 | 63 | 58 | 54 | 49 | 46 |
| | | temperature difference (°C) | 10 | 10 | 9 | 9 | 7 | 5 | 5 | 5 | 4 | 4 | 5 |
| | 23°C | Inside temperature (°C) | 96 | 93 | 88 | 83 | 77 | 74 | 67 | 62 | 58 | 53 | 48 |
| | | Outside temperature (°C) | 85 | 81 | 77 | 73 | 70 | 66 | 61 | 57 | 53 | 48 | 45 |
| | | temperature difference (°C) | 11 | 12 | 11 | 10 | 7 | 8 | 6 | 5 | 5 | 5 | 3 |

Table 3. The different temperatures of inner and outer wall in the different wind speed

| wind speed | ambient temperature | hot spot temperature (°C) | 99 | 95 | 90 | 85 | 80 | 75 | 70 | 65 | 60 | 55 | 50 |
|------------|---------------------|-----------------------------|----|----|----|----|----|----|----|----|----|----|----|
| 0 | 23°C | Inside temperature (°C) | 96 | 93 | 88 | 83 | 77 | 74 | 67 | 62 | 58 | 53 | 48 |
| | | Outside temperature (°C) | 85 | 81 | 77 | 73 | 70 | 66 | 61 | 57 | 53 | 48 | 45 |
| | | temperature difference (°C) | 11 | 12 | 11 | 10 | 7 | 8 | 6 | 5 | 5 | 5 | 3 |
| 1 | 23°C | Inside temperature (°C) | 96 | 93 | 89 | 84 | 79 | 74 | 69 | 64 | 58 | 54 | 48 |
| | | Outside temperature (°C) | 72 | 68 | 65 | 61 | 58 | 54 | 51 | 47 | 44 | 42 | 41 |
| | | temperature difference (°C) | 24 | 25 | 24 | 23 | 21 | 20 | 18 | 17 | 14 | 12 | 7 |
| 2 | 23°C | Inside temperature (°C) | 98 | 94 | 89 | 85 | 80 | 74 | 69 | 65 | 60 | 54 | 49 |
| | | Outside temperature (°C) | 69 | 65 | 61 | 57 | 54 | 50 | 47 | 45 | 43 | 41 | 40 |
| | | temperature difference (°C) | 29 | 29 | 28 | 28 | 26 | 24 | 22 | 20 | 17 | 13 | 9 |
| 3 | 23°C | Inside temperature (°C) | 98 | 94 | 88 | 84 | 79 | 74 | 70 | 64 | 58 | 54 | 49 |
| | | Outside temperature (°C) | 69 | 65 | 61 | 58 | 55 | 51 | 47 | 44 | 42 | 41 | 40 |
| | | temperature difference (°C) | 29 | 29 | 27 | 26 | 24 | 23 | 23 | 20 | 16 | 13 | 9 |

Similarly, when there is 23°C, for example, according to the experimental data, the different temperatures of inner and outer wall are obtained in the different wind speed, which is shown in Table 3.

According to Table 3, under condition of 23°C, the fitting functions of the outer wall temperature and

correction value are:(outer wall temperature:x, correction value:ΔT)

Wind speed is 0:

$$\Delta T_0 = 0.21657x - 6.55123$$

Wind speed is 1:

$$\Delta T_1 = 0.49184x - 8.32535$$

Wind speed is 2:

$$\Delta T_2 = 0.61694x - 9.80792$$

Wind speed is 3:

$$\Delta T_3 = 0.58742x - 8.87181$$

In the conditions of other ambient temperature and wind speed, we can derive the same way.

5 Summary

On the basis of referring to the classical model, through the analysis of the cooling process of the interior of transformer, thermoelectricity analogy principle and the influence of the environmental temperature and wind speed on the transformer, the paper improved the model of literature [2] and make a transformer winding hot spot temperature calculation model based on the transformer wall temperature. Under the condition of the constant hot-spot temperature of transformer, the major influencing factors of the transformer outer wall temperature are the ambient temperature and wind speed. Thereinto, the impact of the wind speed is significant.

By considering the influence of the external environment factors on the measurement of the transformer oil temperature, transformer hot-spot temperature can be monitored more objective and more authentic, which is of great significance to the operation of the transformer safely and efficiently.

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