ANALYSIS OF WINDING TEMPERATURE FIELD UNDER DYNAMIC VARIABLE LOAD OF OIL-IMMERSED TRANSFORMER

by

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The research on the temperature field of the transformer winding under dynamic variable load is of great significance for ensuring the safe operation of power systems. This paper takes an SSP-360000/500 transformer as the research object, establishes a 2-D simulation model, and uses the finite volume method to analyze the high voltage winding and low voltage winding temperature distribution of the transformer under dynamic variable load. The simulation calculation results have been fully verified by the experimental data to make the successful prediction of the overall temperature and hot spot temperature position of forced oil circulation transformers with a guided structure. The results show that the most significant temperature raise occurs at the secondary end of the winding. In the case of dynamic variable load. The temperature raise of the winding becomes larger as the load increases, but before the rated load is in the stable temperature rise range, it can run safely for a long time. However, during overload operation, the average temperature raise of the high voltage winding may exceed its limit, the insulation material is damaged.

Key words: *temperature field, dynamic variable load, high voltage winding, low voltage winding, oil flow distribution*

Introductions

Winding temperature rise during transformer operation is one of the important indicators affecting transformer performance [1]. Through calculation analysis and monitoring research, it is found that a large number of transformer operation failures and accidents are caused by the temperature rise problem of the winding hot spot [2-4]. The hot spot of the transformer winding is the highest point of the winding temperature when the transformer is running. The hot spot temperature is too high, the insulation aging is accelerated, and the life of the transformer is shortened. If the hot spot temperature is too low, the capacity of the transformer is not fully utilized, which affects economic benefits [5-8]. The load of the power transformer is not constant during operation and will change with the demand of electricity [9]. Therefore, it is important to accurately calculate the temperature field of transformer winding under dynamic variable load for the safe operation of the equipment.

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A lot of research focus on the oil flow distribution and winding temperature of large-capacity transformers [10, 11]. Combining the advantages of finite element method and finite volume method, a new hybrid calculation method of transformer temperature field distribution has been proposed [12-17]. The effectiveness of the method was verified by experiments. While [18, 19] used the control volume method to calculate the 2-D temperature distribution of the winding by solving a set of differential equations representing the fluid-solid-thermal coupling. Combining the boundary conditions of the transformer with the initial conditions, the 2-D temperature distribution of the obtained winding is calculated. With this method, the relative error can be controlled within 5%.

In this paper, the temperature distribution of high voltage and low voltage winding of a SSP-360000/500 forced oil circulating oil-immersed water-cooled transformer (cooling method: ODWF) is simulated and analyzed. The finite volume method software FLUENT is used to simulate the 2-D transformer winding under dynamic variable load. The FLUENT software can use different colors to represent different values for these grids, commonly known as *cloud map*, which can intuitively reflect the temperature distribution. The simulation results are fully verified by the experimental data [20]. These studies have important implications for the assessment of transformer life, the safety and reliability of the system, the improvement of economic benefits, and the optimal design of the structure.

Mathematical

When the oil-immersed transformer is running, the heat generated by the winding and the iron core and the heat transfer of the transformer oil cause the temperature of the transformer oil to rise continuously. The temperature of the transformer oil rises and the density decreases. The hotter oil flows to the top of the tank. The transformer is equipped with a set of connected systems, including oil pumps, oil filters and water coolers. Cooling water is supplied inside the water coolers, and the upper layer of the transformer is extracted by the oil pump and flows into the outside of the water cooler. The cooling water takes away the heat of the oil. After the hot oil is cooled by the water cooler, it flows back from the lower part of the tank to the transformer, and then the core and winding of the transformer are cooled, and finally the temperature field reaches a thermal equilibrium state.

The analysis of large oil-immersed water-cooled transformers focuses on the heat-flow coupling problem. The heat-flow coupling field should follow the conservation laws of mass conservation, momentum conservation and energy conservation.

The continuity equation is the mass conservation equation, and any flow problem must satisfy the law of conservation of mass. The net mass of the transformer oil flowing out of the tank per unit time is equal to the mass that is reduced by the density change in the tank at the same time. The differential form of the mass conservation equation:

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho u_x)}{\partial x}+\frac{\partial(\rho u_y)}{\partial y}+\frac{\partial(\rho u_z)}{\partial z}=0 \tag{1}$$

where u_x, u_y, and u_z are the transformer oil velocity components in the three directions x, y, z, t – the time, and ρ – the transformer oil density.

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For a constant stream, $\partial \rho/\partial t = 0$ its form becomes:

$$\frac{\partial(\rho u_x)}{\partial x}+\frac{\partial(\rho u_y)}{\partial y}+\frac{\partial(\rho u_z)}{\partial z}=0 \tag{2}$$

The essence of the momentum equation satisfies Newton's second law, which can derive momentum equations in three directions: x, y, and z:

$$\frac{\partial(\rho u_x)}{\partial t}+\nabla(\rho u_x\vec{u})=-\frac{\partial p}{\partial x}+\nabla(\mu \mathrm{grad} u_x)+S_{ux} \tag{3}$$

$$\frac{\partial(\rho u_y)}{\partial t}+\nabla(\rho u_y\vec{u})=-\frac{\partial p}{\partial y}+\nabla(\mu \mathrm{grad} u_y)+S_{uy} \tag{4}$$

$$\frac{\partial(\rho u_z)}{\partial t}+\nabla(\rho u_z\vec{u})=-\frac{\partial p}{\partial z}+\nabla(\mu \mathrm{grad} u_z)+S_{uz} \tag{5}$$

where S_{ux}, S_{uy}, and S_{uz} are generalized source term, ∇ – the Hamilton differential operator, p – the transformer oil pressure, and μ – the transformer oil movement viscosity coefficient.

The essence of the energy equation is the First law of thermodynamics, the energy differential equation:

$$\rho c\left(u_x\frac{\partial T}{\partial x}+u_y\frac{\partial T}{\partial y}+\right)u_z\frac{\partial T}{\partial z}=k\nabla^2 T+Q \tag{6}$$

where k is thermal conductivity, Q – the micro-heat generation, and c – the specific heat capacity.

The heat source of the oil immersed transformer includes a winding and an iron core. The basic ways of heat transfer are heat conduction, heat radiation and heat convection. For the inside of the coil, consider heat conduction and heat convection (thermal convection is relatively small, engineering calculations are ignored), for transformer tanks, only the heat radiation is considered for the air surface, and the heat side, heat convection and heat conduction are considered on the oil side.

Basic formula for heat transfer:

$$Q = kA\Delta t_m \tag{7}$$

where k is the heat transfer coefficient, A – the heat transfer area, and Δt_m – the average temperature difference of heat transfer.

The internal heat of the winding and the iron core is mainly the heat conduction process, and the differential equation of heat conduction follows the law of conservation of energy:

$$\rho c\left(\frac{\partial T}{\partial t}\right)+V_x\frac{\partial T}{\partial x}+V_y\frac{\partial T}{\partial y}+V_z\frac{\partial T}{\partial z}=\left[\frac{\partial}{\partial x}\left(\lambda_x\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda_y\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda_z\frac{\partial T}{\partial z}\right)\right]+\dot{\Phi}_V \tag{8}$$

where λ is the thermal conductivity along each co-ordinate and $\dot{\Phi}_V$ – the heat generation rate per unit volume.

The formula for calculating the heat source density of the core and winding of a large oil-immersed transformer:

$$q_v=\frac{p}{V} \tag{9}$$

where p is the total loss of the core or winding and V is the volume of the core or winding.

Boundary conditions have an important effect on numerical calculations. The boundary conditions with convection heat transfer and radiation heat transfer is a typical third type of boundary condition:

$$-\lambda\left(\frac{\partial t}{\partial n}\right)_w = h(t_w - t_f) \tag{10}$$

Some physical parameter settings for studying heat transfer analysis are shown in tab. 1:

Table 1. Material thermal conductivity parameters

Material	Thermal conductivity [$\mathrm{Wm^{-1}K^{-1}}$]
Half-hard copper wire	320
Q345B structural steel	80
20MN23AL low magnetic structural steel	65
500 kV oil impregnated insulating paper	0.08
Karamay DB-45 naphthenic mineral	0.3

Simulation analysis of temperature field

Calculation condition

The SSP-360000/500 transformer studied in this paper is a three-phase forced oil circulating power transformer with rated capacity of 360 MVA, rated voltage of 500 kV, high voltage side of 550 kV, low voltage side rated voltage of 18 kV, voltage regulation method is neutral point non-excitation, rated frequency is 50 Hz. The initial temperature of the transformer studied is the ambient temperature in this paper, T_0 = 35 °C.

This simulation uses a triangular mesh division. The core of the heat source, the grid near the high voltage and low voltage winding is relatively dense, and the outer grid is sparse. The accuracy of the calculation is guaranteed, and the calculation cost is not too high due to the meshing.

Tables 2 and 3 show the calculation parameters of the main performance parameters of the oil-immersed transformer and the dimensional parameters of the winding.

Table 2. Main performance parameters

Parameter	Design value
Short circuit impedance [%]	14.75
Load loss [kW]	762.4
No-load loss [kW]	138.3
Total loss [kW]	900.7
No-load current [%]	0.05
Top oil temperature rise [K]	30.7
Winding average temperature rise [K]	High voltage 47.2, low voltage 53.9
Rated tap zero sequence reactance [%]	14.75

Table 3. Winding parameter

Winding parameter [mm]	Coil inner diameter [mm]	Coil outer diameter [mm]	Inner diameter side oil passage [mm]	Outer diameter side oil passage [mm]
Low voltage coil	⌀1226	⌀1385	8	9
High voltage coil	⌀1603	⌀1925	9	12

The high voltage and low voltage coils are divided into eight sections by the guide partition. The cold oil enters the transformer coil from the lower end and then goes up. The oil flows through each zone and flows out of the transformer coil into the cooler. The oil flows smoothly, there is no dead oil zone, and each zone is well cooled.

It is assumed that the high voltage and low voltage sides are symmetrically operated, and the three phases are balanced. Calculate the steady-state temperature field of the transformer operating at 50%, 75%, and 100% load state, and the temperature field of the winding hot spot temperature of 140 °C under the overload condition of 120%, 130%, and 150%, and the continuous running time when the temperature reaches 140 °C.

When the oil flow passes through the guiding partition, there will be a local flow rate increase, which results in better heat dissipation condition of the topmost winding of each guiding section, and the temperature is lower than that of the adjacent same-area winding.

According to the oil flow calculation, the axial oil flow rate on the inner diameter side of the low voltage coil is about 0.15 m/s, the axial flow velocity on the outer diameter side is about 0.1 m/s, and the radial (lateral) flow velocity inside the transformer coil is about 0.08 m/s. The axial oil flow rate on the inner diameter side of the high voltage coil shaft is about 0.18 m/s, the axial flow velocity on the outer diameter side is about 0.13 m/s, and the radial (lateral) flow velocity inside the transformer coil is about 0.1 m/s.

Temperature field calculation results under rated load

This section calculates the temperature field distribution of the winding under rated conditions (100% load, steady-state).

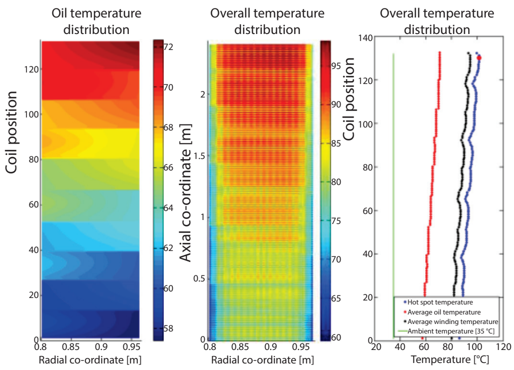

Figure 1. The 100% load high voltage winding

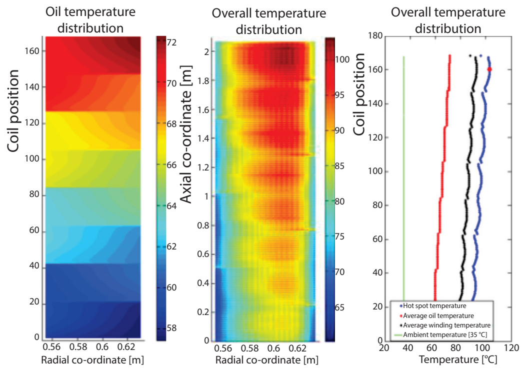

Figure 2. The 100% load low voltage winding

Table 4 .Temperature rise calculation table under rated load

Projects	Calculated value [K]	Limit value [K]
Temperature rise of top oil	29.8	40
Average temperature rise of high voltage winding	52.2	60
Average temperature rise of low voltage winding	50.4	60
Hot spot temperature rise of high voltage winding	66.6	78
Hot spot temperature rise of low voltage winding	68.2	78
Temperature rise of tank	49.5	70

Transformer temperature rise experimental data is measured by electrical resistance method: The average temperature of the low voltage coil is 81.5 °C, and the average temperature of the high voltage coil is 82.7 °C, infrared scan data of the fuel tank, the highest temperature: 73 °C. (experimental environment temperature: 34.5 °C)

Summary: The average temperature rise of the low voltage coil is 53 K, the average temperature rise of the high voltage coil is 54.2 K, and the temperature rise of the tank is 44.5 K. It is basically consistent with the calculated values in the tab. 4 and can be used as the basis for judgment. According to the calculation results, the temperature rise of the hot spot is lower than the rated temperature rise limit.

Temperature field calculation results under dynamic variable load

This section calculates the steady-state temperature field of the transformer operating under variable load conditions of 50%, 75%, 100%, and 110% load, the temperature field of the transformer hot spot temperature of 140 °C under overload conditions of 110%, 120%, 130%, and 150%, and calculate the time of continuous operation when the temperature reaches 140 °C.

Temperature field distribution of the winding under rated state (50% load, steady-state)

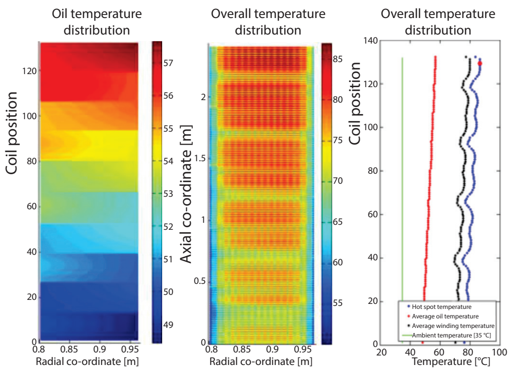

Figure 3. The 50% load high voltage winding

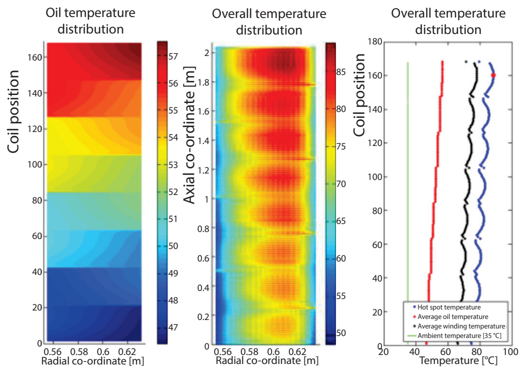

Figure 4. The load low voltage winding

Table 5. Temperature rise under 50% load

Projects	Calculated value [K]	Limit value [K]
Temperature rise of top oil	16.9	40
Average temperature rise of high voltage winding	39.7	60
Average temperature rise of low voltage winding	37.2	60
Hot spot temperature rise of high voltage winding	52	78
Hot spot temperature rise of low voltage winding	53.8	78
Temperature rise of tank	–	70

It can be seen from tab. 5 that the temperature rise of the top layer of the oil is only 16.9 K, which is closely related to the good heat dissipation condition of the top layer of the oil. The temperature rise of the hot spot of the low voltage winding is 53.8 K, which is obviously lower than the limit. It can be seen that the operating state at this time is very good, which is beneficial to the heat dissipation of the transformer. Therefore, the temperature rise of the transformer is not obvious under the condition of 50% load, and the operation of the transformer does not cause serious faults.

Temperature field distribution of the winding under rated state (75% load, steady-state)

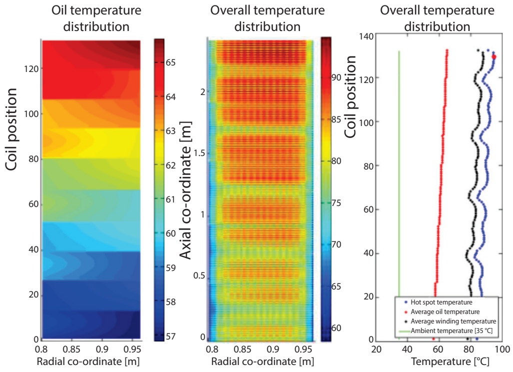

Figure 5. The75% load high voltage winding

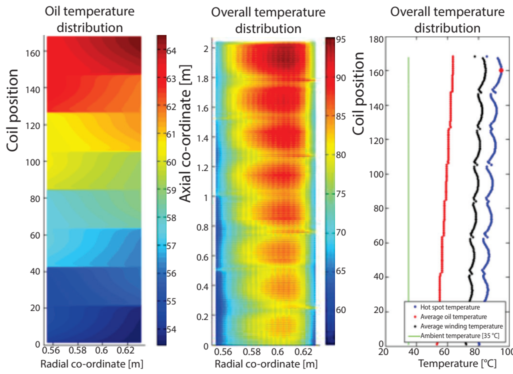

Figure 6. The 75% load low voltage winding

Table 6. Temperature rise under 75% load

Projects	Calculated value [K]	Limit value [K]
Temperature rise of top oil	26.2	40
Average temperature rise of high voltage winding	47.5	60
Average temperature rise of low voltage winding	43.4	60
Hot spot temperature rise of high voltage winding	59.9	78
Hot spot temperature rise of low voltage winding	60	78
Temperature rise of tank	–	70

It can be seen from tab. 6 that the temperature rise of the top layer of the oil is only 26.2 K, which is closely related to the good heat dissipation condition of the top layer of the oil. The temperature rise of the hot spot of the low voltage winding is up to 60 K, which is obviously lower than the limit. Comparing the data under 50% load in tab. 5, it can be seen that the temperature rise of each part is improved, but it still does not exceed the limit. It can be seen that the temperature rise of the transformer is not obvious, and the operation of the transformer does not cause serious faults.

Temperature field distribution of the winding under 110% load, standby coolers are put into use

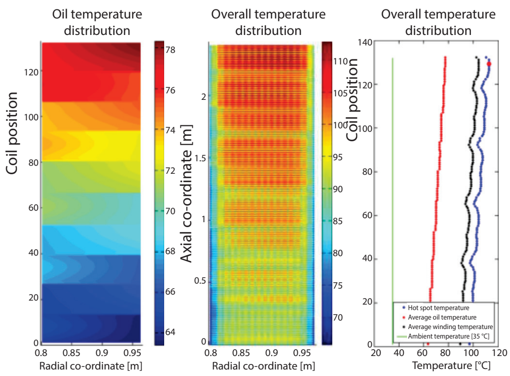

Figure 7. The 110% load high voltage winding

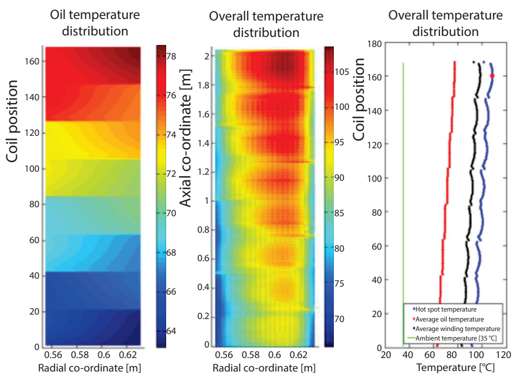

Figure 8. The 110% load low voltage winding

Table 7. Temperature rise under 110% load

Projects	Calculated value [K]	Limit value [K]
Temperature rise of top oil	36	40
Average temperature rise of high voltage winding	61.7	60
Average temperature rise of low voltage winding	55.9	60
Hot spot temperature rise of high voltage winding	77.9	78
Hot spot temperature rise of low voltage winding	73.8	78
Temperature rise of tank	–	70

As can be seen from the tab. 7, the temperature rise of the top layer of the oil is the lowest, and its value is 36 K. The high voltage winding hot spot has the highest temperature rise, with a value of 77.9 K, which is close to the limit. Comparing the data under 75% load in tab. 6, it can be seen that the temperature rise of each part is obviously improved. Therefore, although the standby cooler is put into operation, the average temperature rise of the high voltage winding has exceeded the limit, the temperature rise of the high voltage winding hot spot is very close to the upper limit.

Temperature field distribution of the winding under 120% load, the standby coolers are put into use, after 2 hours of continuous operation

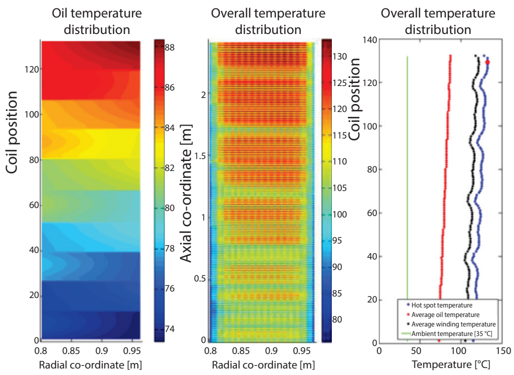

Figure 9. The 120% load high voltage winding

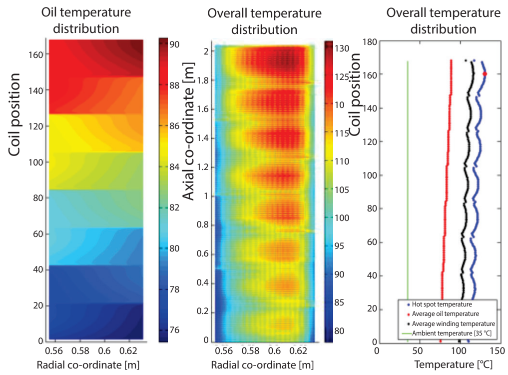

Figure 10. The 120% load low voltage winding

Although the standby coolers are put into operation, due to the large overload ratio and long overload time, all the temperature rises exceed the limit, and the hot spot of the winding is close to 140 °C. At this time, the winding insulation should be slightly thermally damaged, and the transformer should be stopped according to the signal. Subsequent time and temperature are meaningless and no longer calculated.

The 30% overload for about 18 minutes, 50% overload for about 5 minutes. The calculation result is the same as the overload of 20% for about 120 minutes and will not be listed.

Analysis and discussion

The temperature rise distribution of the winding under dynamic variable load is studied, some common phenomena can be obtained from the winding temperature rise diagram of the previous section:

– The low voltage winding temperature is higher than the high voltage winding temperature, and the temperature difference between the low voltage winding and the oil is lower than the temperature difference between the high voltage winding and the oil.
– The temperature distribution of the high voltage winding and the low voltage winding is not uniform, the temperature increases sequentially along the axial height of the winding, the temperature reaches a peak at the secondary end, and decreases slightly at the end.

According to the analysis of heat transfer theory, the low voltage winding temperature is higher than the high voltage winding temperature. This is mainly because the low voltage winding is distributed inside the high voltage winding, and the loss density is sequentially decreased from the inner layer to the outer layer, so that the high voltage winding temperature is lower than the low voltage winding.

The high voltage coil is thicker due to the insulation of the wire, so the high voltage winding is in poor contact with the transformer oil, so that the cooling effect of the low voltage winding is better than that of the high voltage winding. Therefore, the temperature difference between the high voltage winding and the oil is also higher than that between the low voltage winding and the oil.

The temperature distribution of the high voltage and low voltage winding increases in the axial direction, and the hot spot temperature rise occurs at the secondary end and decreases slightly at the end. Analysis of the reasons, the loss density distribution in the axial division is not large enough to generate a large temperature difference. However, when the transformer is running, the transformer oil temperature increases due to heat generation, and the density decreases. The hot oil flows toward the top of the transformer tank, and the hot oil rises and flows through the water coolers. The oil is cooled by the water coolers and flows into the transformer from the bottom of the oil tank, which causes the temperature to increase along the axial direction of each layer.

Since the upper end of the transformer is connected to the water cooler, and the secondary end is only in contact with the rising hot oil, the heat of the top winding is partly taken away, so the upper end is at a lower temperature than the secondary end. It can be seen from the simulation results that the highest temperature rise appears approximately 1.18% from the upper end.

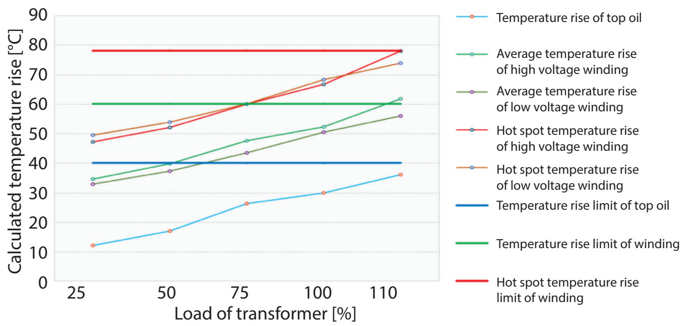

Figure 11. Schematic diagram of winding temperature rise under dynamic variable load

It can be clearly seen from fig. 11 that each measurement value shows an upward trend. When the load is less than 100%, each measured temperature rise value is lower than the limit, and it can run for a long time. When the load is 110%, the average temperature rise of the high voltage winding has exceeded its limit, the insulation material is damaged, the transformer loss increases, and the hottest temperature rise that appears at the secondary end of the winding approaches the limit. At this time, if the load is increased, the limit will be exceeded, and a huge accident such as transformer burnout may occur.

Conclusions

This paper takes practical engineering approaches as the starting point, and uses the finite volume method software to establish a 2-D model of the transformer, and analyzes the temperature distribution of the high voltage and low voltage winding under dynamic variable loads.

- The temperature of the winding is higher than the temperature of the oil flow, but the overall distribution trend of the two is the same, and the temperature difference between the winding of the high voltage coil and the oil flow is higher than that of the low voltage coil. The most significant temperature raise appears at the secondary end, focusing on some heat dissipation measures at the secondary end.
- In the case of dynamic load, the temperature raise of the winding becomes larger with the increase of the load, but the temperature raise stays in a stable range before hitting the rated load, and it can run safely for a long time.
- Under the condition of 110% load, the high voltage winding will exceed the temperature raise limit. Therefore, although the standby coolers are deployed, the average temperature raise of the high voltage winding has exceeded the limit value, and the hot point temperature raise of the high voltage winding is very close to the upper limit. Under the condition of 120% load, it can be seen that all temperature raises exceed the limit, and the hottest point of the winding is close to 140 °C. At this time, the winding insulation should have slight thermal damage, and the transformer is not allowed to run.

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