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Design of Dry Transformer Cooling

Abstract: The transformer lifetime is largely affected by overheating of windings and then the insulation ages and it reduces its electrical insulating properties. Therefore, the proper placing of the relevant parts of the transformer can help to ensure more uniform distribution of temperature field and thus to increase the lifetime of the transformer.

Keywords: temperature field; ANSYS; transformer insulation aging

I. INTRODUCTION

The issue of cooling of power equipment is an actual topic that needs to be dealt because the power electric devices transfer more and more power, thereby there are increased losses, which can be expressed in the form of heat, and so it is necessary to ensure the cooling of these devices. One of the main electric devices is transformer that is commonly used in power system for changing the voltage level. During the transformers operation there arise the heat losses, which are necessary to take away from the transformer to the surrounding using of different types of cooling.

Today, with the systematic need of size reducing of electric devices there are growing requests for their cooling. Therefore it is very important to optimize cooling and thus to ensure their failure-free operation.

II. DESIGN OF COOLING OF DRY DISTRIBUTION TRANSFORMER

Before the result determination that the transformer is overheated in particular parts or not, it is necessary to create the adequate – sufficiently precise – transformer model, where we set the main components that most affect the warming and then neglect particular parts that cannot influence the calculation. As an example of determining of temperature field distribution there was chosen dry distribution transformer during the full load operation and with the following parameters:

- rated power: 630 kVA,
- primary voltage: 22 000 V,
- secondary no-load voltage: 400 V,
- frequency: 50 Hz,
- resistance of primary winding (high voltage): 7,47 Ω,
- resistance of secondary winding (low voltage): 0,00183 Ω,
- current of primary winding (high voltage): 16,53 A,
- current of secondary winding (low voltage): 909,53 A,
- magnetic flux density of core: 1,513 T,
- core weight: 1211,35 kg.

A. *Calculation of losses in the transformer windings*

Since in the transformer windings there are generated Joule losses and the other losses can be neglected (eddy currents, hysteresis, and others), so in this calculation were considered only those losses and they were determined according to the following formulas:

- Joule losses in the primary winding (high voltage) of one phase:

$$\Delta P_{\mathrm{hv1}} = R_{\mathrm{hv1}} \cdot I_{\mathrm{hv1}}^2 = 7{,}47 \cdot 16{,}53^2 = 2041{,}11\,\mathrm{W} \quad (1)$$

- Joule losses in the secondary winding (low voltage) of one phase:

$$\Delta P_{\mathrm{lv1}} = R_{\mathrm{lv1}} \cdot I_{\mathrm{lv1}}^2 = 0{,}00183 \cdot 909{,}53^2 = 1513{,}86\ \mathrm{W} \quad (2)$$

- Total Joule losses in both windings:

$$\Delta P_{\mathrm{J}} = 3 \cdot \Delta P_{\mathrm{hv1}} + 3 \cdot \Delta P_{\mathrm{lv1}} = 3 \cdot 2041 + 3 \cdot 1513 = 10664{,}91\,\mathrm{W} \quad (3)$$

B. *Calculation of losses in the transformer core*

Losses in core depend on the weight of plates and they are given by relative hysteresis volume loss of transformer sheets for the specific magnetic flux density, which is estimated from the hysteresis loss curve of steel sheets. The proportional losses for magnetic flux density $B = 1{,}513$ T are $\Delta p_{\mathrm{Fe}} = 1{,}1\ \mathrm{W \cdot kg^{-1}}$. The losses are also given by a coefficient reflecting the quality of the sheet processing k_z, that is in the range of 1,1 to 1,25. But in this case, there was considered the average value of $k_z = 1{,}17$. Since the core of the transformer is the construction type without junction, so the losses are determined by the following formula:

$$\Delta P_0 = (m_{\mathrm{Fe}} \cdot \Delta p_{\mathrm{Fe}}) \cdot k_z = (1211{,}35 \cdot 1{,}1) \cdot 1{,}17 = 1559\,\mathrm{W} \quad (4)$$

C. *Overall losses*

The overall losses of the transformer are the sum of the losses in the windings and in the core of transformer:

$$\Delta P_{\mathrm{C}} = \Delta P_{\mathrm{J}} + \Delta P_0 = 10664{,}91 + 1559 = 12223{,}91\,\mathrm{W} \quad (5)$$

D. *Calculation of the temperature warming of the transformer*

The warming should be determined separately for the primary and secondary windings and especially for the transformer core. Individual windings are flowed by air around the outer side and inner side, where winding transmit the generated heat from their surfaces to surrounding area. Iron core also transfers the heat by its surface, but the surfaces between each transformer plate sheets are not considered, since they are significantly less effective than the outer surface of the core. Therefore, in this paper it was considered only with the outer surfaces heat transmission.

The transformer is designed as a dry transformer with the epoxy insulation of F-type temperature class. So, it is possible to determine the maximum allowed warming of the transformer on the base of the temperature class. Because the expected maximum ambient temperature around the transformer is $\vartheta_{\mathrm{air}} = 40$°C and the isolation of temperature class F have a maximum permissible temperature of $\vartheta_{\max} = 155$ °C, so with the respecting of temperature reserve of $\vartheta_{\mathrm{res}} = 10$ °C it is possible to determine the maximum warming as follows:

$$\Delta \vartheta_{\mathrm{allowed}} = \vartheta_{\max} - \vartheta_{\mathrm{air}} - \vartheta_{\mathrm{res}} = 155 - 40 - 10 = 105\,°\mathrm{C} \quad (6)$$

Cooling surfaces sizes of transformer:

- cooling surface of primary winding (high voltage): $S_{\mathrm{hv}} = 2{,}2549\ \mathrm{m^2}$,
- cooling surface of secondary winding (low voltage): $S_{\mathrm{lv}} = 1{,}425\ \mathrm{m^2}$,
- cooling surface of transformer core: $S_{\mathrm{Fe}} = 4{,}2525\ \mathrm{m^2}$.

It was considered the heat transfer coefficient in the air of $\alpha_{\mathrm{air}} = 15\ \mathrm{W{\cdot}m^{-2}{\cdot}K^{-1}}$, when calculating the warming of particular transformer parts, because for the calculation of dry transformers there is commonly used empirically obtained value which takes into account the neglected radiation ($\alpha_{\mathrm{air}} = 10 \div 15\ \mathrm{W{\cdot}m^{-2}{\cdot}K^{-1}}$ [8]). The following individual warming was determined for transformer operation at the rated power.

Winding warming can be calculated as follows:

$$\Delta\vartheta_{\mathrm{hv}} = \frac{\Delta P_{\mathrm{hv1}}}{\alpha_{\mathrm{air}} \cdot S_{\mathrm{hv}}} = \frac{2041{,}11}{15 \cdot 2{,}2549} = 60{,}35\,^{\circ}\mathrm{C} \quad (7)$$

$$\Delta\vartheta_{\mathrm{lv}} = \frac{\Delta P_{\mathrm{lv1}}}{\alpha_{\mathrm{air}} \cdot S_{\mathrm{lv}}} = \frac{1513{,}86}{15 \cdot 1{,}425} = 70{,}82\,^{\circ}\mathrm{C} \quad (8)$$

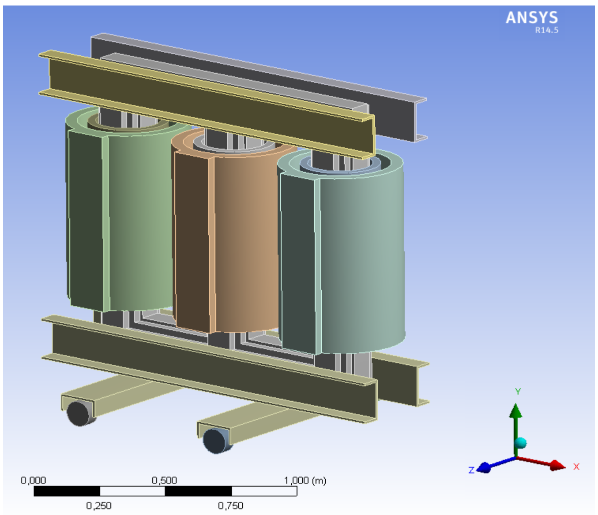
Transformer core warming can be calculated as follows:

$$\Delta\vartheta_{\mathrm{Fe}} = \frac{\Delta P_{\mathrm{Fe}}}{\alpha_{\mathrm{air}} \cdot S_{\mathrm{Fe}}} = \frac{1559}{15 \cdot 4{,}2525} = 24{,}44\,^{\circ}\mathrm{C} \quad (9)$$

III. SOLUTION OF COOLING OF DRY DISTRIBUTION TRANSFORMER IN ANSYS

It was necessary to create the 3D model of the transformer for simulation in ANSYS. The model was created on the base of the manufacturing drawings for the mentioned transformer. Due to the complexity of the transformer it was considered only with those parts of the transformer, which could significantly affect the temperature field of the transformer, and the other parts of transformer were neglected.

The presented transformer was placed in a metal case according to following dimensions: 1560 × 2030 × 950 mm (height × width × depth), which was sufficient also for the other accessories of transformer.



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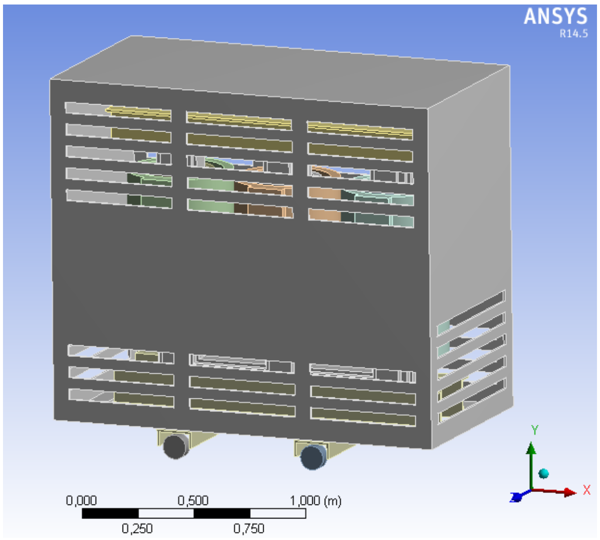

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Figure 1. a) 3D transformer model b) 3D model of the transformer case

There were subsequently calculated the heat losses of particular transformer parts in order to specify the conditions for the temperature simulation of the transformer as follows:

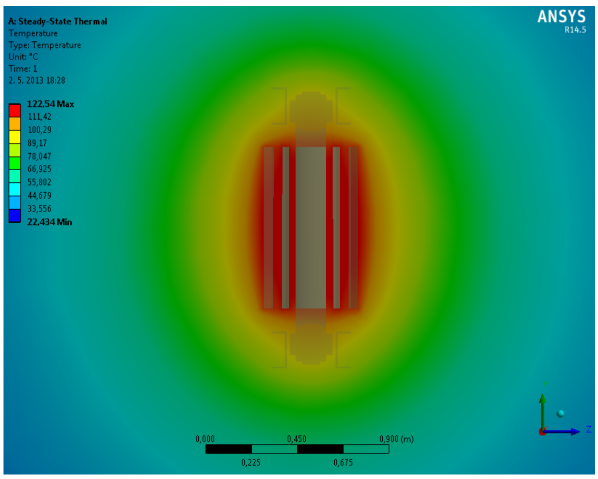
$$\boldsymbol{q}_{\mathrm{hv}} = \frac{\Delta P_{\mathrm{hv}}}{V_{\mathrm{hv}}} = \frac{2041{,}11}{0{,}0479} = 42611{,}89\ \mathrm{W \cdot m^{-3}} \quad (10)$$

$$\boldsymbol{q}_{\mathrm{lv}} = \frac{\Delta P_{\mathrm{lv}}}{V_{\mathrm{lv}}} = \frac{1513{,}86}{0{,}02058} = 73559{,}8\ \mathrm{W \cdot m^{-3}} \quad (11)$$

$$\boldsymbol{q}_{\mathrm{Fe}} = \frac{\Delta P_{\mathrm{Fe}}}{V_{\mathrm{Fe}}} = \frac{1559}{0{,}177} = 8807{,}9\ \mathrm{W \cdot m^{-3}} \quad (12)$$

A. The solution of temperature field without transformer case

The transformer reached the maximum temperature of 122,54 °C at ambient temperature of 22 °C in the first simulation (Fig. 2a), which represents warming of 100,54 °C. This value is still below the maximum allowable warming of 105 °C, that is in normal transformer operation – without the case – so it is not necessary to be cooled. However, during the overloading there would have been occurred a temperature increase above the allowed value, so it would be required to ensure the switched forced air ventilation in the room (transformer cell), where it would be placed, thereby it would be ensured even against the possible overloads.



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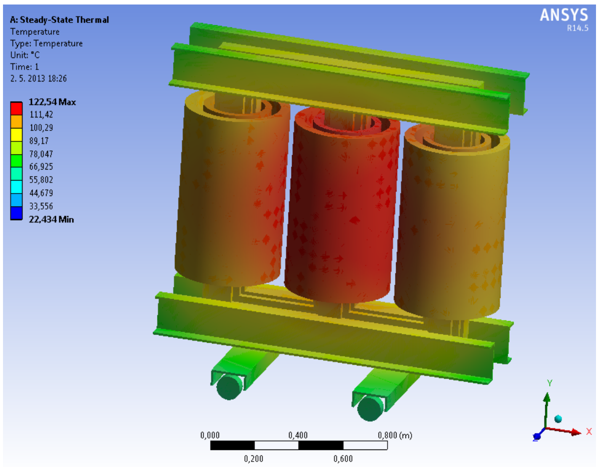

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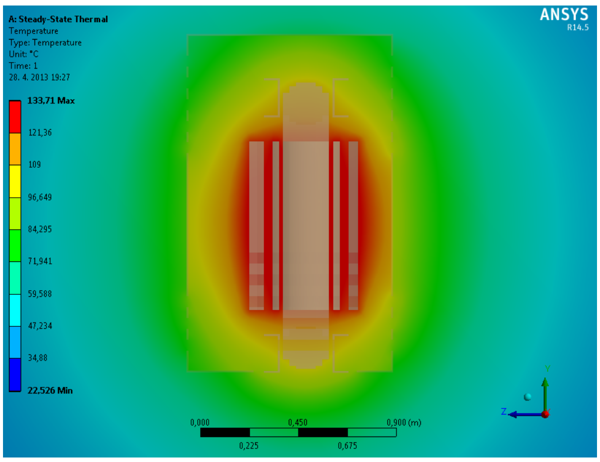
Figure 2. a) Cross section of the transformer without the case; b) Transformer without the case

Because the simulation did not consider the air flow and the transformer model was considered as a solid body, one can see that the heat is homogeneously spread into the environment from the cross section of the transformer (Fig. 2a). In fact, the cold air would flow from the bottom of the transformer, where it would heat up from the transformer areas and by convection it would be taken upwards into the environment. One can see from this figure (Fig. 2a) that mainly heated are windings, which also significantly heat up the core of the transformer.

B. The solution of temperature field with transformer case

In this simulation, it can be expected that the warming of particular transformer parts will be even higher than in the previous case, since the transformer case reduces the heat transfer to the surroundings, what will cause the next warming-up of the transformer.



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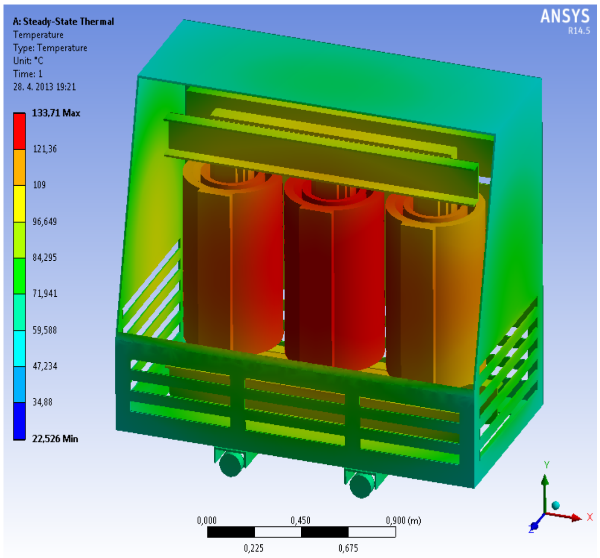

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Figure 3. a) Cross section of the transformer with the case; b) Transformer with the case

One can see from the cross section of the transformer with the case (Fig. 3) that the transformer case partially keeps the heat inside of the transformer, but there is a modest increase in the transformer temperature, since on this case there are enough of vents. The temperature field was just approximated, because the flow is neglected. In real transformer, the cold air should flow through the lower vents, where it would be heated up by the transformer surfaces and then through the upper vents it should flow away by convection to the environment.

Based on the results of this simulation it is possible to say that the highest temperature was observed on the secondary winding of the second phase of transformer and it is 133,71 °C, what represents (after subtracting an ambient temperature 22 °C) warming of about 111,71 °C. This temperature is higher than the maximum allowed warming of the transformer. The influence of such high temperature could lead to a significant lifetime reduction of the transformer, since every 10 °C above the permissible temperature may reduce the lifetime by half. Due to this reason it is necessary to cool transformer and thus to ensure the electricity supply reliability as well as to maximize the transformer lifetime.

C. The solution of temperature field of transformer with an additional cooling

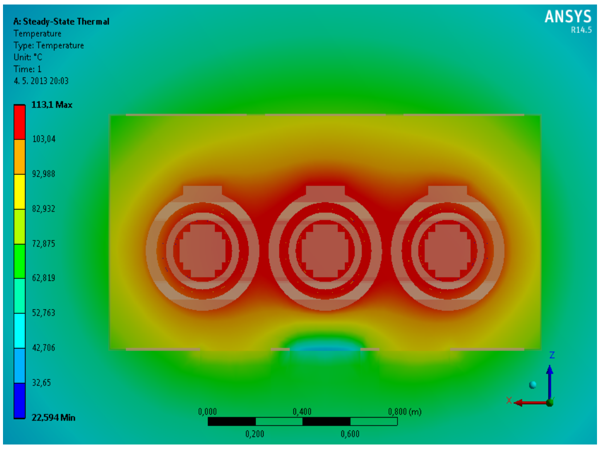
The ABB fans were used for cooling of the transformer, which are intended for cooling of transformers. There were used three fans for cooling with these cooling bore dimensions 195 × 298 mm (height × width) and input power 40 W. These fans were placed on the back-side of the transformer case because the transformer itself is located closer to this side and thus it should be provided the better heat transfer from the transformer windings. The following illustration shows used fan.

Figure 4. Centrifugal fan

It was necessary to recalculate the fan input power to heat flux from the surface, because there was considered the fan effectiveness of 95% as follows:

$$\boldsymbol{q}_{\text{fan}} = \frac{P_{\text{fan}} \cdot \eta_{\text{fan}}}{S_{\text{fan}}} = \frac{40 \cdot 0{,}95}{0{,}195 \cdot 0{,}298} = 653{,}93\ \text{W} \cdot \text{m}^{-2} \tag{13}$$

According to Fig. 3 for the need of cooling during the normal operation it is sufficient to use only one fan of that type, which sufficiently transfers away the heat from the transformer case. This fan may not be operated continuously and therefore it was proposed its switching by the heat sensor that starts-up the fan when the transformer warming is more than 92 °C. This will ensure that the temperature of the transformer will be below the maximum long-term warming of 97 °C that was set for this transformer.



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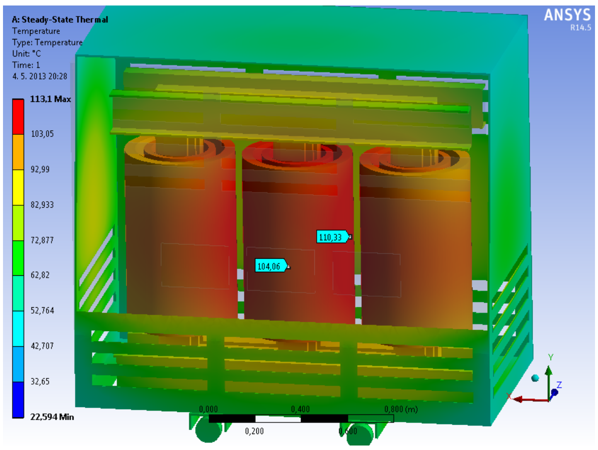

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Figure 5. a) Top view of a transformer in cross section b) Transformer cross section from the side of fans

One can see from the simulation (Fig. 5a), that there was a significant decrease in the maximum temperature of the transformer from 133,71 °C to 113,1 °C. One can see in Fig. 4 that the heat transfers from the transformer windings by a fan, but there cannot be seen that the heat comes out from the transformer case, because of the model conditions entering (there was neglected surrounding behind the fans). Thus, the heat removed by the fans was taken away outside of the simulated model. However, it can be seen that the fan removes the heat from the windings of the transformer and thus it cools the transformer. The highest observed temperature was again on the inner side of the secondary winding of the second phase of the transformer. Based on the maximum observed temperature of 113,1 °C (and after subtracting an ambient temperature 22 °C), there was warming of 91,1 °C, i.e. the fan sufficiently decreases the temperature compared to the value of maximal long-term transformer warming of 97 °C. There are represented the surface temperatures of the transformer in Fig. 5b, where it can be seen that the fan reduced the winding temperature.

Based on these observed values one can say that this fan can provide also the long-term operation of the transformer at rated power. However, it is also appropriate to provide the backup of a fan and also operate a transformer during the possible overload. For this reason, there was also considered option with the other two fans to ensure operation in these cases.

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