To protect tanks from leakage fields of the windings, magnetic shields in the form of packages of electrical steel (shunts) are usually used, which are attached to the surface of flat parts of the tank

Application of surface-mounted radiators to reduce local heating of ferromagnetic tanks of power transformers

ABSTRACT

Local heating in parts of ferromagnetic tanks of power transformers can occur in cases of concentration of magnetic fluxes from magnetic shunts and from multi-ampere leads. It is proposed to reduce such heating by surface-mounted finned radiators made of aluminium with a flat base. This reduction is provided by heat exchange between the part of the tank and the radiator and its cooling with ambient air. The results of numerical modelling and examples of practical application are presented.

KEYWORDS:

local tank heating, power transformer, surface-mounted radiator

1. Introduction

Increased unacceptable local heating of the walls and covers of the ferromagnetic steel tank of power transformers occurs in cases of concentration of magnetic fluxes from magnetic shunts and from multi-ampere leads [1, 2].

To protect tanks from leakage fields of the windings, magnetic shields in the form of packages of electrical steel (shunts) are usually used, which are attached to the surface of flat parts of the tank. There are optimal ratios of the sizes and positions of the shunts with respect to the leakage fields of the windings, which in some cases are difficult to realize due to size limitations or for other reasons. For example, branches with significant currents run parallel to the walls or under the covers of the tanks. At the same time, concentrated magnetic flux from shunts or branches can cause increased local losses and heating.

The design of high-current lead systems is challenging. Traditionally, it is recommended to use a two-layer low voltage winding with an exit of the ends at the top of it, connection of the phase ends of the windings directly to the corresponding inputs. It is practiced, if possible, to increase the distance between the branch and the surface of the cover; a close mutual arrangement of leads of different phases; separation of the lead into parallel wires. Electromagnetic shielding is also used with copper or aluminium plates, which are attached at a certain distance from the protected parts. In [1, 2], the implementation of an insert into the tank cover made of non-magnetic steel with high electrical resistivity is considered. Additionally, packages of limited dimensions made of electrical steel, the so-called magnetic flux dividers, are installed on the surface of the non-magnetic covers. They lead to fragmentation of eddy current circuits and a decrease in local losses in non-magnetic inserts.

However, despite the presence of sufficiently developed methods of computational design and significant experience in the manufacture of power transformers, there are cases when increased local heating during type tests of new designs of transformers forced the ferromagnetic tank covers to be replaced with structures made of non-magnetic steel and those found in service - to limit the workload of the equipment.

> **Power dissipated by radiators is mainly determined by the external conditions of heat transfer and the geometric parameters of the radiators**

At the design stages of transformers, both analytical and numerical methods are used to determine magnetic fields, losses, and tank heating [1, 2]. The losses in the ferromagnetic tank of the transformer are determined by known methods of surface or volumetric losses. Thermal calculations are carried out using the calculated empirical values of the coefficients of heat transfer to the cooling medium or by numerical CFD modelling. Therefore, the calculated and/or measured directly on a real transformer heating of the structural parts will be considered known.

2. The essence of the proposed method

To reduce the above heating, the use of over-mounted heat-dissipating radiators with a flat aluminium base and fins was tested in [3]. A similar method is used to cool parts of the structure of electronic devices [4]. The radiator transfers heat from the source (from the tank) to the drain (to the outside air). The surface of the flat base of the radiator is defined as primary (carrier). To intensify heat dissipation, the primary surface develops using flat strips – fins. In [4], it was concluded that the power dissipated by radiators is mainly determined by the external conditions of heat transfer and the geometric parameters of the radiators. The thermal conductivity of the material of the fins and their thickness isof secondary importance and should be selected from design and technological considerations. It is recommended to ensure thermal contact of the fins with the base by casting, welding or soldering, while the total heat transfer surface of the radiator should not significantly exceed the base surface. In addition, the surface of the radiator should be coated with paints with a high degree of blackness. General issues of heat transfer on developed surfaces, calculation and design of heat exchangers for various purposes are presented in [5].

However, the methods considered in [4, 5] are not acceptable for reducing the local heating of structural elements in power transformers. First of all, it is necessary to take into account the peculiarities of the separation of losses in ferromagnetic steel with nonlinear surface magnetic resistance. The second feature is the presence of three methods of heat exchange: convection from the inner surface layer of the tank into the cooling oil, due to thermal conductivity during thermal contact of the flat base of the radiator with the tank, convection and radiation from the surfaces of the flat base and radiator fins into the air space.

Note that the electromagnetic field of the windings and leads hardly penetrates through the ferromagnetic tank of the transformer and cannot lead to eddy currents and losses in the conductive base and in the fins of the radiators. On the contrary, the above is possible for parts of the tank made of non-magnetic steel. Therefore, the method is not applicable in this case.

3. Examples of method implementation

3.1. Transformer of 500 MVA

On this transformer, the effectiveness of the use of surface-mounted radiators was tested during special heating tests at a current of 120 % of the nominal current with the cooling system turned off – Fig. 1(a) shows the transformer. The maximum cover temperature on the outer surface reaches 120 °C at an ambient temperature (AT) of 20 °C (thermogram in Fig. 1(b)). Throughout the thickness of the steel tank, the temperature drop is insignificant (~ 1 K). Therefore, the maximum temperature on the inner surface on the tank cover is (120+1) °C, and the excess over AT will be 121 - 20 = 101 K. This value is significantly higher than the permissible 75 K for metal constructions that are in contact with solid insulation, and 85 K, where there is no solid insulation – according to GOST R 52719-2007.

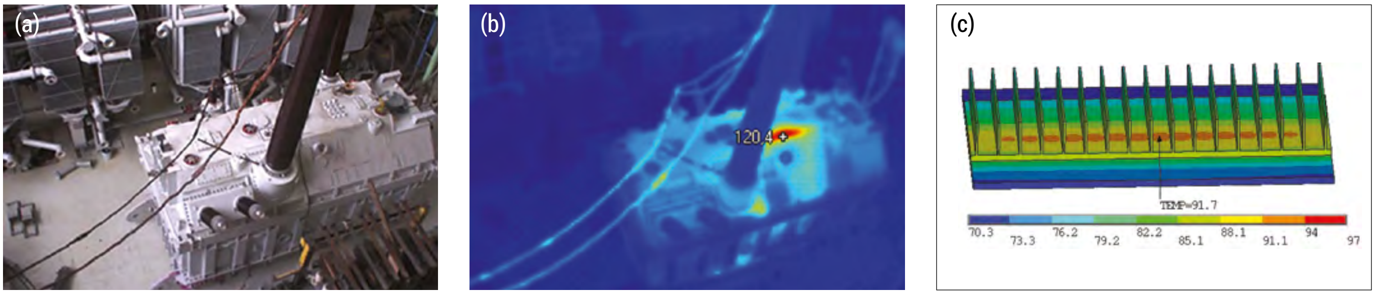


Figure 1. Surface-mounted radiator on the tank cover of a 500 MVA transformer: (a) – general view of the transformer, (b) – thermogram of the tank cover, (c) – calculated temperature distribution of the tank cover with a surface-mounted radiator

> **Installing a radiator at the bottom of the tank wall (below the horizontal connector of the transformer) provides temperature reduction from 111 °C to 87 °C**

Fastening a heat-dissipating radiator to the cover of the tank ensures a decrease in temperature to 97 °C – Fig. 1(c). The aluminium radiator has a 20 mm thick-flat base, vertical fins 110 mm high, 6 mm wide, and a 60 mm fin spacing.

Installing a radiator at the bottom of the tank wall (below the horizontal connector of the transformer) provides temperature reduction from (110 + 1) °C to 87 °C – Fig. 2.

We emphasize that the indicated significant heating of the tank elements is caused by magnetic fluxes at a current of 120 % of the nominal. For the rated current of the transformer, the heating of these parts of the tank does not exceed the permissible ones, which confirms the correct design of the vertical magnetic shunts on the tank.

3.2. Transformer of 200 MVA

During operation, a temperature of 103 °C was recorded on the tank cover and in the upper part of the tank wall between the boxes of low-voltage bushings of adjacent phases (thermogram in Fig.3 (a)) at an ambient temperature (AT) minus 12 °C. At an AT of 20 °C, the absolute temperature on the inner surface of the tank could reach 103 + 1 + 12 + 20 = 136 °C. Therefore, the temperature rise of the inner tank surface in oil over AT is 136 – 20 = 116 K. The indicated increased local losses and heating are due to the horizontal part of the lead, which is located at a close distance from the cover and from the wall of the transformer tank.

To reduce the local heating of the tank cover, surface-mounted radiators with cut-outs (Fig. 3(b)) were installed in the gaps between the mounting flanges of the input boxes of adjacent phases. In the upper part of the tank wall (in the area of the magnetic fields of the windings' leads together with the stray field of the windings), the radiators are attached between the vertical ribs of the tank – Fig. 3(c).

Let us consider in more detail the method of choosing radiators for this transformer.

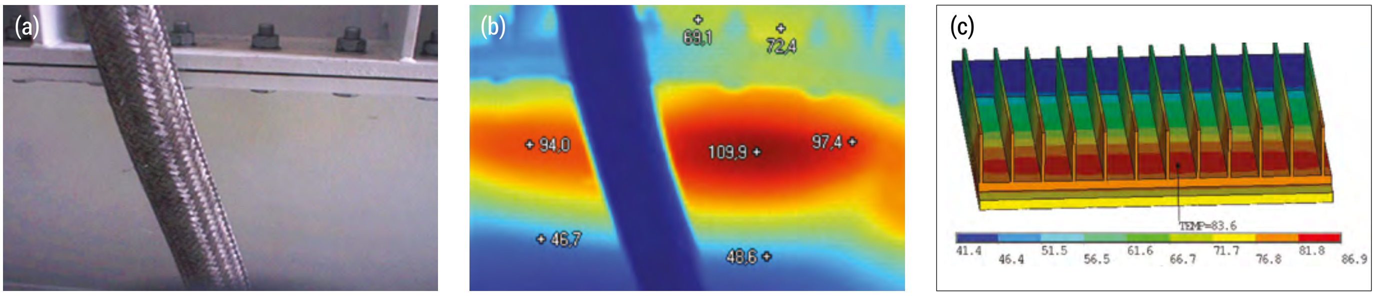


Figure 2. Surface-mounted radiator on the tank wall of a 500 MVA transformer: (a) – photo of the tank wall below the connector, (b) – thermogram of the tank wall, (c) –calculated temperature distribution of the tank wall with a surface-mounted radiator

Figure 3. Surface-mounted radiators on the tank of a 200 MVA transformer: (a) – thermogram of the tank cover, (b) – radiator on the tank cover, (c) – radiator on the tank wall

> **To reduce the local heating of the tank cover, surface-mounted radiators with cut-outs were installed in the gaps between the mounting flanges of the input boxes of adjacent phases.**

To install radiators, you can select a part of the tank cover (14 mm thick) of the transformer with dimensions: 1046 × 1110 mm. The first dimension is between the entry boxes. The second is the width of the cover. Note that the zone of maximum losses and heating is concentrated on a narrow strip, which is typical for the magnetic field of the lead action. The zone width is approximately one-fifth of the width of the selected cover part, that is, about 200 mm. It is important that the radiator base width on the cover is much greater than the indicated size of the losses concentration zone.

A plate of two layers of finite width is taken as a thermal model of the part of the cover or wall of the tank with surface release of losses. The inner layer immersed in oil with surface losses has a thickness of about 1 mm due to the insignificant depth of penetration of the electromagnetic field of industrial frequency into the nonlinear ferromagnetic half-space. The other air-facing part of the cover (wall) is defined as the outer layer of the plate but without highlighted losses.

In the similar thermal model of a ferromagnetic plate and a radiator, the thermal resistance of the contact between the tank surface and the flat base of the radiator can be neglected, which can arise due to the microroughness of a pair of surfaces [4]. This factor is eliminated by applying a special adhesive mixture based on zinc oxide with a working temperature of 180 °C and with a final value of the thermal conductivity coefficient on the surface of the tank that has been previously cleaned from paint. Bolting the radiator base to the tank provides the required level of downforce.

The heat transfer coefficients to the oil from the heated and from the unheated inner surface of the tank are taken equal to 100 and 50 W/(m2 × K), respectively, on the outer surface of the tank and on the radiators, the resulting heat transfer coefficient is determined by the sum of the coefficients of convective and radiant heat transfer to the air and is taken equal to 14 W/(m2 × K) [2]. The thermal conductivity of ferromagnetic steel, aluminium and copper are taken to be 47, 200 and 397 W/(m × K), respectively.

Several design options for a surface-mounted radiator have been investigated. The results are shown in Fig. 4 and in Table 1, where the highest temperatures on the inner surface of the tank are given. The temperature distribution of the base model of a ferromagnetic part without an attachment heat sink is shown in Fig 4(0). Losses in the inner layer of the design plate in a strip 300 mm wide are selected in such a way that the maximum temperature on the surface of the tank in air reaches a measured value of (103 + 1) °C under the tank surface.

> **In the thermal model of a ferromagnetic plate and a radiator, the thermal resistance of the contact between the tank surface and the flat base of the radiator can be neglected**

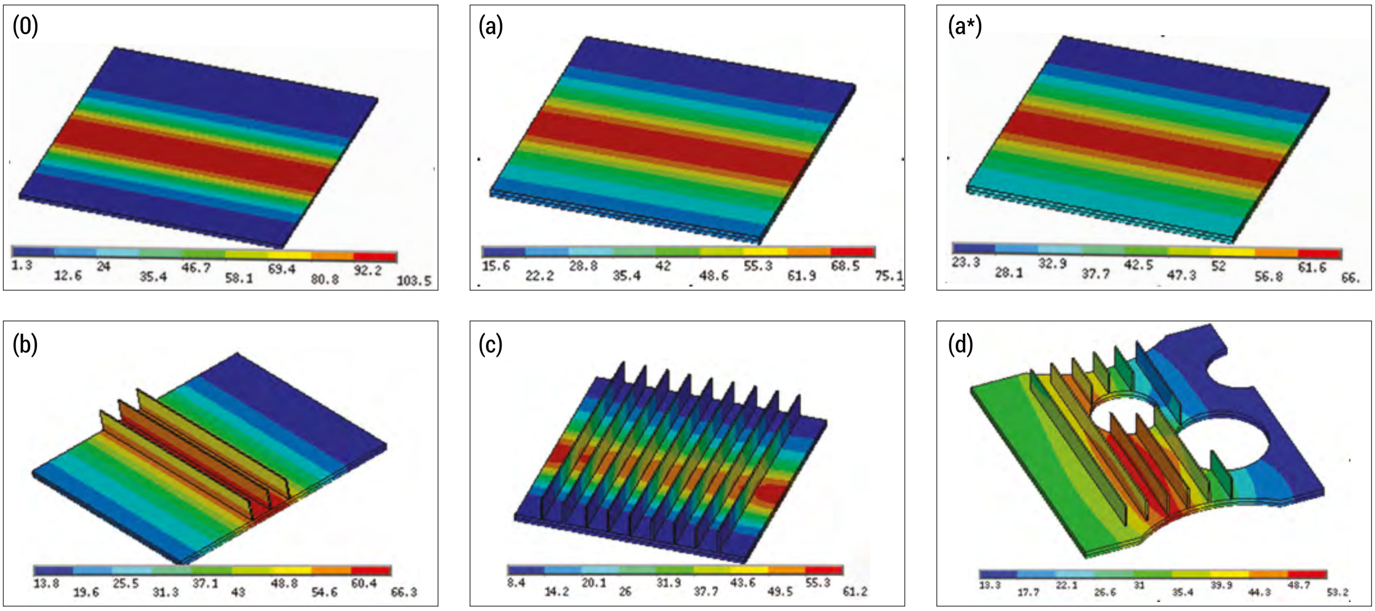


Figure 4. Temperature distribution in models of surface-mounted radiators for a 200 MVA transformer tank: (0) – a part of the tank cover without a radiator, (a) – with a radiator in the form of a flat aluminium base, (a*) – a flat base made of copper, (b) – a flat aluminium base with longitudinal fins in the high-temperature zone, (c) – an aluminium radiator with transverse fins (for the tank wall), (d) – an aluminium radiator with longitudinal fins and cut-outs (for the tank cover on the part between inputs)

> **Analysis of the simulation results shows that the main decrease in heating of the inner surface of the tank occurs due to the thermal coupling of the tank cover with the flat base of the radiator**

Table 1. The highest temperature of the inner surface of the transformer tank of 200 MVA and the decrease in this temperature for different radiators

Option, i	T_i,°C	$\Theta_{0\text{-}i}$, K
0	104	-
a	75	29
a*	66	38
b	66	38
c	61	43

The temperature distribution in the model of a radiator in the form of a flat aluminium base is shown in Fig. 4(a), and in copper – in Fig. 4(a*). The high thermal conductivity of copper, as a result, leads to increased heat dissipation and a decrease in temperature to 66 °C, which is more efficient than aluminium. However, for technological reasons, a cast design of surface-mounted radiators with aluminium fins was adopted. When the cover is only thermally coupled with a flat aluminium base, the plate temperature decreases by 28 K. By another 9 K, a small group of longitudinal vertical fins reduces the highest temperature under the tank cover by heat transfer to the air. The design with transverse fins across the entire width of the plate (for the tank wall) provides a similar temperature reduction. For comparable designs (a)–(c), Table 1 shows the temperature values compared to the base model of the ferromagnetic part without a heat sink. The realized design on the tank cover of a surface-mounted radiator with longitudinal fins and cut-outs (Fig. 4(d)) ensures the highest temperature under the tank cover of 53 °C. This temperature value is explained both by the effect of installing a radiator and by the presence of structural cut-outs. A radiator with transverse fins is installed on the vertical wall of the tank, reducing the highest temperature to 61 °C.

Analysis of the simulation results shows that the main decrease in heating of the inner surface of the tank occurs due to the thermal coupling of the tank cover with the flat base of the radiator, especially for the base made of copper - the result of modelling options (a) and (a*). By conductive heat exchange, the zone of elevated temperatures in the volume of the cover expands with a simultaneous decrease in the maximum value. The above observation corresponds to the statement [5] that "when the finned surface is in a medium with a uniform temperature, then the fin surface is less efficient in terms of heat transfer than the main surface on which the fins are fixed".

So, the design of installed surface-mounted radiators made of aluminium with fins on the cover and on the upper part of the wall of the 200 MVA transformer tank is shown in Fig. 3. The further operation of

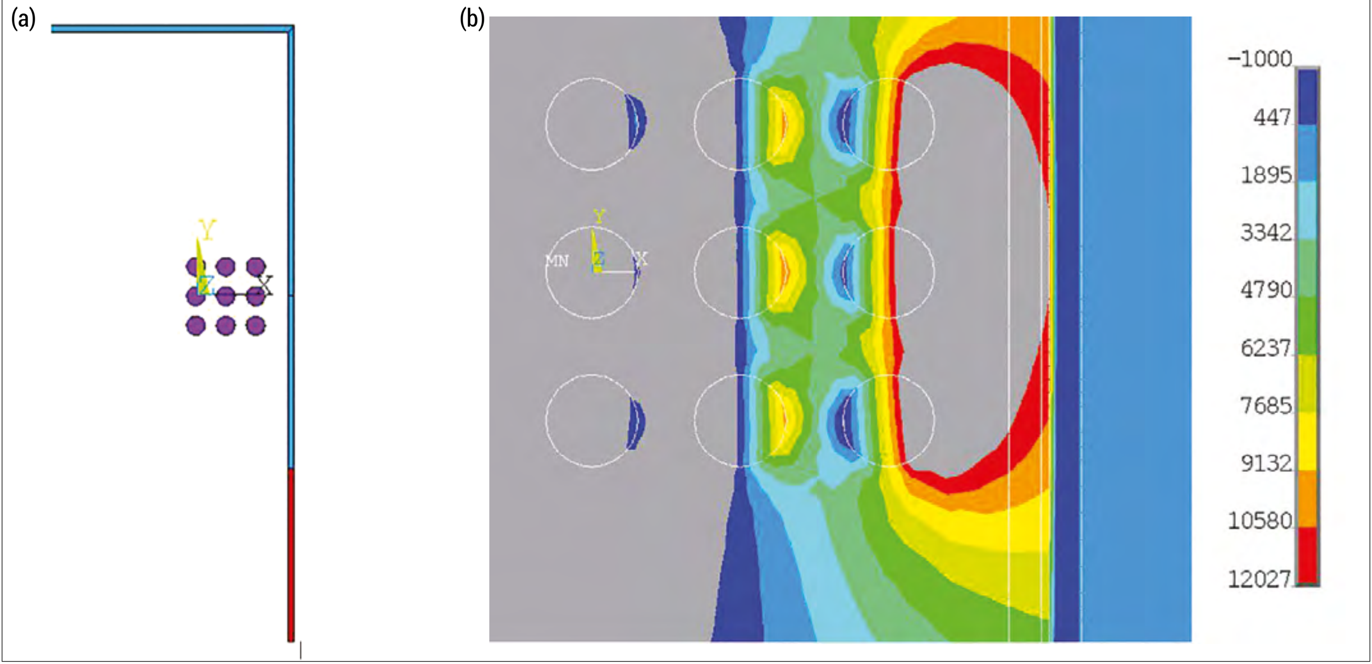


Figure 5. Determination of the magnetic field on the wall of the tank of the 45 MVA transformer: (a) –a numerical electromagnetic model of the tank and the group of leads, (b) – distribution of the magnetic field strength in the computational domain and on the surface of the tank

the transformer was ensured without any remarks and at increased load.

The calculation of the magnetic field was carried out by numerical simulation methods, taking into account the nonlinear properties of the ferromagnetic structural steel of the tank

Note that in power transformers, in a number of cases, there are increased local heating of the metal elements of the active part, in particular, yoke beams, clamping plates. In [3], using the example of a single-phase transformer of 533 MVA, the efficiency of installing a radiator in the form of a copper plate on the horizontal shelf of the lower yoke beam is shown. By conductive heat exchange of the shelf and plate, as well as their convection heat exchange with the ambient oil, this provided a decrease in the absolute temperature from 117 °C to the permissible 91 °C (excess over AT is 71 K). On application of the method, it is necessary to pay attention to the fact that eddy currents and additional losses from the magnetic fields do not arise in the flat bases of the radiators.

3.3. Transformer of 45 MVA

During the development of this single-phase converter transformer, significant heating of the upper part of the longitudinal ferromagnetic wall of the tank originated from the horizontal group of nine leads of the regulation windings with a total current of 9 × 971.2 A, which, due to dimensional limitations, are located quite close to the tank wall – Fig. 5.

To assess the heating of the tank wall from the magnetic field of the bends, a plane-parallel model of the horizontal cover and vertical tank wall and the indicated group of bends was used – Fig. 5(a). The calculation of the magnetic field was carried out by numerical simulation methods, taking into account the nonlinear properties of the ferromagnetic structural steel of the tank (surface effect), the dependence of the electrical conductivity coefficient on temperature.

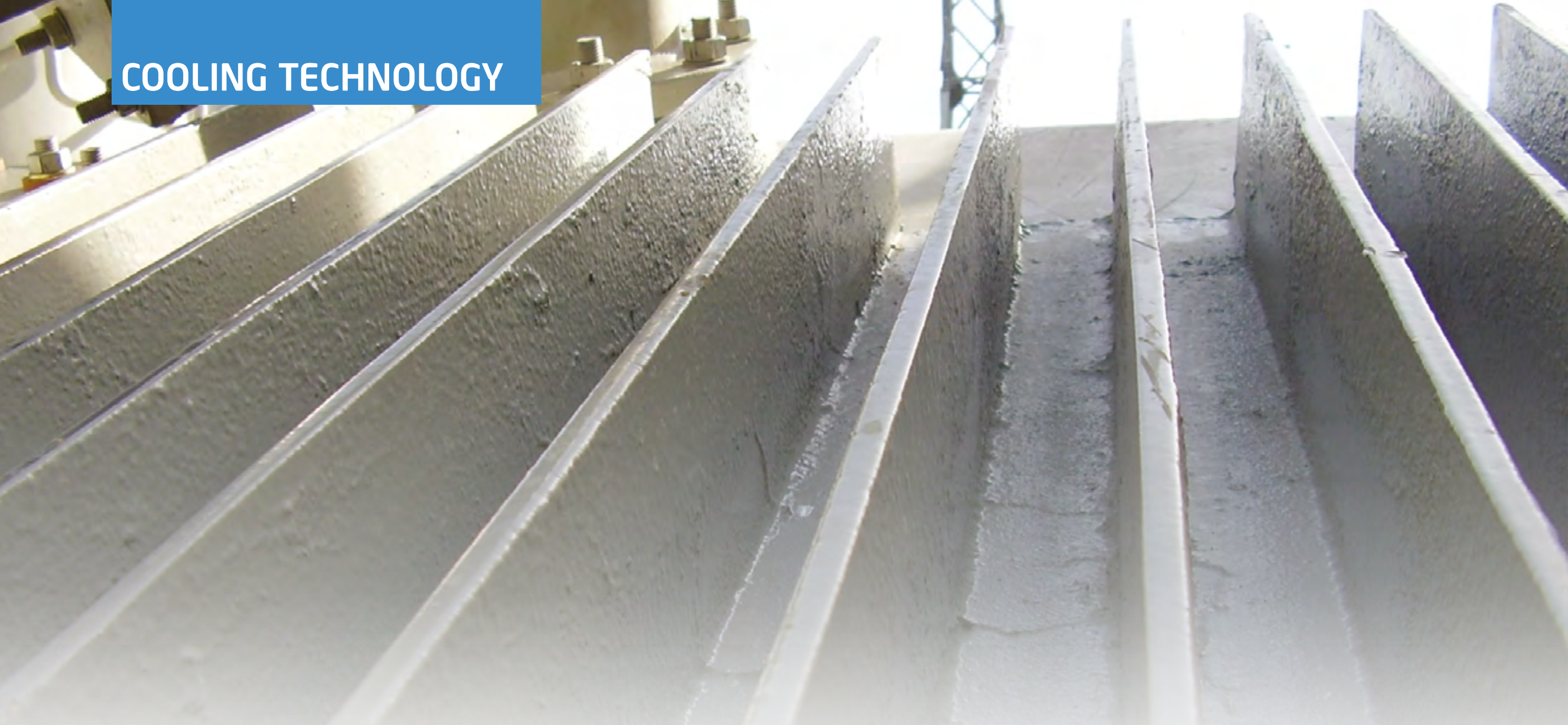
Fig. 5(b) shows the distribution in the part of the calculated model of the amplitude values of the vertical component of the magnetic field strength. It is tangent to the surface of the tank wall, determines surface losses, and its maximum value is H_m = 12 kA/m. The well-known empirical dependence of surface losses $p(H_m)$ on the value H_m was used to estimate losses [2]. For example, for the applied steel St. 3, this dependence in the range from 4 to 12 kA/m is approximated by the next expression $p(H_m) = 6.7 \cdot H_m^2 + 535 \cdot H_m - 796$. Additionally, their values are increased by the factor of 1.29 calculated for structural steel for higher harmonics for the investigated converter transformer. Therefore, the surface losses are $P = p(H_m) \times 1.29 = 8500$ W/m².

The heat transfer coefficient from the vertical surface for the adopted cooling system of the OFWF type transformer is determined by the relationship $\alpha = 7.16 P^{0.33}$ [2], and the value α = 141 W/(m²×K) is obtained. Therefore, the temperature rise of the inner surface of the tank over the cooling oil is $\vartheta = P / \alpha = 57$ K, according to the total losses of the transformer. It is calculated that the temperature of the upper oil in the transformer tank is 67 °C. Consequently, the temperature of the investigated part of the under-tank wall without radiators reaches the highest value, 57 + 67 = 124 °C. According to the above approach, a numerical model of a ferromagnetic two-layer plate with the distribution of losses according to Fig.5(b) was investigated. Its calculated heating was obtained at 124 °C – top Fig. 6(a).

Mounting on the wall of the tank radiators made of aluminium with a base thickness of 20 mm and with transverse finning ensured a decrease in the highest temperature of the inner surface of the tank wall to 91 °C, as shown in the lower part of Fig. 6(a). According to the results of measurements, (93 + 1) °C was obtained - thermogram in Fig. 6(c).

Significant heating of the upper part of the longitudinal ferromagnetic wall of the tank originate from the horizontal group of nine leads of the regulation windings

Fig. 6. Reduction of heating of the tank wall of the transformer 45 MVA: (a) – top – basic thermal model of the tank wall part, – bottom – thermal model with a surface-mounted radiator, (b) – installation of surface-mounted radiators on the wall of the transformer tank, (c) – thermogram of the tank wall of a 45 MVA transformer with installed surface-mounted radiators



Surface-mounted flat radiators with fins made from aluminium can be used to reduce local heating of the ferromagnetic parts of the tanks of large transformers

4. Conclusion

The efficiency of application of surface-mounted flat radiators with fins made from aluminium for reduction of the local heating of the ferromagnetic parts of the tanks of large transformers is shown. The efficiency of using radiators is about 20–40 %.

5. Acknowledgments

The authors thank **Vitaly Gurin** for preparing the article for the editor.

Bibliography

[1] V. F. Ivankov, A. V. Basova, I. V. Khimyuk, *Losses and heatings of tank covers of large transformers. Theory, calculation, experiment*, LAP LAMBERT Academic Publishing, 2015, 96 p., ISBN: 978-3-659-28296-6. https://www.lap-publishing.com/catalog/details/store/gb/book/978-3-659-28296-6/losses-and-heatings-of-tank-covers-of-large-transformers

[2] V. F. Ivankov, A. V. Basova, I. V. Khimyuk, *Methods of modelling transformers and reactors*, Kyiv: Nash Format, 2017, 490 p., https://previous.ied.org.ua/files/monograf2_2017.pdf (in Ukrainian)

[3] V. F. Ivankov, A. V. Basova, I. V. Khimyuk, *Reduction of local heats in tanks of powerful transformers by heat-removing local radiators with a ribbed*, Kyiv: Proceedings of the Institute of Electrodynamics of the National Academy of Sciences of Ukraine, 2021, issue 58, pp. 82-89, https://prc.ied.org.ua/index.php/proceedings/article/view/16/16 (in Ukrainian)

[4] G. N. Dul'nev, *Heat transfer in electronic devices*, M.-L.: Gosenergoizdat, 1963, 288 p. (in Russian)

[5] D. Kern, A. Kraus, *Developed heat transfer surfaces*, M.: Energiya, 1977, 464 p. (in Russian)

Authors

Viktor F. Ivankov, candidate of technical sciences, Senior Researcher, ex-head of the calculation and research laboratory of PrJSC "ZTR", Zaporizhzhia, Ukraine. Research interests: theoretical electrical engineering, methods of mathematical modelling of electromagnetic, thermal and mechanical processes, computer-aided design systems for power transformers and electrical reactor.

Anastasia V. Basova, candidate of technical sciences, leading researcher of the calculation and research laboratory of PrJSC "ZTR", Zaporizhzhia, Ukraine. Research interests: theoretical electrical engineering, methods of electromagnetic and thermal calculations of structural elements of power transformer equipment based on numerical and analytical models.

Ivan V. Khimyuk, candidate of technical sciences, senior researcher at the Institute of Electrodynamics of the National Academy of Sciences of Ukraine, Kyiv. Research interests: theoretical electrical engineering, methods of mathematical and numerical modelling of electromagnetic processes and fields of electrical machines and static electrical equipment.

Mr. Khimyuk has sadly passed away before publication of this article.