Distribution Transformer Cooling System Improvement by Innovative Tank Panel Geometries

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ABSTRACT

Increase of temperature rise and hot spot values affects dramatically transformer aging and life expectancy. The present article investigates several improved designs of ONAN transformer cooling system by means of advanced numerical heat transfer-fluid flow model. Novel tank designs are examined in conjunction with other crucial parameters, as the number and location of the winding cooling ducts, so as to define the best geometry that ensures maximum efficiency of the transformer cooling system, with the aim of expanding transformer lifetime.

Index Terms — **Distribution transformers, Cooling, Insulation Life, Finite Element Methods, Hydrodynamics, Fluid flow.**

1 INTRODUCTION

LIFE expectancy of transformers operating at varying temperatures is not accurately known. Fluctuating load conditions and changes in ambient temperatures make it difficult, if not impossible, to arrive at such definitive information. To ensure reliable cooling operation, a large margin of safety must be designed into a transformer. Design criteria include winding wire size, insulation material, and core size. Transformer cooling assists in maintaining the temperature rise of various parts within permissible limits. The heat, which comes from the windings and core depending on load conditions, is dissipated from the transformer tank and the radiator to the atmosphere. In particular, tanks, which are assembled by cold rolled/hot rolled steel plates through welding, are equipped with radiators or corrugated steel sheets (panels) in accordance with the capacity of the transformers. Cooling system is properly designed to have proper self thermo siphon system which helps to minimize the temperature gradient between winding and oil [1][2].

In case of oil-immersed transformer, cooling is provided by the circulation of the oil. Transformer oil acts as both insulating material and cooling medium in the transformer. As a result, a number of different cooling methods exist. The cooling systems for oil-immersed transformers are: 1) Oil Natural Air Natural Type (O.N.A.N.), 2) Oil Natural Air Forced Type (O.N.A.F.), 3) Oil Forced Air Natural Type (O.F.A.N.), and 4) Oil Forced Air Forced Type (O.F.A.F.) [3]-[6].

Transformer cooling system improvement involves minimization of the size of transformer panels and cooling ducts while retaining high efficiency in the dissipation of transformer losses. Thermal performance of power transformers has been extensively studied through analytical or advanced numerical techniques as in [7]-[11]. Recently, optimization of coils and cooling ducts in dry-type transformers with the aim to minimize the average and maximum winding temperatures has been carried out [12]. However, although transformer panels play an important role in the cooling system performance and optimization, no specific study on their shape optimization can be encountered in the relevant literature [4]. The present paper introduces novel shape configurations of transformer panels as a part of overall cooling system improvement of oil-immersed ONAN transformers. The analysis is conducted through advanced design optimization and coupled heat transfer-fluid flow FEM model, yielding robust and reliable results for the derivation of the optimum transformer cooling system.

2 COUPLED HEAT TRANSFER-FLUID FLOW TRANSFORMER MODEL

The heat transfer mechanism in a transformer occurs by three modes, i.e. conduction, convection and radiation. In oil

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cooled transformers, convection plays the most important role and conduction the least important. The coupled thermal and fluid flow processes, taking place inside the transformer, are analyzed by the use of a coupled three-dimensional computational fluid dynamics-thermal finite element model, developed and experimentally verified in [13][14]. For better representation purposes, the whole transformer geometry is modeled, consisting of four iron cores, three primary and three secondary windings of the active part and finally the oil tank that surrounds them (Fig. 1). To remove the heat from within the tank effectively, the convection and radiation area of the tank walls is enhanced by typical rectangular panels (fins) (Fig.2 (a)) welded to its side surfaces. In order to accurately model the heat exchanges between the tank and the ambient air, the model geometry contains not only the device itself, but also its surrounding air (i.e. the model is surrounded by an outer air domain of sufficiently large dimensions compared to the transformer dimensions). The tank is modeled as a material of certain thickness, and is enclosed in a large box of air (therefore the problem is solved in a closed boundary domain), thus the heat fluxes on the interfaces between the oil and the internal tank walls, as well as between the external tank walls and the external surrounding air can be obtained, representing real operating conditions. It must be noted that, as depicted in Fig. 1, the examined transformers are wound core transformers. Generally, in distribution transformers, wound core design predominates, whereas in larger power transformers, stacked cores are more common. However, the proposed methodology is also suitable for stack core transformers, as explained in Section 3.

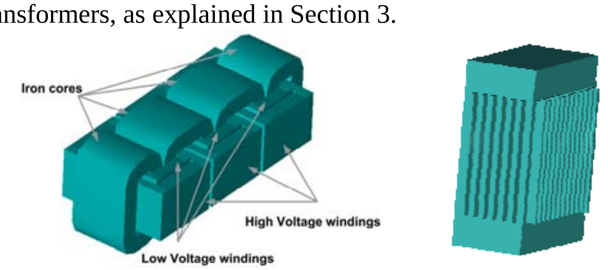

Fig. 1. Perspective view of the examined transformer active part (left picture) and the typical transformer oil tank (right picture).

For the derivation of the transformer thermal distribution, the thermal and fluid flow equations are solved iteratively, for a prescribed loss density in the transformer core and windings, derived by the loss values of the considered design. Only an initial guess for the transformer temperature and oil velocity has to be defined, providing the initial condition for the coupled FEM solver. The initial guess for the transformer temperature and oil velocity is used only for the first iteration step. The heat equations are solved first, deriving an initial temperature field, based on the initial values provided by the user. The non-linear equations of the heat solver are linearized. Two different linearization strategies are available, namely the Picard linearization and the Newton linearization. The iterative solver begins with the Picard iterations, and if the given convergence tolerance between two iterations is not met before the iteration count takes its maximum value, the iteration type is switched to Newton until convergence is achieved. If still convergence is not attained, then the solution is not feasible and the user has to redefine the initial values of temperature and oil velocity conditions. After the convergence of the heat solver, the fluid flow equations solution begins by the Computational Fluid Dynamics (CFD) FEM solver, using the temperature field values provided by the heat solver. The Picard and Newton iterations sequence is similar to the one described for the heat solver, and if convergence is not achieved initial conditions must be redefined. In order to deal with the intrinsic non-linear characteristics of the Navier-Stokes and thermal equations as well as the effect of the particular non-linear material properties involved in their solution, the FEM solver used in the methodology adopts a hybrid linearization scheme, involving two methods of linearization instead of only one. Therefore, Picard and Newton linearization methods are used successively, as they ensure complementary advantages in terms of stability and fast convergence to the solution [15]. This process is repeated for all the *s* iterative steps of the solution, where the temperature and oil velocity conditions computed in the *s-1* iteration are used as initial conditions for the *s* iteration.

The convection at the interface boundaries between the transformer active part, oil and tank is computed by the FEM solver by coupling the velocity field to the heat equation during each iteration. More specifically, during iteration *s*, the non-linear heat solver calculates the thermal distribution. This distribution includes the heat fluxes and the temperature in the boundaries between the transformer active part and oil, as well as the boundaries between the tank and the oil and the tank and outer air. These data are passed to the CFD FEM solver of *s* iteration and the heat convection coefficients are calculated prior to the solution process. The results of CFD FEM of *s* iteration (namely, the oil velocity field) are used as input for the thermal equations solution process by FEM of the *s+1* iteration and so on. Therefore there is no need to define convection coefficients at these boundaries. Only the initial guess of the transformer temperature and oil velocity provided by the user is used for the first time step of the solution, a guess that is not however crucial for the convergence of the method, since it is later refined by the updated results of the coupled solver. Moreover, in our case of oil cooled transformer, no radiation effects need to be taken into consideration as in the case of air-cooled ones [16].

3 IMPROVEMENT OF TRANSFORMER COOLING SYSTEM

The proposed novel tank panel geometries are investigated for a given transformer design. The design is derived according to transformer specifications by means of Mixed Integer Non-Linear Programming (MINLP) methodology described in [17]. More specifically, 16 transformer inputs (i.e. nominal power, primary and secondary winding material, primary and secondary line-to-line voltage, winding connection type, conductor type and current density, operating frequency, type of magnetic material, guaranteed no load and load losses and short-circuit impedance) are used. The MINLP for optimizing the transformer design is based on the minimization of the overall transformer cost function:

$$\min Z(\underline{x}) = \min_{\underline{x}} \sum_{j=1}^{8} c_j f_j(\underline{x}) \tag{1}$$

where c_j and f_j are the unit cost (€/kg) and the weight (kg) of each component j (active and mechanical part, Fig. 1), and $\underline{x}$ is the vector of the four design variables, i.e. the number of low voltage turns, the magnetic induction magnitude (B), the width of core leg (D) and the core window height (G). the software package is designed to be as interactive as possible, providing access to all design parameters so that its users have the ability to customize the design to meet their own inventory needs. The software package implementing the MINLP methodology is designed to be as interactive as possible, providing access to all design parameters so that its users have the ability to customize the design to meet their own inventory needs. Apart from the 16 necessary input parameters, the engineer can modify in total 184 parameters regarding the initial stage of the transformer design, if it is required. It is important to note that the transformer engineer often uses international standards in order to set the limits of many specifications, such as the percentage of short-circuit impedance, the maximum guaranteed no load and load losses, the maximum temperature of the insulating materials. In our case, the minimization of the cost of the transformer active part is subject to the constraints that are based on the tolerances specified by IEC 60076-1 [18].

Having completed the optimum transformer design with rectangular panels [17], different panel geometries are investigated, maintaining same cooling surface [19]. The cooling surface is kept constant, in order to derive an improved tank design with the same tank material as the one of the conventional design, thus not increasing the material cost. In particular, based on the rectangular panel area (Fig. 2(a)), three different panel geometries are designed with equivalent surface area (Fig. 2(b)(c)(d)). The examined shapes aim to improve the heat dissipation achieved by the oil flow. Curved panel surfaces enable better thermal performance since they enhance dynamic oil circulation characteristics. The above curved shapes are examined in conjunction to different winding ducts arrangements, in order to derive an overall optimum transformer cooling system.

The investigation involves four steps, depicted in the flowchart of Fig. 3, requiring the interaction of different software packages and their parameterization for the examined transformer problem. In the first step, the methodology presented in [17] was used to derive the optimum transformer geometry, based on the transformer input data. The detailed model of the transformer active and mechanical part according to the design specifications was produced by the design software package (Transformer Design Optimization-TDO) presented in [20][21], generating the appropriate geometry files to be used as input for the FEM model creation. Next, in a second step, a separate software package (GMSH) was employed to create and optimize the 3D FEM mesh needed for the solution of FEM equations [22]. In the third step, a finite element software (ELMER) was used for the solution of the coupled problem [23], using the mesh files created in the second step as input and generating the temperature distribution output files. The final step involves the post-processing of the finite element solver files produced in the third step, which is also conducted by the software package of the first step [21].

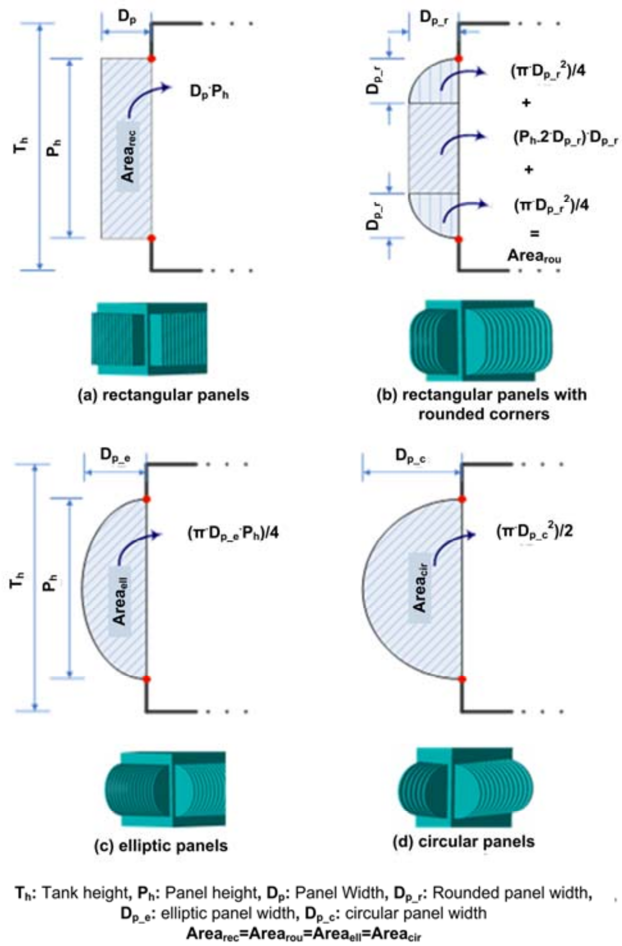

Fig. 2. Equivalent surface of different corrugated tank panel geometries for the improvement of transformer cooling system.

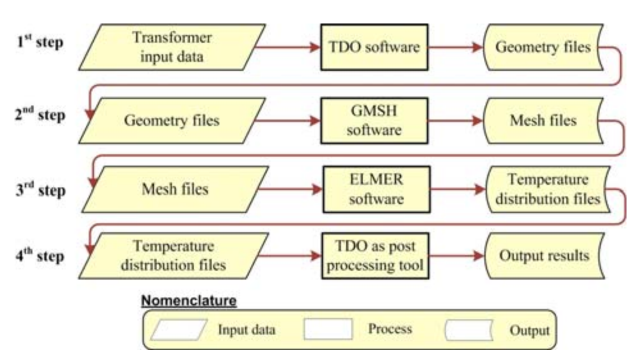

Fig. 3. Flowchart depicting the software implementation of the investigation of novel tank geometries.

The methodology can be applied to transformers with different core designs from the one examined in the paper, e.g. stack core design. The designer can implement the presented technique to stack core transformer using the appropriate analytical equations during the design process of the 1st step of Fig. 3. In this case, the geometry and mesh files will be constructed accordingly and the CFD analysis of the 3rd step will take into account the different core geometry during the derivation of the thermal distribution results.

4 RESULTS AND DISCUSSION

4.1 APPLICATION TO A 160 KVA TRANSFORMER

Two different kVA ratings have been considered in terms of cooling system performance improvement. First, a 160 kVA, with no load losses equal to 431 W and load losses equal to 2130 W, ONAN, 20/0.4 kV distribution transformer has been designed and modeled through the process of Fig. 3. The 16 required input parameters (Section 3) for the design of the 160 kVA transformer are listed in Table 1. It must be noted that the designed load losses are 6.5% larger than the guaranteed load losses in Table 1, while the no load losses are 14.93% larger than the guaranteed no load losses in Table 1 (both deviations are smaller than the maximum tolerances defined by IEC standard, as described in Section 3). Three basic parameters of the cooling system have been modified in order to compare the four tank geometries of Fig. 2, namely the number of High Voltage (HV) and Low Voltage (LV) winding ducts, the panel width D_p (also depicted in Fig. 2) and the number of panels (distributed along the width and length). Four different cooling system arrangements derived, designated as C_1 to C_4 in Table 2. For each one of these arrangements, the four proposed panel geometries were used in the coupled CFD-thermal model, yielding the temperature distribution results along desired contours of the active part geometry, as well as other global parameters (e.g. hot spot location and temperature). The initial cooling system design corresponds to the C_2 configuration with rectangular panels (5 ducts in the HV and LV winding). The number of ducts for the other three configurations are selected so as that C_1 corresponds to the next lower number of ducts (i.e. 4 ducts) while C_3 and C_4 correspond to the next higher number of ducts (i.e. 6 and 7, respectively), in comparison to the initial design. The investigation of much lower or higher number of ducts would not be of practical meaning for this rating, since it would either result to inadmissible active part cooling (in the case of number of ducts lower than 4) or significant increase in the coils diameter (in the case of number of ducts larger than 7) and the overall material cost.

The average time required for the derivation of the results per step is: the first step requires 2 min, the second step requires 5 min producing an optimized 3D mesh of approximately 70000 nodes, later on, the solution of the coupled CFD-FEM solver of the third step requires 30 min, and finally, the fourth step requires one min (AMD Athlon X2 Dual-Core QL-60 1.90 GHz, RAM 4 GB). It must be noted that for each cooling system configuration, the first step is performed only once for the rectangular panels (for the rest of the panel geometries the parameters of C_1-C_4 remain the same) and the fourth step is performed only once after the derivation of the thermal distributions corresponding to the four panel geometries. Therefore, the total analysis for each cooling configuration requires approximately 143 minutes, i.e.

$$2 + 4 \cdot 5 + 4 \cdot 30 + 1 = 143 \text{ min}.$$

Figs 5 to 8 depict the temperature variation along the contours of Fig. 4, i.e., along the inner corner of the second iron core (the second iron core is selected since it is one of the two iron cores that surround the middle LV winding, where the temperature is expected to be higher due to more limited circulation of oil compared to the LV windings of the first and third phase) and the inner corner of the middle LV winding in the case of cooling system C_1 and C_2 for the four examined panel geometries. The LV winding is selected since it generally exhibits the higher temperatures in the transformer active part.

Table 1. Main input parameters for the design of the 160 kVA transformer of Section 4.1.

Parameter Description	Value	Parameter Description	Value
Nominal Power (kVA)	160	Secondary winding conductor type	Sheet
Primary winding material	Copper	Operating frequency (Hz)	50
Secondary winding material	Copper	Type of magnetic material	HiB
Primary line-to-line voltage (kV)	20	Primary winding current density (A/mm^2)	2.5
Secondary line-to-line voltage (kV)	0.4	Secondary winding current density (A/mm^2)	3.25
Primary winding connection type	Delta	Guaranteed no load loss (W)	2000
Secondary winding connection type	Star	Guaranteed load loss (W)	375
Primary winding conductor type	Single Circular Wire	Guaranteed short-circuit impedance (%)	4

Table 2. Main parameters of the four cooling system arrangements examined for the 160 kVA transformer of Section 4.1.

Cooling System Arrangement	Number of HV-LV ducts	Number of panels across tank length	Number of panels across tank width	D_p (mm)
C_1	4	22	10	70
C_2	5	22	10	70
C_3	6	21	10	60
C_4	7	21	11	60

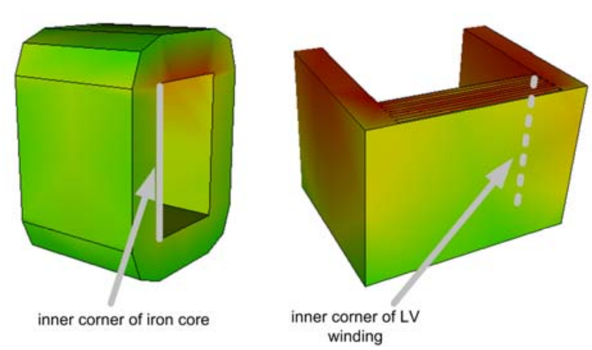

Fig. 4. Active part contours used for the visualization of the temperature distribution results of Figs. 5-8.

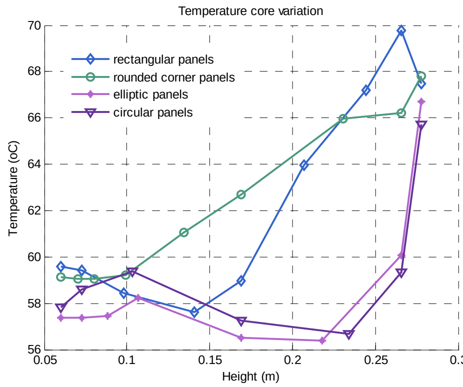

Fig. 5. Temperature variation along the inner corner of the iron core for the cooling system arrangement C_1 of the 160 kVA transformer (Section 4.1).

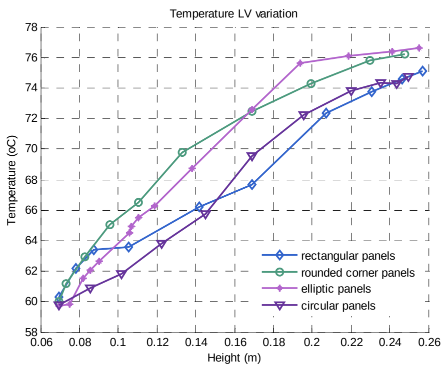

Fig. 6. Temperature variation along the inner corner of the LV winding for the cooling system arrangement C_1 of the 160 kVA transformer (Section 4.1).

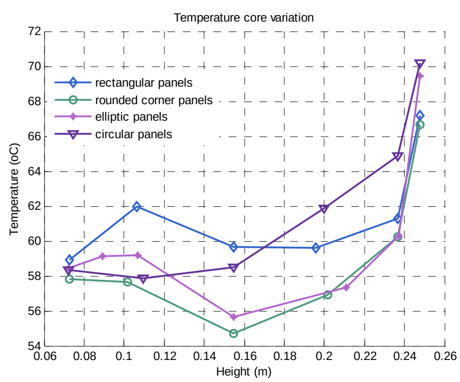

Fig. 7. Temperature variation along the inner corner of the iron core for the cooling system arrangement C_2 of the 160 kVA transformer (Section 4.1).

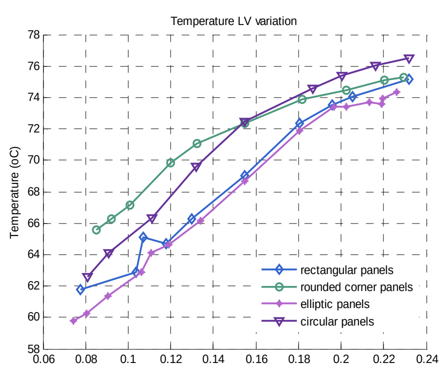

Fig. 8. Temperature variation along the inner corner of the LV winding for the cooling system arrangement C_2 of the 160 kVA transformer (Section 4.1).

The observation of Figs. 5-8 leads to the conclusion that rectangular and circular panels exhibit better thermal performance in the examined contours in the case of cooling system arrangement C_1, while elliptic panels are the most efficient in the case of the second arrangement C_2. However, it must be noted that the maximum transformer temperature does not occur along the contours of Figs. 5-8 and cannot be used as a criterion for the selection of the optimal panel geometry and cooling system arrangement.

Fig. 9 illustrates the variation of the hot spot temperature for the four panel geometries as a function of the number of HV-LV ducts (corresponding to cooling systems C_1-C_4 of Table 2). The calculated hot spot values are also listed in Table 3. The variation of the hot spot temperature of Fig. 9 is not straightforward, i.e. although the number of ducts increases, the hot spot temperature does not necessarily decrease, since it is also affected by the other parameters appearing in Table 2. This behavior renders the selection of the optimal cooling system configuration a multi-variant non-linear optimization problem, depending on several parameters apart the panel geometry. According to Fig. 9 and Table 3, the lowest hot spot temperature corresponds to the elliptic panel geometry in the case of the second cooling system arrangement (with 5 HV-LV ducts, 32 panels and D_p=70 mm). According to Table 3, the best performance for each configuration does not correspond to the same panel shape, i.e. the rectangular panel results to the lowest hot spot in the case of C_1 and C_3, whereas in the case of C_2 and C_4, the elliptic and rectangular panel shape, respectively result to the lower hot spot value. This is also attributed to the fact that the thermal performance is influenced not only by the shape of the panels, but from the number of panels and cooling ducts as well. However, the overall best performance corresponds to the elliptic panel shape, provided that the suitable panel and duct number is selected.

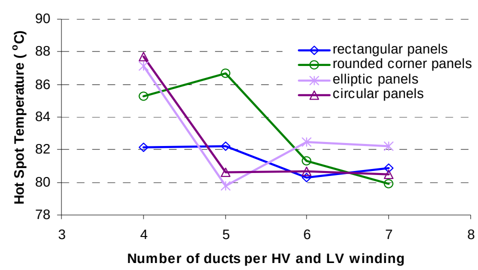

Fig. 9. Variation of the hot spot temperature of the 160 kVA transformer (Section 4.1) as a function of the number of HV and LV ducts for the four panel geometries.

Fig. 10 compares the 160kVA transformer active part thermal distribution for (a) C_1 configuration with circular panels (i.e. the worst cooling system according to Table 3) and (b) C_2 configuration with elliptic ducts (best cooling system according to Table 3). It can be observed that most elements of the best configuration have lower temperatures by several degrees Celsius compared to the worst configuration.

The cooling surface of each arrangement is kept constant, to derive an improved tank design with the same tank material as the one of the conventional design. Thus, the material cost is not increasing nor decreasing, due to the fact that each different geometrical shape is designed to have equivalent surface area with the one of the rectangular panel area, having though different dimensions but exactly the same area and thus material weight. As far as the difference in the number of ducts and panels in each cooling system arrangement is concerned, it is quite small and therefore results to negligible weight, dimensions and cost differences.

Table 3. Hot spot temperatures for the different panel geometries and the four cooling system arrangements examined for the 160 kVA transformer of Section 4.1.

Cooling System Arrangement	Calculated hot spot temperature (°C)			
	Rectangular panels	Rounded Panels	Elliptic panels	Circular panels
C_1	82.17	85.25	87.14	87.68
C_2	82.24	86.69	79.78	80.61
C_3	80.29	81.29	82.84	80.68
C_4	80.87	79.91	82.23	80.48

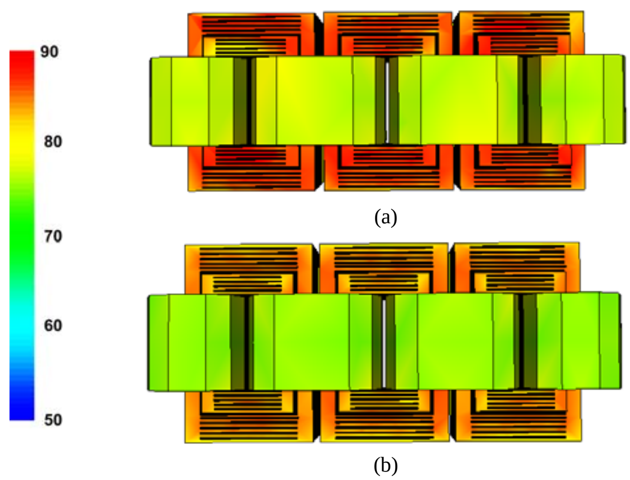

Fig. 10. Top view of the 160kVA transformer active part thermal distribution: (a) C_1 configuration with circular panels (worst cooling system according to Table 3), (b) C_2 configuration with elliptic ducts (best cooling system according to Table 3).

4.2 IMPROVEMENT OF INSULATION LIFE EXPECTANCY

Oil-paper is the main type of transformer internal insulation and will degrade over time. The life of transformers is principally determined by the thermal degradation rate of cellulose paper. The influences of thermal aging on paper's electrical and mechanical properties as well as the corresponding mechanisms become the concerns of aging diagnosis and residual lifetime predictions for transformers [24]. Aging or deterioration of insulation is a time function of temperature, moisture content, and oxygen content. Transformer oil suffers continuous deterioration and degradation due to the sustained application of the electric and cyclic thermal stresses because of loading and climatic conditions [25]. With modern oil preservation systems, the moisture and oxygen contributions to insulation deterioration can be minimized, leaving insulation temperature as the controlling parameter. Since, in most apparatus, the temperature distribution is not uniform, that part that is operating at the highest temperature will ordinarily undergo the greatest deterioration [26]. Therefore, in aging studies it is usual to consider the aging effects produced by the hot spot temperature. Fig. 11 illustrates the variation of insulation Relative Ageing Rate (RAR) for the four panel geometries as a function of the number of HV-LV ducts (corresponding to cooling systems C_1-C_4), according to the IEC standard [27], provided by the following formula:

$$RAR = 2^{(\theta_h - 98)/6} \qquad (2)$$

where θ_h is the hot spot temperature (in °C).

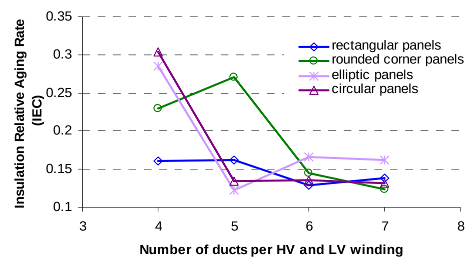

Fig. 11. Variation of insulation relative ageing rate of the 160 kVA transformer (Section 4.1) as a function of the number of HV and LV ducts for the four panel geometries.

4.3 APPLICATION TO A 630 KVA TRANSFORMER

The investigation of different tank geometries has been repeated in the case of a 630 kVA, with no load losses equal to 1424 W and load losses equal to 4288 W, ONAN transformer, examining various cooling system configurations (involving 8, 9 and 10 HV and LV ducts) and the four proposed panel geometries, as listed in Table 4. The input parameters for the design of the 630 kVA transformer are identical to the ones presented in Table 1, apart from the nominal power, which is equal to 630 kVA, the primary and secondary winding current density, which is equal to 2 A/mm^2, the guaranteed load losses, which are equal to 4000 W, the guaranteed no load losses, which are equal to 1300 W and the guaranteed short-circuit impedance, which is equal to 6%. The initial cooling system design corresponds to the C_5 configuration with rectangular panels (8 ducts in the HV and LV winding). The number of ducts for the other two configurations are selected so as that C_6 and C_7 correspond to the next higher number of ducts (i.e. 8 and 9, respectively), in comparison to the initial design. The investigation of much lower or higher number of ducts would not be of practical meaning for this rating, since it would either result to inadmissible active part cooling (in the case of number of ducts lower than 8) or significant increase in the coils diameter (in the case of number of ducts larger than 10) and the overall material cost. The respective calculated hot spot results are listed in Table 5. The elliptic panel in conjunction with 8 cooling ducts (arrangement C_5 of Table 4) is the optimal cooling system configuration, exhibiting a hot spot temperature equal to 78.73 ^oC while the respective hot spot of the next most efficient configuration (circular panels with 8 ducts) is equal to 82.34 ^oC. Thus, a decrease of up to 4.38% of the hot spot temperature is achieved, which is more significant than the one presented in Fig. 9 (the two most efficient cooling system configurations are the elliptic and circular panel geometry and the difference in the hot spot between them is less than 1^{o}C). Moreover, a decrease of 11.68% compared to the respective hot spot value of the classical (rectangular) panel geometry for arrangement C_5, which corresponds to 89.14^{o}C according to Table 5, is observed. Fig. 12 illustrates the variation of the hot spot temperature for the four panel geometries as a function of the number of HV-LV ducts (corresponding to cooling systems C_5-C_7 of Table 4). As in the case of the 160kVA transformer, the overall best cooling system performance corresponds to the elliptic panel shape, provided that the suitable panel and duct number is selected. Fig. 13 illustrates the variation of insulation Relative Ageing Rate (RAR) for the four panel geometries as a function of the number of HV-LV ducts (corresponding to cooling systems C_5-C_7 of Table 4), according to equation (2).

Table 4. Main parameters of the four cooling system arrangements examined for the 630 kVA transformer of Section 4.3.

Cooling System Arrangement	Number of HV-LV ducts	Number of panels across tank length	Number of panels across tank width	D_p (mm)
C_5	8	34	15	60
C_6	9	33	15	60
C_7	10	33	16	60

Table 5. Hot spot temperatures for the different panel geometries and the three cooling system arrangements examined for the 630 kVA transformer of Section 4.3.

Cooling System Arrangement	Calculated hot spot temperature (^{o}C)			
	Rectangular panels	Rounded Panels	Elliptic panels	Circular panels
C_5	89.14	84.87	78.73	82.34
C_6	85.9	84.08	85.30	84.77
C_7	84.3	83.90	84.00	84.00

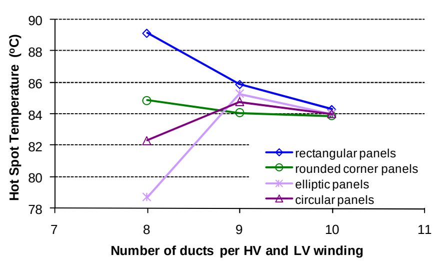

Fig. 12. Variation of the hot spot temperature of the 630 kVA transformer (Section 4.3) as a function of the number of HV and LV ducts for the four panel geometries.

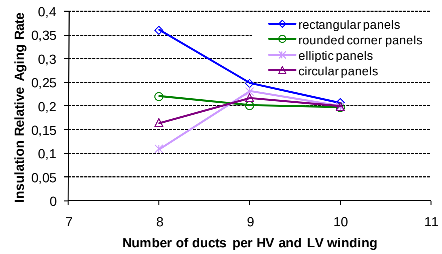

Fig. 13. Variation of insulation relative ageing rate of the 630 kVA transformer (Section 4.3) as a function of the number of HV and LV ducts for the four panel geometries.

5 CONCLUSION

In this paper, a new cooling system is designed in terms of shape configuration, improving transformer thermal conditions. In particular, innovative tank panel geometries of oil-immersed ONAN transformer for the improvement of their cooling system are introduced. The investigation is carried out by means of a suitable coupled heat transfer-fluid flow FEM model. The results of the analysis in different ratings proved that the influence of the panel geometry in the cooling system performance is important and cannot be predicted in a straightforward manner but has to be examined in conjunction with the ducts number and location as well as other parameters such as the panels' number and surface. The elliptic panel shape has resulted to a decrease of up to 11.68% in the transformer hot spot temperature in the case of larger transformer rating, which enhances significantly the insulation life expectancy. However, the thermal performance is influenced not only by the shape of the panels, but from the number of panels and cooling ducts as well, which must be properly selected. Experimental validation of the improvement of the thermal performance achieved by the curved panel geometries is an important next step of the analysis. This step will be implemented by carrying out temperature rise tests when the manufacturing process of transformers with the proposed novel tank designs is completed and comparing the results to those obtained with the existing conventional designs.

REFERENCES

[1] S. V. Kulkarni, S. A. Khaparde, *Transformer Engineering Design & Practice*, New York: Marcel Dekker, 2004.

[2] B. Kennedy, *Energy Efficient Transformers*, New York: Mc-Graw-Hill, 1998.

[3] *Use and Maintenance of ELVIM Oil-Immersed Distribution Transformers*, Inofyta, Greece: Schneider Electric AE, 2001.

[4] E. I. Amoiralis, M. A. Tsili, A. G. Kladas, "Transformer design and optimization: a literature survey, IEEE Trans. Power Del., Vol. 24, pp.1999-2024, 2009.

[5] IEC 60076-2: Power transformers, Part 2: Temperature rise, 1993.

[6] IEEE Std C57.12.00: IEEE Standard for Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers, 2006.

[7] K. Preis, O. Bíró, G. Buchgraber, I. Ticar, "Thermal-electromagnetic coupling in the finite-element simulation of power transformers," IEEE Trans. Magn., Vol. 42, pp. 999-1002, 2006.

[8] J. M. Mufuta, E. Van den Bulck, “Modelling of the mixed convection in the windings of a disc-type power transformer,” Appl. Thermal Eng., Vol. 20, pp. 417-437, 2000.

[9] N. El Wakil, N.-C. Chereches, J. Padet, “Numerical study of heat transfer and fluid flow in a power transformer,” Int. J. Ther. Sci., Vol. 45, pp. 615–626, 2006.

[10] J. Smolka, D.B. Ingham, L. Elliott, A.J. Nowak, “Enhanced numerical model of performance of an encapsulated three-phase transformer in laboratory environment,” Appl. Therm. Eng., Vol. 27, pp. 156–166, 2007.

[11] L.J. Zhou, G.N. Wu, J.F. Yu, X.H. Zhang, “Thermal overshoot analysis for hot-spot temperature rise of transformer," IEEE Trans. Dielectr. Electr. Insul., vol.14, no.5, pp.1316-1322, 2007.

[12] J. Smolka, A. Nowak, A, "Shape optimization of coils and cooling ducts in dry-type transformers using CFD and GA," IEEE Trans. Magn., Vol. 47, No. 6, pp. 1726-1731, 2011.

[13] M. A. Tsili, E. I. Amoiralis, A. G. Kladas and A. T. Souflaris, “Coupled 3D Fluid Flow-Thermal FEM Model for Power Transformer Temperature Analysis,” Proc. 17th Inter. Conf. Comp. Electromagnetic Fields, Florianopolis, Brazil, November 2009.

[14] M.A. Tsili, E.I. Amoiralis, A.G. Kladas, A.T. Souflaris, “Power transformer thermal analysis by using an advanced coupled 3D heat transfer and fluid flow FEM model,” Int. J. The. Sci, submitted for publication.

[15] M. ur Rehman, C. Vuik, G. Segal, “A comparison of preconditioners for incompressible Navier–Stokes solvers,” Int. J. Numer. Meth. Fluids, Wiley IntersScience, 2007.

[16] F. Farahmand, F.P. Dawson, J.D. Lavers, “Temperature rise and free-convection heat-transfer coefficient for two-dimensional pot-core inductors and transformers,” IEEE Trans. Ind. Appl., Vol. 45, no. 6, pp. 2080-2089, 2009.

[17] E. I. Amoiralis, P. S. Georgilakis, M. A. Tsili, A. G. Kladas, “Global transformer optimization method using evolutionary design and numerical field computation,” IEEE Trans. Magn., Vol. 45, pp. 1720-1723, 2009.

[18] IEC 60076-1, “Power transformers – Part 1: General,” 2000.

[19] E. I. Amoiralis, M. A. Tsili, A. G. Kladas and A. T. Souflaris, “Geometry optimization of transformer cooling system based on coupled 3D FEM-CFD analysis,” Proc. 14th Biennial IEEE Conf. on Electromagnetic Field Computation (CEFC 2010), Chicago, USA, May 2010.

[20] E. I. Amoiralis, Energy savings in electric power systems by development of advanced uniform models for the evaluation of transformer manufacturing and operating cost, Ph.D. dissertation (in Greek), Tech. Univ. Crete, Greece, 2008. Online Available: http://www.library.tuc.gr/artemis/PD2009-0001/PD2009-0001.pdf

[21] E. I. Amoiralis, P. S. Georgilakis, M. A. Tsili, A. G. Kladas and A. T. Souflaris, “A complete software package for transformer design optimization and economic evaluation analysis,” Mater. Sci. Forum, Vol. 670, pp. 535-546, 2011.

[22] C. Geuzaine and J.-F. Remacle, “Gmsh: a three-dimensional finite element mesh generator with built-in pre- and post-processing facilities,” Int. J. Numerical Methods in Engin., Vol. 79, pp. 1309-1331, 2009.

[23] Elmer, Open Source Finite Element Software for Multiphysical Problems, http://www.csc.fi/english/pages/elmer.

[24] Yang Lijun, Liao Ruijin, Caixin Sun, Zhu Mengzhao, “Influence of vegetable oil on the thermal aging of transformer paper and its mechanism,” IEEE Trans. Dielectr. Electr. Insul., Vol.18, No.3, pp.692-700, 2011.

[25] M. A. A. Wahab, M. M. Hamada, A. G. Zeitoun, G. Ismail, “Novel modeling for the prediction of aged transformer oil characteristics,” Elec. Power Syst. Res., Vol. 51, pp. 61-70, 1999.

[26] IEEE Std C57.91-1995(R2002). IEEE Guide for Loading Mineral-Oil-Immersed Transformers.

[27] IEC/TS 62332-1 ed1.0 (2005). Electrical insulation systems (EIS) - Thermal evaluation of combined liquid and solid components - Part 1: General requirements.

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