CASE STUDY ON THERMAL OPTIMIZATION OF OIL IMMERSED TRANSFORMER USED IN SOLAR POWER PLANT BASED ON GENETIC ALGORITHM AND COMPUTATIONAL FLUID DYNAMICS

by

Emir YUKSELEN[a*] and Ires ISKENDER[b]

[a] Electrical and Electronics Engineering Department, Gazi University, Ankara, Turkey
[b] Electrical Electronics Engineering Department, Cankaya University, Ankara, Turkey

Original scientific paper
https://doi.org/10.2298/TSCI221109051Y

Transformers are one of the most capital investments in the solar power generation. Their safe and stable operations in the electrical networks are important. The main failure factor of transformers is the high temperature generated by the losses during operation, which increases the probability of insulation damage that significantly affects the useful life of transformer. Considering the importance of oil temperature and its effects on the life of the transformer, a numerical method is developed in this paper to optimize the cooling system of the transformer. In this regard, genetic algorithm is used as an optimization method to minimize the total cost of the cooling system while maintaining the required thermal conditions of the transformer. A comprehensive parametric study is carried out among the effective cooling geometry parameters using 3-D electromagnetic and thermal models of the photovoltaic transformer to evaluate and analyze the temperature distribution. The accuracy and feasibility of the proposed method is established by comparing the numerical results with those obtained from the experimental test. The results of the proposed method are found to be in a good agreement with the experimental and simulation results.

Key words: *thermal analysis, heat transfer, CFD, genetic algorithm, transformer*

Introduction

Transformers are the most important component in the generation and distribution of electricity from solar power plants. The core and conductor power losses of the transformer, which are converted into heat, cause the temperature of the transformer to increase. The temperature increases significantly when the heat is not efficiently emitted by a suitable cooling system. If the oil temperature is higher than the relative standard limits, the lifetime expectancy of the transformer will be shorted due to deterioration of the insulation material. Recently, the total losses of the transformer have been minimized due to the EU transformer regulation, resulting in higher cost. Therefore, manufacturers are constantly seeking to reduce the total weight and volume of transformers. Consequently, the thermal design of the transformer with the appropriate cooling system has become more important in maintaining the relevant target performance as well as optimum cost. In the last few years, investigative efforts have been carried out to develop and experiment thermal models of transformers considering convection heat transfer [1-12].

* Corresponding author, e-mail: emir.yukselen@gazi.edu.tr

Due to the complexity of convective heat transfer, limited studies are available as reviewed in the followings. The 3-D electromagnetic and thermal modelling of the dry type isolation transformer has been carried out to investigate the cooling requirement of the core and winding at a certain rated power level and special non-linear load in [13], but this method could not be applied to the oil immersed transformers. In Cordoba *et al.* [14], author applied a model to simulate the natural-convection in ONAN distribution transformer using slice model of the transformer. The CFD model presented in [15] is used to estimate the heat transfer performance of the distribution transformer in nanofluid. The numerical analyses are carried out in [16-18], to study and optimize the effects of important parameters on thermal performance of distribution transformers. The study [19], aims to optimize the thermal parameters of a transformer by integrating a set of pre-physical models into the dynamic thermal modelling procedure, however, some required thermal parameters are obtained from the experiments. In Tsili *et al.* [20], author presents the development of an advanced 3-D finite element model for the coupled solution of heat transfer and fluid-flow equations governing transformer thermal performance. In Gong *et al.* [21], a fluid-thermal coupled analysis method is used to compute the temperature distribution in a certain power transformer. In Taheri *et al.* [22], a novel method using the thermal resistance model with solar radiation is carried out to predict the thermal behavior of the transformer in overloading condition. Though acceptable amounts of works have been carried out on thermal behaviors of transformer, investigating on the optimizing the cooling system of the transformer considering a 3-D simulation of convective heat transfer with the complete geometry of the transformer has not been performed previously.

The main objective of this study is to present a novel method for optimum geometry design of the transformer cooling. This target is achieved by the following steps. Firstly, electromagnetic modelling of a 1000 kVA PV transformer was carried out and then, the cooling system of the transformer was designed using genetic algorithm (GA) technique. The results of the design were used in the 3-D thermal fluid-flow and heat transfer model of the transformer for evaluating and analyzing the temperature distribution in the transformer. The effects of the different geometric parameters were also numerically investigated. Finally, the accuracy of proposed model was validated by the experimental results.

Description of the model

Nowadays, an optimal design is important due to the competitive markets and economical risks. Engineering optimization helps to achieve optimal performance as well as cost competitiveness.

According to the recently increasing raw material costs, transformer manufacturers give more importance to optimization studies in order to increase their competitiveness or reduce production costs. Therefore, transformer manufactures use cost optimization techniques during the design stage to provide optimum and competitive design while meeting the requirements of international standards and user specifications. In this study, the main goal is to present GA optimization technique that deals with minimization of manufacturing cost in the design of cooling system of the transformer.

Genetic algorithm technique

The GA is a search algorithm based on the prediction of natural selection and genetics [23]. The features of GA are multi-path that searches many peaks in parallel, and hence reduces the possibility of local minimum trapping. The GA works with a coding of parameters instead of parameters themselves helping the genetic operator to evolve the current state into the next state with minimum computations. The GA evaluates the fitness of each string to guide its search instead of the optimization function. The GA only needs to evaluate objective function guide its search and required no derivatives or other auxiliary knowledge for computation of derivatives or other auxiliary functions [24-26].

The GA is achieved by the selection, reproduction and mutation. The operation of these three procedures is dependent upon the fitness of the individuals concerned.

Geometric specification of the model

Transformers as an electrical machine, have complex structure with various components such as magnetic core, windings, tank, cooling surface, insulation material, bushings and other accessories. The core and windings are immersed into oil tank. During the field operation of the transformer, losses occur in the windings and core of the transformer causing these components to heat up. Accordingly, the oil temperature increases and as a result, the oil moves upward and flows into the corrugated fins where it could be cooled down to keep the temperature at the safe level. In this study a special type double stack non-circular winding transformer is considered as a case study. A summary of the geometric parameters for active part of the transformer are presented in tab. 1.

Table 1. Transformer magnetic core and windings geometric parameters

Parameters	LV_{upper}	HV_{upper}	LV_{lower}	HV_{lower}
Inner diameter of the winding [mm]	162-246	279-374	162-246	261-358
Outer diameter of the winding [mm]	257-352	382-489	237-334	381-490
Winding axial height [mm]	460	462	460	462
Core cross-section [cm²]	306			
Core center distance between legs [mm]	395			
Core windows height [mm]	1000			

The active and the structural part of the case study are shown in fig. 1. The active part of the transformer consists of the magnetic core and windings, and the structural part consists of the tank and cooling fins.

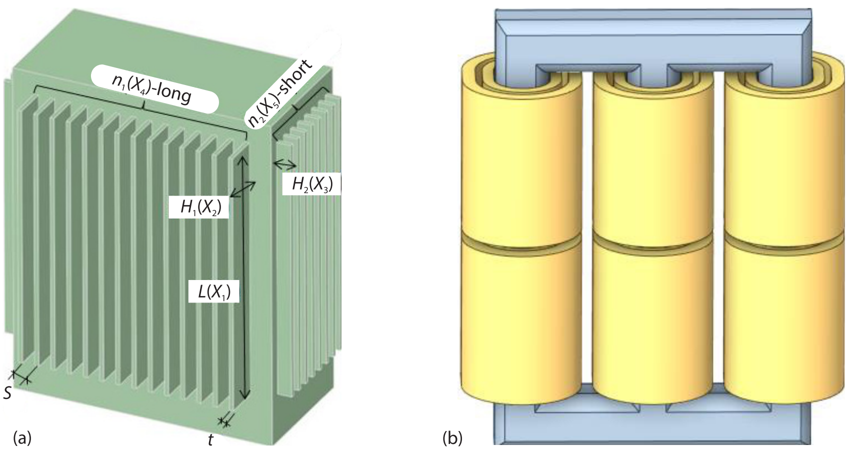

Figure 1. (a) Transformer tank and cooling system and (b) transformer active part

Technical specifications of the transformer

In this study, a 3-phase, Dyn5d0, 1000 kVA, 10/0.72-0.72 kV, PV transformer with two stacked low voltage windings which fed by two inverters is considered. The low voltage windings of the subjected transformer are operating separately while the high voltage windings are operating in parallel.

The electrical design requirements of PV transformer are briefly presented in tab. 2.

Table 2. Transformer technical requirements

Type	1000 (500+500) kVA, 50 Hz
Cooling system	Oil natural air natural (ONAN)
Primary voltage /secondary voltage [V]	720-720/10000
Vector group	Dyn5d0
No load loss	693 W + 15%
Load loss	7600 W + 10%
Short circuit impedance	6% ±10%

Fluid-thermal field model

The mechanism of heat transfer inside the transformer can be analyzed by solving the equations governing the oil motion and heat transfer. Because the transformer oil is considered as incompressible Newtonian fluid where the material density is constant within a fluid parcel based on the operational conditions, the flow is governed by the incompressible Navier-Stokes and energy equations. In the Navier-Stokes equation, the buoyancy term is introduced using the Boussinesq approximation, which is the tendency of an object to float in a fluid, to model the natural-convection for the oil. The heat exchange process inside a transformer can be explained by the following equations [27].

Mass or continuity: It states that mass cannot be created or destroyed during a process:

$$\nabla \rho V = 0 \tag{1}$$

Momentum: It states that the net force acting on the control volume is equal to the mass times the acceleration of the fluid element within the control volume, which is also equal to the net rate of momentum outflow from the control volume:

$$\rho \nabla V = F - \nabla p + \mu \nabla^2 V \tag{2}$$

Energy: It states that during a steady-flow process, the total energy content of a control volume remains constant, and the amount of energy entering a control volume in all forms must be equal to the amount of energy leaving it:

$$\rho c V \nabla T = \nabla (k \nabla T) + q \tag{3}$$

where ρ is the density, V – fluid velocity, F – the stands for the body force vector, p – the pressure, μ – the dynamic viscosity, k – the thermal conductivity, c – the specific heat capacity, T – the temperature, and q – the indicates heat source per volume inside the transformer. The heat generated by winding and core is transferred from the interior of the windings and core to the surfaces of the windings and core by heat conduction. The heat from the surfaces of the windings and core is then transferred to the oil by convection. Near the windings and core, the oil density decreases and the heated oil flow upward due to buoyancy effect. The oil cooling through the tank surface flows down and hence oil circulation takes place in the transformer tank. The main heat transfer process of the transformer tank is realized by the natural-convection mechanism from the outer surfaces of the tank to the ambient air. The following equation is used to calculate the total rate of convection heat transfer from the transformer tank to the ambient air [28]:

$$\dot{q} = hA(T_{\text{tank}} - T_{\text{ambient}}) \tag{4}$$

where h is the convective heat transfer coefficient, A – the heat transfer area of the transformer tank, T_{tank} – the outer surface temperature of the tank and is considered as 95 °C for the calculation of h, and T_{ambient} – the ambient temperature.

Numerical implementation and simulation study

Due to the geometrical, mechanical and thermal complexity of a real transformer, some simplifications have to be considered in simulation study as follows:
– The windings are considered to be cylinders.
– Interlayer insulation material is not considered.
– Core clamps and bushing connections are not considered.

Electromagnetic analysis

A 3-D transient analysis is performed employing the ANSYS Maxwell on the subjected transformer. The 3-D magnetic transient time domain solution is used for the electromagnetic analysis. The magnetic transient solver computes time varying magnetic fields in time domain and solves for instantaneous magnetic fields at each time step. The basic equations used for electromagnetic analysis are given below.

Faraday's Law: It states that the work per unit charge required to moving a charge around a closed loop is equal to the rate of change of the magnetic flux through the closed surface:

$$\nabla \times E = -\frac{\partial B}{\partial t} \tag{5}$$

Gauss's Law: It states that net outflow of the magnetic field through a closed surface is zero:

$$\nabla \times B = 0 \tag{6}$$

Ampere's Law: It states that electric and displacement currents are associated with a proportional magnetic field along any enclosing curve:

$$\nabla \times H = J \tag{7}$$

where H is the magnetic field strength. For the 3-D transient model, natural boundaries are assigned to the surface between objects. The Neumann boundary conditions are assigned to the box covering the active part of the transformer. In the electromagnetic analysis the mesh is created manually using *inside selection* to create elements throughout the volume of the objects.

The results obtained from the simulation and the experiments are compared in tab. 3. In this table, it is seen that the difference between the experimental and simulation results corresponding to different parameters is low and at an acceptable level. The maximum error is related to the load losses of 13.11%. The reason for this is that the eddy current losses in the windings are not taken into account in the simulation studies. Stray losses in the tank, core clamps of the transformer and connection losses are also neglected as the simulation runs only with active part of the transformer.

Table 3. Results obtained from ANSYS simulation and experiments

		Experiment	Simulation	Deviation [%]
Secondary voltage [V]		10000	10055	0.55
Primary voltage [V]		720	720	0
Secondary current [A]		57.74	57.67	–0.12
Primary current [A]		400.94	400.08	–0.21
No load loss [W]		790	805	1.90
Load loss [W]	HV ohmic	4105	4020	–2.07
	LV ohmic	3554	3180	–10.52
	Stray	627	–	–
	Total	8286	7200	–13.11

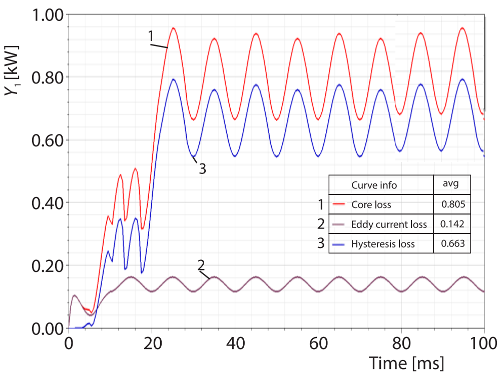

Figure 2. Hysteresis, eddy, and No load losses

The core losses of a transformer including two main components of eddy current and hysteresis losses are shown in fig. 2.

Cooling surface optimization analysis by genetic algorithm

Electrical and magnetic losses in transformers are converted into heat, which raises the operating temperature. At steady-state operation the power losses should be equal to rate of heat transfer from the tank. The purpose of optimization is to derive the dimensions of the fins of tank to minimize the cost function given in eq. (8). The cost is composed of total oil cost inside the tank and the cost of fins. During the optimization process, some restrictions imposed by international standards, transformer characteristics and dimensional limitations of fins in the market should be taken into account. These constraints are given in tab. 4. The objective function is expressed:

$$\text{Cost} = \text{Cost}_{\text{Oil}} + \text{Cost}_{\text{Fin}} \tag{8}$$

The objective function has been written in MATLAB and optimized by GA tool. Input parameters in the optimization process are as follows: tank interior length, tank interior width, tank height, specified temperature rise, and total losses of the transformer.

Table 4. Constraints considered in this study

Design variable	Symbol	Possible bounds
Fin length, L	X_1	$400 \leq X_1 \leq 1600$ mm
Fin long side height, H_1	X_2	$70 \leq X_2 \leq 400$ mm
Fin short side height, H_2	X_3	$70 \leq X_3 \leq 400$ mm
Long side fin number, n_1	X_4	$12 \leq X_4 \leq 29$ mm
Short side fin number, n_2	X_5	$6 \leq X_5 \leq 14$ mm
Fin thickness, t	X_6	$6 \leq X_6 \leq 10$ mm
Fin spacing	S	$40 \leq S \leq 100$ mm
Top oil temperature rise	θ	≤ 60 °C
Top oil pressure	P_r	$\leq$ Setting value of the pressure relief device [mbar]

Due to the geometric complexity of the transformer, the exact mathematical calculation for transformer heat transfer is quite difficult. This is why empirical formulas are mostly used by designers. In the current study the total heat dissipated by convection from the cooling surface of the transformer can be derived from eq. (9). The accuracy of this formula has been validated by comparing the calculation results with those of experiments performed on 96 different types of transformers. The average error of this comparing is about 6%:

$$\dot{Q}_{\text{Fin}} = \frac{5.58\times(S+2\times H)L\times n}{\left[1+8.55\times\left(\dfrac{H}{S}\right)^{0.1}\right]^{1.25}\cdot 10^{3}} \tag{9}$$

The top oil temperature rise can be obtained from the eq. (10) [29]:

$$\theta = 55\times\left(\frac{P_{\text{total}}}{\dot{Q}_{\text{total}}}\right)^{0.8} \tag{10}$$

where P_{total} is the total loss of the transformer and $\dot{Q}_{\text{total}}$ – the total rate of heat transfer from the fins. To improve the search efficiency the crossover fraction (the genetic operation from the existing parents to generate new children) is selected as 0.8. The two-point crossover is selected to pick randomly two points from the parents. The double vector population type is selected with the initial population of 50 and constraint dependent mutation type is selected to ensure that feasible parents give rise to feasible children in respect to bounds and linear constraints. The results of the GA optimization based on the MATLAB optimizationol, the best fitness of the optimization function in each generation *vs*. iterations, the best individual variables with the best fitness function value and the range of the fitness function value in each generation are shown in fig. 3.

The results of the MATLAB optimization application are given in the first column of tab. 5. The results of MATLAB optimization are modified to obtain feasible values for the parameters, taking into account the market conditions, and are shown in the second column of the table. The optimization process is performed using GA and some empirical equations. The results of this process are confirmed by thermal analysis.

Table 5. Transformer tank and cooling geometry parameters

	MATLAB output		Optimal design	
	Long side	Short side	Long side	Short side
Length [mm]	1306.17	1306.17	1300	1300
Height [mm]	166.57	69.86	170	70
Spacing [mm]	91	88	87	76
Total number	13.41	7.03	14	8
Thickness [mm]	6		6	
Oil weight [kg]	981		990	
Fin weight [kg]	180.03		189	
Oil cost [$]	1926		1980	
Fin cost [$]	396		416	
Total cost [$]	2358		2396	

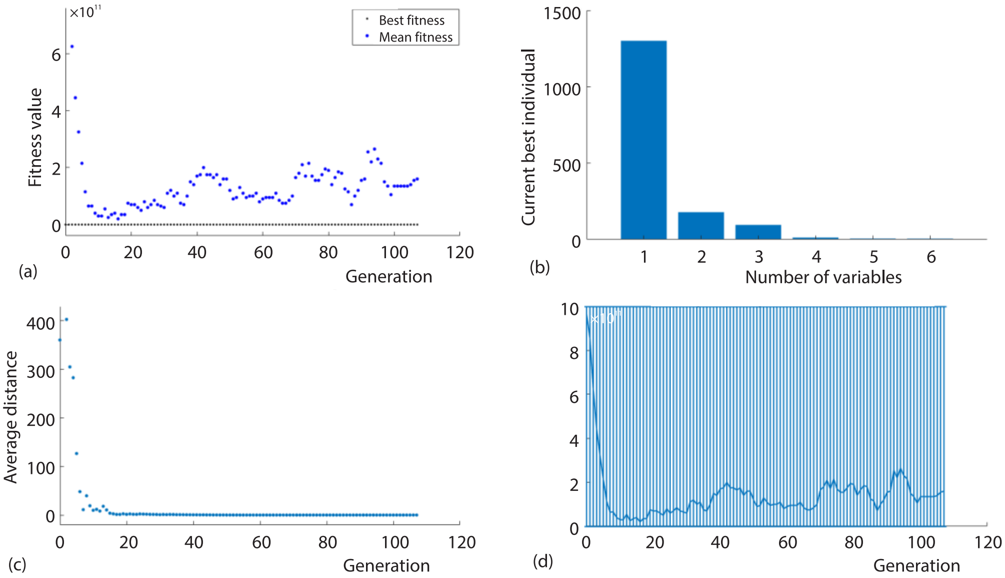

Figure 3. Variation of the cooling system parameters for cost optimization; (a) best: 579.056, mean: 1.6 · 10^{+11}, (b) current best individual, (c) average distance between individuals, and (d) best, worst and mean scores

Fluid-thermal model

The simulation study was carried out using the ANSYS-FLUENT. In the simulation the solver set-up is set to *steady pressure* based type and the gravity is activated. The energy equation is selected as *realizable k-ε* turbulence model. The pseudo transient setting is used for the calculation. Core and winding losses, given in tab. 3, obtained from solving electromagnetic field analysis are modeled as a constant heat source at their interface with transformer oil. These losses are used as input data for thermal analysis.

In transformers, electrical and magnetic losses of the active part, including core and winding losses, are the main sources of heat generation. The heat generated in the core and windings obtained by solving the electromagnetic field are modeled as a constant heat flux at their interface with the transformer oil. The solution of the electromagnetic field provides the heat generation distribution, which appears as a source term in the solution of the transformer thermal field.

Considering the fact that the core and windings are made of electrical steel and aluminum with high thermal conductivities, it is reasonable to assume that the generated heat losses are distributed uniformly within their volume. To simulate the heat source, the core and load losses which are equal to 805 W and 7200 W, respectively, considered as a constant heat flux applied to the core and winding surface. Regarding the fins, a convection wall with the ambient air temperature of 40 °C is considered. The oil viscosity is considered temperature variant and the other thermal dependence properties of the oil are taken as constant value. The empirical equation, eq. (9), is used for the calculation rate of heat transfer from the fin surfaces. The related boundary conditions are summarized in tab. 6.

Table 6. The boundary conditions

Zone	Thermal parameter	Boundary condition value
Core	Heat rate	5071 W/m^3
HV windings	Heat rate	22045 W/m^3
LV_{Upper} windings	Heat rate	29673 W/m3
LV_{Lower} windings	Heat rate	45228 W/m^3
Fin long side	Convection heat transfer coefficient	11.4 W/m^{2}K
Fin short side	Convection heat transfer coefficient	14.4 W/m^{2}K

Mesh generation of the computational domain is carried out in ANSYS FLUENT. For the considered geometry, the generation of mesh is implemented in two steps. In the first step, the edge size and inflation mesh are selected for the fin geometry, the body size mesh is selected for the core, windings and oil inside the tank. In the second step, the tetragonal patch confirming method is generated throughout the whole geometry. In order to find the appropriate mesh size, a grid independency study is carried out on the values of the average and maximum temperature of the transformer as presented in the tab. 7.

Table 7. Grid independency tests

	Grid 1	Grid 2	Grid 3	Grid 4
Cell numbers	6980100	9035666	10364310	14769742
Maximum temperature [ºC]	89.07	93.58	94.45	94.96
Average temperature [ºC]	87.806	86.709	86.736	87.700

It can be seen from tab. 7 that the change in the maximum temperature from Grid 1 to Grid 4 is about 5 °C but, the difference of maximum temperatures between Grid 3 and Grid 4 is very low and is about 0.51 °C. The average temperature is nearly remained constant for all grids. Considering the accuracy and the computational time of the numerical solution, the mesh system of Grid 3 with the total cell number of 10364310 is selected as the mesh system for numerical simulations of this study. The thermal parameters of each material are shown in tab. 8.

Table 8. Thermal parameter of the material

Thermal properties	Winding (AL)	Tank (ST37)	Core (E. steel)	Mineral oil
Conductivity [Wm^{-1}°C^{-1}]	239	60.5	45	0.11
Heat capacity [Jkg^{-1}°C^{-1}]	900	434	460	1860
Kinematic viscosity [cSt]	–	–	–	$0.0014T^2 - 0.3084T + 18.51$
Density [kgm^{-3}]	2700	8900	7650	895

Parametric analysis is performed in ANSYS workbench tool to confirm the accuracy of the optimization study and to determine the effects of the cooling geometry parameters on thermal performance of the transformer. Different designs were considered by keeping the oil temperature rise value the same as the optimum design. In alternative Design 1, the fin length and number of fins were changed while keeping the fin height the same as that for optimum design. In alternative Design 2, the number of fins was kept the same as the number of fins in the optimum design while changing the fin length and fin height of short side. In alternative Design 3, the height and number of long side fins were changed, while other parameters remained the same as in the optimum design. In alternative Design 4, while the short side fin height and fin number were changed, the values of other parameters were remained the same as in the optimum design. The results of optimal and different alternative designs are compared in tab. 9. As it is shown in the given table, the lowest cost is corresponding to the optimal design approach.

Table 9. Parametric study results of the ANSYS

	Optimal design		Alternative Design 1		Alternative Design 2		Alternative Design 3		Alternative Design 4	
	Long side	Short side	Long side	Short side	Long side	Short side	Long side	Short side	Long side	Short side
Length [mm]	1300	1300	1200	1200	1200	1200	1300	1300	1300	1300
Height [mm]	170	70	170	70	170	120	200	70	170	100
Spacing [mm]	87	76	76	59	87	76	100	76	87	95
Total number	14	8	16	10	14	8	12	8	14	6
Thickness [mm]	6		6		6		6		6	
Oil weight [kg]	990		1000		997		991		992	
Fin weight [kg]	189		197		193		191		192	
Oil Cost [$]	1980		2000		1994		1982		1984	
Fin Cost [$]	416		433		425		420		422	
Total Cost [$]	2396		2433		2419		2402		2406	
Top oil temperature rise [C°]	54.5		54.1		54.4		54.5		54.5	

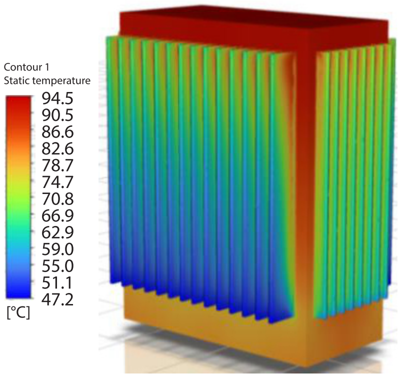

Figure 4. Thermal distribution of the transformer based on simulation result

Figure 4 demonstrates temperature distribution of the optimal design transformer. As it is shown, the top oil temperature of the transformer is 94.5 °C. Therefore, considering the ambient temperature of 40 °C, the top oil temperature rise of the transformer is calculated as 54.5 °C (the ambient temperature = top oil temperature - top oil temperature rise).

In Raeisian *et al.* [17], an optimization study was carried out on the cooling system of a 200 kVA distribution transformer. In the related study, the hot spot temperature was taken into account and optimum geometric values were obtained by using CFD and response surface method. The optimization method used in the related study as well as the power and structure of the transformer, are different from those in our study. Despite these differences, the results of this study are consistent with the results of our studies. One of the similar results is that the effect of fin length on transformer temperature is higher than that of other parameters.

Experimental measurements

Experimental test was performed on the transformer to validate the simulation results and verify the operational thermal performance of the transformer. The *K*-type thermocouple with the measurement uncertainty of ±0.2 ºC was used for the measurement of the top oil temperature located at the top cover of the transformer. General definitions and terms related to the requirements for temperature rise tests of transformer are given in [29]. The experimental set-up used to measure the temperature rise is shown in fig. 5.

The results obtained from the simulation study and experiments are compared in tab. 10.

Table 10. Analysis results

	Experiment	Simulation	Deviation [%]
Top oil temperature rise [ºC]	52	54.5	4.8

Figure 5. The experimental set-up used in this study

Conclusions

Optimization plays an important role today, especially in the industrial field, by helping lower costs leading to higher profits and success in business competition. This article focuses on the cooling surface optimization of the oil-immersed transformer by applying the CFD model of the transformer and the GA optimization method. To verify the accuracy of the method, numerical and experimental verification was performed on the transformer in question. The following conclusions are drawn based on the performed study.

- The GA model was developed to calculate the optimum cooling surface design of the transformer. Then, an optimum design was achieved by using the optimization outputs. Next, a CFD model was created for the 3-D coupled electromagnetic-fluid thermal analysis.
- The performance of the cooling system was determined by the CFD analysis. Therefore, the temperature value of the transformer could be estimated before the production of the prototype.
- According to the simulation results, the upper winding temperature is higher than the lower winding temperature in this type of transformer. Therefore, designers should be aware of the impact of this problem and pay special consideration in design stage to reduce the occurrence of unexpected problems.
- According to the results of the parametric study, it is observed that the effect of fin length and fin number on transformer temperature is higher than that of fin height.
- The calculations and analyses applied in this study show that the top oil temperature error corresponding to experimental and simulation results is very low (2.5 °C over 94.5°C or 2.6%).
- This study helps to better understand the thermal behavior of the transformer in the design stages and improve its thermal requirements. Consequently, keeping the transformer temperature at a safe level prevents the probability of the transformer failure and increases the life expectancy of the transformer.

Acknowledgment

The author would like to thank SEM Transformator Inc. and Elektro Trans Ar-Ge. Muh. Tek. Dan. Elektronik Yaz. Taa. San. Tic. Ltd. Sti. for providing all the necessary supports.

Nomenclature

A – surface area through which convection heat transfer takes place, [m^2]
B – magnetic flux density, [T]
c – specific heat, [Jkg^{-1}°C^{-1}]
E – electric field strength, [Vm^{-1}]
F – body force vector, [N]
H_1, H_2 – fin height, [mm]
h – convection heat transfer coefficient, [Wm^{-2}K^{-1}]
J – current density, [Am^{-2}]
k – thermal conductivity, [Wm^{-1}°C^{-1}]
L – fin length, [mm]
n_1, n_2 – number of fins
$P_{\rm total}$ – transformer total losses, [W]
p – pressure, [N]
$\dot{Q}_{\rm fin}$ – total rate of heat transfer by convection from the fins of the transformer, [W]
q – volumetric heat source, [Wm^{-3}]
$\dot{q}$ – rate of convection heat transfer, [W]
S – fin spacing, [mm]
T – temperature, [°C]
V – fluid velocity, [ms^{-1}]

Greek symbols

θ – top oil temperature rise, [°C]
μ – dynamic viscosity, [Nsm^{-2}]
ρ – density, [kgm^{-3}]

Acronyms

GA – genetic algorithm
HV – high voltage
LV – low voltage

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Paper submitted: November 9, 2022
Paper revised: January 23, 2023
Paper accepted: January 25, 2023