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Research Paper

Oil Immersed Distribution Transformer HST Reduction using Vegetable Oils and ONAN Cooling

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Abstract. Today, the use of electricity sources is increasing as cities are growing. With the increasing use of mineral oils for transformers cooling in the distribution network, due to the problems encountered using these oils, an alternative fluid should be used inside the transformers instead of mineral oils. Therefore, mineral oils should be replaced with fluids that are more compatible with nature due to the environmental hazards and high costs. Hence, vegetable oils can be used as suitable alternatives for the mineral oils in transformers due to their low risk and the renewability. On the other hand, compared to the mineral oils that have a fire point of about 151 Celsius degrees, vegetable oils have fire points higher than 311 Celsius degrees. As a result, from this viewpoint, they are considered as harmless fluids. Vegetable oils are simply degraded in the nature, and due to their different chemical structures compared to the mineral oils, they can increase the life of the equipment. Besides, the most important point is that they improve the transformer cooling performance, in terms of thermal analysis. Thus, in this paper, the distribution transformer electromagnetic-thermal analysis and conjugate heat transfer, in presence of different types of vegetable oils, and different types of cores such as grain-oriented silicon steel, amorphous and vitroperm alloy are investigated. Afterwards, the obtained results, especially hot spot temperature, are compared with distribution transformer containing mineral oil. ANSYS software has also been used for simulations.

Keywords: Transformer, Oil natural air natural (ONAN) cooling, Vegetable oil, Vitroperm alloy, Hot spot temperature (HST).

1. Introduction

One of the most vital components of power transmission and distribution network are transformers. In the distribution network, oil-filled transformers are usually used more than dry-type transformers. On the other hand, in these types of transformers, oil also plays the role of insulation, so that the combination of cellulose and petroleum mineral oil is the most widely used insulation system. Mineral oils have been used in transformers for more than 111 years, mainly due to their availability and low cost. Unfortunately, although mineral oil is widely used, it is not degradable [1]. In addition, mineral oils are not safe because they have a high risk of fire. From an economic point of view, due to the reduction of oil reserves, an increase in the price of this type of oil is inevitable. Therefore, according to the mentioned problems, we should look for alternative fluids instead of mineral oils, such as vegetable oils [2, 3]. Vegetable oils such as canola, sunflower, soybean, corn and other edible oils have the potential to be substitutes for mineral oils due to their higher fire point and non-toxicity. These oils are more environmentally friendly and have much lower prices than mineral oils. Distribution transformers are divided into different types in terms of insulation and cooling [4, 5]:

- Oil transformer which its oil is connected to the outside air. In this case, the oil is in contact with the ambient air through a dehumidifier and expands and shrinks in the expansion chamber.
- Oil transformer which its oil is not connected to the outside air. In this case, the oil does not come into contact with the ambient air and the increase in volume of the oil is removed either by the resilience of the tank with a concave wall or can be compensated by using a radiator tank with rigid walls where part of the upper space is filled with an inert gas such as nitrogen. In the second case, changing the volume and pressure of the gas changes the volume of the oil.

In transformers, excitation (voltage) is applied to a coil, causing losses in the core and coils that cause heat to be generated in the transformer. This heat leads to a rise in the transformer temperature. This factor itself reduces the life (premature aging) of the transformer [6]. For this reason, cooling of transformers, which is done through oil heat transfer in oil transformers, is of special importance.

In [7, 8], properties of various vegetable oils for being used in transformers have been studied, and their performance in old age has also been shown. By reviewing the results, soybeans, sunflower and canola have been mentioned as the best cooling fluid. The breakdown voltage as well as the insulating properties of the transformer oil must be high enough to prevent partial discharge and failure of the transformer. Many experiments have been performed in different references on the breakdown voltage of vegetable oils [9, 10]. The heat transfer efficiency of oil transformers depends on its oil properties, so that, viscosity, specific heat capacity

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and thermal conductivity have been considered as the most effective properties [11]. In [12] the behavior of vegetable oil in comparison with mineral oil in real transformers has been studied. In [13], thermal analysis of a 15 kV distribution transformer is performed using finite volume method. In this article amorphous core and vegetable insulating oil have been employed in the transformer. This article also examines and compares the properties of vegetable and mineral oils. It is possible to reduce the no load losses about 75% and the total losses about 25% with mentioned method.

It should be noted that numerical modeling related to vegetable oils is limited and most studies have been devoted to mineral oils. Disk-type transformer windings parametric design with oil zigzag cooling have been presented in [14, 15]. It has been shown that, this technique is superior compared to conventional methods. In [16], it has been shown that for heat transfer enhancement, directed oil forced cooling is better than non-directed oil forced cooling in power transformer windings. Temperature distribution in disc-type and layer type transformer winding are numerically investigated in [17-19]. In [20], hydraulic network model has been applied for thermal modeling of the power transformer. It has been also stated that oil zigzag cooling is more effective than other cooling method in power transformer. Besides, although many papers have presented modeling and thermal simulation of transformers, but in many of these papers, the geometry of transformers has been modeled in two dimensions, and many simplifications have been used in the simulations [21, 22]. In [21], only a 2D model is proposed to simulate temperature distribution in transformer disc windings without considering conjugate heat transfer. Two-dimensional thermal modeling without use of CFD is also proposed in [22]. On the other hand, in the thermal analysis of the transformer, the combination between the thermal modeling and the fluid flow is not applied, which means that the structure of the transformer, which is the stationary part of the problem, is not analyzed simultaneously with the fluid part [23-25].

Petroleum oils have long been used as insulators or coolers in oil-filled transformers to provide acceptable performance for transformers. Decreasing reserves and increasing demand for petroleum products and existing constraints have pushed up the price of these materials. For this reason, alternative and renewable materials such as vegetable oil have been considered. Vegetable oils are less expensive and more efficient than petroleum oils, and their production technology is advancing rapidly [26]. Another advantage of vegetable oils over mineral oils encompasses environmental issues and the compatibility of vegetable oils with the environment and their non-toxicity. Therefore, it can be hoped that in the future, vegetable oils will be used for cooling and insulation in transformers. Humidity is one of the most important factors in insulation fluid which depends on the chemical structure. Moisture breaks down cellulose in the insulation, reducing the life of the transformer. According to research on the lifespan and aging of solid insulators, the lifespan of transformers increases with the use of vegetable oils [27]. In this section, properties such as density, heat capacity, viscosity, thermal conductivity, breakdown voltage and fire point of vegetable oils are compared with mineral oils.

The measurement results show that the density of vegetable oil is lower than mineral oil. On the other hand, the density of both oils decreases linearly with temperature. Another parameter is the specific heat capacity that is related to heat storage and heat transfer. Higher heat capacity means that more energy is needed to raise the temperature. This allows the temperature to be maintained at lower values for a given temperature. The specific heat of vegetable oil is about 22% higher than mineral oil [8].

One of the most basic properties of fluid in convection transfer is viscosity, which means that, if the fluid viscosity is lower, the natural convection becomes better. Therefore, low viscosity brings about better convective heat transfer from the coils and the core to the tank walls, and hence, the transformer temperature will experience more reduction. At low temperatures, the viscosity of vegetable oil is much lower than that of the mineral oil. At higher temperatures, this difference in the viscosity becomes lesser. However, even at 81 °C, the viscosity of vegetable oils is 29% lower than the viscosity of mineral oils.

Thermal conductivity is another important property of the transformer oil. Higher thermal conductivity improves heat transfer and reduces the temperature of the transformer. The thermal conductivity of vegetable oils is 33% higher than that of mineral oils, which results in better cooling of the transformer. Breakdown voltage is another factor related to the quality of the oil, which depends on the moisture content of the oil. The amount of breakdown voltage is usually obtained by testing via placing the oil in vacuum at a temperature of 61(°C). Hence, the breakdown voltage of vegetable oil is about 48% higher than that of the mineral oil [28, 29].

Another characteristic of the oil is its fire point. According to the studies, the fire point of vegetable oils is more than 311(°C), while the fire point of mineral oils is about 151(°C). Therefore, in the spaces in which the fire safety is important, such as subway tunnels and shopping malls, vegetable oil is less flammable and is a better choice [30, 31]. Table 1 shows the property values of both vegetable and mineral oils at 80 (°C).

The main objective of this paper is the distribution transformers electromagnetic-thermal analysis containing several types of vegetable oils using CFD in three dimensions by ANSYS software. Therefore, in the second part of this article mathematical model, studied distribution transformer specifications and boundary conditions are brought. The third section presents the results of the electromagnetic simulation of the transformer with grain-oriented silicon steel, amorphous and vitroperm alloy core types, and the results of thermal-fluid flow simulation of the transformer with vegetable oil are also proposed in this section. On the other hand, the results are compared with the transformer containing mineral oil and, besides, the HST estimation will be presented.

2. Methods

Losses in the transformer are divided into two parts: core losses and copper losses. Core losses include hysteresis losses and eddy current losses. Hysteresis losses depend on the hysteresis loop of core ferromagnetic material, as well as the frequency and the type of core material. Therefore, the value of these losses is proportional to the area of the hysteresis loop. As the transformer's ferromagnetic core has electrical resistances and there is a time-varying flux in the transformer, losses called eddy currents occur. Eddy current losses can also occur in coils. The amount of these losses varies in different parts of the core and the windings. The eddy current distribution must be obtained by solving the electromagnetic field equations. Core losses are also known as no-load losses. The main part of transformer no-load losses is dependent directly on the core and its quality. In distribution transformers, always no-load losses exist, either when the load is connected to the transformer or when the load is not connected to it. The copper losses in the windings are due to the windings resistances that is proportional to the square of the current.

Table 1. Properties of vegetable oils compared to mineral oils at 80(°C) [8, 13, 30].

Property	Vegetable Oil	Mineral Oil
ρ (kg·m^{-3})	835	842
C_p (J·kg^{-1}·K^{-1})	2580	2275
η (kg·m^{-1}·s^{-1})	0.0026	0.0035
k_f (W·m^{-1}·K^{-1})	0.19	0.145
Breakdown Voltage (kV)	73.8	50
Fire Point (°C)	311	151

Electric current density is the main factor of heat in the transformer. By possessing the electric current density, the temperature distribution in different parts of the transformer can be obtained. Electric current density also has a direct relation with the intensity of the electric field. The amount of current density is inserted in the energy equation of the static part of the transformer, and is coupled with the fluid equations.

With combination of Ampere's law and Faraday's induction law, and applying the magnetic vector potential, we have:

$$-\frac{1}{\mu}\nabla^2\vec{A}+\sigma(\frac{\partial\vec{A}}{\partial t}+\vec{\nabla}V)=\vec{J}_s \tag{1}$$

where A is the magnetic vector potential, V is the electric potential, E is the electric field intensity, J is the electric current density, σ is the electrical conductivity and μ is the magnetic permeability. The electric field intensity is also calculated as follows:

$$\vec{E}=(-\frac{\partial\vec{A}}{\partial t}-\vec{\nabla}V) \tag{2}$$

The fluid continuity equation in a steady state condition can be written as:

$$\nabla\cdot(\rho\cdot\vec{V}_f)=0 \tag{3}$$

where V_f is the velocity flow vector and ρ is the transformer oil density which depends on the temperature. Oil in the transformer can be assumed as an incompressible fluid, because we can ignore the fluid compression by the pressure. Momentum conservation equation in a steady state condition can be expressed for incompressible fluid as:

$$\rho(\vec{V}_f\cdot\nabla)V_f=\nabla\cdot(\eta\nabla V_f)-\nabla p+\vec{F} \tag{4}$$

where P is the fluid pressure and η is the fluid dynamic viscosity which varies with temperature. Actually, F is the vector of volume force, which can be divided to two fundamental terms as follows:

$$\vec{F}=\vec{f}_b+\vec{f}_l \tag{5}$$

where, f_b is the term defining buoyancy body force, while, f_l indicates the Lorentz force term. Here, if the gravitational body force f_g, is given by the following term:

$$\vec{f}_g=\rho\vec{g} \tag{6}$$

The resulting momentum conservation equation with consideration of the buoyancy term, will be written as:

$$\rho(\vec{V}_f\cdot\nabla)V_f=\nabla\cdot(\eta\nabla V_f)-\nabla p+\rho\vec{g}(1-\beta\cdot\Delta T)+\vec{f}_l \tag{7}$$

where, β is the thermal expansion coefficient, g denotes the acceleration due to gravity, and the variation in the fluid temperature is signified by ΔT. In order to complete the definition of the existent forces, the last term f_l can be explained through the following equations:

$$\vec{f}_l=\vec{J}\times\vec{B}=\sigma(\vec{E}+\vec{V}\times\vec{B})\times\vec{B} \tag{8}$$

where B is defined as the magnetic flux density vector. Finally, by substituting (8) into (7), we have the following momentum conservation equation:

$$\rho(\vec{V}_f\cdot\nabla)V_f=\nabla\cdot(\eta\nabla V_f)-\nabla p+\rho\vec{g}(1-\beta\cdot\Delta T)+\sigma(\vec{E}+\vec{V}\times\vec{B})\times\vec{B} \tag{9}$$

The conservation of energy in the fluid can be written as follows [32-34]:

$$\rho C_p\vec{V}_f\cdot(\nabla T)=\nabla\cdot(k_f\nabla T)+Q \tag{10}$$

where T is the temperature, C_p is the fluid specific heat capacity, k_f is the fluid thermal conductivity and Q is the heat generation rate or the heat flux density inside the transformer. Furthermore, the losses obtained from equations (1) and (2) can be replaced in the following energy equation for the solid parts of the transformer:

$$k_s\nabla^2 T+\frac{|\vec{J}|^2}{\sigma_s}=0 \tag{11}$$

where, k_s is the thermal conductivity of the transformer solid parts.

The specifications of the studied distribution transformer are given in Table 2. In Fig. 1, a comparison has been made between the B-H curves of the grain-oriented silicon steel, amorphous and vitroperm alloy cores. The steps to obtain the HST of the transformer are as follows:

1- Select core type
2- Select oil type
3- Declare core B-H characteristics
4- Perform transformer electromagnetic analysis and find flux density
5- Calculate transformer core and windings losses
6- Obtain temperature dependent heat generation rates for transformer solid parts
7- Specify heat transfer coefficients of the transformer walls
8- Perform transformer CFD analysis, obtain temperature distribution of transformer and HST values

9- Is the core losses acceptable? If it is not, then go to the step 1
10- Elect the best core for subsequent analysis
11- Is the HST acceptable? If it is not, then go to the step 1
12- Elect the best oil for subsequent analysis
13- Calculate mean heat transfer coefficient of the selected oil
14- End

The flowchart of the proposed scheme is shown in Fig. 2.

With the intention of accurate analysis of the pure mineral oil and vegetable oil influences on transformer cooling performance, the study of a 100 kVA, ONAN three-phase transformer, is considered in this paper. Moreover, a detailed procedure is given by the flowchart in Fig. 2 depicting the required steps for system electromagnetic and thermal modeling with the help of the initial data comprising the characteristics and properties provided in this study. Again, the intention of designating the finest oil among the mentioned types in terms of lower coolant fluid temperature plus HST rates is pursued.

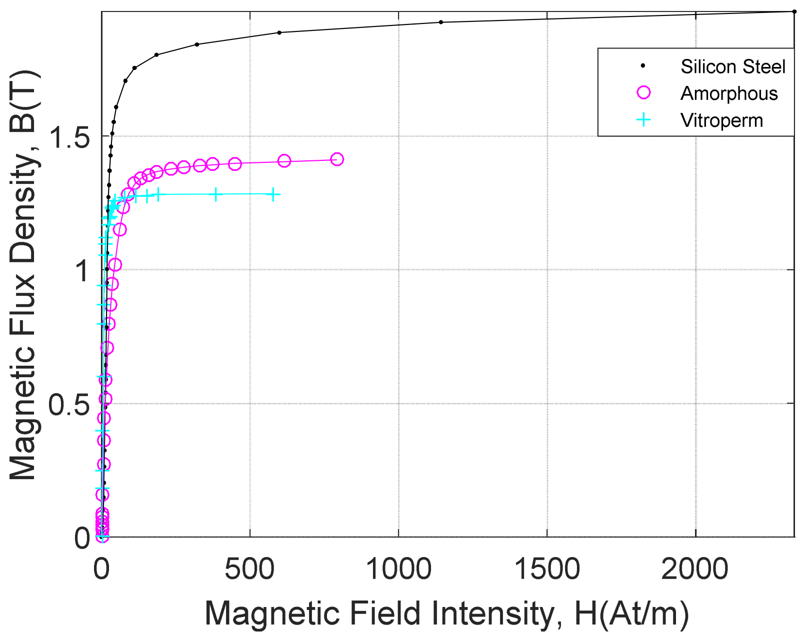

Fig. 1. Comparison of grain-oriented silicon steel, amorphous and vitroperm alloy *B*-*H* curves.

Table 2. Studied distribution transformer specifications.

Power	100kVA
Frequency	60Hz
Voltage of HV winding	11kV
Voltage of LV winding	400V
Connection type	Dyn11
Core diameter	114mm
Core window height	490mm
Distance between center of two neighbor legs	265mm
Number of core steps	9
HV winding connection	Δ
Conductor diameter of HV winding	1.7mm
Conductor with insulation diameter of HV winding	1.9mm
Conductor turn number per phase of HV winding	3512
Coils number per phase of HV winding	4
Coil turn number of HV winding	878
Inner diameter of HV winding	182mm
Outer diameter of HV winding	252mm
LV winding connection	Y
Conductor cross section area of LV winding	49.5mm^2
Conductor cross section area with insulation of LV winding	55.86mm^2
Conductor turn number per phase of LV winding	76
Coils number per phase of LV winding	1
Coil turn number of LV winding	76
Inner diameter of LV winding	120mm
Outer diameter of LV winding	162mm

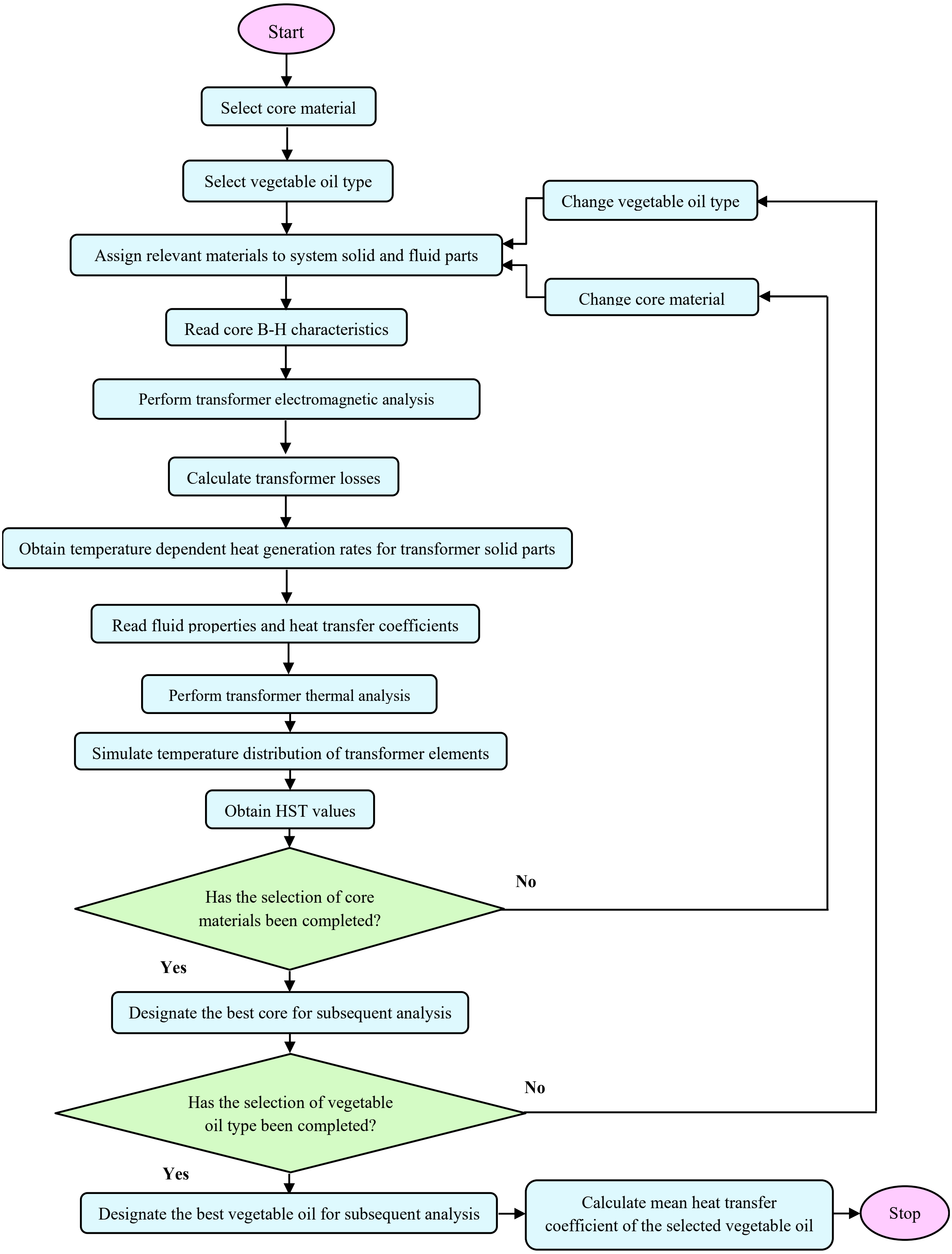

Fig. 2. Flowchart of the proposed scheme.

3. Results

In the present study, the electromagnetic simulations of the three-phase transformer are performed through the Ansys Maxwell software. The solid parts of the studied transformer, including the core, high and low voltage coils, along with the complete structure of the tank and side radiators, are shown in Figs. 3 and 4. With a vertical cut that passes through the x-z plane, the three-dimensional geometry of the transformer is divided into two halves, the rear part of which can be seen in Fig. 5. The meshed geometries of the side radiator, core and coils are also shown. In the same way, a more comprehensive meshed model considering parts of the tank and the oil inside it, is given in Fig. 6. Of course, it should be added that the mentioned models also become more complete by adding front radiators. Figure 7 shows magnetic flux density distribution in no-load conditions in the core of the transformer for grain-oriented silicon steel, amorphous and vitroperm alloy cores. On the other hand, Fig. 8 shows loss density distribution in no-load condition in the core of the transformer. As it can be seen from Fig. 8 the vitroperm alloy core has the lesser losses and therefore has superiority against the other core types. Table 3 shows core loss enhancement in percent.

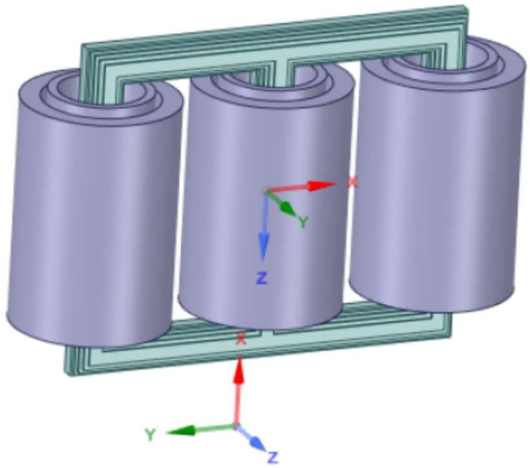

Fig. 3. Core and windings of the studied transformer.

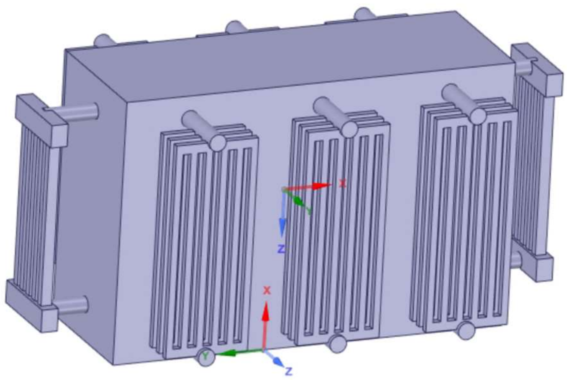

Fig. 4. Tank and radiators of the studied transformer.

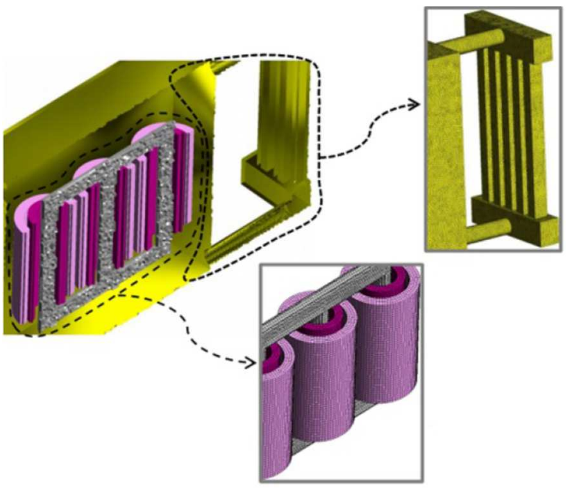

Fig. 5. 3D model of solid parts of the studied transformer.

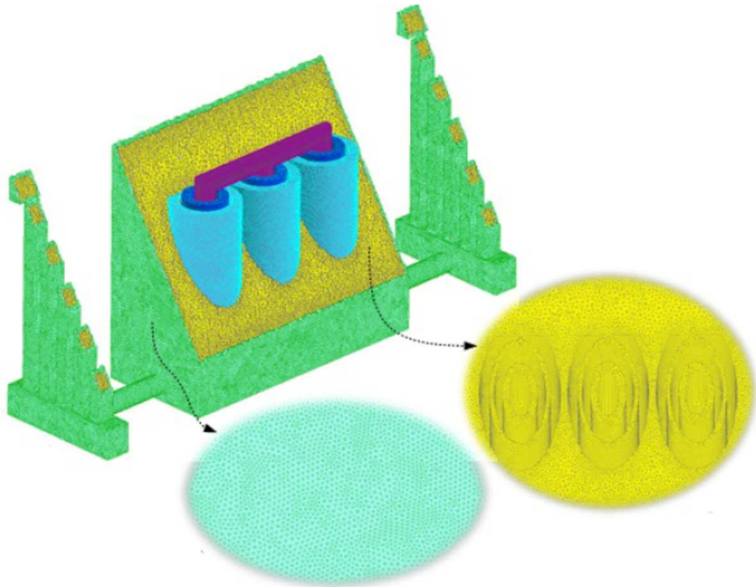

Fig. 6. Meshing of the transformer.

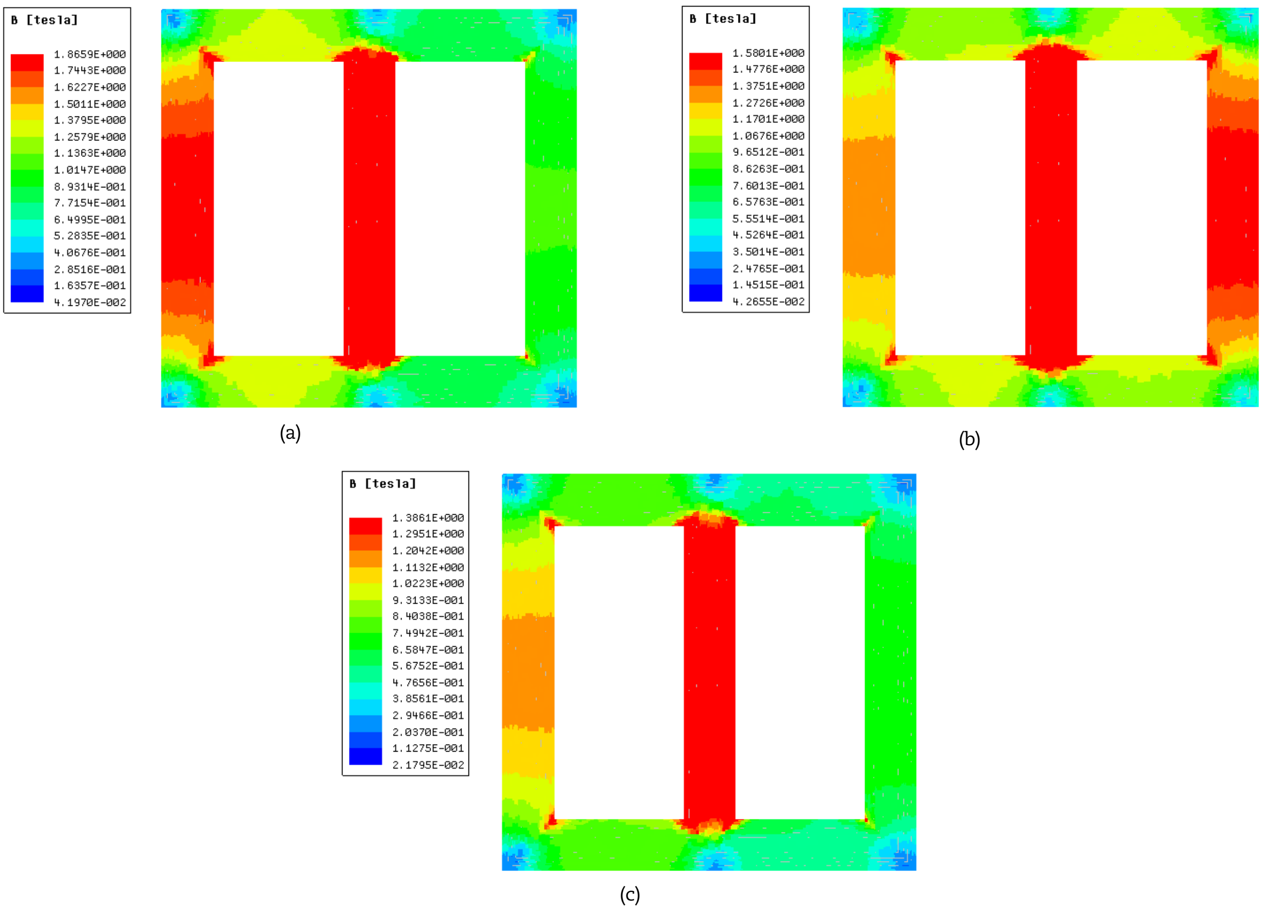

Fig. 7. Magnetic flux density distribution in the transformer cores made of: (a) Silicon steel, (b) Amorphous, and (c) Vitroperm alloy.

Grain-Oriented silicon steel, amorphous alloy and Vitroperm alloy cores losses comparison in full load condition are shown in Fig. 9.

Table 3. Core losses enhancement.

Assessed Material	Average core loss (W)	Core loss enhancement (%)
Grain-Oriented silicon steel	752.81	---
Amorphous alloy	198.26	73.66
Vitroperm alloy	59.135	92.14

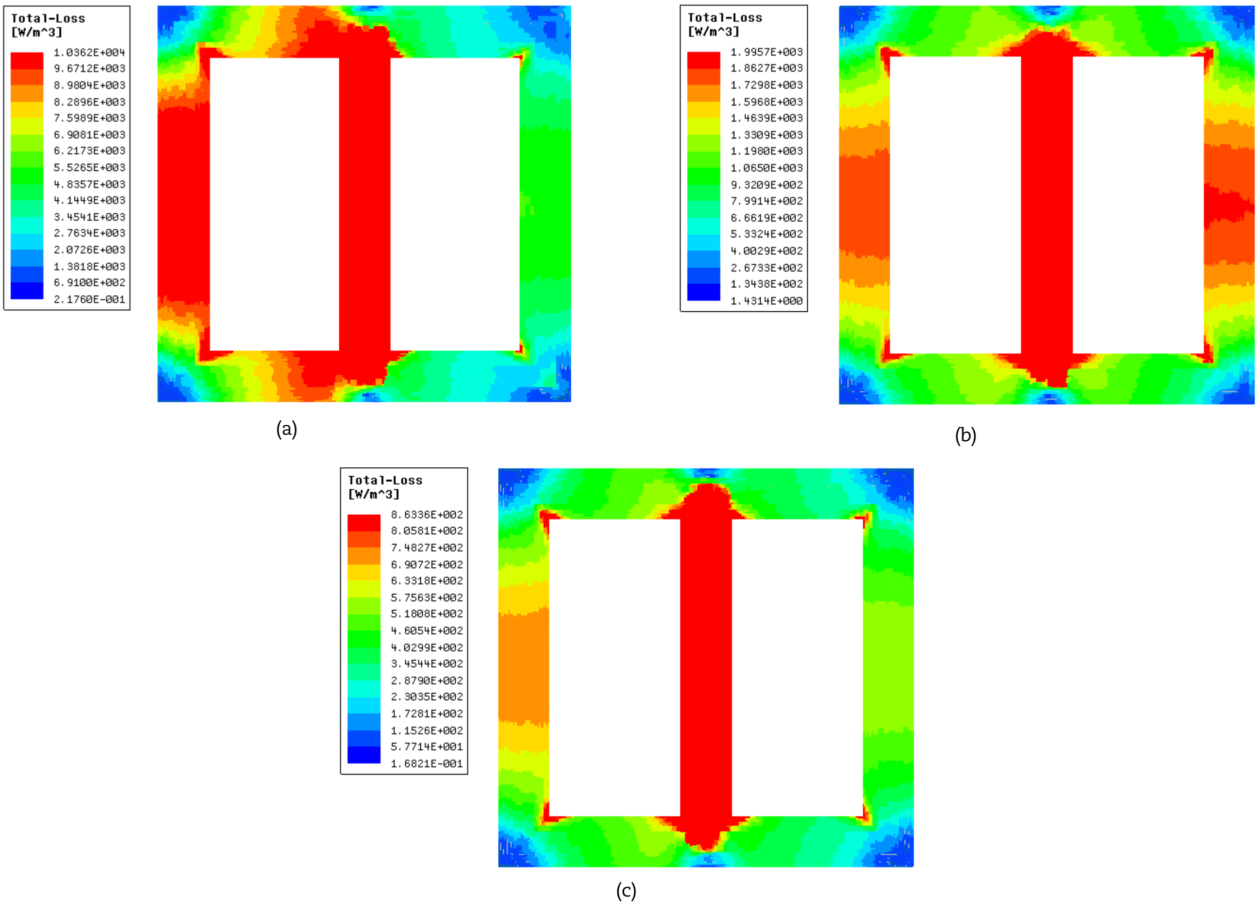

Fig. 8. Loss density distribution in the transformer cores made of: (a) Silicon steel, (b) Amorphous, and (c) Vitroperm alloy.

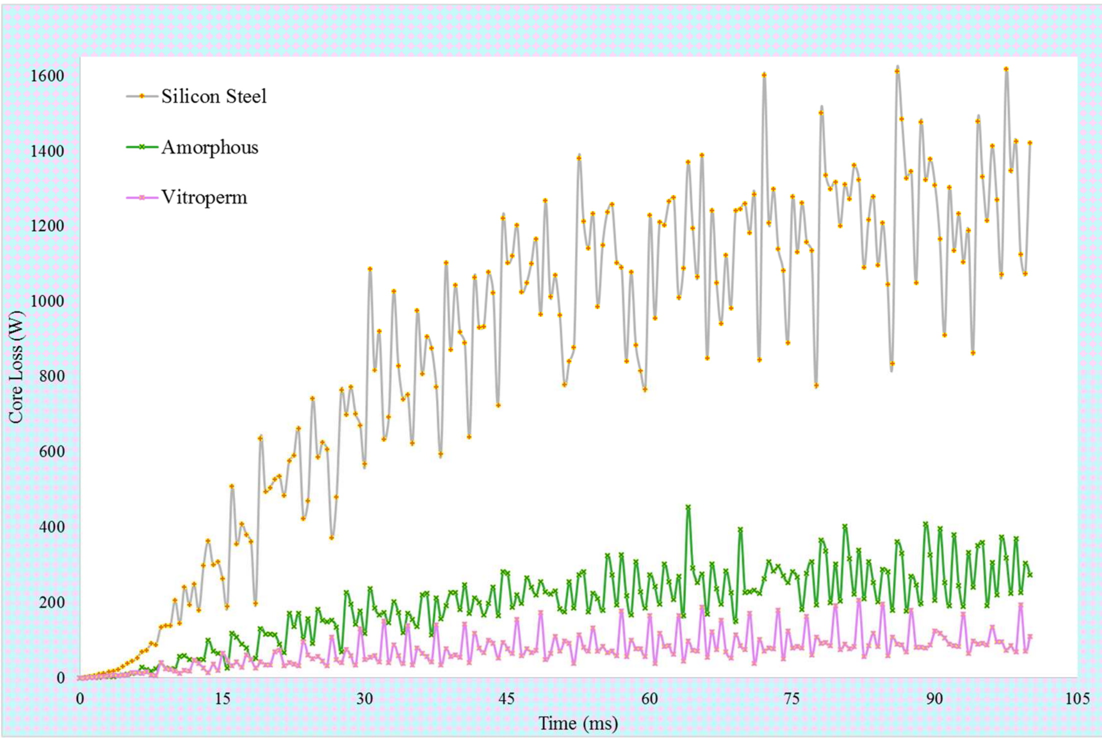

Fig. 9. Grain-Oriented silicon steel, amorphous alloy and Vitroperm alloy cores losses comparison in full load condition.

Table 4. Transformer tank and radiator specifications.

Specification	Dimensions (mm)
Tank length	835
Tank width	335
Tank height	905
Thickness of the sides of the tank	3.15
Thickness of the upper and lower walls of the tank	5
Radiator depth	40
Radiator height	700

Table 5. Heat transfer coefficient of tank walls in full load conditions [35, 36].

h	Wall
4.8	The upper wall of the tank
3.4	The bottom wall of the tank
3.8	The side walls of the tank

Table 6. Mesh independency in simulation to find the appropriate HST.

Grid	Number of elements	HST (°K)
1	5125632	361.73
2	6069208	360.81
3	7383731	359.60
4	7703066	358.97
5	8803520	358.86

In this section, in addition to the modeling of the transformer structure, the oil tank and radiators should also be modeled. The inside of the tank is filled with oil so that all the components of the transformer are completely immersed in the oil. The outer surface of the tank transfers the inner heat of the transformer to the outside. The reason for the presence of radiators in transformers is that increasing the load of the transformer causes heating of the windings and transformer oil. Therefore, in order to prevent uncontrolled increase of the temperature, radiators are installed in the vicinity of the transformers so that the oil will be in more contact with the air, and the cooling of the transformer oil is performed better. Radiators, which have the role of setting the oil in contact with the surrounding environment, are usually made of pressed steel sheets with a thickness of about 1.2 mm, and are connected to each other by pipes. Radiators are usually made using an automatic welding process. Depending on their use, radiators can be equipped with colored coatings or galvanized to prevent rust and chemical corrosion. Depending on the type of connection to the transformer tank, radiators are divided into two categories: radiators which are installed on the transformer, and the radiators that are installed, separately. Table 4 shows the specifications for the transformer tank and the radiator.
Transformer thermal analysis - fluid flow is performed by ANSYS software. All simulations have been done using a computer with Intel Core i9-9900K CPU, 3.6 GHz, 8 Cores and 64.0 GB RAM. The processing time of a simulation is about 2 hours. In this simulation, oil natural-air natural cooling system is used to cool the transformer. In this system, the air is naturally in contact with the outer surface of the transformer radiators, and the radiators are naturally cooled by the air. Also, the oil circulation in the transformer takes place naturally, that is, the hot oil moves up and the cold oil replaces it. This type of cooling system is specific to low-power transformers, because as the power of the transformer increases, the temperature of the windings increases, and hence, the oil must be in contact with the outside air more quickly, and the cooling must be performed more quickly. The viscosity changes of different types of oils with temperature are obtained approximately from the following equation [18]:

$$\mu = a \cdot e^{-b \cdot T} \tag{12}$$

where a and b are constant values for each oil.

The transformer core is made of vitroperm alloy, the windings are made of copper and the transformer tank and its radiators are made of aluminum. In the present thermal analysis, the effect of changes in copper loss density due to temperature changes is considered as:

$$Q = \frac{|J_0|^2}{\sigma} \cdot (1 + \alpha_c \Delta T) = Q_0 \cdot (1 + \alpha_c \Delta T) \tag{13}$$

In this analysis, in the cases that heat conduction and convection exist, appropriate boundary conditions must be considered. Therefore, the heat transfer coefficient of tank walls in full load condition must be applied. In Table 5, the heat transfer coefficients of tank walls are given. On the tank walls, the velocity is assumed to be zero. On the other hand, the heat transfer coefficient is applied for each of the tank walls according to Table 5.

One of the important steps of simulation is meshing the desired geometry because it directly affects the accuracy and result of the simulation. Therefore, proper meshing of a transformer that has a complex geometry must be done accurately. Accordingly, if the maximum size of the elements in the mesh exceeds a certain limit, the correct results or even convergence will not be formed. On the other hand, if the mesh is too small, there may be high computational cost will occur. Therefore, in this paper, in order to study the independence of the solution from the mesh, first the size of the elements is assumed to be larger so that the number of elements is less. In the following, the meshing is considered to be progressively finer, and the repetition of the simulation continues until the HST of the transformer has no significant changes. Thus, table 6 shows the independence of the mesh by considering 5 grids to achieve the most appropriate result for the HST of the transformer under full load conditions and at an ambient temperature of 300°K.

Based on Table 6, it can be concluded that the most optimal state belongs to mesh 4 with 7703066 elements, because in the next mesh which has a finer mesh, no specific change in HST has been achieved. In this regard, it should be pointed out that although the number of elements in grid 5 is more than in case 4, the percentage difference of the HST between the mentioned two grids is only about 0.03%, which shows the accuracy of the results obtained by considering grid 4. Therefore, the number of elements and nodes are considered 7703066 and 1539427, respectively, to perform accurate calculations and achieve a reasonable result. Figures 10 and 11 show the temperature distribution (core, coils and oil) of transformers containing mineral oil and canola vegetable oil, respectively. From these results, it is observed that the maximum temperature of the transformer containing vegetable oil is less than the transformer with mineral oil. HST of the transformer containing vegetable oil is about 84.47°C, but HST of the transformer filled with mineral oil is about 85.97°C. Figure 12 shows studied transformer front radiators temperature distribution with canola vegetable oil used as coolant. As it can be seen, oil with high temperature move from the top of the radiators to the bottom of the radiators and give the heat to the ambient air.

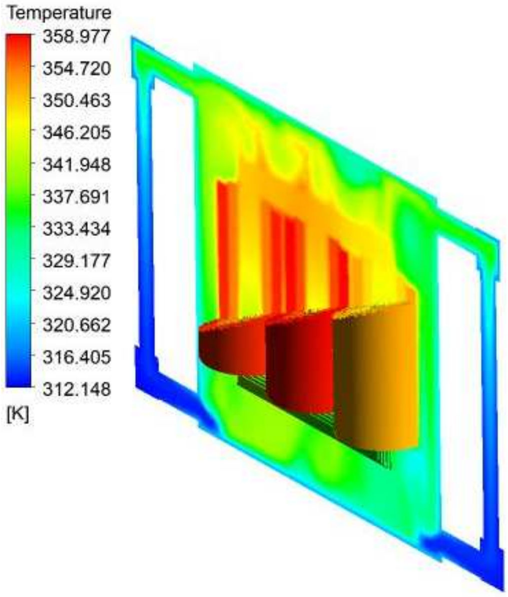

Fig. 10. Transformer temperature distribution with mineral oil used as coolant.

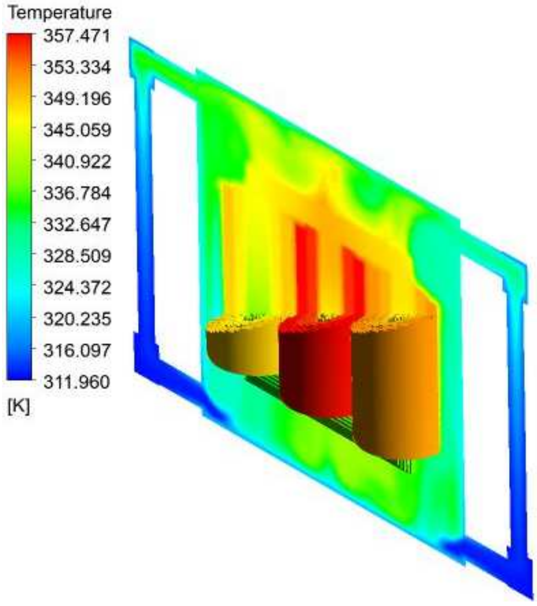

Fig. 11. Transformer temperature distribution with canola vegetable oil used as coolant.

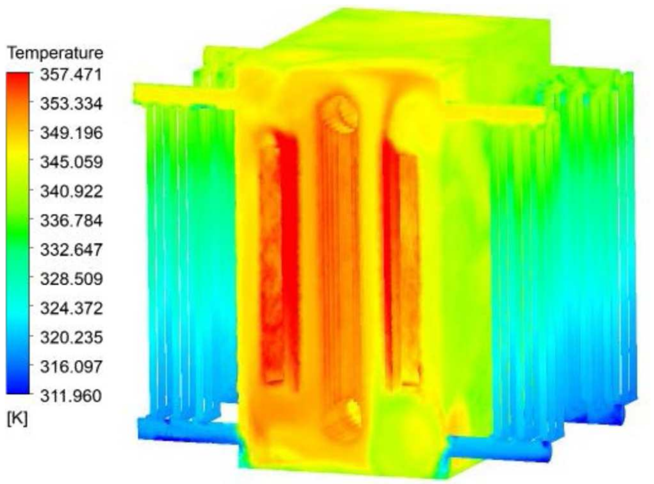

Fig. 12. A cut of temperature distribution in transformer radiators with canola vegetable oil used as coolant.

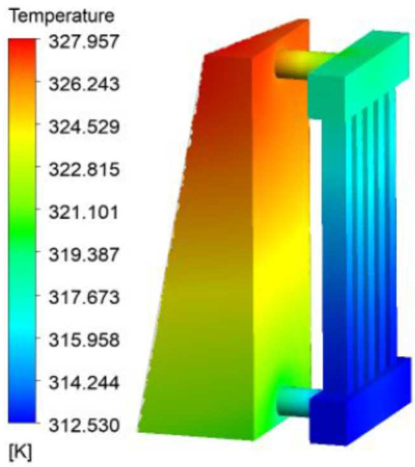

Fig. 13. Temperature distribution in radiator of 100 kVA transformer at full load with mineral oil used as coolant.

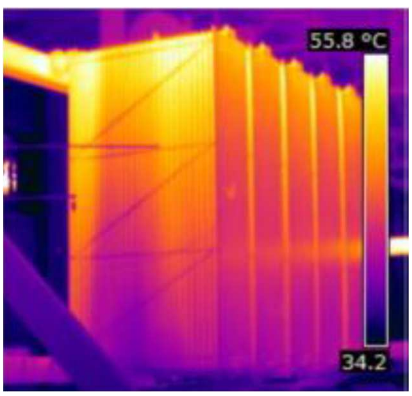

Fig. 14. Transformer radiator temperature distribution at full load with mineral oil used as coolant derived from experimental tests via infrared camera [37].

Table 7. Transformer HST values in Celsius degrees at various loads considering different oils.

Load (%)	Mineral oil	Canola vegetable oil	Flaxseed oil
50	68.02	66.33	67.82
60	71.50	69.11	70.31
70	76.40	74.73	75.93
80	80.10	78.52	78.82
90	83.31	81.90	81.11
100	85.97	84.47	85.09
110	89.40	88.22	89.05
120	94.81	93.40	94.12

In this part has been made an effort to compare the simulation results acquired through pursuing the proposed approach, with the experimental tests performed in this field in previous works, resorting to qualitative analysis. A three-phase transformer has been evaluated in Fig. 13, in term of local temperature distribution under full-load condition and oil natural cooling via simulation, and meanwhile, has been discussed against the result (via infrared camera) which has been presented by earlier work [37].

In [37] study has been done on a group five radiators, with each of them consisting of 27 fins (steel + oil channel) with 2.5 m height, 0.52 m width and 0.0085 m thickness. The fins are horizontally spaced with a gap of 50 mm. As it can be seen in Fig. 13, radiators possess the lowest temperatures among different elements of the transformer, depicting a small cross section of the tank for better clarification. The simulation results and the thermal image [37] confirm the truth of the issue and also the notable rise of the temperature from lower parts to upper sections of the radiator, which is about 15 °K in the studied transformer. Subsequently, as the most significant item, the core and windings local temperature distribution analysis is considered. High rates of heat generation in the windings of transformer operating at full-load, give rise to quite higher temperatures in these components, particularly at upper parts of the middle windings. As can be seen in Fig. 13, the temperature distribution of the 100 kVA transformer qualitatively conforms to Fig. 14 from the mentioned reference.

In transformer life estimation, measuring or estimating the HST is not negligible at all. The maximum temperature or hot spot temperature directly affects the life of the insulators and their quality in the transformer. On the other hand, increasing the transformer load and the ambient temperature will be the other factors which cause increases in the hot spot temperature and also reduction of the transformer life. Various methods for predicting or estimating HST have been proposed in other standards or articles. Table 7 shows the hotspot temperature variations for the transformer with increasing load in presence of mineral oil, canola oil and flaxseed oil. As can be noticed from Table 7, the HST derived by consideration of different oils, rises as load increases, but in this case, the maximum temperature of the transformer containing vegetable oils is lower than that of the transformer with mineral oil, as well.

Mean heat transfer coefficient (HTC) is specified by the following equation:

$$\bar{h} = \frac{\int_0^L \frac{q''}{\left(T_{wall}(x) - T_{fluid}(x)\right)} dx}{L} \tag{14}$$

where q'' is the heat flux density, T_{wall} is the calculated wall temperature and T_{fluid} is the fluid temperature. Figure 15 shows the variation of heat transfer coefficient with temperature versus load variations. As it can be seen from Fig. 15, canola vegetable oil has superior heat transfer coefficient comparing with two other oils. On the other hand, it can be derived from Fig.15, with increasing the load, the mean heat transfer coefficient increases, but at superior loads canola vegetable oil has more increases in mean heat transfer coefficient compared to other oils.

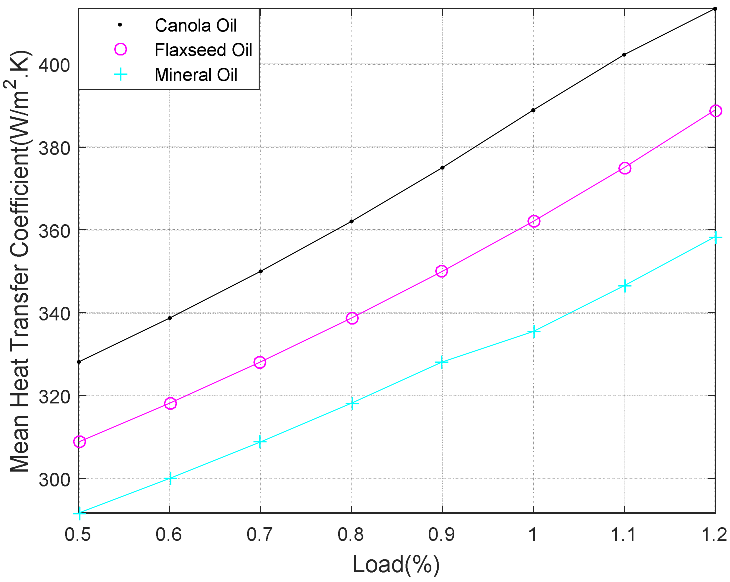

Fig. 15. Mean heat transfer coefficient at various loads considering different oils.

4. Conclusions

In this paper, thermal analysis of distribution transformer with vegetable oils natural cooling was presented. Therefore, at first, electrical characteristics, fire point, chemical properties, renewability and cheap price of vegetable oils were introduced, and it was concluded that vegetable oils can be used in transformers instead of mineral oils. Also, a comparison was made between vegetable oils and mineral oils (which are usually used for cooling in transformers), and the advantages and disadvantages concerning each oil usage were explained. In order to analyze the cooling of the transformer, a 100 kVA distribution transformer with grain-oriented silicon steel, amorphous and vitroperm alloy core types and containing several types of vegetable oils was simulated by ANSYS software. Conjugate heat transfer of core, coils and transformer oil was assessed using CFD. In this simulation, the cooling qualities of some vegetable oils were compared with the cooling performance of the mineral oil. It was shown that in a transformer in which vegetable oil was used, compared to a transformer in which mineral oil was used, better heat transfer was detected, and the core and coil temperatures decreased. Then, the simulation results were compared qualitatively with other reference to verify the accuracy of the results. On the other hand, at different loads, it was found that the hot spot temperature in the transformer containing mineral oil was higher than the transformer with vegetable oil. According to the comparison, canola oil was shown to reduce the hot spot temperature more effectively than other oils. It should also be noted that although this temperature difference is not so high, but this small difference (slight decrease in temperature) will have a significant effect on increasing the life of the transformer, in a long term period.

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Conflict of Interest

The author declared no potential conflicts of interest concerning the research, authorship, and publication of this article.

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Data Availability Statements

All data generated or analyzed during this study are included in this published article.

Nomenclature

Latin symbols		P	Pressure: N·m^{-2}
A	Magnetic vector potential: V.s.m^{-1}	Q	Copper losses density: W·m^{-3}
B	Magnetic flux density: T	T	Temperature: K
CFD	Computational fluid dynamics	V	Electric potential: V
C_p	Specific heat capacity: J·kg^{-1}·K^{-1}	V_f	Velocity of the fluid: m·s^{-1}
E	Electric field intensity: V.m^{-1}	*Greek letters*	
g	Acceleration due to gravity: m.s^{-2}	α_c	Thermal expansion coefficient: K^{-1}
h	Heat transfer coefficient: W·m^{-2}·K^{-1}	η	Dynamic viscosity: kg·m^{-1}·s^{-1}
HST	Hot spot temperature	ρ	Density: kg·m^{-3}
HV	High voltage	σ	Electrical conductivity: Ω^{-1}·m^{-1}
J	Electric current density: A·m^{-2}	μ	Magnetic permeability: T.m.A^{-1}
k_f	Thermal conductivity of fluid: W·m^{-1}·K^{-1}	*Subscripts*	
k_s	Thermal conductivity of solid: W·m^{-1}·K^{-1}	s	solid
LV	Low voltage	f	fluid

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