
EXPERIMENTAL AND SIMULATING OF DRY-TYPE TRANSFORMER THERMAL ANALYSIS WITH A NEW APPROACH FOR OUTDOOR APPLICATIONS

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Abstract: Since dry type transformers (DTT) has many advantages over the oily ones, this study focuses on the realibility, feasibility and cost of DTT to be used at outdoor applications. On this respect the core and winding temperatures of the 1500 VA DTT transformer model is measured by thermal camera The operational highest temperature of the transformer is obtained by this way. The DTT is simulated by ANSYS with the design parameters based On the physical model, and the simulation values and the real ones are compared to satisfy the procedure. Then in the light of simulation results, an outer cover is designed for outdoor applications which is the goal of the paper. The real hot spot temperature of the 1500 VA DTT is 129 ° C remains the same with the new cover simulation designed DTT that naturally cooled. Furthermore, the temperature of the new design DTT is reduced by about 4.6% to 123 ° C by forced cooling. So the new cover design not only provide to be used at outdoors applications, it also increases the lifetime of the device, and reduces the operation costs.

Keywords: Dry-type transformer, thermal analysis, lifetime, hot spot temperature

Kuru Tip Transformatörlerin Dış Ortamlarda Kullanılabilmesi İçin Deneysel Ve Simülasyon İle Termal Analizine Yeni Yaklaşım

Öz: Kuru tip transformatörlerin (KTT) yağlı tip transformatörlere göre avantajları göz önünde bulundurulduğunda, dış mekânlarda da kullanılabilir duruma getirilmesi bu çalışmanın esas amacını oluşturmaktadır. Bu noktadan yola çıkılarak ilk önce 1500 VA kuru tip transformatörün termal kamera ile çekirdek ve sargılarındaki sıcaklıklar ölçülmüştür. Böylelikle transformatörün çalışma sırasında ulaşabileceği en yüksek sıcaklık değeri elde edilmeye çalışılmıştır. Fiziksel model baz alınarak elde edilen tasarım değerleri ile Ansys programında tasarlanan KTT simüle edilmiş, çıkışın yüklü durumunda en yüksek sıcaklık değeri ile gerçek değer karşılaştırılarak simülasyon test edilmiştir. Daha sonra bu elde edilen sıcaklık değerine göre trafonun dış ortamlarda da kullanılabilmesi için bir mahfaza tasarlanmıştır. 1500 VA KTT'nin termal kamera test düzeneği ile ölçülen 129 ° C en sıcak nokta sıcaklık değerinin Ansys Fluent (Ansys Inc., Canonsburg, PA, ABD) ile simüle edilen tabi soğutmalı mahfaza içindeki sıcaklık ile aynı olduğu görülmüştür. KTT' nin zorlamalı soğutma alanındaki sıcaklığı, yaklaşık % 4,6 azalarak 123 ° C'ye düşürülmektedir. Bu şekilde tasarlanan yeni mahfaza, transformatörün dış mekânlarda kullanılabilirliğini sağlamakta ve elde edilen düşük sıcaklık KTT' nin kullanım ömrünü de artırmaktadır, dolayısıyla maliyetini de düşürmektedir.

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Anahtar Kelimeler: Kuru tip Transformatör, termal analiz, faydalı ömür, en yüksek sıcaklık

1. INTRODUCTION

Transformers are main components of electricity transmission and distribution systems. One of these components is dry type transformers. Among the various transformer technologies, the dry-type technology does not have any liquid for the cooling system and is not flammable, but is more reliable and more environmental. The dry type transformers have useful in indoor application and become a market place for urban areas, hospitals, schools, buildings, etc. It is used in where high safety and reliability standards are required. Also, DTT are more expensive than oil-type transformers and have some limitations in power applications. Accordingly, the defects in the parts of these transformers mean a great deal of financial and time loss. Therefore, it should be designed and manufactured to meet the specific use requirements, cost and failure conditions in accordance with the limits defined in international standards such as IEC-76 and IEEE C57.12.50-1981 (Finocchio et al., 2017). The key to reducing service life, performance and costs is the design of power transformers as a complex process, as well as the technological modification of various materials, methods and production processes. Studies in which a large number of interrelated variables such as winding materials and insulation materials have an effect on the transformer model during this complexity design have been conducted (Amoiralis, Georgilakis, and Gioulekas, 2006; Wang, Wang, and Zhao, 2015). The main purpose of transformer design is to increase the efficiency of the transformer. The minimization of losses. are related to winding and core losses and also depend on parameters such as internal temperature, resistance of windings, operating current, nominal voltage, load and quality of the copper. The increase in losses also affects the temperature regime in the transformers (Yadav et al., 2011). This temperature regime causes thermal stress, failure of the insulation material and thus loss and faults (Jian Sheng Chen, Hui Gang Sun, Chao Lu, Qing Zheng, 2013). Hence, a number of studies have been published to determine the internal temperature (or the value of the temperature increase) in the transformer windings where one of the most important steps in transformer design (Amoiralis, Georgilakis, and Gioulekas 2006; Geromel and Souza 2002; Jabr, 2005). In this sense, many studies deal with oil-type transformers to minimize production costs, estimate the highest temperature value, and to determine core losses, stranded losses and no-load losses (El Wakil, Chereches, and Padet, 2005; Kweon et al., 2012; Oommen and Prevost, 2006; Lundgaard et al., 2004; Gastelurrutia et al., 2011). There other ones show that dry type transformers have the highest temperature point among the power transformers (Lee et al., 2010; Adly and Abd-El-Hafiz, 2014). In addition, a few studies are done for the use of the thermal model and dry type transformer in the outer environment (M. A. Arjona, C. Hernandez, R. Escarela-Perez, 2014; Yaman, Altay, and Yaman, 2019).

In this study, the highest temperature values in the naturally cooled windings will be experimentally measured with the thermal camera and the results of these will be compared with the Ansys simulation results. In this way, a new cover will be designed for outdoor applications and to reduce the temperature. This new design n, the DTT can be used more widely in the industry, and consequently the life time of the device will be increased efficiently.

2. THERMAL MODEL OF DRY-TYPE TRANSFORMER

Equations used in heat transfer are expressed by similar electrical parameters; also known as "thermo-circuit simulation". For instance, the Fourier law, which forms the basis of heat transfer is similar to the Ohm law in electrical circuits. Thermal equations can be solved according to well-known Kirchhoff's laws.

Table 1. Thermal equivalents of electrical terms

Variables	Electric	Thermal
Through variable	Current I [Amps]	Heat transfer rate q [Watts]
Across variable	Voltage V [Volts]	Temperature θ [$^{\circ}\text{C}$]
Dissipation element	Electric resistance R_{el} [Ohms]	Thermal resistance R_{heat} [$^{\circ}\text{C}/\text{Watt}$]

Electrical and magnetic circuits include windings, core, lead and steel components. These components are the heat source when the device is in operation and have some thermal characteristics. The losses of Electrical and magnetic components are converted into heat during operation. Stranded loss accounts for 80% of the transformer total loss, which is the basic heat generator of transformer. Assuming the heat generation is constant and uniform, the heat generator of winding P is mainly composed of winding copper loss and iron loss, as shown [16]:

$$P = P_R + P_{Fe} = I^2R + P_{Fe} \quad (1)$$

Where I is the transformer winding current, R is the transformer winding resistance, P_{Fe} is iron loss. P is divided by winding volume V into heat source q , shown as Smolka and Nowak, 2008):

$$q = \frac{P}{V} \quad (2)$$

Transformers are designed according to different cooling types to perform the heat transfer. They are oil type transformers which transfer the heat from transformer to oil and dry ones transfer through air. The dry-type transformer scheme is shown in Fig. 1.

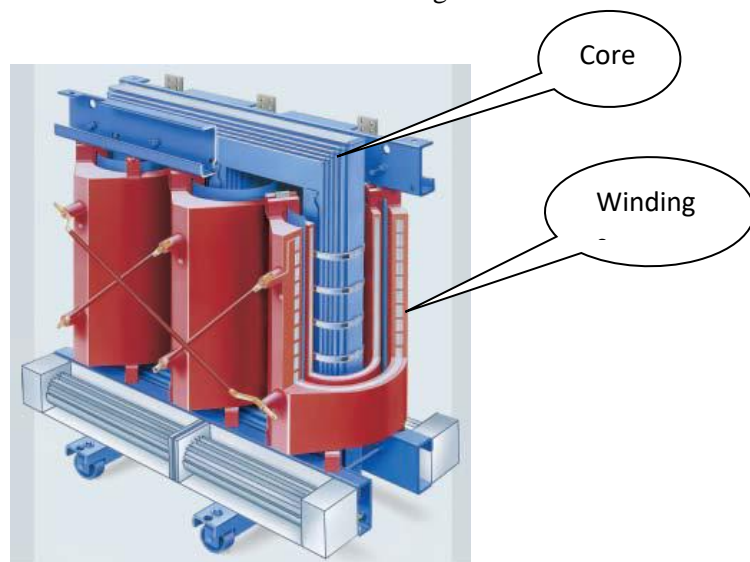


Figure 1:
Scheme of dry-type transformer

In Fig. 1, the heat transfer of core is made with natural convection and radiation on the outer surface and the heat transfer of windings are made natural convection, conduction and radiation with each other and outer surface.

2.1 Natural Convection

Mainly the heat transfer is made by natural convection in the core and windings. This heat transfer is expressed by Pierce and Holifield, 1999.

$$q_{conv}'' = h \cdot A_s \cdot (T_s - T_{air}) \quad (3)$$

where q_{conv}'' is heat transfer rate (W/m^2), h is convection heat transfer coefficient for outdoor surface ($W/m^2 K$), A_s is surface area (m^2), T_s is surface local temperature (K) and T_{air} is ambient temperature (K).

The outdoor surface of high voltage acts as vertical plate so, to get the value of heat transfer coefficient, we use empirical correlations (Incropera et al., 2007) as:

$$Gr_z^* = \frac{g\beta q'' z^4}{\nu^2} \quad (4)$$

$$Pr = c\mu/k \quad (5)$$

$$Nu_z = \left[\frac{2}{(360)^{1/5}} \right] \left[\frac{Pr^2}{0.8+Pr} \right]^{1/5} \cdot Gr_z^{*\frac{1}{5}} \quad (6)$$

$$h(z) = \frac{Nu_z \cdot k_{air}}{z} \quad (7)$$

Where, Nu_z , k_{air} ($W/m K$), Pr , Gr , g (m/sec^2), β ($1/K$), q'' (W/m^2), $Z(m)$, ν (m^2/sec), μ ($\frac{kg}{m} sec$) are Nusselt number, air thermal conductivity, Prandtl number, Grashoff number, gravity acceleration, fluid volumetric expansion, z location heat flux, vertical distance, fluid kinematics viscosity and fluid dynamic viscosity respectively.

The equation 4 and the others are valid over the Grashoff number in rang $10^5 \leq Gr^* \leq 10^{10}$ and all the parameters of air are dependent for unknown temperatures. Also equation 5 and the others are valid over the Prandtl number (Incropera et al., 2007). Both Grashoff and Prandtl numbers are obtained from thermal parameters table of material in thermodynamic sources.

2.2 Radiation on the Outer Surface

Radiation heat has a significant effect on the all distribution heat in the model. One of the heat transfer type is radiation occurs at outer surface of winding and iron core and it can be calculated as follows (Smolka and Nowak, 2008):

$$q_r'' = \varepsilon\sigma F_{ij}(T_1^4 - T_2^4) \quad (8)$$

Where, q_r'' (W/m^2), ε , σ ($5.67 \cdot 10^{-8} W/m^2 K^4$), F_{ij} , T_1^4 ($^{\circ}K$), T_2^4 ($^{\circ}K$), are radiation heat transfer rate, surface emissivity coefficient, Stephan Boltzman's coefficient, view factor, first surface temperature and second surface temperature or air temperature respectively.

2.3 Conduction in the Windings

Conduction heat transfer parts are made in windings with each other's. Equation of the heat transfer through conduction (Incropera et al., 2007):

$$q = -k \cdot A \frac{\partial T}{\partial x} \text{ (W/m}^2\text{)} \tag{9}$$

where q represents the transferred heat; k (W/m.K) represents the conductivity coefficient of air; A (m²) represent the surface area and T represents the surface temperature.

3. MEASURING AND SIMULATING RESULTS OF DRY-TYPE TRANSFORMERS TEMPERATURE

In this study, 1500 VA dry type transformer is selected as a base model which its boundary conditions are given in Table 2.

Table 2. 1500 VA Dry-type Transformer Boundary Conditions

Power (VA)	Vin- Vout(V)	N1- N2 (turns)	Material	T (out door°C)	Convection	Radiation	Conduction
1500	220-380	174- 300	Cu-Fe Nomax- Air-M27 steel	20	Yes- Natural/Forced	Yes-Black Dot	Yes

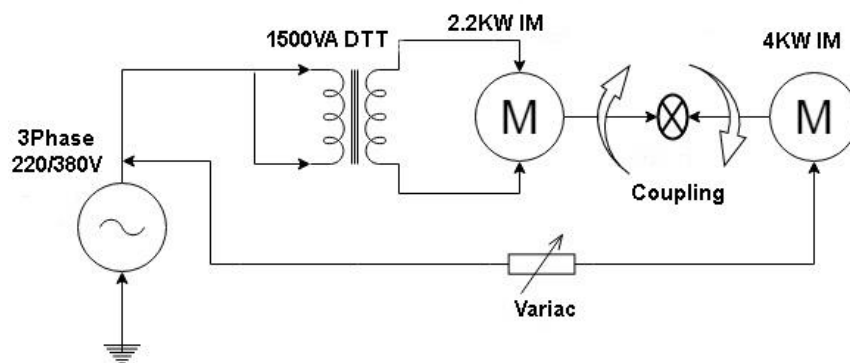


Figure 2:
Test set up of Dry-Type transformer

The test setup for dry type transformer temperature measurement is shown at Fig.2. 2,2 kW induction motor is connected to the output of the dry type transformer, and this motor is connected to another induction motor of 4 KW at the coupling point for dynamic load. The voltage and current values of load are controlled by variac.

Table 3. Properties of The Thermal Camera

Properties	Value
Resolution	320x240 pixel
Temperature Sensitivity	0.05 °C
Range of heat	-20 / +650 °C

In the experimental analysis made, the current values per phase are measured at the different voltage levels of the 4 KW motor, the values of heat are obtained in the transformer with the thermal camera given in Table 3.

The temperature values of the transformer for 70 Volts of these voltage-current values are shown in Fig 3-a Core temperature of transformer is 86,8 °C and Fig 3-b Windings temperatures of transformer are 96 °C.

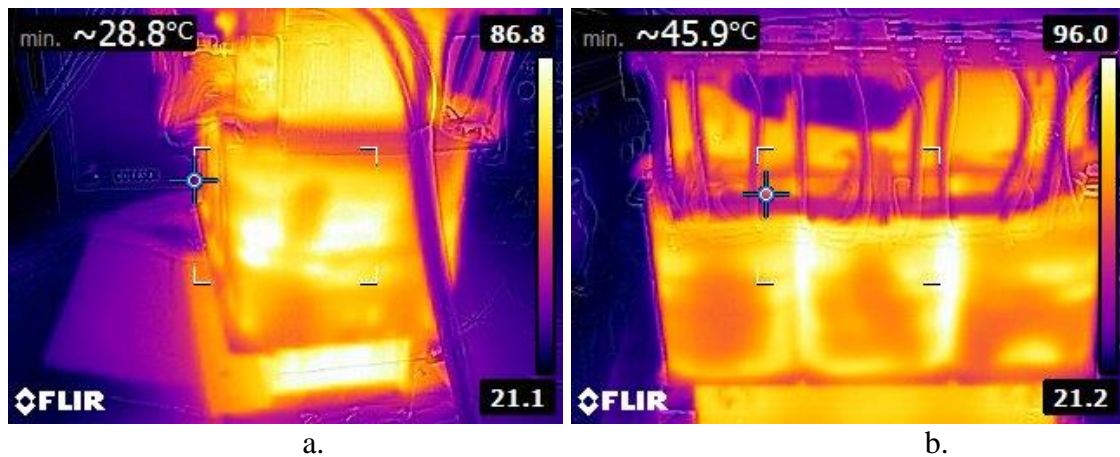


Figure. 3:

*The temperatures of Voltage values is 70 volts in Dry Type Transformer
a. Core temperature of transformer b. Windings temperatures of transformer*

The temperature values of the transformer for 85 Volts of these voltage-current values are shown in Fig 4-a Core temperature of transformer is 107 °C and Fig 4-b Windings temperatures are 120 °C.

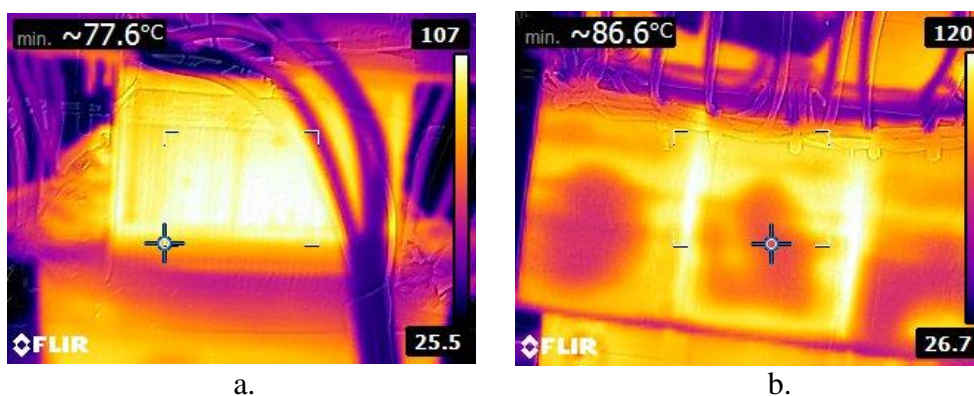


Figure 4:
The temperatures of Voltage values is 85 volts in Dry Type Transformer
 a. Core temperature of transformer b. Windings temperatures of transformer

The temperature values of the transformer for 100 Volts of these voltage-current values are shown in Fig 5-a Core temperature of transformer is 120 °C and Fig 5-b Windings temperatures are 129 °C.

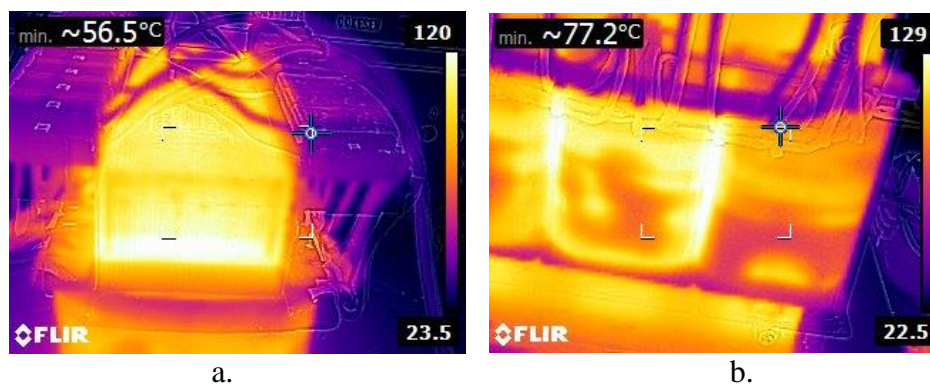


Figure 5:
The temperatures of Voltage values is 100 volts in Dry Type Transformer
 a. Core temperature of transformer b. Windings temperatures of transformer

All thermal camera values of DTT are summarized in the Table 4. Hence, the transformer temperature increases by load current.

Table 4. Temperatures Values of Dry-Type Transformer under load

Variac Voltage (Volt)	Phase Current Values(Ampere)	Core Temperature	Winding Temperature
70	4.17	86.8	96
85	4.9	107	120
100	5.7	120	129

The variation in temperature according to the voltage value of variac is given in the Fig.6.

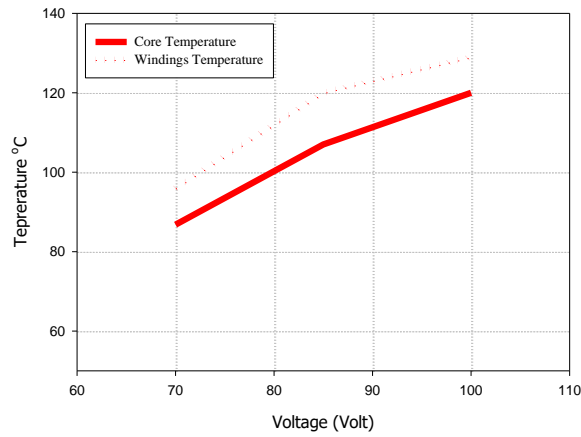


Figure. 6:
Temperature variation of Dry-type transformer core and windings

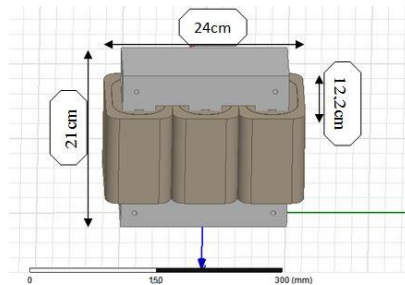


Figure. 7:
Physical dimensions of testing DTT

The test DTT dimensions are shown in Fig.7. This dimensions are used for new cover design. In order to reduce the transformer temperature after the test results new transformer cover for outdoor application is designed for DTT model which is shown in Fig.8.

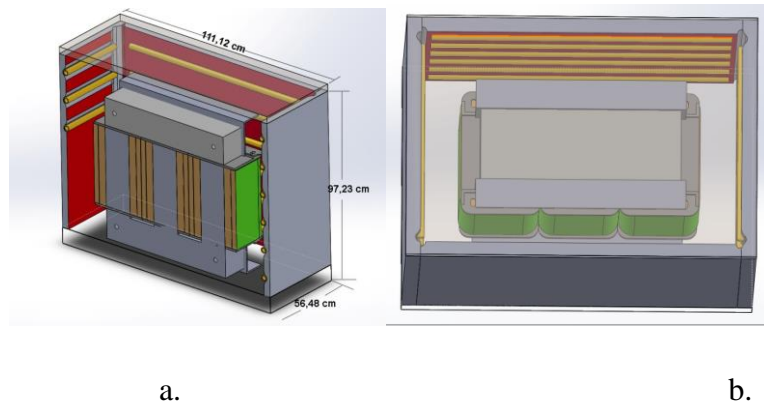


Figure. 8:
Cover Design of the 1500 VA Dry-Type Transformer
a. Cross-section of Cover b. Upper section of Cover

It shows the totally closed shape covered with aluminum sheet design by using copper pipes laid around the edges. These copper pipes are used to prevent DTT from heating through forced air flow. The heat analysis will be performed both using forced air flowing through the copper pipes and without it. The cover sizes are calculated using eq. 3. Eq.3 is calculated with A_s in eq.10:

$$\frac{1}{A_s} = \frac{1}{h_1} + \frac{L_1}{k_1} + \frac{1}{h_2} \tag{10}$$

Where, h_1 (W/m²K), k_1 (W/m²K), L_1 (m) (Özen Metal, 2018) and h_2 (W/m²K) are denote thermal conductivity of DTT, thermal conductivity of this material, aluminum sheet material thickness, outdoor thermal conductivity respectively

Where the values required for the calculation of the surface area A_s , h_1 is calculated in eq.7 for thermal conductivity of DTT.

Table 5. Surface area calculation parameters

Symbol	Unit	Value
h_1	(W/m ² K)	5.48
k_1		177
L_1	(m)	0.002
h_2	(W/m ² K)	25

The surface area of the new cover is calculated from equation 10 which is 0.84 m² for 95.6W stranded losses. The surface area of the new cover then will be as follows from the calculated surface area of DTT: Height: 111.12cm, Width: 97.23cm and Thickness: 56.48cm.

Industrial designs for the use of distribution type dry type transformers are rare. Therefore, the experimental design and theoretical analysis have been carried out in order to contribute to the lifetime of the transformer, both for outdoor and indoor using. In the theoretical analysis, the value obtained in the natural cooled dry type transformer analysis by Ansys with the new cover design is the same as the experimental value as shown in Fig 9.

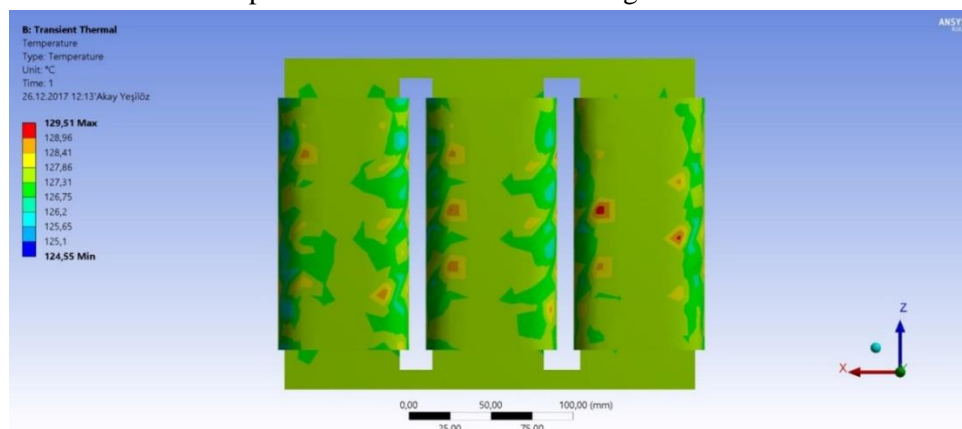


Figure. 9:
Natural cooled Thermal Analysis of the 1500 VA DTT in the new cover design

In Fig 10, analysis result of the dry type transformer in the new cover design has a lower value by forced cooling system.

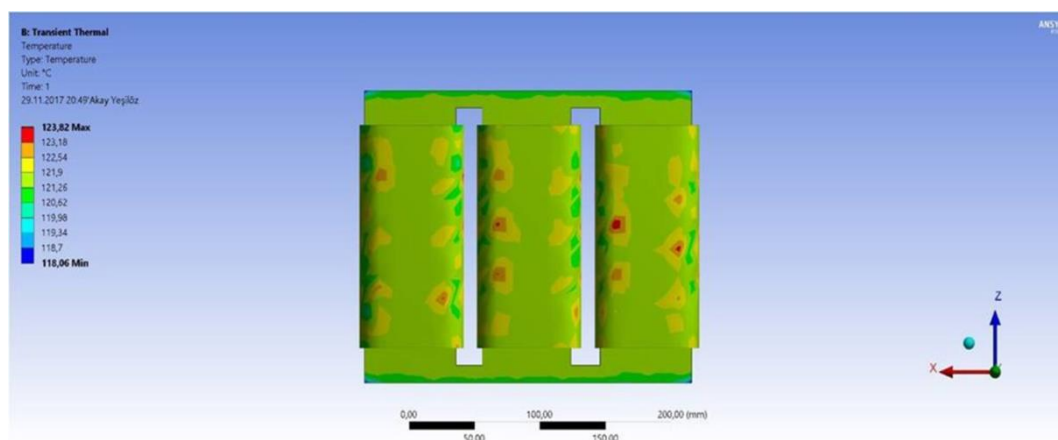


Figure. 10:
*Thermal Analysis of the 1500 VA Dry-Type Transformer
in new cover design by forced cooling.*

4. CONCLUSION

This study presents a thermal analysis of a distribution dry-type transformer in a new cover design for commercial outdoor application. Also DTT life time is extended with new design. The materials utilized in the DTT affect the lifetime of the systems. As the lifetime of the materials is a function of temperature, effective cooling of DTT has vital importance. Maximum temperature of DTT aims at to be reduced by the cover design relating with the experimental research.

The highest temperature value of the 1500 VA dry type transformer is measured as 129 °C, and the simulation results give the temperature of 123 °C with the new cover by forced cooling. % 4.6 ratio of decrease of temperature has been achieved. Thus dry type distribution transformers can be used more widely in the outdoor application as well as oil transformers and also life time will be increased. Therefore, the operational cost of the transformer will also reduce.

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