TEMPERATURE DISTRIBUTION IN POWER TRANSFORMERS

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TEMPERATURE DISTRIBUTION IN POWER TRANSFORMERS

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ABSTRACT

TEMPERATURE DISTRIBUTION IN POWER TRANSFORMERS

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As in all other electrical equipments it is essential to estimate the temperature distribution in transformer components in the design stage and during the operation since temperatures above thermal limits of these components might seriously damage them. Thermal models are used to predict this vital information prior to actual operations. In this study, a three dimensional model based on the Finite Element Method (FEM) is proposed to estimate the temperature distribution in the three phase, SF_6 gas insulated-cooled power transformer. This model can predict the temperature distribution at the specific discredited locations in the transformer successfully.

Keywords: Finite element method, heat transfer, power transformer

ÖZ

GÜÇ TRAFOLARINDA SICAKLIK DAĞILIMI

Karadağ, Rukiye

Yüksek Lisans, Elektrik Elektronik Mühendisliği Bölümü

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Bütün diğer elektriksel ekipmanlarda olduğu gibi bir trasformatörün bileşenlerindeki sıcaklık dağılımının tasarım ve operasyon aşaması için öngörülmesi önemlidir, çünkü ısıl limitlerin üzerindeki sıcaklıklar bileşenlere ciddi bir şekilde zarar verebilir. Isıl modeller bu çok önemli bilgiyi gerçek operasyonlardan önce öngörmek için kullanılır. Bu çalışmada üç fazlı SF6 gaz izoleli-soğutmalı güç trafosundaki sıcaklık dağılımını tahmin etmek için sonlu elemanlar yöntemine dayanan üç-boyutlu model kullanılmıştır. Bu model, trafonun içindeki ayrıştırılmış belli bölgelerdeki sıcaklık dağılımını tahmin edebilir.

Anahtar kelimeler: Sonlu elemanlar yöntemi, ısıl transfer, güç transformatörü

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CHAPTER 1

INTRODUCTION

Power transformers are most essential and consequential elements in electricity transmission and distribution. Therefore, in order to have a transformer working at optimum level, many researches and tests have been being performed. The goal of these tests and researches is reducing the amount of losses and extends lifetime of a power transformer. In this study, warming or overheating of a power transformer and its results has been analyzed. During the conversion of the electricity in a transformer, some losses occur. These losses occur at windings and core of the transformer and they turn into heat. This heat diffuses in the transformer and also to the air via its insulation material such as oil or SF_6 located in the transformer. The heat inside the transformer has also been analyzed during this study. There are three ways of heat transfer;

- Conduction
- Convection
- Radiation

While observing a heat transfer, differential equations called "heat transfer equations" would be helpful and useful. Due to difficulty of solving these equations with analytical methods, they can only be solved by numerical analyzing methods. One of the most common numerical analyzing methods is "Finite Elements Methods" and this method was used in the study. In this method, the body which will be examined is going to be split up into smaller pieces that are called elements in order to reach the approximate result. In addition, the software called "ANSYS Version 13" which is developed by ANSYS.Inc was also used as a tool during the preparation of the study with "Finite Elements Method".

In the scope of this study; temperature distribution in the transformer "15/30/33(33.75) MVA GNAN/GFAN(GFAN) , 275/11 kV" which was manufactured by Mitsubishi Corp had been modeled in 3 dimensions with using Finite Elements Methods. All results reached by analyzing at three different loading levels of the transformer (15/30/33.75 MVA) were stated in the study. Afterwards, these results have been compared with;

- The values published by designers. [1]
- One of the previous analyses which was performed in 2 dimensions with using Finite Difference Method. [2]
- One of the previous analyses which was performed in 2 dimensions with using Finite Elements Method. [3]

Lastly, transformer that is still being used by TEİAŞ (Türkiye Elektrik İletim A.Ş), is the Turkish electricity transmission grid operator, was examined in the study. The temperature distribution inside the transformer “50(62.5) MVA, ONAN (ONAF), 154/33.6 kV” was modeled in 3 dimensions and the results were obtained by using Finite Elements Method. Afterwards, a comparison had been made between the results and temperature tests which were performed by TEİAŞ.

CHAPTER 2

TEMPERATURE DISTRIBUTION IN POWER TRANSFORMERS

The heat is generated in the windings and core of the transformer. As it was mentioned in Chapter 1, the heat could be transferred in 3 different ways.

- Conduction
- Convection
- Radiation

In this chapter, heat transfer in a power transformer will be examined.

2.1. Heat Generation in Power Transformers

The reason for heat transfer is the temperature difference between two different ambiences. The heat transfer starts with heat generation. The temperature of the medium in a heat generated ambience is higher than the medium where heat is not generated. This means, a heat transfer occurs from high temperature ambience to low temperature ambience.

In a power transformer, heat generation occurs due to iron loss and copper loss. Iron loss occurs at the core of transformers when transformers run at no–load operation or in other words when there is no load on secondary side. During the operation at no–load, the current which goes through primary side is very low. Therefore, only iron loss can be considered. Iron loss causes heat generation in the core of the transformer.

The heat generated per unit volume per unit time of the iron core in a transformer is [3]

$$q^{o}_{core} = \text{iron loss (W)/volume of the core (m}^3\text{)} \qquad (2.1)$$

Copper loss occurs at the windings because of the current which goes through the windings. This loss varies depend on the current which goes through the windings. At the end, copper loss causes heat generation too.

The total heat generated in the windings is [3]

$q_{windings}$ = [load in VA/full load VA]^2 x copper loss (W) (2.2)

The heat generated per unit volume per unit time of the copper windings is [3]

$q^o_{windings} = q_{windings}$ (W)/volume of the windings (m^3) (2.3)

2.2. Heat Transfer in Power Transformers

The heat, generated at the windings and core of the transformer, is transferred in different ways. Below stages, more detail of heat transfer in a transformer is explained.

2.2.1. Heat Conduction in Power Transformers

Conduction is the transfer of energy from the more energetic particles of a substance to the adjacent less energetic ones as a result of interactions between the particles. Conduction takes place in all forms of matter, such as solids, liquids, gases and plasmas. Conduction is the most significant means of heat transfer within a solid or between solid objects in thermal contact. Conduction is greater in solids because the network of relatively close fixed spatial relationships between atoms helps to transfer energy between them by vibration.

Conduction is governed by *Fourier's law,* which in one-dimensional form is expressible as

$$q \equiv -k \; \nabla \mathrm{T} \qquad (2.4)$$

where

q : rate of heat flow (W/m^2)

∇T : the rate of change of temperature with the distance in the direction of the flow of heat.(^{0}C/m)

k : thermal conductivity; it is a characteristic property of material through which the heat is flowing and varies with temperature.(W/m.^{0}C)

The thermal conductivity of a material is a measure of the ability of the material to conduct heat. A high value for thermal conductivity indicates that the material is a good heat conductor, and a low value indicates that the material is a poor heat conductor or insulator. [4]

In a power transformer, the heat transfer by conduction mechanism as follows;

- from inner part of core and windings to their surfaces,
- between windings and core,
- inside the insulation material (oil or SF_6) and
- through the wall of the transformer tank.

2.2.2. Heat Convection in Power Transformers

Convection is the mode of heat transfer between a solid surface and the adjacent liquid or gas that is in motion, and it involves the combined effects of conduction and fluid motion. The faster the fluid motion, the greater the convective heat transfer.

The rate of convection heat transfer is observed to be proportional to the temperature difference, and is conveniently expressed by *Newton's law of cooling gas*;

$$q = h A_s (T_s - T_\infty) \quad \text{(W)} \tag{2.5}$$

where h is the *convection heat transfer coefficient* in W/m$^2\cdot$°C, A_s is the surface area through which convection heat transfer takes place, T_s is the surface temperature and T_∞ is the temperature of the fluid sufficiently far from the surface. The convection heat transfer coefficient h is not a property of the fluid. It is an experimentally determined parameter whose value depends on all the variables influencing convection such as the surface geometry, the nature of fluid motion, the properties of the fluid, and the bulk fluid velocity. Since h is not a property, its values cannot be tabulated as is the case with thermal conductivity, enthalpy, density, etc. Nevertheless, it is useful to have a rough idea of its magnitude for common processes and fluids. Table 2.1 gives the approximate range of *h* for various conditions. [5]

Process	*h* ($W/m^2.^oC$)
Free convection	
Gases	5-30
Liquids	20-1000
Forced Convection	
Gases	20-300
Liquids	50-20.000
Liquid Metals	5.000-50.000
Process	***h*** **($W/m^2.^oC$)**
Phase Change	
Boiling	2.000-100.0000
Condensation	5.000-100.000

Table 2.1: Typical values of h

There are numerous methods for calculating the heat transfer coefficient in different heat transfer modes, different fluids, flow regimes, and under different thermo hydraulic conditions. In transformers; heat transfers from the surface of the core and windings to the insulation material (i.e. oil, SF_6), from the SF_6 gas to inner surface of the tank and outer surface of the tank to the ambient by convection.

2.2.3. Thermal Radiation in Power Transformers

Thermal radiation involves the transfer of heat by electromagnetic radiation that arises due to the temperature of a body. Radiant heat transfer does not need a medium, such as air or metal, to take place. Any material that has a temperature above absolute zero gives off some radiant energy. [6]

Unlike conduction and convection, thermal radiation between two surfaces or between a surface and its surroundings is not linearly dependent on the temperature difference and is expressed instead as [7]

$$q = \sigma A F (T_1^4 - T_2^4) \qquad (W) \qquad (2.6.)$$

Where *F* includes the effects of surface properties and geometry and σ is the Stefan-Boltzmann constant, $\sigma = 5.669 \times 10^{-8}\ W/m^2 \cdot K^4$.

The intensity of radiation is defined as the rate of emitted energy from unit surface area through unit solid angle. The radiation from a surface has different intensities in different directions.

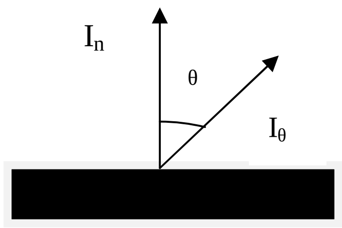


Figure 2.1: Emitted radiation from a surface

The intensity of radiation along a normal to the surface is known as intensity of normal radiation. For a surface at absolute temperature (T) and emissivity (ε), from Figure 2.1:

$$I_n = \varepsilon\sigma T^4/\pi \qquad (W/m^2) \qquad (2.7)$$

As it is seen in the formula 2.7., the intensity of the radiation depends on the emissivity (ε) of the object. Very often the radiant heat transfer from cooler bodies can be neglected in comparison with convection and conduction. But heat transfer process that occur at high temperature or with conduction or convection suppressed by evacuated insulations, usually involve a significant fraction of radiation. [8]

In power transformers; heat transfers from the surface of the core and windings to the inner surface of the tank and transfers from outer surface of the tank to the ambient by thermal radiation.

CHAPTER 3

TEMPERATURE DISTRIBUTION IN 30 MVA (GFAN) POWER TRANSFORMER

In Chapter 2, mechanism of heat transfer in transformers was analyzed and some differential equations were mentioned. Alike in many differential equations, the solution of this equation with analytical way is not possible either. Therefore, numerical analyzing method is used. In this study, the heat transfer in a 30 MVA (GFAN) SF_6 insulated power transformer will be analyzed with using one of the numerical analyzing methods called “Finite Elements”.

3.1. Finite Elements Method

Finite Elements Method (FEM) is a numerical technique for finding approximate solutions of partial differential equations as well as of integral equations. [9] The basic idea of FEM is to divide the body into finite elements, often just called elements, connected by nodes and obtain an approximate solution. The stages of finding approximate solution with FEM method is as follows:

Step (i): Discretization of the structure

The first step in the Finite Elements Method is to divide the structure or solution region into subdivisions or elements. Hence, the structure is to be modeled with suitable finite elements. The number, type, size, and arrangement of the elements are to be decided.

Step (ii): Selection of a proper interpolation or displacement model

Since the displacement solution of a complex structure under any specified load conditions cannot be predicted exactly, we assume some suitable solution within an element to reach the unknown solution. The assumed solution must be simple from a computational standpoint, but it should satisfy certain convergence requirements. In general, the solution or the interpolation model is taken in the form of a polynomial.

Step (iii): Derivation of element stiffness matrices and load vectors

From the assumed displacement model, the stiffness matrix $[K^{(e)}]$ and the load vector $\vec{P}^{(e)}$ of element "e" are to be derived by using either equilibrium conditions or a suitable variational principle.

Step (iv): Assemblage of element equations to obtain the overall equilibrium equations

Since the structure is composed of several finite elements, the individual element stiffness matrices and load vectors are to be assembled in a suitable manner and the overall equilibrium equations have to be formulated as

$$[\underset{\sim}{K}]\,\underset{\sim}{\vec{\Phi}} = \underset{\sim}{\vec{P}} \tag{3.1}$$

where $[\underset{\sim}{K}]$ is the assembled stiffness matrix, $\underset{\sim}{\vec{\Phi}}$ is the vector of nodal displacements, and $\underset{\sim}{\vec{P}}$ is the vector of nodal forces for the complete structure.

Step (v): Solution for the unknown nodal displacements

The overall equilibrium equations have to be modified to account for the boundary conditions of the problem. After the incorporation of the boundary conditions, the equilibrium equations can be expressed as

$$[K]\vec{\Phi} = \vec{P} \tag{3.2}$$

For linear problems, the vector $\vec{\Phi}$ can be solved very easily. However, for nonlinear problems, the solution has to be obtained in a sequence of steps, with each step involving the modification of the stiffness matrix $[K]$ and/or the load vector $\vec{P}$.

Step (vi): Computation of element strains and stresses

From the known nodal displacements $\vec{\Phi}$, if required, the element strains and stresses can be computed by using the necessary equations of solid or structural mechanics.

In this study, software called ANSYS is used in order to analyze the heat transfer. ANSYS, Inc. (NASDAQ: ANSS) is an engineering simulation software (computeraided engineering, or CAE) developer that is headquartered in Canonsburg, Pennsylvania, United States. All Finite Elements Methods' stages which are explained above have been developed by ANSYS.

The core product of Ansys Inc is its ANSYS Multiphysics/Structure mechanics module. This code is based on the Finite element method and is capable of performing static (stress) analysis, thermal analysis, modal analysis, frequency response analysis, transient simulation and also coupled field analysis. The Ansys multiphysics can couple various physical domains such as structural, thermal and electromagnetics. Many researchers and engineers prefer this module because of its parametric language known as Ansys Parametric Design Language (APDL). The APDL allows users to execute all the commands required to preprocess, solve and post process the problem, from a separate text file known as macro. [10]

While analyzing the heat transfer in a transformer with ANSYS, below data needed to be known;

- Dimensions of the transformer
- Thermal properties of transformer components (k, h an ε values)
- The areas in the transformer where the heat is generated
- The volume of generated heat in the transformer (q values).

3.2. Properties of the Power Transformer

In this thesis, a 3-phase, SF_6 gas insulated-cooled power transformer will be examined. The picture of the transformer is as below;

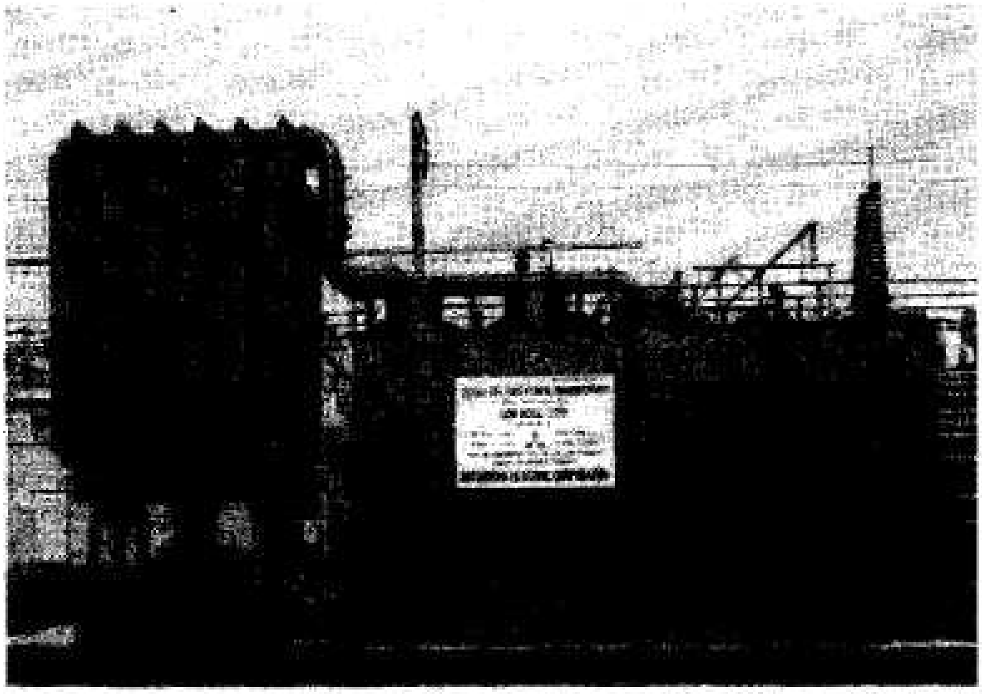


Figure 3.1: 15/30(33.75) MVA Power Transformer

Ratings and features of the transformer are given in Table 3.1[1]:

Phase		Three
Capacity		15/30/(33.75) MVA
Cooling Type		GNAN/GFAN/(GFAN)
Primary Voltage		288,75 kV ~275 kV ~ 206,25 kV
Secondary Voltage &		11 kV
Frequency		50 Hz
Thermal Insulation Class		E (Coil temperature limit is 75 ^{o}C by
Gas pressure (Main tank)		240 kPa at 20 ^{o}C
Sound level		55 dB at 2 m.
Dimensions	**Inside the tank**	W 2.3 x L 6.5 x 3.4 m
	Overall	W 4.5 x L 12.4 x 5.75 m
Weight of core and coil		45000 kg
Total weight		106000 kg (Including sound proof walls)

Table 3.1: Ratings and features of the 15/30/(33.75) MVA transformer

SF_6 gas inside the transformer which is used as an insulator also cools down the components' temperature. There are two ways of cooling down.

- Between 15-30 MVA loading via Gas Natural Air Natural (GNAN)
- Over 30 MWA loading via Gas Forced Air Natural (GFAN)

GNAN cooling occurs due to circulation caused by the temperature difference between the heat inside the transformer and surrounding air. On the other side, circulation of the gas inside the transformer at GFAN cooling can be occurred by a pump. In this case, the gas inside the transformer had been cooled down outside before pumping into the transformer. Thereby, the gas temperature stays at certain level. The losses occured in the core and the windings taken from Reference [1] are as follows;

- No Load Loss = 14 kW
- Load Loss at 75^{o}C, 30 MVA base (275/11 kV tap) = 162 kW

3.3. Iron and Core Losses of the Transformer

In a transformer the electrical losses are converted into thermal energy. To find the temperature distribution of the transformer, the heat generation within the transformer due to iron and copper losses must be initially determined. To obtain the heat generation of the equipment, the losses must be divided by the volume of the core and windings.

3.3.1. Calculation of the Volumes

According to the dimensions in Table 3.1., the volume of the core and windings are calculated as below: [2]

Volume of the Core;

$$V_{core} = V_{total\ core} - V_{core\ windows}$$

$$V_{core} = [(2.2x2.9x1)x2] - [(1.54x2.02x1)x2]$$
$$V_{core} = 6.54 \ m^3$$

Volume of the windings;

$$V_{windings} = V_{total\ windings} - V_{core\ leg}$$
$$V_{windings} = [3x(\pi x0.9^2 x1.9)] - [3x(1x0.44x1.9)]$$
$$V_{windings} = 11.97 \ m^3$$

3.3.2. Calculation of Heat Generation of the Core and Windings

Designers presented iron loss and copper loss for 30 MVA (GFAN) transformers as follows.

- Iron loss : 14 kW
- Total loss : 162 kW
- Core loss : 162 kW-14 kW = 148 kW

Heat generation values for core and windings can be calculated with using the formulas given in Chapter 2.

$$q_{windings} = 162 \text{ kW} - 14 \text{ kW} = 148 \text{ kW}$$
$$q^o_{core} = 14 \text{ kW} / 6.54 \text{ m}^3 = 2140.64 \text{ W/m}^3$$
$$q^o_{windings} = 148 \text{ kW} / 11.97 \text{ m}^3 = 12363.24 \text{ W/m}^3$$

3.4. Assumptions

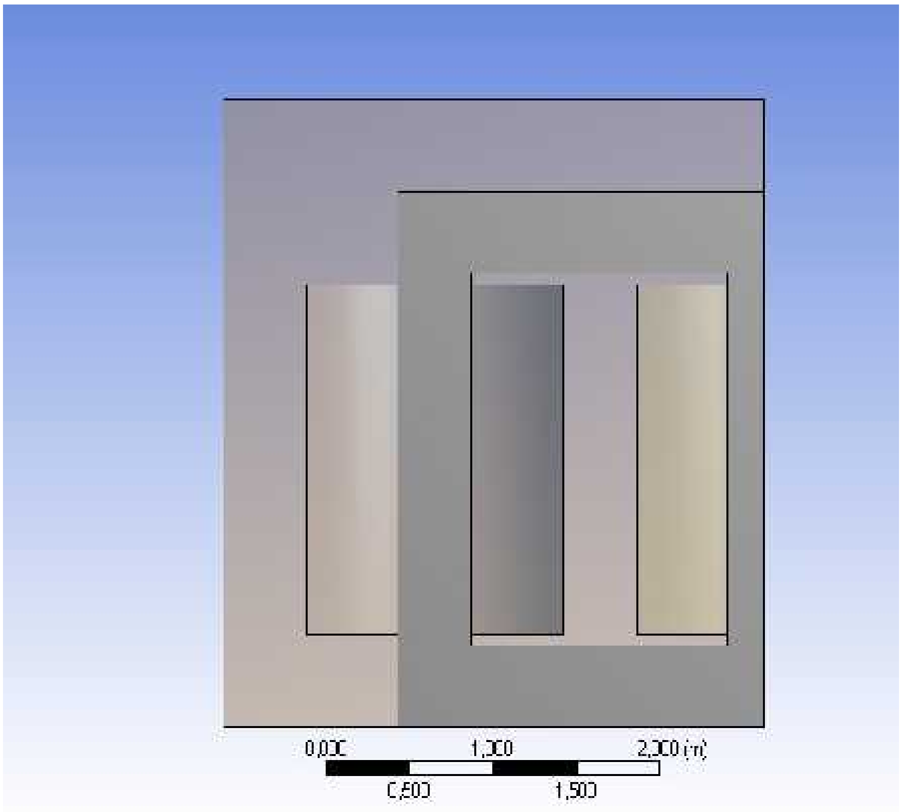
Some assumptions are used to simplify the computations in this study.

- The heat generated per unit volume per unit time in the core and windings are uniformly distributed.
- The dielectric loss on the winding insulation is not taken into account since it is significantly small compared to the copper loss. [3]

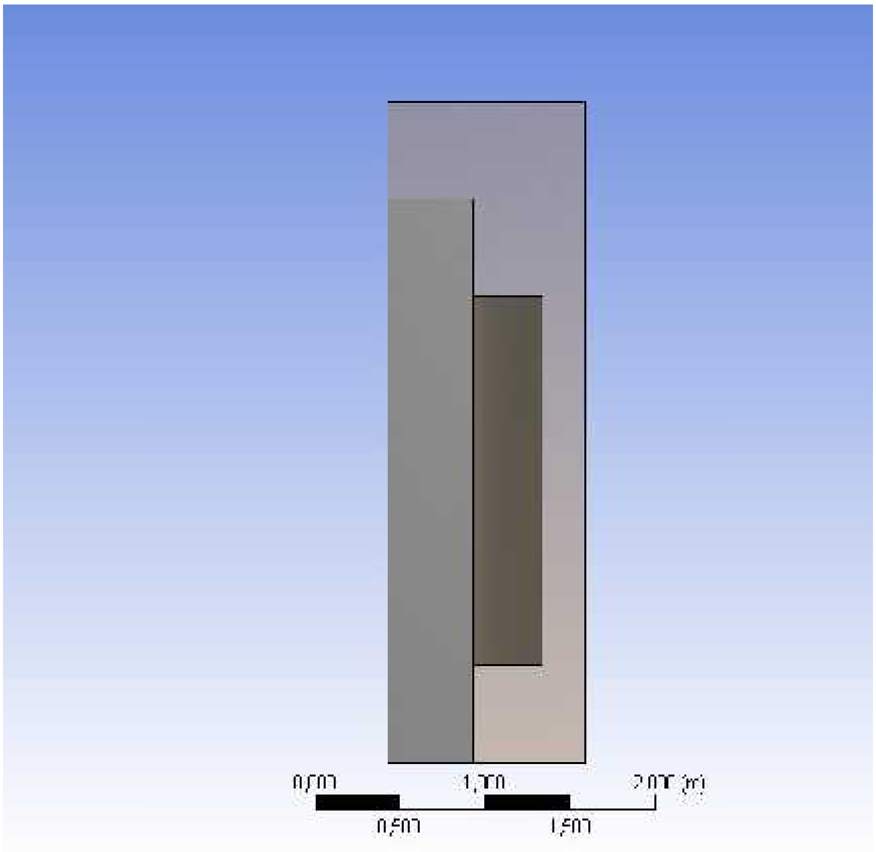
- Considering the symmetry on x and z axis of a transformer, only ¼ of the transformer was modeled. This simplification results decrease in computation time.
- In order to simplify the calculation, the core is assumed to be in the rectangular shape and the winding is assumed to be in the circular shape. [2]
- The bottom of the transformer was totally insulated and no heat transfer occurred from there.

3.5. Geometry of the Transformer

The SF_6 gas insulated-cooled transformer used in this thesis was first produced in the world by Mitsubishi Electric Corporation, Japan in 1990. In 1993, designers of the transformer published a letter about the design principles and performance of the transformer. [1]
The drawing of the transformer on ANSYS was developed by using all of the geometric features stated up to now. The drawing can be seen below.



Front View



Side View

Figure 3.2: Side and Front view of developed transformer

Only ¼ of the power transformer is modeled and with using its symmetrical structure, the solution will be achieved.

3.6. Mesh Generation of the Transformer

It was stated before that the body was broken into small pieces called elements during the Finite Element Analysis Method. In this case, the transformer which was designed with ANSYS has to be broken into optimum number of small pieces by mesh generation method. There are two points that should be considered while mesh generation is being carried out. Enough number of elements with proper dimensions must be available. If dimensions of elements are too small, then too much elements will be created. This situation might slow down the program and therefore the program may not be able to complete the analysis. On the other hand, if elements with big dimensions would be used in the analysis, then solution will be much easier. At this point, the possibility of reaching the right solution would be less.

That is why; too many experiments have been tried during mesh generation in order to reach optimum element quantity. At the end of all these tries, the proper mesh design can be seen on Figure 3.2 below.

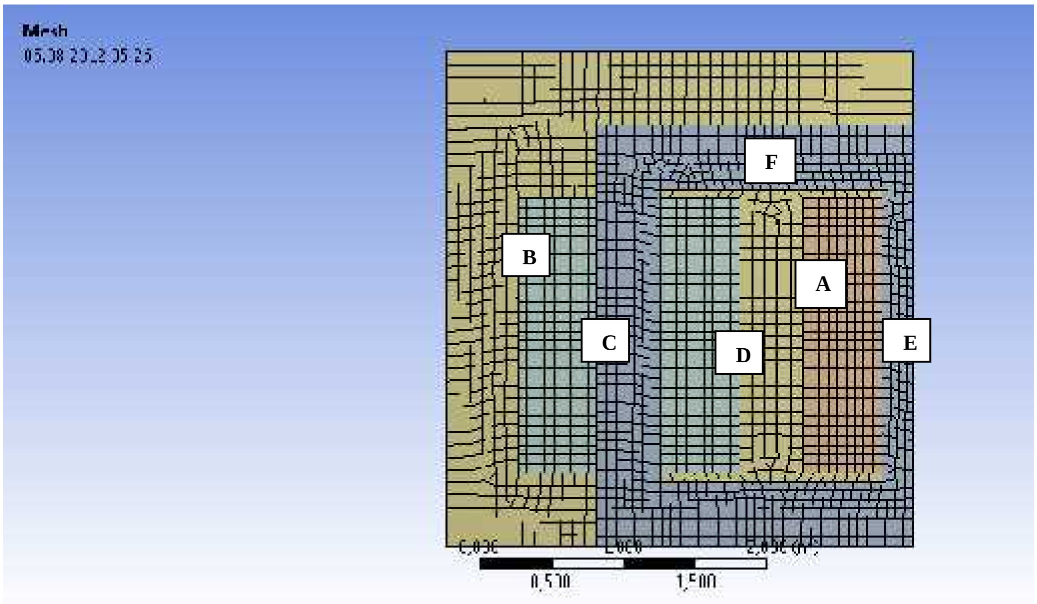


Figure 3.3: Mesh Generation of the Transformer

On the Figure 3.2

- A and B regions show SF6
- C, D, E regions show windings,
- F region shows the Core

The designed mesh was developed by 34733 various elements which are in various shapes (triangles, squares etc) and 152697 nodes which creates these elements.

3.7. Physical Data of the Transformer

First, boundary conditions of a transformer must be determined before examining the heat transfer in it. If we start from where the heat is generated, boundaries can be observed as follows;

1- Conduction Boundary:
   - Between windings and core
2- Convection Boundary:
   - Between SF_6 and windings,
   - Between SF_6 and core,
   - Between SF_6 and inside surface of the tank,
   - Between air and tank
3- Radiation Boundary:
   - Between windings, core and inside surface of the tank.

The required thermal property for "conduction boundary conditions" is the thermal conductivity (k) of the material. This value was stated in formula 2.4. It is different for iron core and copper windings; 50 W/(m^{o}C) for iron core and 395 W/(m^{o}C) for copper windings. The thermal conductivity of SF_6 is tabulated below [11].

T (^{o}C)	**k (W/m^{o}C)**
0	0.0105
20	0.01235
40	0.01412
60	0.01564
80	0.01714
100	0.01864
150	0.02226
200	0.02573

Table 3.2: Thermal conductivity of SF_6

In order to determine convection boundary conditions, the heat transfer coefficient (h) which was stated in the formula 2.5. must be known. This value is given by the designers

- For SF_6 gas: 55 W/($m^{2o}C$) at 30 MVA (GFAN) loading condition
- For air: 25 W/($m^{2o}C$) for natural convection. [1]

4 thermal radiation boundaries exist in the transformer

1- The radiation from the tank outer surface to ambient
2- The radiation from the windings to inner surface of the tank
3- The radiation from the core to inner surface of the tank
4- The radiation from the core and windings surfaces

As it is seen from the Formula 2.7.; the effective coefficient in thermal radiation is emissivity. In the power transformer; the tank is made of stainless steel and its' emissivity is 0.23. The core is iron and its' emissivity value is 0.44. The windings are copper and their emissivity is 0.04.

3.8. Solution of Heat Transfer Problem of the Transformer

Up to now, in order to observe the heat transfer at a transformer with ANSYS, below steps were determined.

- Heat generation values and points
- Structure (geometry) of the transformer
- Thermal properties of transformer components
- And mesh was developed.

Based on the values above, the result with ANSYS is shown on Figure 3.3.

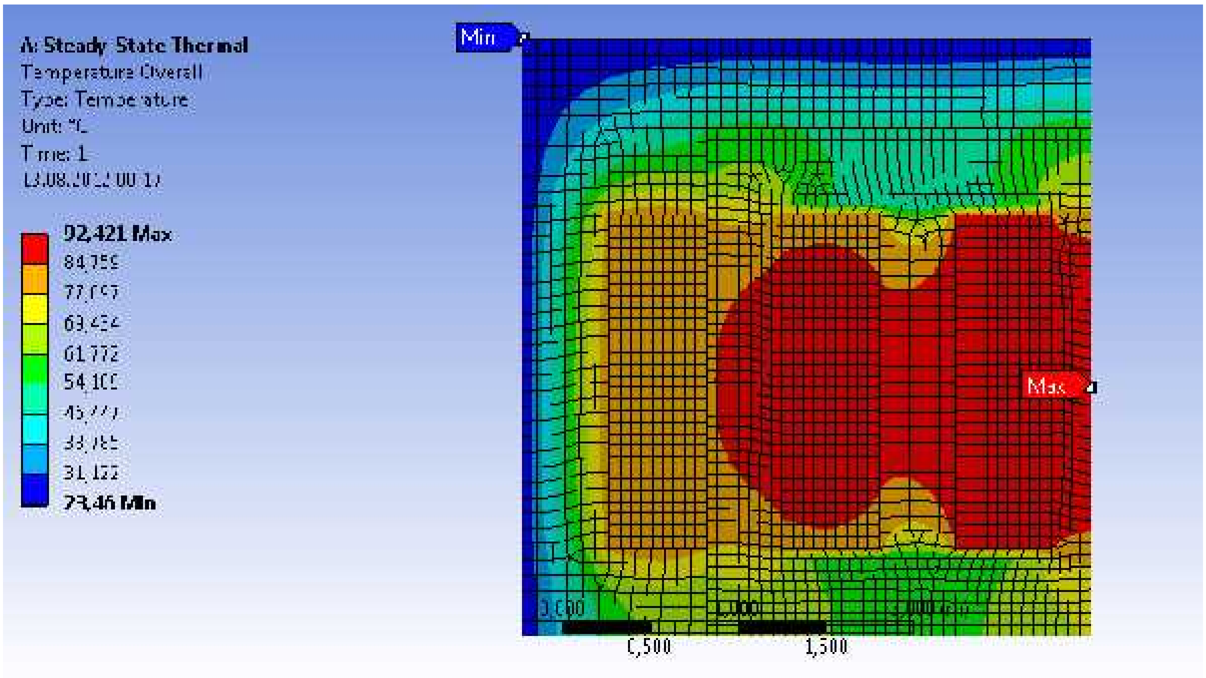


Figure 3.4: Temperature Distribution of 30 MVA Transformer

As it is seen in the Figure 3.3;

- Maximum winding temperature : 92.06 ^{o}C
- Minimum winding temperature : 78.32 ^{o}C
- Maximum core temperature : 92.42 ^{o}C
- Minimum core temperature : 46.89 ^{o}C
- Maximum SF_6 temperature : 90.15 ^{o}C
- Minimum SF_6 temperature : 23.46 ^{o}C

It can be seen in the Figure 3.3. that heat is being transferred from where it was generated to air via SF_6 gas by conduction and convection. The hottest point is observed on top of the core and the coldest point was seen at the point where SF_6 is transferred to air.

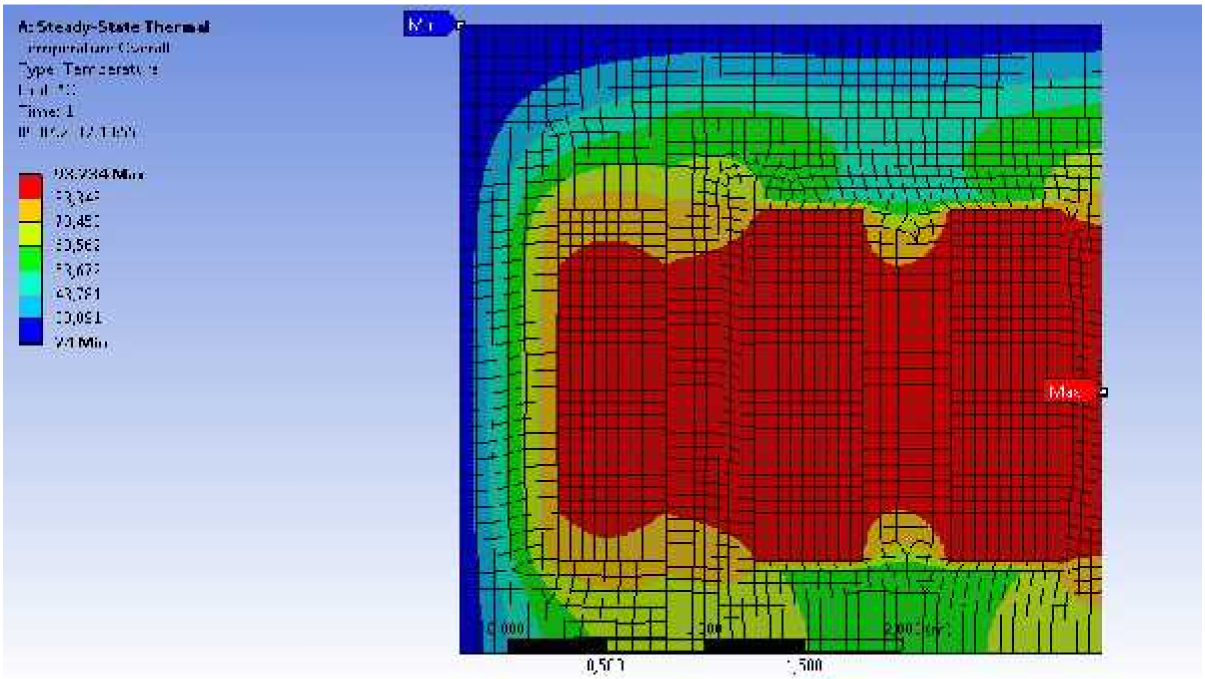
The temperature measurements of the transformer, which has been worked on, were done by the designers. Although, maximum winding temperature was measured 84.50 ^{o}C by designers, it was measured 92.06 ^{o}C in this study. [1] Moreover, heat transfer value of the same transformer modeled in 2 dimensions with Finite Elements

Method was found 87.50 ^{o}C. [3] On the other hand, finite difference method was used for the beforementioned transformer and the temperature was measured 84 ^{o}C. [2]. Too many factors might be the reason for the difference between the temperature values reached by designers and values found in this study.

First, temperature distribution of the transformer at 30 MVA was solved. The temperature difference at windings in our study was found (92.06 ^{o}C). Comparison of the winding temperatures between our study and designers was found 8 ^{o}C. The reason for this, can be explained as follows; designers used fiber sensors during measurement and these sensors were located at the top and outside of the low voltage winding. Therefore, measured temperature actually is the temperature of the winding at that point. As it can be presumed, maximum temperature would not be occurred at that point. In other words, measured value is not the maximum winding temperature. However, winding temperature value found with ANSYS is between 78.32 ^{o}C ~92.06 ^{o}C. This shows us that same temperature value (obtained by designers) can be reached at another similar point on windings where measurement had been done. As a matter of fact, if probe was located at another point similar to the place where designers used, the temperature values would have been found 82 ^{o}C~83^{o}C. These values are almost same with designers' outputs.

Then, due to know-how reasons, thermal properties of transformer components and SF_6 gas were not shared by OEMs. Therefore, the values stated in literature were used in the study. Furthermore, dimension of the components located inside the transformer were also not shared accurately by OEMs. That is why; the geometry was developed alike in the previous study. [3] The reason for obtaining different results from this study and two other previous studies is the modeling of the transformer. In the previous studies, transformer was modeled in 2 dimensions. However, 3 dimensions modeling were used in this study and detailed information regarding that is in Chapter 4.

Radiation boundary is commonly effective for the material which has higher emissivity values. The material who has the highest emissivity value called black body and the emissivity value of this material is 1. The emissivity value of transformer components is relatively low. Therefore, radiation boundary in a transformer can be neglected. In below figure (Figure 3.4.), radiation boundary was



neglected.

Figure 3.5: Temperature Distribution of 30 MVA Transformer
(Radiation Boundary was neglected)

Temperature values are found as follows

- Maximum winding temperature : 92.86 ^{o}C
- Minimum winding temperature : 79.57 ^{o}C
- Maximum core temperature : 93.23 ^{o}C
- Minimum core temperature : 48.50 ^{o}C
- Maximum SF_6 temperature : 90.91 ^{o}C
- Minimum SF_6 temperature : 24.00 ^{o}C

The comparison of these values with values obtained with radiation boundary is as follows;

The value	Obtained With Radiation	Obtained Without Radiation	Amount of The Difference
Maximum winding temperature	92.06 ^oC	92.86 ^oC	0.8 ^oC
Minimum winding temperature	78.32 ^oC	79.57 ^oC	1.25 ^oC
Maximum core temperature	92.42 ^oC	93.23 ^oC	0.81 ^oC
Minimum core temperature	46.89 ^oC	48.50 ^oC	1.61 ^oC
Maximum SF_6 temperature	90.15 ^oC	90.91 ^oC	0.76 ^oC
Minimum SF_6 temperature	23.46 ^oC	24.00 ^oC	0.54 ^oC

Table 3.3: Comparison of the results with and without radiation

As it is seen from the table 3.3., the difference of the obtained temperature values were between 0.54~1.61 ^oC. The distribution of the temperature didn't change. Thus, thermal radiation can be neglected. It will not affect the truth of the solutions. It helps the software to reach the solution easily and reduces the evaluation time. Hereafter, radiation boundary conditions will be neglected in all modeling analyses in order to save time and enable software to reach the result easily.

CHAPTER 4

HEAT TRANSFER APPLICATIONS IN POWER TRANSFORMERS

The modeled transformer in Chapter 3 is same as the transformer which had been previously modeled and tested. A comparison has been made between previous and current results. Up to now, it has been assumed that bottom of the transformer is insulated. In this chapter, observation was done assuming that bottom of the transformer is not insulated at 30MVA loading. Additionally, 15 MVA with natural cooling condition and 33.75 MVA overloading with forced cooling condition were observed. Besides, in order to evaluate the results from previous studies, the same transformer was modeled in 2 dimensions at 30 MVA loading with forced cooling condition. On top of all these, the transformer "50(62.5) MVA, ONAN (ONAF)" which is currently being used by Turkish electricity transmission grid has been modeled in 3 dimensions. All results were compared with the results which were given in Appendix.

4.1. Transformer with Non Insulated Bottom

In Chapter 3, the analyses had been resolved by assuming:

- Convection Boundary on top, left side and rear surfaces of the transformer
- Symmetric Boundary on right side of the transformer
- Insulated Boundary on the bottom of the transformer

However, in reality transformers have wheels and stay on the rails. Hence, their bottom surfaces are not connected to the ground. Because of the air circulation between the bottom of a transformer and ground, convection boundary occurs. In this section, the temperature distribution of convection boundary is analyzed. In order to do this, air whose heat transfer coefficient is 25 W/ ($m^{2o}C$) had been added to the bottom surface of the transformer and solution is obtained as shown in Figure 4.1.

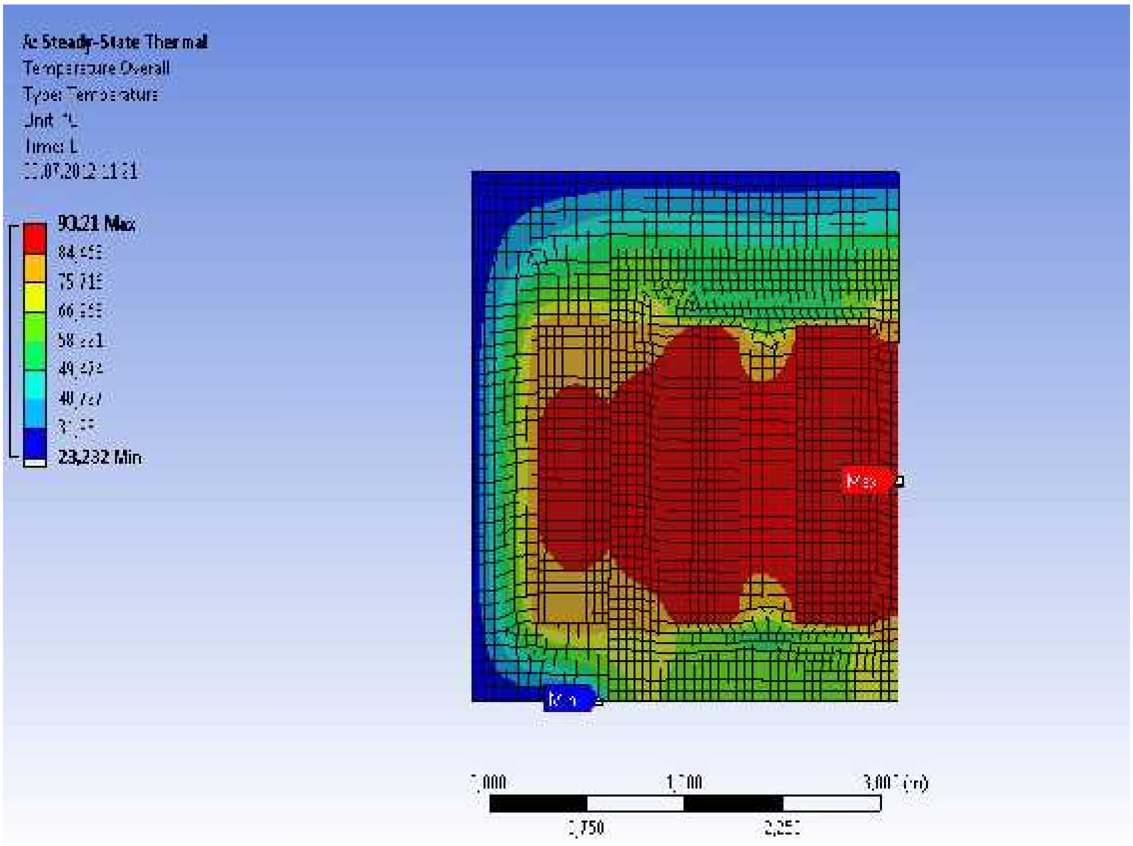


Figure 4.1: 30 MVA (GFAN) (Non Insulated Bottom) Temperature Distribution

As it is seen in the figure above;

- Maximum winding temperature : 92.40 ^{o}C
- Minimum winding temperature : 79.21 ^{o}C
- Maximum core temperature : 92.76 ^{o}C
- Minimum core temperature : 47.41 ^{o}C
- Maximum SF_6 temperature : 90.47 ^{o}C
- Minimum SF_6 temperature : 23.43 ^{o}C

Although, maximum SF_6 temperature was found 90.91^oC in Chapter 3, it is found 0.5^oC less in this chapter. Due to ascending of heated air, the coldest point SF_6 gas is at the bottom of the transformer. Thus, insulating the bottom of the transformer could be logical. Within last years, in order to decrease displacement of a transformer during an earthquake, they have been seated on the ground. These kinds of applications can be seen in Turkish electricity transmission grid. Therefore, modeled transformers in this study were assumed that they all have an insulated bottom.

4.2. 2D Modeling of 30 MVA (GFAN) Transformer

30 MVA (GFAN) transformer was modified and analyzed in 3 dimensions in Chapter 3. On the other hand, in the two previous studies, same transformer was modeled in 2 dimensions. [2], [3]. In order to make a comparison with aforementioned studies, 30 MVA, GFAN was modeled in 2 dimensions and solution was achieved via this way in this chapter. The input values of the program (thermal characteristics of materials, boundary conditions and transformer geometry) were same as stated in Chapter 3. The solution of the mesh modeled in 2 dimensions can be seen in Figure 4.2.

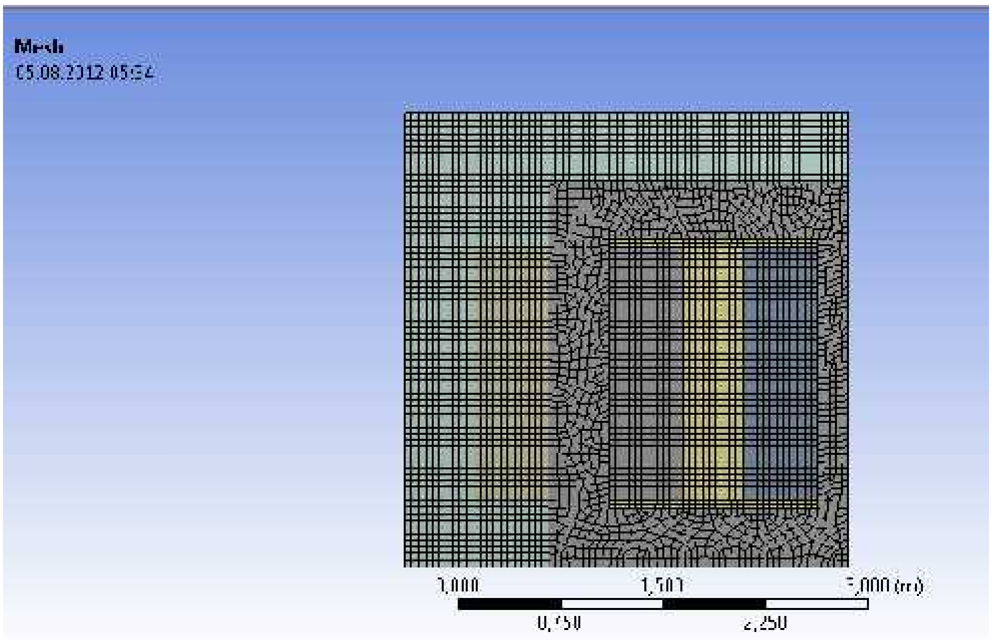


Figure 4.2: 2D Mesh Generation of the Transformer

The designed mesh was developed by 4120 various elements which are in various shapes (triangles, squares etc) and 13481 nodes which creates these elements. When the data is entered into the program, solution of temperature distribution in 2 dimensions is found as below;

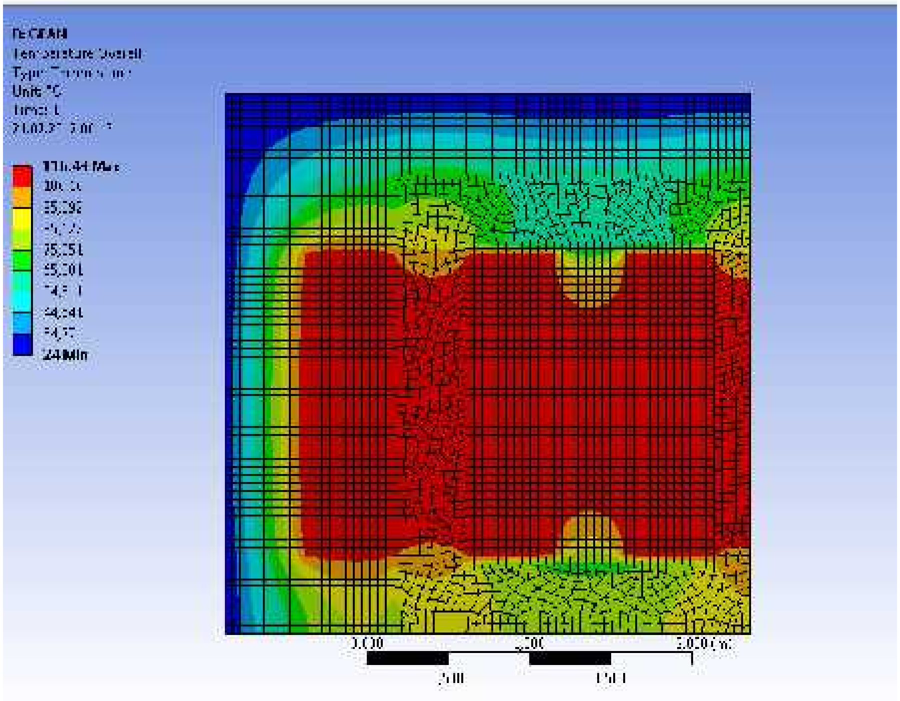


Figure 4.3: Temperature Distribution of 30 MVA Transformer (2D Modeling)

At the end of the analysis, alike the temperature distribution in 3 dimensions in Chapter 3, new temperature values are achieved as shown in below;

- Maximum winding temperature : 115.92 ^{o}C
- Minimum winding temperature : 103.89 ^{o}C
- Maximum core temperature : 116.43 ^{o}C
- Minimum core temperature : 57.186 ^{o}C
- Maximum SF_6 temperature : 113.07^{o}C
- Minimum SF_6 temperature : 24.00 ^{o}C

The temperature values achieved in here are 20-25 ^{o}C higher than the values of the same transformer which is designed in Chapter 3. The reason for this is 2 dimension modeling does not present the whole system. Temperature distribution of SF_6 gas (modeled in 2 dimensions) can be seen in below Figure 4.4. In the figure;

- There is no direct contact between SF6 gasses located in A and B areas
- SF6 gas in A location has very high temperature because it is closed to the area where heat is generated. It does not cool down easily because it can only transfer its heat to the SF6 located in B area via core and windings.

For these reasons, due to high temperature of SF6 gas which enables to cool down the transformer components does not help much. Therefore, components do not get cool down either. Hence, temperature values are achieved higher than the temperature values in 3 dimensioned models.

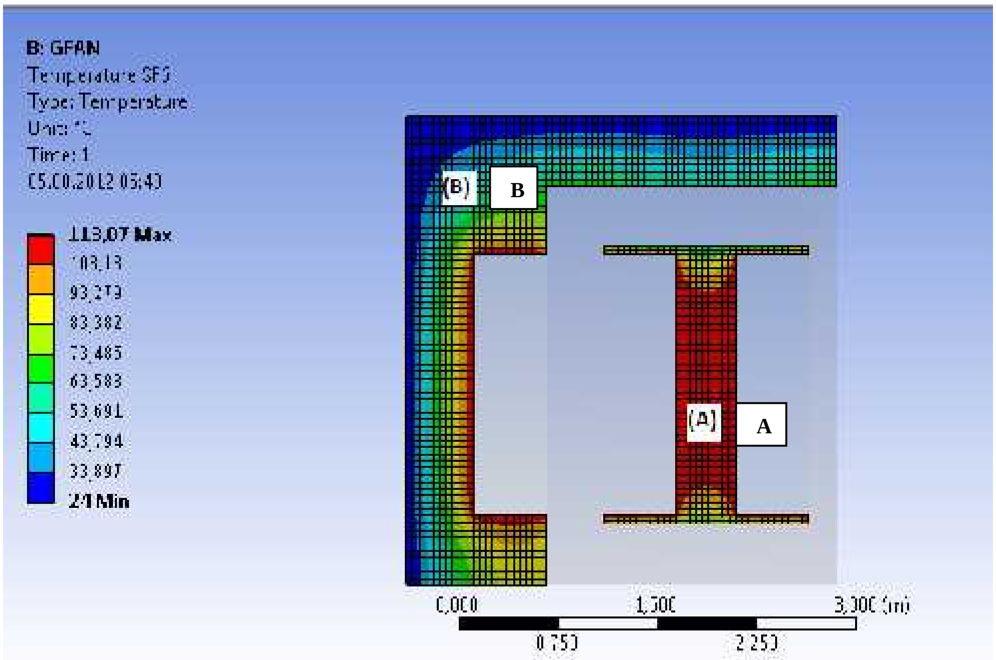


Figure 4.4: Temperature Distribution of SF_6 (2D Modeling)

In 3 dimension modeling (considering z dimension), SF6 gas can be found everywhere inside the whole transformer. That means, all gasses inside the transformer has direct contact to each other. In other words, SF6 gas in A area has direct contact with SF6 located in B area. This situation lets a direct heat transfer from A area to B.

Figure 4.5 shows the temperature distribution of SF6 from front view and Figure 4.6 shows the distribution from side view.

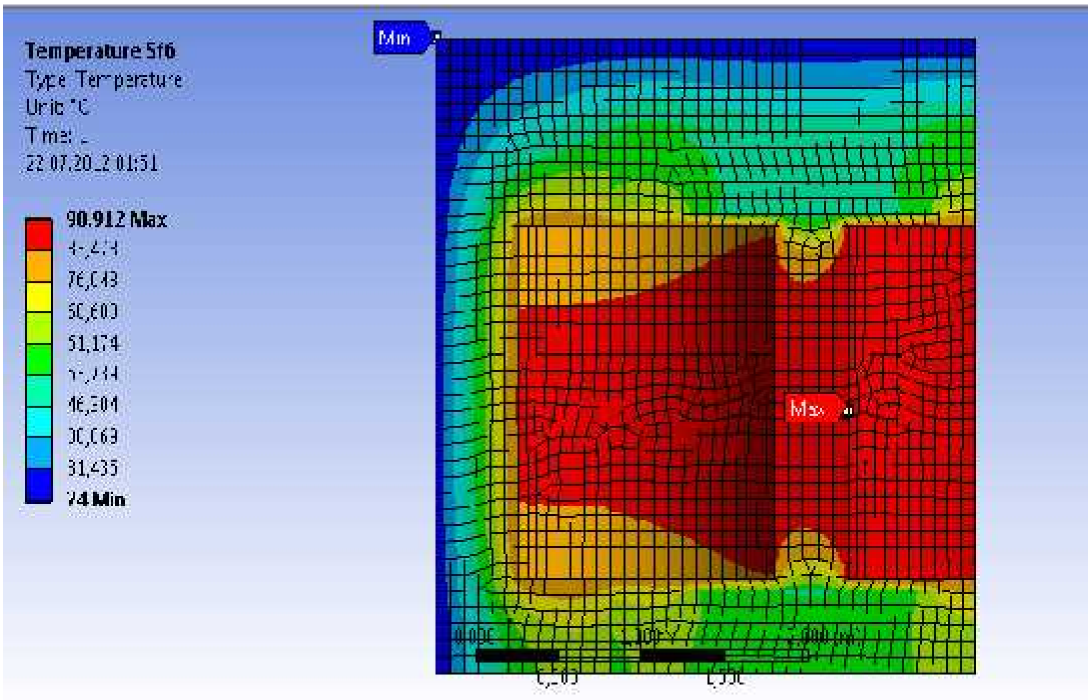


Figure 4.5: Temperature Distribution of SF6 (3D Modeling) - Front View

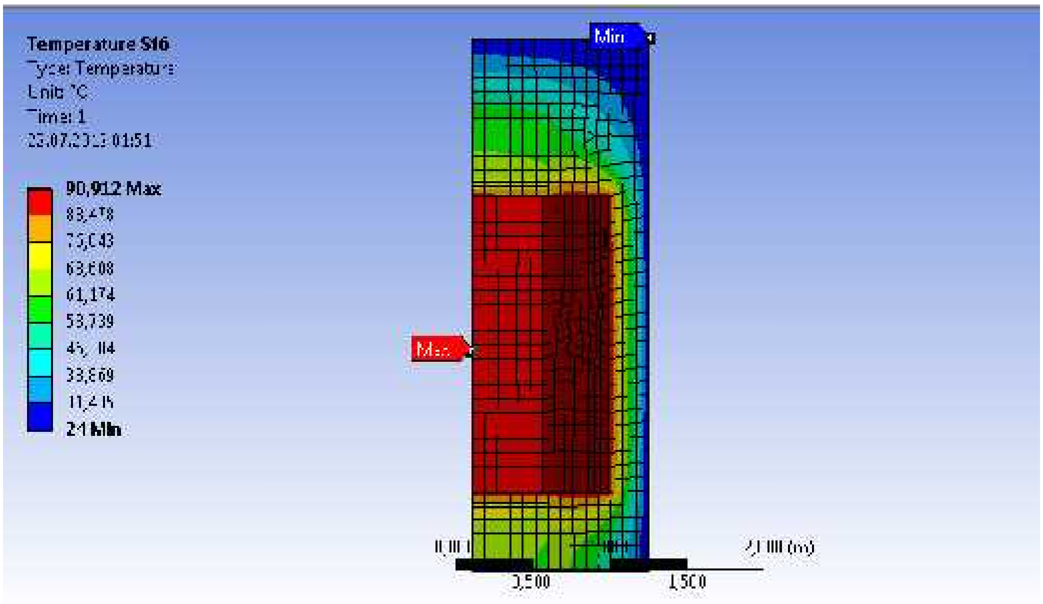


Figure 4.6: Temperature Distribution of SF6 (3D Modeling) - Side View

Based on the explanations above, it is obvious that modeling in 2 dimensions would not present right solutions. Therefore, all studies were performed in 3 dimensions during this study.

4.3. 15 MVA (GNAN) Power Transformer

Up to now, transformer was analyzed at 30 MVA (GFAN) loading. As shown on Table 4.1, this transformer can be used at 15 MVA (GNAN) loading as well. In this case, cooling down would be natural due to load decrease. Because of the load difference, heat generation value would be changed. Plus, due to the difference in the way of cooling down, heat transfer coefficient value would also change.

Copper and the iron losses for the transformer operated at 30 MVA (GFAN) rating were calculated in Chapter 4. When the transformer is operated at 15 MVA (GNAN) rating, the core loss (and so the q^o_{core}) will not change, but the copper loss (and so the $q^o_{windings}$) will change. Copper loss value for 30 MVA was 162 kW. With using the formulas stated in 2.2. and 2.3;

$$q_{windings} = (15/30)^2 \times 148000 = 37000 \text{ W}$$

$$q^o_{windings} = 37000 / 11{,}97 = 3091 \text{ W/m}^3$$

The heat transfer coefficient of the SF_6 is given 15 W/ (m^2 ^oC) for 15 MVA (GNAN) loaded transformer and the 25 W/ (m^2 ^oC) for the air by the designers. [1] By using these parameters, the temperature distribution solution is obtained as below;

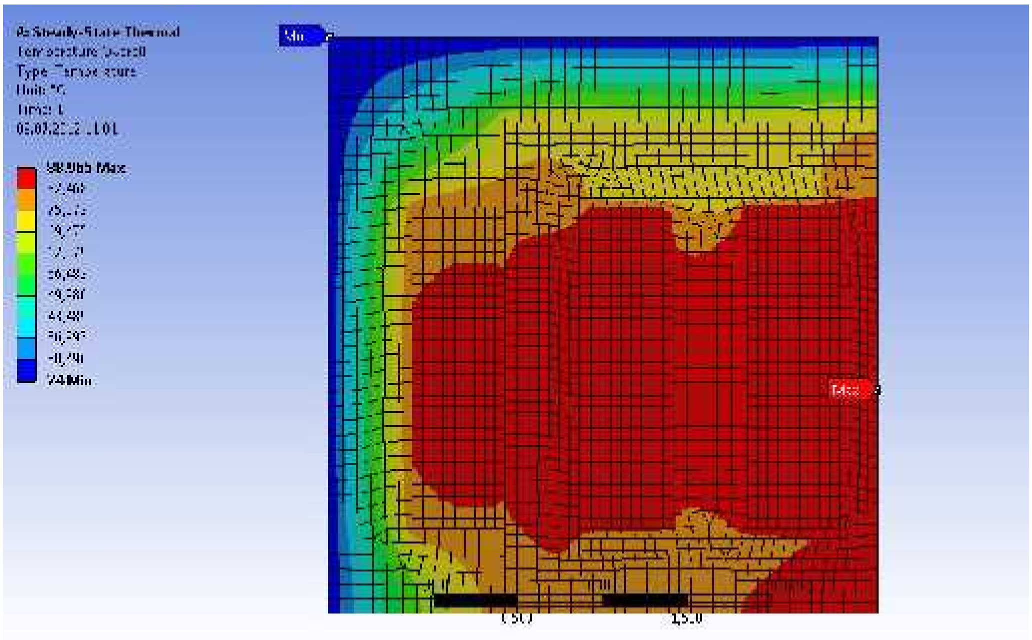


Figure 4.7: Temperature Distribution of 15 MVA Transformer

As it is seen in the figure above;

- Maximum winding temperature : 88.18 ^{o}C
- Minimum winding temperature : 81.09 ^{o}C
- Maximum core temperature : 87.46^{o}C
- Minimum core temperature : 67.37 ^{o}C
- Maximum SF_6 temperature : 87.46^{o}C
- Minimum SF_6 temperature : 24.00 ^{o}C

When above values are examined, it can be seen that temperature values are less compare to 30 MVA (GFAN) transformer. The reason for that is the transformer power decreased to its half value and power which was converted to heat decreased to its ¼ value. Although cooling was natural, temperatures did not increase a lot. Thus, natural cooling is proper at this loading level.

4.4. 33.75 MVA (GFAN) Power Transformer

In this chapter, transformer was examined at overloading condition. Transformers work with 10% more (approximately) of their power under extreme conditions for a short period of time.

If the transformer loaded at 33.75 MVA, again the core loss (and so the q^{o}_{core}) will not change, but the copper loss (and so the $q^{o}_{windings}$) will change. By using the formulas 2.2 and 2.3;

$$q_{windings} = (33.75/30)^2 \times 148000 = 37000 \text{ W}$$

$$q^{o}_{windings} = 187.312,5 \; / \; 11,97 = 15648.50 \text{ W/m}^3$$

The heat transfer coefficient of the SF_6 is given 55 W/(m^2 ^oC) for 15 MVA (GNAN) loaded transformer and the 25 W/(m^2 ^oC) for the air by the designers. [1]

With using above parameters the temperature distribution solution is obtained as below;

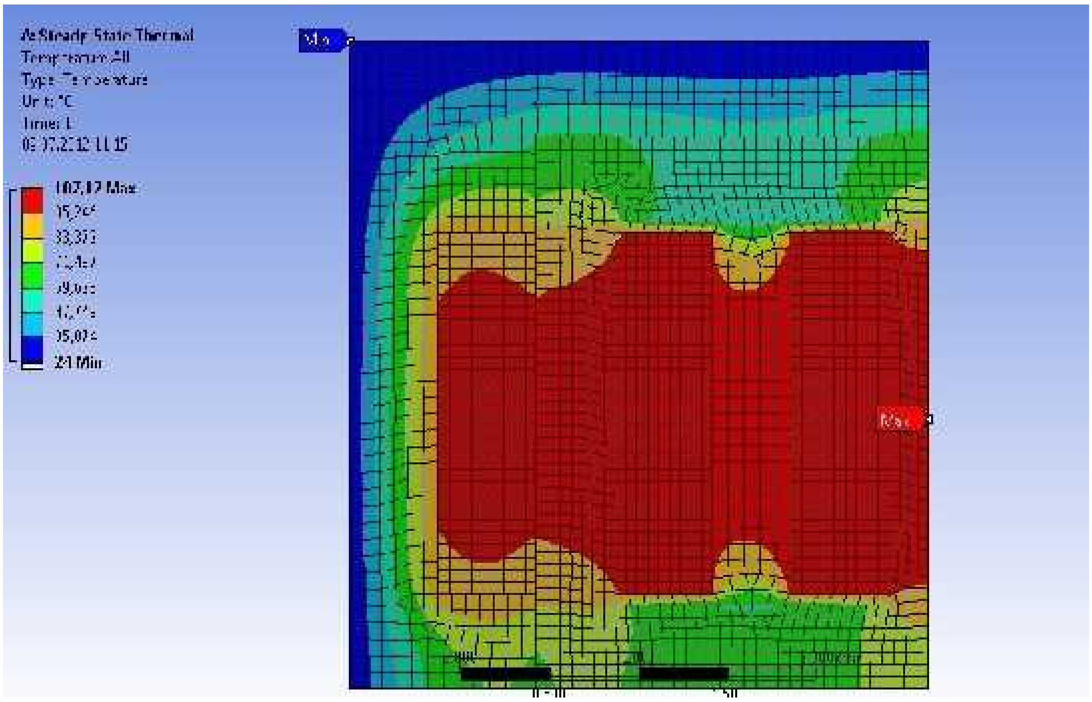


Figure 4.8: 33.75 MVA GFAN Temperature Distribution

As it seen in the figure above;

- Maximum winding temperature : 106.9 ^{o}C
- Minimum winding temperature : 90.02 ^{o}C
- Maximum core temperature : 107.12^{o}C
- Minimum core temperature : 49.53^{o}C
- Maximum SF_6 temperature : 104.51^{o}C
- Minimum SF_6 temperature : 24.00 ^{o}C

As it can be seen in the Figure 4.8 above, there are no major changes at the temperature distributions. However, there is 15 degrees increase on temperature values. The temperature distribution of 15/30/33.75 MVA transformers has been observed and temperature increase on windings is found as shown below;

Transformer Loading	**Maximum Temperature of the Windings**
15 MVA (GNAN)	88.18 ^{o}C
30 MVA (GFAN)	92.86 ^{o}C
33.75 (GFAN)	106.9 ^{o}C

Table 4.1.: Maximum Windings Temperatures

Temperature of a transformer under overloading conditions at this level will let transformer components to be overheated and cause a decrease at transformer's lifetime. One of the most critical issue which effects the transformer's lifetime is the durability of the insulations on windings. The lifetime of the insulation has direct effect to transformer lifetime. The dielectric materials on windings would lose its properties because of heat and as a result transformer's life time decreases. Therefore, additional cooling precautions are taken at overloading condition. Transformers are used at this level when it is necessary. However, it is found that temperature does not go up to higher values at 15 MVA loading condition. Hence, natural cooling would be enough to cool down the transformer in this case.

4.5. 50(62.5) MVA ONAN (ONAF) Power Transformer

Up to now, only “15/30(33.75) MVA GNAN/GFAN (GFAN)” cooling transformer had been analyzed and worked on. Cooling and insulation are done by SF6 in these transformers. We should also state in here that cooling and insulation with SF6 is not really recommended by Turkish electricity transmission grid as well as others in the world due to environmental factors. Oil-cooled transformers occupy more space than transformers with SF6 cooling. For this reason SF_6 cooling transformers are only recommended to use when restricted spaces are needed. There are few OEM’s manufacturing these types of transformers in the world. Most common applications are usage of dry –type transformers for low power levels and oil-insulated transformers at high power levels. In this section, heat transfer of a 50(62.5) MVA ONAN (ONAF) transformer is analyzed. These types of transformers were purchased by TEİAŞ and are being used in Turkish electricity transmission grid. The insulation and cooling is done by oil in these types of transformers. They are also operated at Oil Natural Air Natural (ONAN) mode at 50 MVA loading and Oil Natural Air Forced (ONAF) mode at 62.5 MVA loading. During purchasing of these transformers from the manufacturer (Balikesir Elektromekanik Sanayi Tesisleri A.Ş.) by TEİAŞ, temperature rise tests were carried out by TEİAŞ authorities. These tests must meet IEC 60076 standards and it is one of the prerequisite conditions for factory acceptance. [13]. Temperature rise tests were done at 62.5 MVA (ONAF) loading and its results are given in Appendix. Additionally, transformer was also analyzed at 62.5 MVA (ONAF) loading in order to compare with tests results.

Picture of the transformer is as in Figure 4.9 and name plate of the transformer is shown in Table 4.2 .

The losses of the transformer are measured at the test report. [Appendix] From the reports;

No Load Loss	=	29412 W				
q^o_{core}	=	29412 W	/	4.5 m^3	=	6536 W/m^3
Load Loss	=	244600 W				
$q^o_{windings}$	=	(244600-29412) W	/	3.6 m^3	=	59774 W/m^3

Figure 4.9: 50 (62.5) MVA Power Transformer

Manufacturer	BEST A.Ş.
Phase	Three
Capacity	50(62.5) MVA
Cooling Type	ONAN(ONAF)
Primary Voltage **&** **Insulation Level (BIL)**	170 kV (25 taps) 650 kV
Secondary Voltage & **Insulation Level**	36 kV 170 kV
Frequency	50 Hz
Dimensions	W 2.3 x L 5.7 x 4 m

Table 4.2: Ratings and features of the 50(62.5) MVA transformer

The detailed dimensions are given by the manufacturer. By using these values, the geometry and mesh of the model is obtained like this;

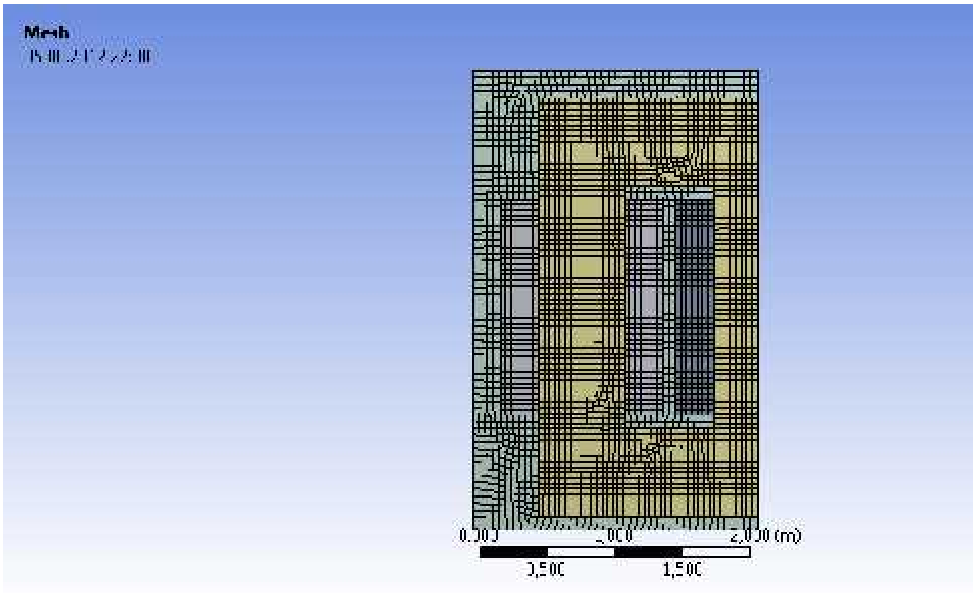


Figure 4.10: Geometry and Mesh of the 50 (62.5) MVA Power Transformer

The designed mesh was developed by 72451 various elements which are in various shapes (triangles, squares etc) and 317006 nodes which creates these elements. Thermal characteristics of transformer components are;

Core Material: Iron

Thermal Conductivity of the Iron: 50 W/ (m ^{o}C)

Windings: Copper

Thermal Conductivity of the Copper: 395 W/(m ^{o}C)

Insulation: Oil

Thermal Conductivity of the oil is tabulated as below. [12]

T (°C)	k (W/(m °C)
-15	0.1341
-5	0.1333
5	0.1326
15	0.1318
25	0.1310
35	0.1303
45	0.1295
55	0.1287
65	0.1280
75	0.1272
85	0.1264
100	0.1253

Table 4.3: Thermal conductivity of Transformer Oil

Heat transfer coefficient is taken for the transformer oil 155 W/ (m^2 °C) and for the air 35 W/ (m^2 °C). The initial temperature of the system is 27 °C. By using these values the temperature distribution solution is evaluated as below;

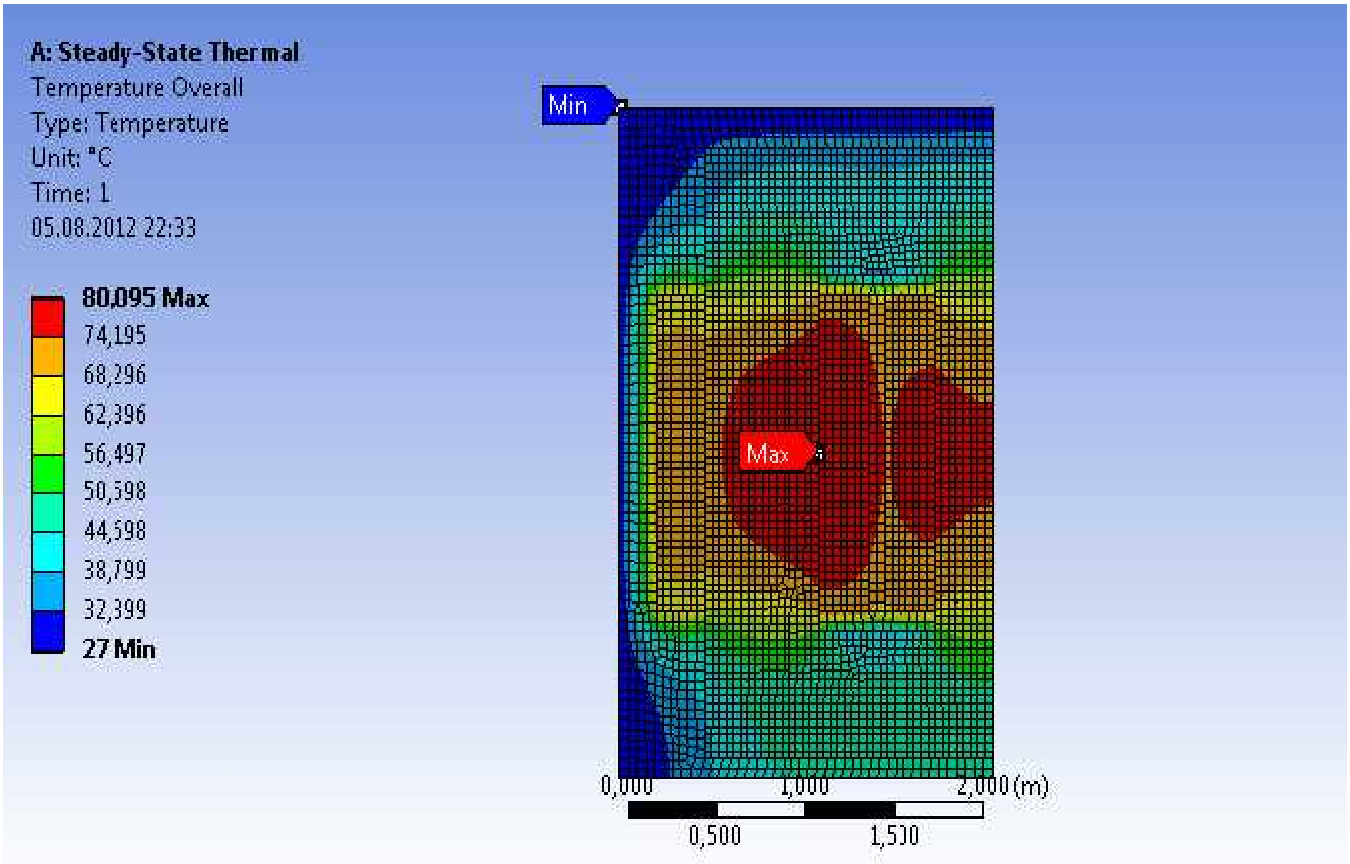


Figure 4.11: 62.5 MVA ONAF Transformer Temperature Distributions

As it can be seen in Figure 4.10;

- Maximum winding temperature : 80.09 ^{o}C
- Minimum winding temperature : 59.99 ^{o}C
- Maximum core temperature : 80.09 ^{o}C
- Minimum core temperature : 30.97 ^{o}C
- Maximum SF_6 temperature : 77.44 ^{o}C
- Minimum SF_6 temperature : 27.00 ^{o}C

These results are similar to the test results and convenient for the IEC 60076. [13] This can be seen in below table.

Temperature Rise Of The Component	**Factory Acceptance Test Results (^{o}C)**	**The IEC Standard Identification (^{o}C)**	**Heat Transfer Analysis Results (^{o}C)**
Windings	56.70	≤60	53.09
Oil	45.10	≤55	50.44
Core	-	≤75	53.09

Table 4.4: Comparison of the Results

The result of overheating in a transformer is decrease lifetime of its components. Especially lifetime of the insulation material on windings is affected by overheating. Below graphic was taken from IEEE Guide for Loading Mineral-Oil-Immersed Transformers document which is published by The Institute of Electrical and Electronics Engineers. This graphic explains the lifetime of transformers. [14].

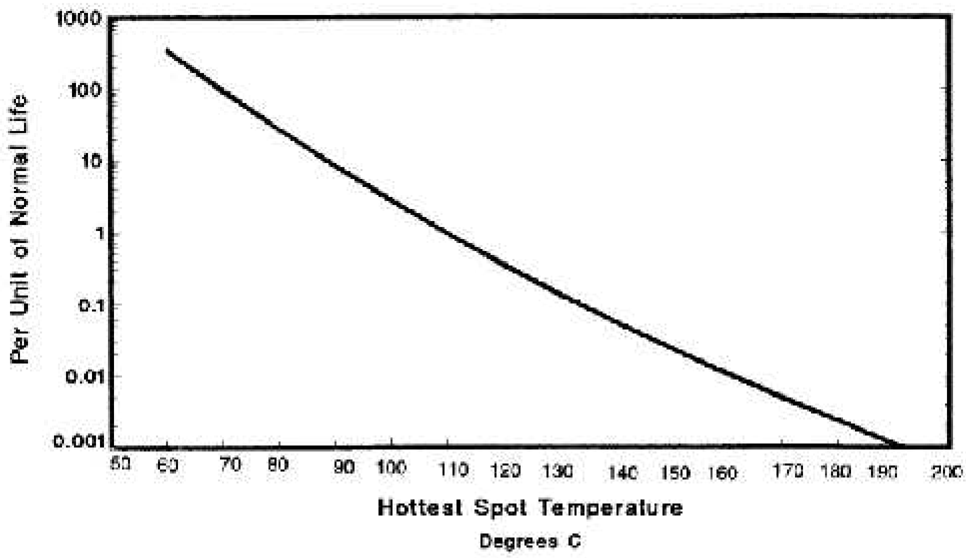


Figure 4.12: Transformer life versus temperature curve (from IEEE Guide for Loading Mineral-Oil-Immersed Transformers)

In the above graphic, hottest spot temperature means maximum windings' temperature. According to this graphic, more winding temperature means less lifetime of a transformer. Therefore, additional cooling systems were added to the system at high loadings in order to cool down the temperature of transformer components. With this way, extending the lifetime of a transformer would be possible. This would also decrease wear out duration of the components. Moreover, transformers are only put in operation at high loadings during emergency situations. For instance, the loading of the transformer analyzed in this study is 50 MVA (ONAN) under normal conditions but our analysis was performed under 62.5 MVA (ONAF) loading in order to obtain the maximum temperature values. Although, tests were done under overloading conditions, it is not recommended to operate the transformer at this level.

CHAPTER 5

CONCLUSIONS

Since large power transformers are one of the most valuable assets in electrical power networks, it is suitable to pay higher attention to these operating resources. An outage impacts the stability of the network and the associated financial penalties for the power utilities can be increased.

During the conversion of electrical energy in a transformer, some losses occur. These losses are mainly come from copper and iron. The losses from iron and copper turns into heat and this heat increases the temperature of the transformer components. Especially, temperature increase of the insulation material on windings may lead overheating of the components. This would decrease the life time of the transformer and even put the transformer out of service. In order not to encounter such incidents like this, temperature distribution should have been determined and all precautions should be taken. In this study, temperature distribution in power transformers and temperatures of the components were tried to be determined.

The steps that need to be taken while using Finite Elements during analyses of the heat distribution in a transformer were stated in Chapter 2. Theoretical information about these steps was also given in Chapter 2.

Heat will flow towards the area of lower temperature. Thus, heat flows from "high temperature" to "low temperature". The generated heat in the core and windings of the transformer is transferred to air by insulation material such as SF6 and oil. During this transition following boundaries are observed.

1- Conduction Boundary:
    - Between windings and core
2- Convection Boundary:
    - Between SF_6 and windings,
    - Between SF_6 and core,
    - Between SF_6 and inside surface of the tank,

- Between air and tank

3- <u>Radiation Boundary:</u>

- Between windings, core and inside surface of the tank.

Heat conduction, convection and radiation formulas are used while obtaining results from these boundaries. These formulas are differential equations and solving them with analytically is not so easy. Therefore, one of the numerical analysis called "Finite Elements Method" was used in the thesis. In this method, the body which was examined had been broken into smaller pieces which are called elements in order to reach the approximate result. The software called "ANSYS Version 13" which is developed by ANSYS.Inc was also used as a tool during the preparation of this study with "Finite Elements Method".

In Chapter 3, 15/30/33.75 MVA (GNAN/GFAN/GFAN) SF_6 insulated-cooled transformer was analyzed in 3 dimensions. The results were compared with the values obtained by designers [1] and the values obtained in previous studies. [2], [3] (Same type of transformer was analyzed in previous studies.)

First, temperature distribution of the transformer at 30 MVA was solved. The temperature difference at windings in our study was found (92.06 ^{o}C). Comparison of the winding temperatures between our study and designers was found 8 ^{o}C. The reason for this can be explained as follows; Designers used fiber sensors during measurement and these sensors were located at the top and outside of the low winding. Therefore, measured temperature actually is the temperature of the winding at that point. As it can be presumed, maximum temperature would not be occurred at that point. In other words, measured value is not the maximum winding temperature. However, winding temperature value found with ANSYS is between 78.32 ^{o}C ~92.06 ^{o}C. This shows us that same temperature value (obtained by designers) can be reached at another similar point on windings where measurement had been done. As a matter of fact, if probe was located at another point similar to the place where designers used, the temperature values would have been found 82 ^{o}C~83^{o}C. These values are almost same with designers' outputs.

In addition, transformer components' exact dimensions, raw materials of them and thermal properties of these raw materials were not known. Therefore, drawings were made with the values from previous study [2] and thermal properties of generally accepted materials were used during temperature measurements. All of these factors might be the reason for obtaining different temperature values.

Convection, conduction and radiation boundaries were taken into consideration during the analyses. Radiation boundary is effective for the materials whose emissivity values are close to 1. The affect of radiation boundary (for these materials) to the heat distribution in a transformer was also analyzed. In order to make an evaluation, two different modeling (one with considering radiation boundary and the other one without considering radiation boundary) was performed. A comparison between two modeling was made as well. The difference between two modeling was obtained in 0.54~1.61^{o}C range. Therefore, radiation boundary was neglected at other analyses in order to let software to analyze the data easily and quickly.

In Chapter 3, bottom of the transformer assumed to be insulated as it was assumed in previous studies. In order to see the insulation affect to the accuracy of modeling, transformer without insulated bottom was analyzed in section.4.1. In this case, convection boundary was considered at the bottom of the transformer. The results with and without insulated bottom were compared. It is observed that temperatures decreased 0,5~1^{o}C due to additional cooling surface from $SF_{6.}$ Thus, this assumption does not have negative effect to the accuracy of the results.

In the studies [2] and [3] which are references to this study, all analyses were done in 2 dimensions. However, analyses during this study were mainly done in 3 dimensions. In order see the contribution of 3 dimensional analyses to the correctness of the results, 2 dimensional analyses were done in section 4.2. The outputs were compared and it was seen that 3 dimensional modeling gives more accurate results. Therefore, analyses were done in 3 dimensions.

The transformer analyzed in this study has usability at 3 different loading levels. These are 15 MVA, 30 MVA and 33.75 MVA power levels. Although transformer is cooled by GNAN-Gas Natural Air Natural at 15 MVA, GFAN-Gas Forced Air Forced is used at 30 and 33.75 MVA levels. In order to find the reason behind this situation, the transformer whose data are given at 30 MVA was analyzed in 3 dimensions at 15MVA and 33.75 MVA loading levels. These analyses can be found in Section 4.3 and 4.4. During these analyses, heat distribution, maximum and minimum temperature values were determined. During the comparison of the values at 3 different loading levels, it is observed that transformer does not get too hot at 15 MVA loading. On the other hand, same transformer gets overheated at 30 and 33.75 MVA loading levels. This result show, GNAN cooling is enough only at 15 MVA loading level and GFAN cooling is required at 30 and 33.75 loading levels.

Due to environmental and economical factors, gas cooled insulated transformers are not widely used by TEİAŞ. (The governor of Turkish electricity grid) Instead of this, oil insulated transformers are preferred. In section 4.5, 50 (62.5) MVA ONAN (ONAF) transformer which is purchased and being used by TEİAŞ was analyzed at 62.5 MVA loading level. The cooling at 62.5 MVA loading level is done by ONAF-Oil Natural and Air Forced. Here, oil circulation was done naturally but air circulation is performed by force. When transformers structure was taken into consideration, it can be observed that forced air circulation has an effect to the oil circulation in radiators. This affect actually changes the convection value of the oil. In other words, the main factor during the cool down of the transformer is oil circulation. This situation is observed with using different convection values for air and oil during modeling. The obtained values for air and oil are within the convection coefficient range shown in Table 1.1. The temperature distribution, maximum and minimum temperature values obtained via this way were compared with the results which were obtained during factory acceptance tests. Then approximate outcomes were determined.

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APPENDIX

FACTORY ACCEPTANCE TEST REPORTS OF 50(62.5) MVA POWER TRANSFORMER

BEST

BALIKESİR ELEKTROMEKANİK
SANAYİ TESİSLERİ A.Ş.

TRANSFORMATÖR
TEST RAPORU

SERİ NO.	: 56217
TİPİ	: YTR 62500 / 170 K
ANMA GÜCÜ	: 50000 / 62500 kVA
ANMA GERİLİMİ	: 154 / 33,6 kV
MÜŞTERİ	:

3 Fazlı Yağlı Tip Transformatör

Sıcaklık Artış Deneyi — **Deney Raporu**

Müşteri :					
Seri No.	56217	Standart :	IEC 60076-2	Sayfa No.:	30/45
Anma Gücü(kVA) :	50000 / 62500	Bağlantı Gr. :	YNyn 0	Rapor No :	
Anma Gerilimi (kV) :	154 / 33,6	Soğutma Tipi :	ONAN / ONAF	Rev. :	

Beslenen sargı : 1U - 1V - 1W   Kısa Devre : 2u - 2v - 2w

Sargı:		YG	AG		
Anma Gücü :	(kVA)	62500	62500		
Deneydeki Kademe: 1 Akım	(A)	275,664	1073,94		
Anma Gerilimi :	(kV)	130,900	33,6		
Yükteki Kayıplar: 75 °C 'de	(kW)	244,600			
Boştaki Kayıplar:	(kW)	29,412			
Toplam Kayıplar:	(kW)	274,012			

Zaman (ss:dd)	Deney Gerilimi (V)	Deney Akımı (A)	Deney Kaybı (kW)	Sıcaklık Değerleri: Ortam (°C) θ_{a1}	θ_{a2}	θ_{a3}	θ_{a4}	Üst Yağ (°C) θ_{t1}	YG tarafı (°C) θ_{sg}	θ_{sc}	AG tarafı (°C) θ_{sg}	θ_{sc}	Ortalama (°C) θ_a	θ_t	$\Delta\theta$ K
20:00	16,223	300,858	273,075	23,8	23,9	24,1	24,0	26,5	26,5	24,2	26,5	24,3	24,0	26,5	2,6
21:00	15,396	285,290	272,080	25,0	25,8	25,8	25,1	46,9	40,9	28,9	44,7	28,6	25,4	46,9	21,5
22:00	15,278	283,101	274,863	26,3	26,8	27,2	26,8	59,2	52,2	35,6	55,7	33,8	26,8	59,2	32,4
23:00	15,204	281,414	273,756	27,0	27,5	28,3	27,5	66,0	58,9	40,3	62,2	37,5	27,6	66,0	38,4
00:00	15,199	281,439	276,132	27,3	27,7	28,3	27,8	69,3	61,7	41,7	65,1	39,0	27,8	69,3	41,5
01:00	15,078	279,093	272,847	27,3	27,7	28,1	27,8	70,8	63,2	42,8	66,6	39,9	27,7	70,8	43,1
02:00	15,127	280,314	275,915	27,2	27,7	28,1	27,8	71,9	64,1	43,4	67,5	40,4	27,7	71,9	44,2
03:00	15,166	280,815	277,132	27,2	27,7	28,0	27,7	72,5	64,8	44,2	68,2	41,0	27,7	72,5	44,9
04:00	15,175	281,285	277,886	27,1	27,5	27,9	27,7	73,1	65,3	44,4	68,7	41,1	27,6	73,1	45,6
05:00	15,177	281,036	277,204	26,9	27,5	27,7	27,6	73,1	65,2	44,8	68,9	41,3	27,4	73,1	45,7
06:00	14,922	276,206	267,792	26,9	27,5	27,7	27,6	72,8	64,9	44,1	68,6	41,1	27,4	72,8	45,4
07:00	14,832	274,369	263,761	26,4	27,0	27,2	27,2	72,4	64,5	43,7	68,2	40,7	27,0	72,4	45,5
08:00	14,875	275,604	265,850	26,2	26,6	27,0	26,8	72,4	64,3	44,5	67,5	40,7	26,7	72,4	45,8
09:00	14,895	276,097	267,046	26,7	26,9	27,3	27,1	72,5	64,5	44,8	67,6	41,5	27,0	72,5	45,5

Not:

θ_{a1}, θ_{a2}, θ_{a3}, θ_{a4} : Çevre Sıcaklıkları
θ_{t1} : Üst Yağ Sıcaklığı
θ_{sg} : Soğutucu Giriş Sıcaklıkları
θ_{sc} : Soğutucu Çıkış Sıcaklıkları

YG sargısı soğuk haldeki direnç değeri:
R = 0,9996 Ω (1U - 1V)
AG sargısı soğuk haldeki direnç değeri:
r = 46,9800 mΩ (2u - 2v)
t= 25 °C

Deneyde kullanılan ölçme cihazları : Güç Analizörü NORMA D6000, Seri Nr.: A460330713
Direnç ölçme cihazı , Seri Nr.: Raytech 262-155
Sıcaklık ölçme cihazı FLUKE, Seri Nr.: 9068013

Deneyi yapan:	Kontrol eden:	Müşteri veya temsilcisi :
Tarih: 22-23.05.2012	Tarih: 22-23.05.2012	Tarih: 22-23.05.2012

BEST

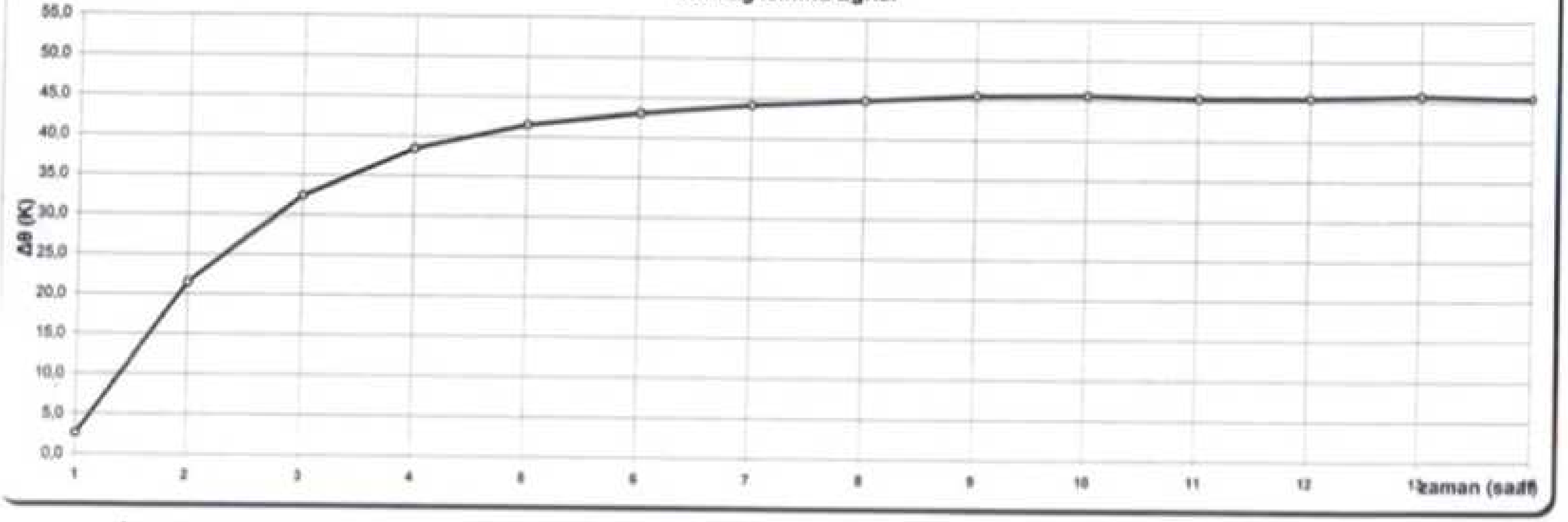
3 Fazlı Yağlı Tip Transformatör

Sıcaklık Artış Deneyi

Deney Raporu

Müşteri :					
eri No.:	56217	Standart :	IEC 60076-2	Sayfa No.:	31/45
nma Gücü(kVA) :	50000 / 62500	Bağlantı Gr. :	YNyn 0	Rapor No :	
nma Gerilimi (kV) :	154 / 33,6	Soğutma Tipi :	ONAN / ONAF	Rev. :	

Üst Yağ Isınma Eğrisi



Ölçülen üst yağ ısınması: 45,6 K   Düzeltme faktörü : (274,012 / 277,204) exp 1 0,9885

Üst Yağ Isınması Δθ : 45,08 K   Garanti edilen : 55 K   Sonuç : Olumlu

eyi yapan:	Kontrol eden:	Müşteri veya temsilcisi :
ih: 22-23.05.2012	Tarih: 22-23.05.2012	Tarih:

BEST

3 Fazlı Yağlı Tip Transformatör

Sıcaklık Artış Deneyi **Deney Raporu**

Üreten :			
Seri No : 56217	Standart : IEC 60076-2	Sayfa No : 32/41	
Anma Gücü(kVA) : 50000 / 62500	Bağlantı Gr : YNyn 0	Rapor No :	
Anma Gerilimi (kV) : 154 / 33,6	Soğutma Tipi : ONAN / ONAF	Rev :	

YG	
R(Ω)	t(dak.)
1,190	01:45
1,192	02:15
1,188	02:45
1,185	03:15
1,182	03:45
1,179	04:15
1,176	04:45
1,173	05:15
1,171	05:45
1,168	06:15
1,156	06:45
1,164	07:15
1,162	07:45

AG	
R(mΩ)	t(dak.)
56,5300	01:45
56,3850	02:15
56,1900	02:45
56,0100	03:15
55,8400	03:45
55,6800	04:15
55,5200	04:45
55,3800	05:15
55,2400	05:45
55,1150	06:15
54,9950	06:45
54,8800	07:15
54,7700	07:45

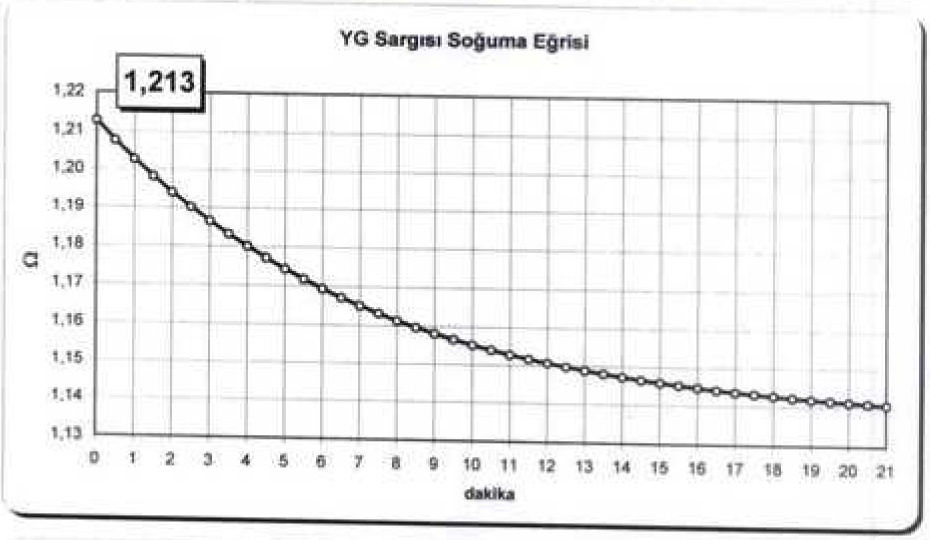
R(mΩ)	t(dak.)

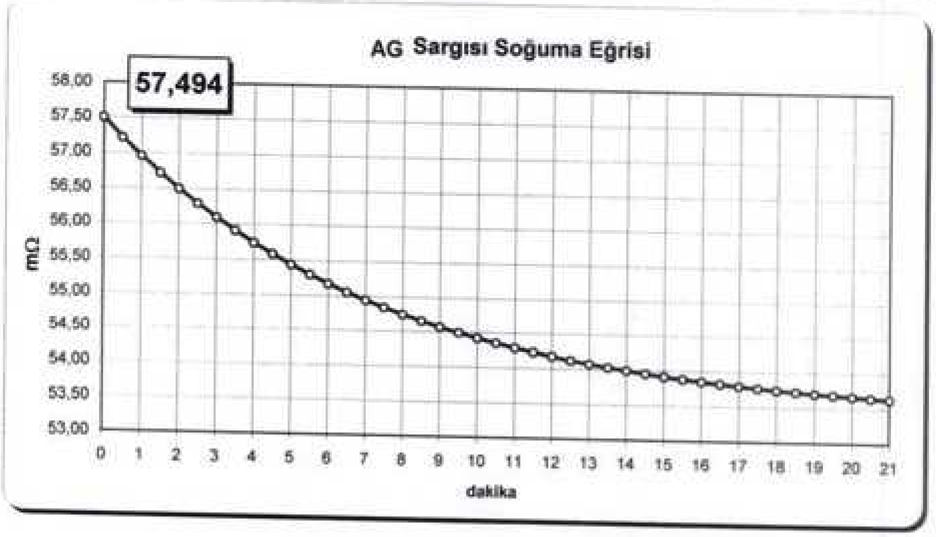
Deneyde kullanılan ölçme cihazları :	Güç Analizörü NORMA D6000, Seri Nr :	A460330713
	Direnç ölçme cihazı , Seri Nr :	Raytech 202-156
	Sıcaklık ölçme cihazı FLUKE, Seri Nr :	9068013
Deneyi yapan :	Kontrol eden :	Müşteri veya temsilcisi :
22-23.08.2012		

3 Fazlı Yağlı Tip Transformatör

Sıcaklık Artış Deneyi **Deney Raporu**

Müşteri :			
Seri No.:	56217	Standart : IEC 60076-2	Sayfa No.: 33/45
Anma Gücü(kVA) :	50000 / 62500	Bağlantı Gr. : YNyn 0	Rapor No : 0
Anma Gerilimi (kV) :	154 / 33,6	Soğutma Tipi : ONAN / ONAF	Rev. : 0





Deneyi yapan:		Kontrol eden:		Müşteri veya temsilcisi :	
arih:	22-23.05.2012	Tarih:	22-23.05.2012	Tarih:	

BEST	3 Fazlı Yağlı Tip Transformatör **Sıcaklık Artış Deneyi**	**Deney Raporu**

Müşteri :

Seri No.: 56217	Standart : IEC 60076-2	Sayfa No.: 34/45
Anma Gücü(kVA) : 50000 / 62500	Bağlantı Gr. : YNyn 0	Rapor No :
Anma Gerilimi (kV) : 154 / 33,6	Soğutma Tipi : ONAN / ONAF	Rev. :

Sıcaklıklar :

A Deney başlangıcında sargı sıcaklığı : 26,5 - [(26,5 - 24,2) + (26,5 - 24,3)] / 4 = 25,4 °C

B Deneyin son çeyreğindeki ortam sıcaklığı : 27,0 °C

C Den. 1. adımında ort. yağ sıcaklık Yükselmesi : 73,1 - 27,0 - [(65,2 - 44,8) + (68,9 - 41,3)] / 4 = 34,1 K

YG Sargısının Sıcaklığı :

D1 Deneyin 2. kısmında ort. yağ sıcaklığı : 72,5 - [(64,5 - 44,8) + (67,6 - 41,5)] / 4 = 61,05 °C

E1 Deney sonunda sargı sıcaklığı : T2 : [1,21269 (235,0 + 25,4) / 0,9996] - 235,0 = 80,9 °C

F1 Yağa göre sargı sıcaklık yükselmesi : E1 - D1 : 80,9 - 61,1 = 19,8 K

G1 Ortama göre sargı sıcaklık yükselmesi : F1 + C : 19,8 + 34,1 = $\boxed{53,9 \text{ K}}$

AG Sargısının Sıcaklığı :

D2 Deneyin 2. kısmında ort. yağ sıcaklığı : 72,5 - [(64,5 - 44,8) + (67,6 - 41,5)] / 4 = 61,05 °C

E2 Deney sonunda sargı sıcaklığı : T2 : [57,4935 (235,0 + 25,4) / 46,98] - 235,0 = 83,644 °C

F2 Yağa göre sargı sıcaklık yükselmesi : E2 - D2 : 83,6 - 61,1 = 22,6 K

G2 Ortama göre sargı sıcaklık yükselmesi : F2 + C : 22,6 + 34,1 = $\boxed{56,7 \text{ K}}$

D3

E3

F3

33

Deney Sonuçları			Ölçülen		Garanti		Sonuç
	Yağ Sıcaklık Yükselmesi		45,1	K	55	K	Olumlu
	Sargı Sıcaklık Yükselmesi	YG	53,9	K	60	K	Olumlu
		AG	56,7	K	60	K	Olumlu

Deneyi yapan:	Kontrol eden:	Müşteri veya temsilcisi :
Tarih: 22-23.05.2012	Tarih: 22-23.05.2012	Tarih: [illegible]