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# Trafodaki Laminasyon Kalınlığının Sıcaklık ve Verimlilik Üzerine Etkisinin İncelenmesi

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**Anahtar Kelimeler**
Trafo, Enerji verimliliği, Kayıplar, Termal analiz, Binalarda Elektrik verimi

**Öne Çıkanlar**

- Laminasyon kalınlıkları sonucu elde edilen demir kayıplarında %20,5 oranında bir değişim elde edilmiştir.
- Laminasyon kalınlıkları sonucu ortaya çıkan demir kayıplarından dolayı nüve sıcaklığından %6,8 lik bir değişim meydana gelmiştir.

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**Amaç**

2050 yılına kadar Avrupa'daki tüm binaların sıfır enerjili binalar olması hedefleniyor. Sıfır enerjili binalarda fosil 2050 yılına kadar Avrupa'daki tüm binaların sıfır enerjili binalar olması hedefleniyor. Sıfır enerjili binalarda fosil yakıt kullanımı ya ortadan kaldırılacak ya da minimuma indirilecek. Böylece ağırlıklı olarak yapı sektöründe kullanılan enerji elektrik olacak. Günümüzde birçok bilimsel çalışma, yapı bileşenlerinin enerji tüketimine odaklanmaktadır. Ancak transformatörler, elektrik sistemlerinde verimlilik açısından incelenmesi gereken en önemli bileşenlerden biridir. Trafo kayıplarının yüksek olması durumunda enerji sistemleri ne kadar verimli olursa olsun binaların toplam enerji yükünde ciddi kayıplara neden olur.

Bu nedenle bu çalışmada, 20 evden oluşan bir site için kullanılabilecek bir transformatörün çekirdek malzemesine bağlı olarak transformatör çekirdeğinde kullanılan iki farklı malzeme kalınlığı için 100 kVA'lık kuru tip transformatör simülasyonu gerçekleştirilerek çekirdek kayıpları ve sıcaklıkları karşılaştırılması amaçlanmıştır. Simülasyonlar sonucunda iki laminasyon arasında çekirdek kaybında %20,5 ve sıcaklıkta %6,8 fark elde edilmiştir.

**Materyal ve Yöntem**

Bu makalede, elektrostatik ve manyetik problemler, ANSYS yazılımının sonlu elemanlar yöntemi kullanılarak çözülmüştür. Çalışmada, 3 fazlı 100 kVA kuru tip bir transformatörün manyetik akı yoğunluğunu ve çekirdek kaybını elde etmek için zamana bağlı elektromanyetik analizler yapılmıştır. Aynı analizler, kullanılan malzemenin manyetik özelliklerindeki farklılıkları karşılaştırmak için M4 ve M5 adlı farklı kalınlıklardaki SiFe malzemeleri için tekrarlanmıştır.

Son olarak zamana bağlı elektromanyetik analizler sonucunda elde edilen kayıp değerleri, transformatörün termal analizi için gerekli ısı kaynağı olarak kullanılmıştır. Elektromanyetik analizler sonrasında elde edilen kayıp değerleri kullanılarak Hesaplamalı Akışkanlar Dinamiği (CFD) analizleri gerçekleştirilmiştir. Bu analizlerde ortam sıcaklığı 22 °C olarak ayarlanmış ve ısı kaynağı olarak elde edilen kayıp değerleri kullanılmıştır. M4 ve M5 için sıcaklık analizleri yapılmıştır.

**Tartışma ve Sonuç**

Bu çalışmada transformatör malzemesinin laminasyon kalınlığının bile transformatörün kayıplarını ve ısınmasını doğrudan etkilediği gösterilmiştir. 100 kVA trafo kullanılarak yapılan analizlerde M5 malzeme kullanılarak yapılanlarda 399W ve 95.894 °C, M4 malzeme kullanılarak yapılanlarda ise 331W ve 89.789 °C olarak elde edilmiştir. Burada görüldüğü gibi, çekirdek malzemesinin laminasyon kalınlığındaki 0.03 mm'lik bir değişiklik, çekirdek kaybında %20,5'lik bir değişime ve sıcaklıkta %6,8'lik bir değişime neden olmuştur.

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# Investigation of The Effect of Lamination Thickness on Temperature and Efficiency in Transformer

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**Highlights:**

- A change of 20.5% was obtained in the iron losses obtained as a result of lamination thicknesses.
- A 6.8% change occurred from the core temperature due to the iron losses resulting from the lamination thicknesses.

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**Abstract**
By 2050, all buildings in Europe are targeted to be zero-energy buildings. The use of fossil fuels in zero-energy buildings will be reduced as much as possible. Thus, the mainly used energy in the building sector will be electrical. It is appropriate to use dry-type transformers that do not have the risk of fire and explosion in zero-energy buildings. This eliminates the losses that will occur during transmission and enables a more efficient system to be used. In this study, transformer losses and their effects on efficiency and temperature change were investigated. For this, a 100 kVA dry-type transformer was simulated for two different material thicknesses used in the core, and core losses and temperatures were compared. As a result of the simulations, a difference of 20.5% in core loss and 6.8% in temperature was obtained between the two laminations.

**Keywords:** Transformer, losses, energy efficiency, thermal analysis

## 1 Introduction

Most of the total energy in the world is consumed in the industry, building, and transportation sectors. A large part of the energy consumed in buildings is used for heating, cooling, and lighting purposes. Electric energy is mainly used for lighting and cooling buildings. For heating, both fossil fuels and electrical energy are used together. Since more than 30% of the total consumed energy is used in buildings, zero builds can greatly contribute to increasing energy efficiency, minimizing the use of fossil fuels, and more efficient and clean energy use, as it focuses on renewable energy sources at the same time. Therefore, the use of electrical energy in buildings is increasing day by day.

It is aimed that all buildings in Europe will be zero energy buildings by 2050. In zero-energy buildings, the use of fossil fuels will either be eliminated or reduced to a minimum. Thus, the energy used predominantly in the building sector will be electrical. Today, many scientific studies focus on the energy consumption of building components. However, transformers are one of the most important components in electrical systems that should be examined in terms of efficiency. In case of high transformer losses, no matter how efficient the energy systems are, it causes serious losses in the total energy load of the buildings. Therefore, in this paper, it is aimed to examine the transformer losses depending on the core material of a transformer that can be used for a site consisting of 20 houses and to compare the effects of these losses on the transformer temperature.

Transformers are electrical machines that do not cause any power change, operate efficiently, and have no moving parts. They are produced with at least two windings, single phase and single core [1]. Transformers work according to the magnetic field principle and induce a voltage in the secondary side. As a result of magnetic inductions between primary and secondary windings, current and voltage can be increased or decreased [2], [3]. Metals used in the production of transformers undergo deformations due to the formation of magnetic fluxes and currents in the windings during the operating period [4], [5]. As a result of electrical and magnetic processes, harmonic disturbances in electrical energy of AC character in metal materials and environmental factors heat transformers [6], [7]. This warming effect causes distortions in the magnetic paths in the transformer windings and cores, in this case, the conversion ratio of the transformer decreases, and the efficiency decreases [8]. All these losses and heatings are the parameters that directly affect the efficiency and lifetime of the transformer. Harmonics affect the flux density distribution and saturation point, so the rate of losses also changes [11]–[12]. The other point is the types of excitation voltage: non-sinusoidal or PWM voltage excitation. In [13]–[14], the effects of temperature rise and cooling systems were investigated.

Loss calculations are used as input for thermal analysis in simulations. Another perspective to increase efficiency is to use different core models [15]-[16].

In addition, recent advances and developments in new magnetic materials once again highlight core losses. In [17], the Finite Element Method (FEM) was used to compare 2 different CRGO core materials under no-load conditions and experimental results. In [18], various thicknesses of CRGO material were investigated for loss in watts per kg. In addition to 3 different electrical sheets of steel, amorphous cores were used, and their efficiency was compared [19]. In [20], nanocrystalline and SiFe cores were analyzed, and their flux density and varying losses were compared. Magnetic properties and characteristics are very influential parameters, [21] shows the relationship between different GOES core magnetic properties and the no-load condition of transformers. [22] also evaluated the core loss performance of nanocrystalline, amorphous, and GO materials.

The literature review has shown that analysis and experimental research are done to reduce core loss or obtain an accurate calculation. In addition, the efficiency and thermal behavior of the transformer are important parameters in determining its performance and life in the area where it is used. Especially in zero builds, they are safe to use inside the building or site, as there is no risk of explosion, unlike oily transformers. This increases the use of such transformers. Therefore, it is important to analyze their yields and temperatures.

In this study, the magnetic flux density distribution and core loss of a 100 kVA 15/0.4 kV 3-phase dry type transformer that can be used for a site with 20 zero builds are simulated according to two different material thicknesses. Then, the effects of different core materials grades on efficiency and temperature were compared. The main purpose and contribution of this study can be summarized as follows:

- Giving detailed information about losses, efficiency and temperature changes of transformers,

- Showing the importance of the thickness variation of the material in design and efficiency,

- Analyzing the magnetic and thermal behavior at the same time and comparing their effects on each other.

The rest of the paper is organized as follows. The materials and methods used for analysis are explained in Section 2. Effects of thermal losses on transformer efficiency and results are given in Section 3. The results and discussion based on the simulation and thermal analyses are given in Section 4. Finally, the conclusion is summarised in Section 5.

## 2 Material And Methods

### 2.1 Losses in Transformers

Considering the losses in transformers is very important for for a number of reasons. The first reason is that losses determine the efficiency of the transformer. Secondly, losses in the transformer are released as heat, which helps to determine the nominal power output at which the transformer will operate healthily. In other cases, the insulation damaged by thermal stress affects the service life of the transformer. It is important to know the losses to accurately detect voltage drops or current components due to losses [23]- [24]. Transformer losses are divided into two and these are copper losses and no-load losses.

#### 2.1.1 No-Load Loss

It is also known as iron losses or core losses. These losses occur in the core of the transformer when the transformer is energized when the secondary winding is left open circuit. It consists of the sum of hysteresis and eddy current losses.

The hysteresis loss can be expressed as; magnetic flux generated when an alternating current-carrying coil is wound around a ferromagnetic core. This magnetic flux causes the core to be magnetized in one direction and then in another. In this process, it is seen that the magnetic flux density (B) lags behind the magnetization force (H). While alternating current flows in one direction in a loop and for a given time interval, energy flows from the grid towards the magnetic core. After that, the energy flows back to the grid. However, the energy flowing from the source to the core is greater than the energy returning from the core to the source. For this reason, a net energy flow from the grid to the magnetic core is observed during the alternating current loop. This energy loss is released as heat in the core. The amount of power that is converted into heat due to the hysteresis effect is called hysteresis loss. The hysteresis loss is proportional to the hysteresis loop. Hysteresis loss accounts for 50 to 80% of iron losses [25].

Eddy current losses occur due to a sudden change in flux density, and the voltage induced in the core produces a circular motion currently. Eddy currents cause the core to heat up, resulting in wasted energy. It accounts for 20% to 50% of operating losses at load [26], [27]. Since the eddy current losses increase in direct proportion to the square of the laminated structure thickness, the laminate thickness is desired to be as little as possible. However, this thickness is limited between 0.30-0.50 mm considering some mechanical reasons.

#### 2.1.2 Copper Losses

Copper losses also referred to as load losses, are the losses caused by the current flowing through the windings due to the winding resistance and are proportional to the square of the current. In general, copper losses occur separately in the primary and secondary windings. The total copper losses are equal to the sum of the losses in the primary and secondary sections.

### 2.2 Finite Element Analyses of Transformers

The finite element analysis (FEA) is a numerical method used in solving linear and non-linear problems most engineering problems involve electromagnetic dissipation, stress analysis, and heat transfer using differential equations. Three-dimensional and two-dimensional finite element analyses used in the analysis of electrical machines enable the behavior of electrical machines such as electric motors and transformers to be designed. Thus, it allows rapid analysis of machines with different geometries and features without the need to create a large number of prototype models. Electrostatic and magnetic problems are solved by using the finite element method of ANSYS software. In this study, time-dependent electromagnetic analysis was carried out to obtain magnetic flux density and core loss of a 3-phase 100 kVA dry-type transformer. The same analysis was repeated for different grades of SiFe materials named M4 and M5 to compare the differences in magnetic properties of the material used. The characteristics of these transformers are shown in Table 1.

**Table 1.** General specifications of 3 phase dry type transformer

| **Specification** | **Value** |
|---|---|
| Power Level | 100 KVA |
| Voltages | 15/0.4 KV |
| Connection Type | Δ/Y |
| Turn Numbers | 3248/50 |
| Core Material | M4/ M5 SiFe |
| Winding Material | Alüminyum |
| Lamination Thickness | 0.27/ 0.3 mm |

The analyses are carried out for two cases: the no-load condition to obtain the core loss and the loaded operating conditions to obtain the winding loss, respectively. 3D modeling was done in Maxwell to realize the network structure in the form of eddy current analysis that connects the transformer body and increases the accuracy of the simulation. As a result of this analysis, the transformer is divided into 387735 tetrahedron elements. Figure 1 shows the mesh structure and the 3D FEM model.

Finally, the loss values obtained as a result of time-dependent electromagnetic analyzes were used as the necessary heat source for the thermal analysis of the transformer. Computational Fluid Dynamics (CFD) analyzes were carried out using the loss values obtained after electromagnetic analyzes. In these analyses, the ambient temperature was set to 22 °C and the loss values obtained as the heat source were used. Two temperature analyzes were also performed for M4 and M5.

### 2.3 Thermal Model of Transformers

Losses in transformers turn into heat, and this heat change is primarily the cause of the temperature increase in its structure and the environment. So there is a heat transfer here. It is known that in thermal analysis solutions, the heat transfer between materials is divided into finite elements by FEA and the heat transfer occurs in three different ways as convection, conduction, and radiation. The characteristics and behavior of materials are different from each other [28].

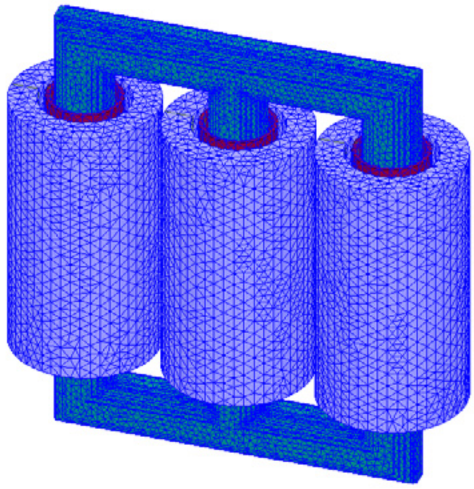

**Figure 1.** Transformer 3D mesh model

As some properties of materials change depending on temperature, electromagnetic fields are also affected by temperature effects. One of the electrical properties that are linearly affected by temperature is electrical resistivity. Therefore, different degrees of heat exchange and transfer occur between the windings, transformer core, and other components [29].

In the heat transfer of dry-type transformers, natural cooling and heat transfer are effective in transferring the heat from the outer surfaces of the transformer to the ambient air. The equation used in 3D thermal modeling can be given by Equation (1) [28].

$$\frac{\partial(pu)}{\partial x} + \frac{\partial(pv)}{\partial y} + \frac{\partial(pw)}{\partial z} = 0 \quad (1)$$

where $u$, $v$, and $w$ are the fluid velocity in the $x$, $y$, and $z$ axes, respectively, and $p$ is the air pressure. This equation can be explained by Equation (2) used in CFD simulation in Fluent software, which depends on the airflow rate [28].

$$\frac{\partial(\rho C_p uT)}{\partial x} + \frac{\partial(\rho C_p vT)}{\partial y} + \frac{\partial(\rho C_p wT)}{\partial z} = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) \quad (2)$$

where $\rho$ is solid and liquid density, $C_p$ is specific heat capacity and $T$ is the temperature in Kelvin.

## 3 Effects Of Thermal Losses On Transformer Efficiency And Results

Every loss on the transformer creates a warming effect on the transformer windings and core. The degree of temperature in these warming events affects transformer usage, life, and efficiency.

The temperature rise is the difference between the temperature of the part in question (usually the average winding rise or the hottest point winding rise) and the ambient temperature. The average winding temperature rise of a transformer is the arithmetic difference between the average winding temperature of the hottest winding and the ambient temperature.

At different power factors, the efficiency of the transformer decreases against load. This event indirectly points to transformer heating. The power factor should be close to 1 in the best conditions for the transformer, but the load increase and the consequent heating losses in the transformer cause the power factor to decrease. In other words, it is understood from the drops in the power factor that the transformer heats and its efficiency decrease during operation.

Since the resistance also changes proportionally with the temperature, copper losses increase with the increase in temperature and decrease in efficiency. Due to the iron losses in the transformer core, the temperature of the sheet pack rises. In addition, with the heating of the windings due to copper losses, the core and the windings have a thermal effect on each other. However, the source of the heating in the transformer and losses are created [30].

As a result, considering all the losses and the loads in the transformer, it is revealed that all losses in the transformer contribute to increasing the temperature.

After the information given throughout the article, it is seen that heating seriously affects transformer efficiency under all conditions. We know that the heating in the transformer increases the losses, but it cannot be said that these losses are significant for every transformer type and size. Such losses and heats are essential for distribution and power transformers used in the field of electricity transmission and distribution in general because these transformers operate at loads of MWs and the operating losses are significant at such high energy values.

**4 Results And Discussion**

In the analyses, a sinusoidal excitation voltage is supplied to the transformer. The values obtained as a result of the analysis are magnetic flux densities, core losses, and maximum temperature values, respectively. The values obtained as a result of the analysis are given in the tables below. The core loss values obtained are shown in Table 2.

**Table 2** Core losses due to materials of different thicknesses

| Material | Core Loss (W) |
|---|---|
| M4 GOES | 331 |
| M5 GOES | 399 |

Since the analyzes are time-dependent and the operating characteristics of the transformers are not linear, the magnetic flux density in the core changes instantaneously. Therefore, the magnetic flux cannot be considered constant in the entire core. For this reason, the maximum magnetic flux density was taken based on the middle leg of the core and the values are shown in Table 3.

**Table 3** Maximum magnetic flux density

| Material | Magnetic Flux Density (T) |
|---|---|
| M4 GOES | 1.62 T |
| M5 GOES | 1.64 T |

After the magnetic analysis of the transformer was completed and the loss values were obtained, thermal analysis was carried out by using these loss values as a heat source for the core and windings in the analysis program used. The maximum temperature values obtained as a result of this analysis are given in Table 4.

**Table 4** Temperature of transformer surface

| Material | Temperature (°C) |
|---|---|
| M4 GOES | 89.789 |
| M5 GOES | 95.894 |

The temperature distribution in the transformer at a steady state is similar to the magnetic flux density distribution. The reason for this is that the losses on the core are directly dependent on the operating frequency and magnetic flux density. In this

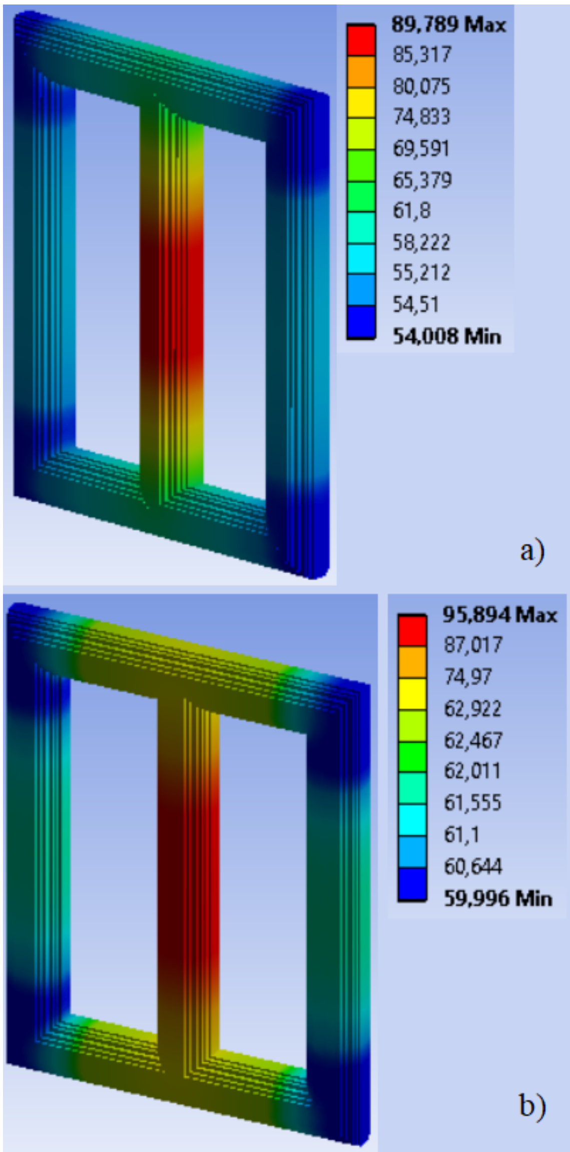


**Figure 2** Temperature differences in a) M4 b) M5

study, the frequency is constant, so the magnetic flux density is the factor that also affects the loss and temperature change. As stated in detail in other sections, transformer losses are the factor that directly affects heating. These temperature increases affect the lifespan and efficiency of the transformer. For this reason, loss and temperature analyzes are taken into consideration before the design is made. Figure 2 shows the temperature distributions occurring on the core. As can be seen from the figures, the hottest point at steady state is the middle leg. When the ambient temperature is 22 °C, the M5 core was obtained as 95.894 °C and M4 as 89.789 °C.

**5 Conclusions**

The electrical power of a house is considered to be 5 kW on average. The effect of the material types examined in this paper on the efficiency of a transformer that can be used for a 20-household site has been investigated. Within the scope of the study, it has been determined that transformer losses can increase by 20% even in the analysis of the same material with different thicknesses of the core. This change is significant for zero-energy buildings. Because it also affects the lifespan and cost of the transformers used along with the efficiency in zero builds. As can be seen, no matter how much effort is made to minimize the total energy of the building, if a suitable transformer is not designed, there can be significant electrical losses. Considering the effect of electrical energy on carbon footprint, it is recommended to investigate transformer losses in zero-energy buildings in more detail. In addition, it is always noted that the change in losses does not take the temperature outside the operating conditions.

In addition, another important point is that dry-type transformers are not explosive, so they are used inside the building. Therefore, in this study, after the factors affecting the thermal properties of the transformer were explained in detail, it was shown that even the lamination thickness in the material used directly affects the losses and heating of the transformer. In the analyzes made using a 100 kVA transformer, 399W and 95.894 °C were obtained for those made using M5 material, and 331W and 89.789 °C for those made using M4 material. As seen here, a 0.03 mm change in the lamination thickness of the core material caused a 20.5% change in core loss and a 6.8% change in temperature. This type of transformer can be used as an efficient power supply system in zero-energy buildings. In future studies, it will be examined how effective the transformers used in the efficiency of zero-energy buildings are. In addition, the effects of the transformer in zero build with different total power capacities will be examined.

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