International Journal of Applied Power Engineering (IJAPE)
Vol. 15, No. 3, September 2026, pp. 995~1008
ISSN: 2252-8792, DOI: 10.11591/ijape.v15.i3.pp995-1008

Effect of power and voltage variations on transformer core losses and geometry for two distinct core materials

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Article Info

Article history:

Received May 27, 2025
Revised Dec 16, 2025
Accepted Jun 10, 2026

Keywords:

Core geometry
Cost
Cross-sectional area
Grain-oriented electrical steel
No-load losses

ABSTRACT

This study presents a comprehensive comparison of transformer core size and no-load losses, focusing on transformers with power ratings ranging from 400 kVA to 3200 kVA. The research evaluates transformer performance at three distinct primary voltage levels: 6 kV, 15 kV, and 33 kV, while maintaining a constant secondary voltage of 0.4 kV. Additionally, the study investigates the impact of two commonly used transformer core materials, M4 and H0, on core design, with a particular focus on their effects on no-load losses. Another central aspect of the analysis is the examination of core geometry, including the cross-sectional area and height of the transformer core, across various power ratings and voltage levels. The results reveal a clear relationship between core size and energy efficiency. M4 cores exhibit higher no-load losses compared to H0 cores; additionally, H0 cores demonstrate better overall efficiency, making them ideal for high-efficiency applications. The findings underscore the importance of selecting the right core materials and geometries to balance performance, efficiency, and size. These insights are intended to guide researchers and transformer designers in making informed decisions when developing energy-efficient solutions for diverse applications across the electrical power industry.

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1. INTRODUCTION

Transformers are crucial components in the electrical power industry, acting as the interface between high-voltage transmission systems and low-voltage distribution networks [1]-[3]. The optimization of transformer designs is essential to improve energy efficiency, reduce operational costs, and ensure reliability in power distribution. While traditional transformer design primarily focuses on the core material, there is a growing need to balance the size, weight, and efficiency factors without compromising performance.

Numerous studies emphasize the significant role of core materials in determining transformer efficiency. Lee *et al*. [4] demonstrated that the use of high-performance laminated core materials can markedly reduce core losses by minimizing eddy currents. Dawood and Tursun [5] further investigated transformer design, with particular emphasis on the role of core materials in influencing losses. Dawood and Tursun [5] highlight the critical relationship between core material selection and no-load losses, emphasizing the need for careful consideration of core materials to minimize these losses. In addition, the geometry of laminated cores is crucial in influencing no-load losses, which in turn affects the overall efficiency of the transformer [5]. These findings underscore the importance of selecting appropriate core materials and optimizing the core design to enhance transformer performance and reduce energy losses.

The application of amorphous core materials has also been extensively explored in the literature as a promising alternative material for enhancing transformer performance. Studies have shown that amorphous materials can significantly reduce hysteresis losses compared to conventional silicon steel [6]-[8]. However, the integration of amorphous materials presents challenges, such as cost, vibrations, and audible noise resulting from magnetostriction. These issues must be carefully considered and addressed during the design phase to fully leverage the benefits of amorphous core materials [9].

The literature also discusses various optimization techniques used in transformer core design. Existing models for predicting core losses, such as the Steinmetz equations, are widely referenced and provide a foundational approach to understanding loss mechanisms [10]. However, newer approaches employing finite-element models are highlighted as valuable tools for accurately predicting core performance in complex geometries [11]-[14]. Recent advancements in simulation techniques further enhance the design process, allowing for the evaluation of loss mechanisms in different voltage levels and power levels of the transformers.

While considerable advancements have been made in understanding the impact of core materials on transformer core losses and magnetic flux density, notable gaps still exist. Specifically, the dynamic behavior of transformer cores under varying power levels and voltage conditions warrants further investigation. This is particularly pertinent in the context of dry-type transformers used in renewable energy applications, where unique operational demands may influence core performance and efficiency.

The main objectives of this work are to provide an in-depth comparison of power transformers with different power ratings, voltage ratings, and core materials. By considering a range of power ratings from 400 kVA to 3200 kVA, the study provides valuable insights into the practical implications of designing transformers for different levels of electrical load. Transformers in this range are widely used in industrial, commercial, and residential applications, and understanding how their size and no-load losses evolve with power ratings is essential for optimizing transformer selection and ensuring effective resource management. Another key aspect of this study is the analysis of transformers operating under different primary voltage ratings: 6 kV, 15 kV, and 33 kV, all with a secondary voltage of 0.4 kV. These voltage ratings represent common configurations found in real-world applications, covering a broad spectrum of voltage levels typically encountered in medium and high-voltage power networks. By examining how these different voltage ratings affect the physical dimensions and efficiency of the transformer cores, the study helps understand how voltage influences the efficiency and overall performance of transformers. This understanding is critical for matching transformers to specific grid requirements, physical dimensions, and operational needs.

Additionally, the study incorporates a comparison of transformers utilizing two distinct core materials, H0 and M4, which are widely used in transformer construction. The choice of core material is a key factor influencing the transformer's efficiency, noise levels, and overall cost. H0 and M4 represent different grades of silicon steel, which vary in terms of magnetic permeability, losses, and mechanical properties. The study further quantifies the no-load losses associated with both M4 and H0 core materials under different power and voltage conditions, providing a thorough understanding of their performance across a range of transformer ratings. By investigating the impact of these two core materials, this research provides a clear understanding of how material selection plays a role in both the performance and cost-effectiveness of transformers.

2. NO-LOAD LOSSES AND MATERIALS USED IN POWER TRANSFORMER CORES

Efficient energy transfer and voltage regulation are the primary functions of power transformers, which are critical components of electrical power systems. A comprehensive understanding of the interrelationship between transformer power and voltage levels, particularly in relation to core losses and transformer dimensions, is essential for optimizing transformer efficiency and operational performance. The selection of core material significantly affects the transformer's performance, efficiency, and operational lifespan. The most commonly used materials for power transformer cores are cold-rolled grain-oriented (CRGO) silicon steel and amorphous steel [15]-[17].

The magnetic properties of conventional iron are improved by silicon steel, which contains a higher percentage of silicon (typically 2-4%). By increasing electrical resistivity, the addition of silicon reduces core losses and enhances permeability. CRGO silicon steel is the most widely employed material in power transformer cores due to its exceptional magnetic properties. CRGO steel is available in various grades, each tailored to meet specific performance requirements, such as high saturation flux density and minimal core losses [17]. The laminations of CRGO steel, which are usually between 0.23 and 0.35 mm thick [18], reduce eddy current losses, which are big at high frequencies. Due to its high efficiency, CRGO steel is the preferred choice for large-scale power applications, where transformer performance is a critical consideration.

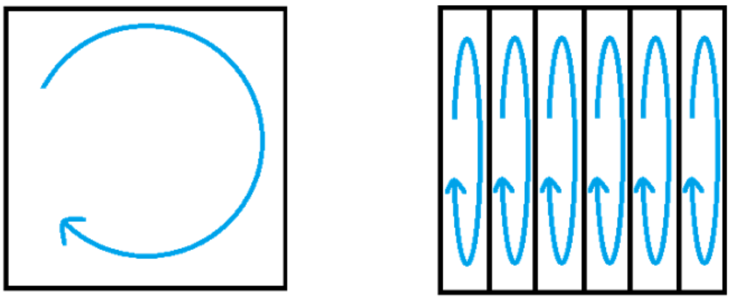
Amorphous steel is becoming a more prevalent substitute for conventional crystalline materials in transformer cores. In contrast to conventional materials, amorphous steel exhibits enhanced magnetic properties and reduced hysteresis losses due to the absence of grain boundaries [19]. Furthermore, the efficiency of amorphous steel can be further improved by reducing eddy currents through the production of narrower laminations. However, the widespread adoption of amorphous steel is limited by certain disadvantages, such as its higher cost and the complexity of the manufacturing process, which involves rapid solidification techniques. Additionally, amorphous steel is more brittle than crystalline materials, making it challenging to handle, cut, and shape during production. Despite these challenges, amorphous steel remains a compelling option for modern power transformers due to its advantages in efficiency and energy savings.

Transformer core losses are a critical aspect of transformer design, significantly affecting efficiency, performance, and operational costs [20]. Core losses primarily consist of hysteresis and eddy current losses, both of which are affected by the choice of core material and geometry. Eddy current losses occur in the metallic parts of a transformer due to currents induced by a changing magnetic field, as explained by Faraday's law of electromagnetic induction. When an alternating current flows through the windings, it generates a changing magnetic field in the transformer core. This changing magnetic field induces an EMF in the core, which causes circulating currents known as eddy currents. These eddy currents result in energy losses. The eddy current losses (P_{eddy}) can be calculated using (1) [5].

$$P_{eddy} = K_e B_m^2 f^2 t^2 V \quad (1)$$

Where K_e, B_m, f, and V are the eddy current coefficient, maximum value of the flux density, frequency, and volume of the magnetic material.

Eddy current losses are influenced by the core's resistance, which depends on its structure. The higher the eddy current, the greater the eddy current losses. The solid core has lower resistance due to the larger cross-sectional area of the solid core, as shown in Figure 1(a). Due to the lower resistance in solid cores, the eddy current in the solid core is higher. The eddy current losses can be reduced by decreasing the magnitude of the eddy currents. This reduction in eddy currents can be achieved by using laminated sheets in the core construction. Generally, thin laminated sheets are used for core construction. The laminated core has higher resistance compared to the solid transformer core due to the smaller cross-sectional area of the laminated core, as shown in Figure 1(b). Because of the higher resistance in laminated cores, the eddy current is reduced, leading to a decrease in the magnitude of eddy current losses.



(a) (b)

Figure 1. Transformer core configurations: (a) solid core and (b) laminated core

Another significant type of core loss is hysteresis loss, which arises from the repeated magnetization and demagnetization of the core material. The hysteresis loss depends on the permeability of the core material; it is lower in highly permeable materials and higher in less permeable ones. The hysteresis loss (P_{hys}) can be calculated using (2) [5].

$$P_{hys} = nB_m^n fV \quad (2)$$

Where, Ƞ is the Steinmetz's constant. Total core losses (P_c) can be determined using (3) [5].

$$P_c = P_{l/kg} \times W_c \quad (3)$$

In (3), $P_{l/kg}$ represents the loss per kilogram of the core material, and W_c denotes the total weight of the transformer core.

Core geometry is a vital determinant of magnetic flux distribution and consequently affects core losses. Voltage levels have a profound impact on no-load losses and the geometry of the core. The optimization of core geometry and material selection is essential to maximize efficiency. Several studies also highlight the importance of modularity in transformer design, suggesting that effective design choices and material selection can lead to improved efficiency. Despite the extensive research on transformer core losses and geometry, several knowledge gaps remain. For instance, while much is known about the influence of various materials on core losses, there is a need for more comprehensive studies focused on the effect of voltage and power levels on no-load losses and the geometry of transformer cores. This gap in understanding highlights the need for further exploration of how dynamic voltage conditions impact core dimensions and losses, especially in the context of dry-type transformers.

3. RESULTS AND DISCUSSION

This study addresses the critical challenges faced by transformer designers by analyzing the relationship between the size and no-load losses of transformers in relation to their power rating, core material, and voltage levels. The focus is particularly on dry-type transformers rated between 400 kVA and 3200 kVA. No-load losses for the M4 core material were assessed at three distinct primary-side voltages (6 kV, 15 kV, and 33 kV), while maintaining the secondary side at a constant 400 V. Power ratings varied from 400 kVA to 3200 kVA, in increments of 100 kVA. All transformers were designed for a 1.7 T magnetic flux density and 6% leakage impedance, with a tolerance of ±10% for both.

In recent decades, the significant advancements in numerical methods have led to the widespread use of finite element analysis (FEA) for assessing various factors and parameters of electrical machines [21]-[25]. Initially, the transformers were designed using the finite element method (FEM) and analytical methods. Details of the FEM modeling, as well as the experimental procedures for the short-circuit and open-circuit tests, are presented in our previous work [4], [26], [27]. Table 1 shows the experimental results of no-load losses for M4 core material at various power ratings and primary voltages.

Table 1. No-load losses for M4 core material at various power ratings and primary voltages (6 kV, 15 kV, and 33 kV)

Power (kVA)	6 kV	15 kV	33 kV
400	K	1.19K	1.54K
500	1.15K	1.30K	1.75K
600	1.28K	1.43K	1.97K
700	1.48K	1.58K	2.15K
800	1.70K	1.81K	2.29K
900	1.82K	1.97K	2.45K
1000	1.95K	2.19K	2.66K
1100	2.10K	2.31K	2.82K
1200	2.23K	2.44K	3.01K
1300	2.38K	2.60K	3.16K
1400	2.51K	2.75K	3.33K
1500	2.72K	2.88K	3.49K
1600	2.86K	3.02K	3.79K
1700	2.99K	3.18K	3.98K
1800	3.11K	3.32K	4.18K
1900	3.21K	3.49K	4.40K
2000	3.36K	3.66K	4.54K
2100	3.59K	3.83K	4.74K
2200	3.76K	3.98K	4.96K
2300	3.83K	4.13K	5.17K
2400	4.02K	4.26K	5.31K
2500	4.20K	4.42K	5.46K
2600	4.33K	4.57K	5.58K
2700	4.54K	4.74K	5.81K
2800	4.64K	4.88K	6.04K
2900	4.79K	5.00K	6.25K
3000	5.01K	5.15K	6.41K
3100	5.16K	5.31K	6.52K
3200	5.28K	5.47K	6.72K

The no-load (open-circuit) test is performed to determine the transformer's no-load losses under specified frequency and temperature conditions. In this procedure, a sinusoidal voltage is applied to the primary winding while the secondary remains open. The assessment of no-load losses is based on a sinusoidal voltage supply. In Table 1, the symbol K represents the no-load losses at a primary voltage of 6 kV for a power rating of 400 kVA. In this context, K serves as the reference value for comparing no-load losses at other primary voltages for different power ratings.

Figures 2 to 4 illustrate the no-load losses for M4 core material at 6 kV, 15 kV, and 33 kV, respectively. The main aim of this study is to examine how power requirements influence the size and efficiency of transformers. By analyzing these factors, the study seeks to provide valuable insights for transformer designers, helping them make informed decisions when selecting transformer configurations for specific applications, whether for large-scale power distribution, industrial plants, or urban grids.

Figures 2 to 4 illustrate that the no-load losses of the M4 core material increase with the power rating. At each primary voltage level (6 kV, 15 kV, and 33 kV), losses increase almost linearly as the power rating rises from 400 kVA to 3200 kVA. At a primary voltage of 6 kV, the no-load losses increase from K at 400 kVA to 5.28K at 3200 kVA. At 15 kV and 33 kV, the losses increase from 1.19K to 5.47K and from 1.54K to 6.72K, respectively.

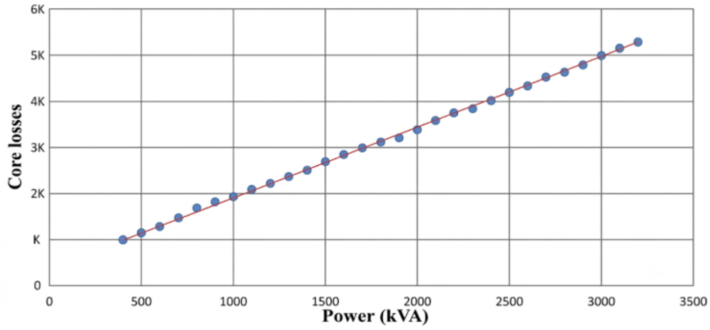


Figure 2. No-load losses for M4 core material at 6 kV

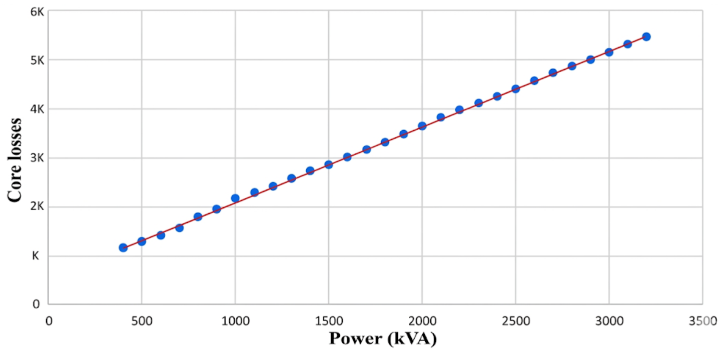


Figure 3. No-load losses for M4 core material at 15 kV

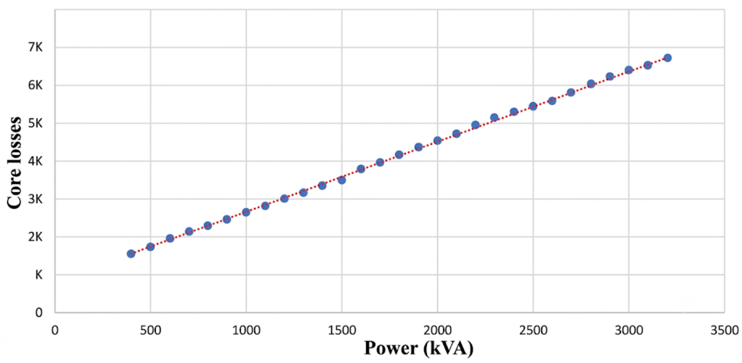


Figure 4. No-load losses for M4 core material at 33 kV

There is a noticeable increase in no-load losses as the primary voltage increases from 6 kV to 33 kV. At 6 kV, the no-load losses are consistently lower compared to those at 15 kV and 33 kV for each corresponding power rating. For instance, at 400 kVA, the no-load loss is K at 6 kV, which increases to 1.19K at 15 kV and 1.54K at 33 kV. This trend is evident across the entire range of power ratings, with losses at 33 kV always being the highest.

To quantify the impact of voltage variation, it can be noted that the difference between the 33 kV and 6 kV measurements increases as the power rating increases. For example, at 3200 kVA, the difference between the 33 kV and 6 kV no-load losses is 1.44K, while at 400 kVA, this difference is only 0.54K. However, the percentage difference decreases as the power rating increases. At 3200 kVA, the percentage difference between the 33 kV and 6 kV no-load losses is 26%, whereas at 400 kVA, this difference is 54%. This observation suggests that the influence of primary voltage on no-load losses becomes less significant in percentage terms at higher power ratings, although the absolute difference in losses increases.

These results suggest that for transformers utilizing the M4 core material, careful consideration of both the operating voltage and the power rating is essential when evaluating no-load losses. Transformer designers must consider the elevated no-load losses at higher voltages, particularly when engineering transformers for high-power applications, to ensure efficiency is optimized. The no-load losses for the H0 core material were also measured under three different primary-side voltages (6 kV, 15 kV, and 33 kV), with the secondary side held constant at 400 V. Power ratings ranged from 400 kVA to 3200 kVA, in increments of 100 kVA. Table 2 shows the no-load losses for H0 core material at various power ratings and primary voltages. Figures 5 to 7 show no-load losses for H0 core material at 6 kV, 15 kV, and 33 kV.

Similar to the M4 core, the no-load losses for the H0 core material show a clear increase with rising power ratings. At each primary voltage level (6 kV, 15 kV, and 33 kV), the losses steadily increase as the power rating rises from 400 kVA to 3200 kVA. For instance, at 6 kV, the no-load losses increase from 0.72K at 400 kVA to 3.84K at 3200 kVA. At 15 kV, the losses increase from 0.88K to 4.35K, and at 33 kV, the losses increase from 1.21K to 5.42K. These results demonstrate a linear-like relationship between no-load losses and power rating, consistent with the behavior expected from transformer core materials.

Table 2. No-load losses for H0 core material at various power ratings and primary voltages (6 kV, 15 kV, and 33 kV)

Power (kVA)	6 kV	15 kV	33 kV
400	0.72K	0.88K	1.21K
500	0.84K	0.98K	1.39K
600	0.98K	1.11K	1.56K
700	1.09K	1.25K	1.71K
800	1.21K	1.39K	1.85K
900	1.31K	1.51K	2.03K
1000	1.41K	1.65K	2.18K
1100	1.53K	1.77K	2.32K
1200	1.63K	1.90K	2.48K
1300	1.74K	2.03K	2.63K
1400	1.84K	2.17K	2.77K
1500	1.95K	2.29K	2.92K
1600	2.09K	2.41K	3.07K
1700	2.20K	2.50K	3.22K
1800	2.28K	2.63K	3.35K
1900	2.42K	2.74K	3.51K
2000	2.55K	2.86K	3.67K
2100	2.68K	3.00K	3.82K
2200	2.72K	3.13K	3.99K
2300	2.85K	3.25K	4.13K
2400	2.93K	3.38K	4.26K
2500	3.03K	3.50K	4.40K
2600	3.11K	3.63K	4.55K
2700	3.26K	3.75K	4.68K
2800	3.34K	3.85K	4.83K
2900	3.42K	3.97K	4.98K
3000	3.55K	4.08K	5.13K
3100	3.72K	4.22K	5.26K
3200	3.84K	4.35K	5.42K

As with the M4 core material, the no-load losses for the H0 core material increase as the primary voltage rises from 6 kV to 33 kV. For each power rating, no-load losses at 33 kV are consistently higher than those at 6 kV and 15 kV. For example, at 400 kVA, the no-load loss is 0.72K at 6 kV, 0.88K at 15 kV, and

1.21K at 33 kV. This trend is evident across all power ratings. To quantify the impact of the primary voltage, the results show that the difference between the 33 kV and 6 kV measurements increases as the power rating increases, as shown in Figure 7. At 400 kVA, the difference between the 33 kV and 6 kV losses is 0.49K, while at 3200 kVA, this difference rises to 1.58K. However, the percentage difference decreases as the power rating increases. For instance, at 3200 kVA, the difference between the 33 kV and 6 kV no-load losses is 41%, while at 400 kVA, this difference is 68%. This trend mirrors the observations for the M4 core material, where the influence of primary voltage on no-load losses becomes less significant in percentage terms at higher power ratings, even though the absolute difference in losses increases.

A comparison of no-load losses across different voltages for the H0 material is shown in Figure 8. Figures 9 to 11 show the comparative results between the M4 and H0 core materials for 6 kV, 15 kV, and 33 kV. When comparing the no-load losses of the H0 core material with those of the M4 core, the H0 core material exhibits lower no-load losses at each corresponding voltage and power rating. For instance, at 400 kVA and 6 kV, the H0 core loss is 0.72K, compared to K for the M4 core. Similarly, at 3200 kVA and 33 kV, the no-load losses for the H0 core material are 5.42K, whereas the M4 core experiences 6.72K. This suggests that the H0 core material is more efficient in terms of reducing core losses, making it a potentially better choice for applications where low no-load losses are a priority.

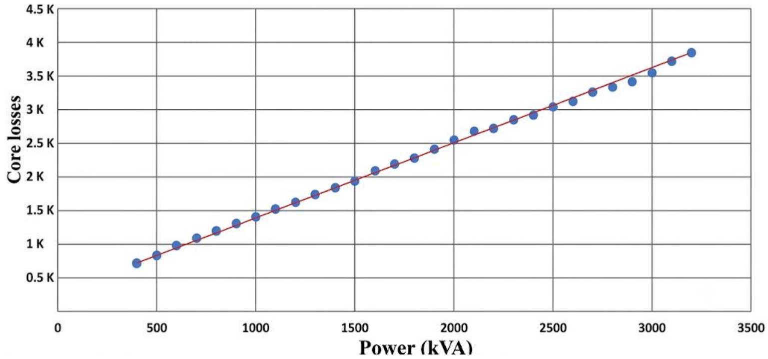


Figure 5. No-load losses for H0 core material at 6 kV

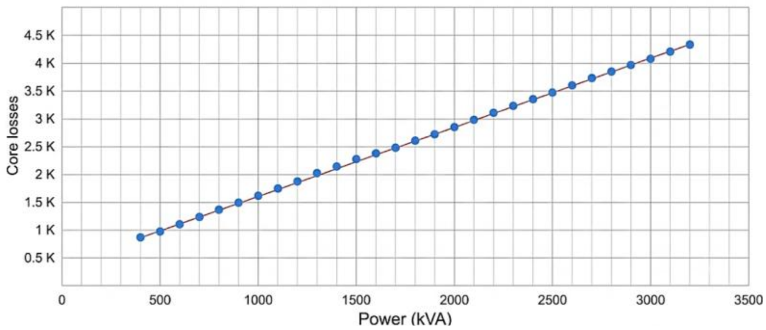


Figure 6. No-load losses for H0 core material at 15 kV

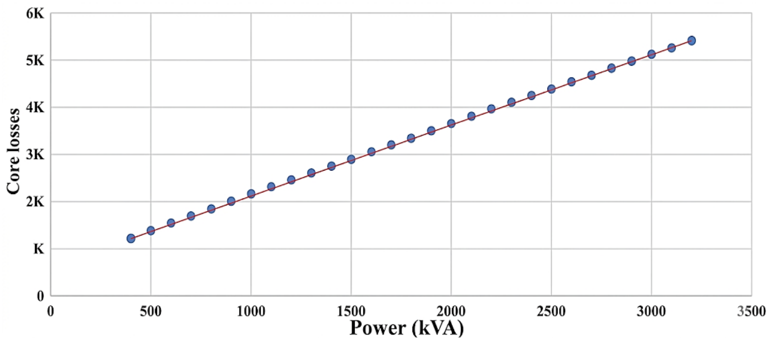


Figure 7. No-load losses for H0 core material at 33 kV

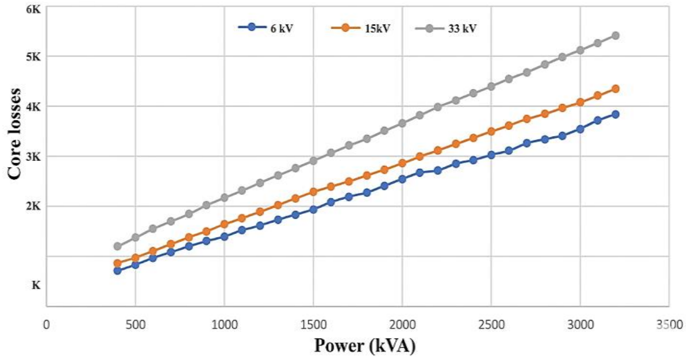


Figure 8. Comparing no-load losses across different voltages for H0 material

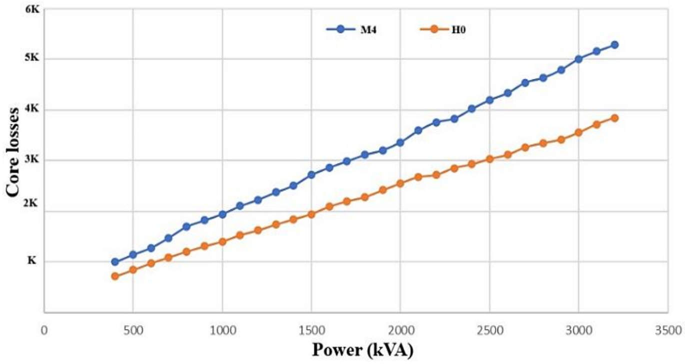


Figure 9. Comparison between M4 and H0 core materials for 6 kV

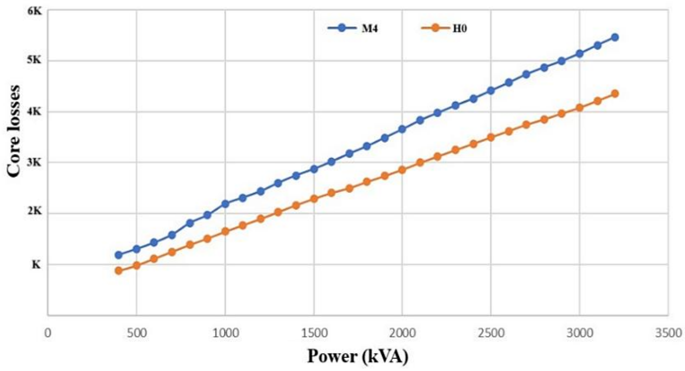


Figure 10. Comparison between M4 and H0 core materials for 15 kV

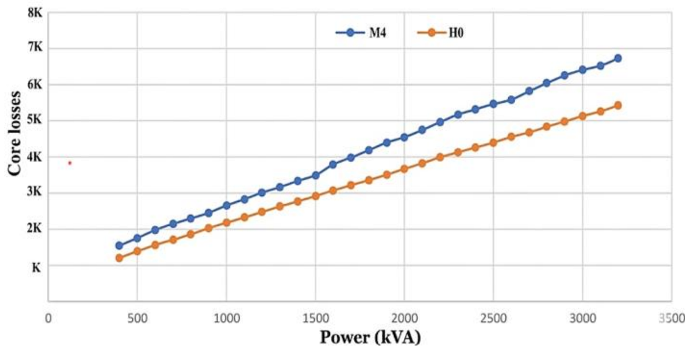


Figure 11. Comparison between M4 andH0 core materials for 33 kV

The results clearly show a progressive increase in no-load losses for the H0 core material as both the power rating and primary voltage increase. However, compared to the M4 core, the rate of increase in no-load losses for the H0 core material is slightly less steep, indicating that it may be more suitable for high-efficiency transformer designs. The higher efficiency of the H0 core material becomes more evident as the power rating exceeds 2000 kVA, where the M4 core material exhibits substantially higher no-load losses.

These results emphasize the importance of core material selection in optimizing transformer efficiency. The H0 core material's lower no-load losses, particularly at higher primary voltages and power ratings, suggest its suitability for applications where minimizing no-load losses is critical, such as in high-power transformers. The results also highlight the need to consider the operating voltage and power rating when designing transformers to ensure that core losses remain within acceptable limits.

The H0 core's lower no-load losses may be advantageous for designs where efficiency is a priority, especially in large power transformers or in scenarios where the transformer operates at higher voltages for extended periods. The M4 core might be chosen for applications where slightly higher no-load losses can be tolerated, and the focus is on cost-effectiveness or other material properties such as mechanical strength or magnetic saturation. At 6 kV, the performance difference between M4 and H0 is notable, with the percentage difference ranging from 30% to 41% across all power ratings. At 15 kV, the percentage difference between M4 and H0 is somewhat smaller compared to 6 kV, ranging from 25% to 36%. At 33 kV, the percentage difference between M4 and H0 further narrows, with values ranging from 20% to 28%.

Figure 12 shows the core-making process in transformer manufacturing. This figure illustrates the stacking and alignment of laminated steel sheets to form the core structure. The laminations are precisely cut and stacked to reduce eddy current losses and achieve optimal magnetic performance. The process ensures uniformity and minimizes gaps in the core assembly.

The cross-sectional area of the transformer core is a key parameter in determining the core's ability to handle the magnetic flux generated by the primary winding. It directly influences the core losses, as a larger cross-sectional area can distribute the magnetic flux more evenly, reducing the likelihood of saturation and core overheating. Figures 13 to 15 present the core geometry (cross-sectional area and height) for M4 core materials across varying power ratings (600 kVA, 1200 kVA, 1800 kVA, 2400 kVA, and 3000 kVA) and at three different primary-side voltage levels: 6 kV, 15 kV, and 33 kV.

Figure 12. Core-making process in transformer manufacturing

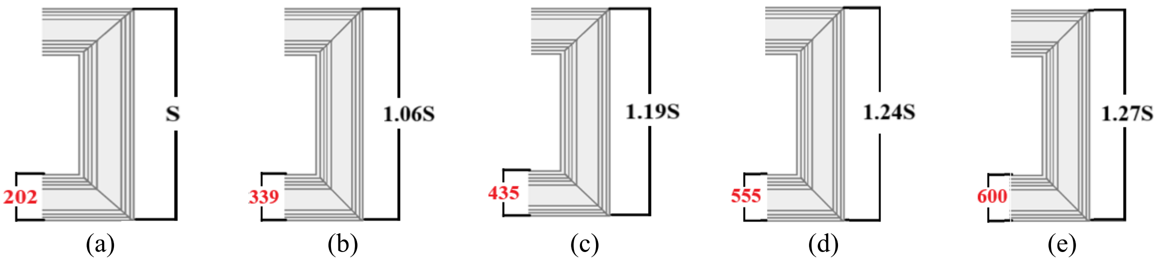


Figure 13. Cross-sectional area and height of M4 material core at 6 kV: (a) 600 kVA, (b) 1200 kVA, (c) 1800 kVA, (d) 2400 kVA, and (e) 3000 kVA

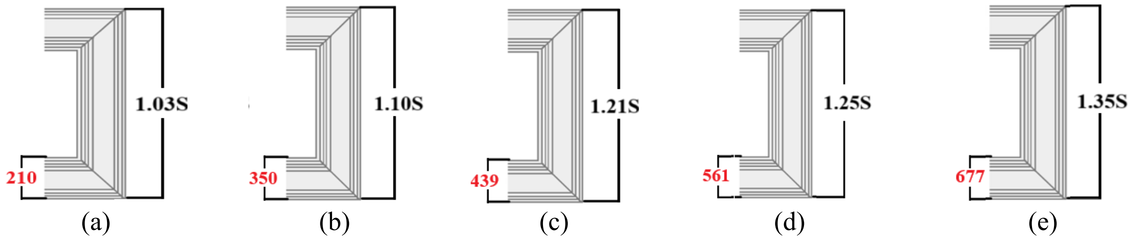


Figure 14. Cross-sectional area and height of M4 material core at 15 kV: (a) 600 kVA, (b) 1200 kVA, (c) 1800 kVA, (d) 2400 kVA, and (e) 3000 kVA

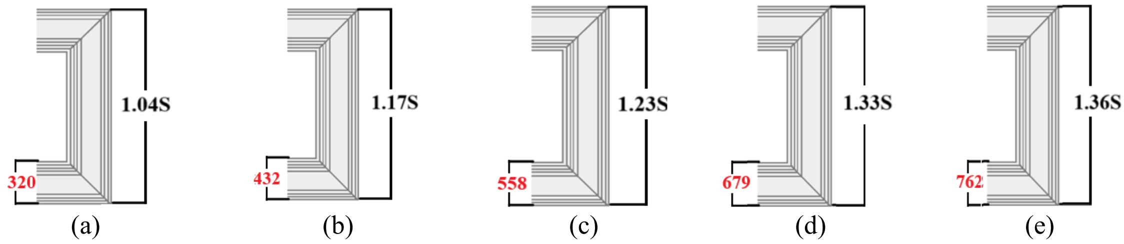


Figure 15. Cross-sectional area and height of M4 material core at 33 kV: (a) 600 kVA, (b) 1200 kVA, (c) 1800 kVA, (d) 2400 kVA, and (e) 3000 kVA

In the above figures, S represents the reference value for the height of the 6 kV, 600 kVA transformer. As the power rating increases, both the cross-sectional area and the height of the core increase for both materials, reflecting the need for a larger core to handle the greater magnetic flux associated with higher power levels. At each primary voltage level, the M4 core material shows an increasing trend in cross-sectional area with increasing power rating. For example, at 600 kVA, the cross-sectional area is 202 cm² at 6 kV, which increases to 320 cm² at 33 kV. As power ratings increase to 3000 kVA, the cross-sectional area rises from 600 cm² at 6 kV to 762 cm² at 33 kV.

The height of the transformer core is another critical factor that affects the design and performance of the transformer. The core height plays a role in determining the total volume of the core material, which contributes to the transformer's overall size and weight. As the power rating increases for the M4 core material, the core height increases as well. At 600 kVA, the height of the core is 1.00 S. This height increases steadily to 1.27 S at 3000 kVA at 6 kV. At higher voltage levels on the high-voltage side, the core height also increases. For example, at 33 kV, the core height increases from 1.04 S at 600 kVA to 1.36 S at 3000 kVA.

Figures 16-18 present the core geometry (cross-sectional area and height) for H0 core materials across varying power ratings (600 kVA, 1200 kVA, 1800 kVA, 2400 kVA, and 3000 kVA) and at three different primary-side voltage levels: 6 kV, 15 kV, and 33 kV. The cross-sectional area and height of the H0 core material are generally slightly larger than those of the M4 core material at comparable power ratings and voltages, indicating that the H0 material may require slightly more material to achieve the same performance, likely due to its different magnetic properties.

H0 generally requires slightly larger cross-sectional areas at each power rating compared to the M4 core. For instance, at 600 kVA, the H0 core's cross-sectional area starts at 209 cm² at 6 kV, compared to 202 cm² for the M4 core. At 3000 kVA, the cross-sectional area of the H0 core reaches 761 cm² at 33 kV, closely matching the M4 core's area but with a marginally higher requirement at all power levels. The need for different cross-sectional areas in the H0 and M4 materials may be attributed to their inherent magnetic properties, which may require different dimensions to achieve equivalent magnetic flux density performance in terms of efficiency and flux handling.

The H0 core material also exhibits an increase in core height with rising power ratings. At 600 kVA, the height of the core is 1.00 S. This height increases steadily to 1.265 S at 3000 kVA at 6 kV. At higher voltage levels on the high-voltage side, the core height also increases. For example, at 33 kV, the core height increases from 1.04 S at 600 kVA to 1.36 S at 3000 kVA.

Figure 19 presents an experimental comparison of transformer cores with different power ratings for M4 material. The smaller transformer core is rated for 400 kVA, while the larger transformer core is rated for 1200 kVA. Both transformers are designed for a 33/0.4 kV voltage level. To minimize eddy current losses, both cores are constructed using laminated steel, with their dimensions and configurations optimized for their respective power ratings.

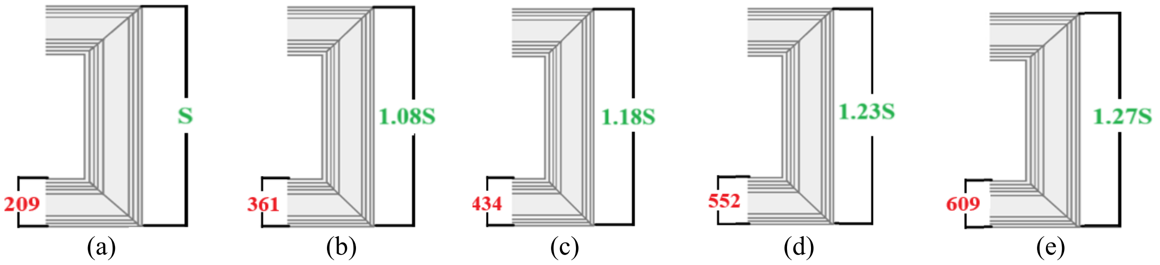


Figure 16. Cross-sectional area and height of H0 material core at 6 kV: (a) 600 kVA, (b) 1200 kVA, (c) 1800 kVA, (d) 2400 kVA, and (e) 3000 kVA

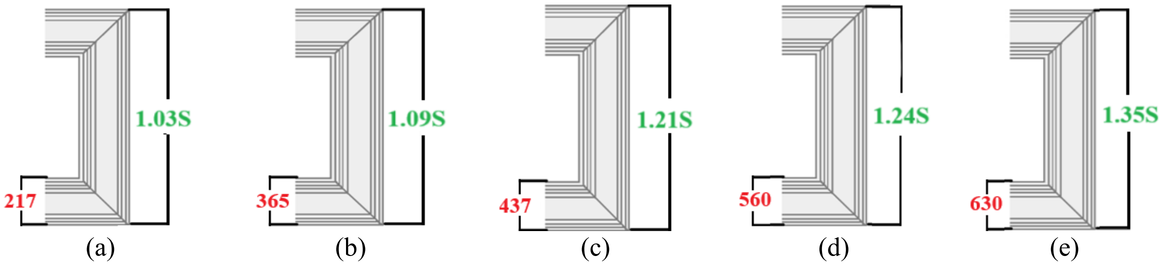


Figure 17. Cross-sectional area and height of H0 material core at 15 kV: (a) 600 kVA, (b) 1200 kVA, (c) 1800 kVA, (d) 2400 kVA, and (e) 3000 kVA

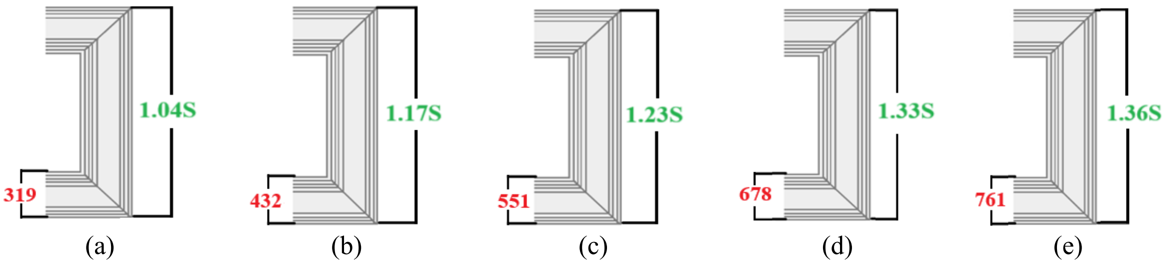


Figure 18. Cross-sectional area and height of H0 material core at 33 kV: (a) 600 kVA, (b) 1200 kVA, (c) 1800 kVA, (d) 2400 kVA, and (e) 3000 kVA

Figure 19. Comparison of transformer cores at 400 kVA and 1200 kVA

As shown in Figure 19, the 1200 kVA core exhibits a significantly larger size compared to the 400 kVA core. The increased size is necessary to handle the higher magnetic flux associated with the larger power rating while maintaining optimal core saturation levels. This visual comparison effectively demonstrates how transformer core design evolves with increasing power ratings.

4. CONCLUSION

This study provides an in-depth analysis of the impact of core material selection, power ratings, and primary voltage levels on the no-load losses of dry-type transformers. It demonstrates that both M4 and H0 core materials exhibit a consistent increase in no-load losses with rising power ratings. However, H0 material consistently outperforms M4, showing reduced core losses and enhanced efficiency. H0 core material proves to be more efficient in terms of no-load losses across all primary voltage levels and power ratings when compared to the M4 core material.

The difference in no-load losses becomes more pronounced as the power rating increases, suggesting that the H0 core would be the preferred choice for high-efficiency transformer designs, especially for high-power applications. Conversely, the M4 core remains a suitable choice for standard applications, though it incurs slightly higher core losses. By analyzing the impact of these operational parameters, the study aims to contribute valuable insights into the optimization of transformer design and performance, with an emphasis on minimizing core losses and improving overall efficiency. The study emphasizes the critical role of core geometry in mitigating eddy current and hysteresis losses, with a larger core size required for higher power ratings to accommodate increased magnetic flux.

From a practical design perspective, engineers can consider the following guidelines: i) Use H0 cores for transformers rated above 1600 kVA or in systems where energy efficiency and long-term operational cost savings are prioritized; ii) Select M4 cores for lower to mid-range power ratings (400–1600 kVA), especially in applications where initial material cost is a stronger constraint than long-term efficiency; and iii) The size difference between M4 and H0 cores decreases as the power rating increases, making H0 cores increasingly advantageous for higher power ratings where efficiency is prioritized. The insights from this study are invaluable for transformer designers aiming to optimize efficiency and performance, especially for dry-type transformers that demand high operational efficiency.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the financial support provided by Astor Enerji and TÜBİTAK.

FUNDING INFORMATION

This work was funded by Astor Enerji and TÜBİTAK under Project No. 118C109.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY

All data supporting the findings of this study are included within the article.

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