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Rüzgâr Türbini Uygulaması İçin Çeşitli Çekirdek Malzemelerin Kullanıldığı SMSG'lerin Karşılaştırmalı Performans Analizi

Burak ESENBOĞA[1*]

[1]Adana Alparslan Türkeş Bilim ve Teknoloji Üniversitesi, Mühendislik Fakültesi, Elektrik-Elektronik Mühendisliği Bölümü, 01250, Adana, Türkiye

[1]https://orcid.org/ 0000-0002-7777-259X
*Sorumlu yazar: besenboga@atu.edu.tr

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ÖZ

Kalıcı Mıknatıslı Senkron Jeneratör (SMSG) çekirdekleri rüzgâr enerjisi performansının belirlenmesinde önemli bir rol oynamaktadır. SMSG'lerin çekirdek malzemeleri manyetik akı yoğunluğunu etkiler, kayıpları en aza indirir, ısı dağılımını kolaylaştırır, mekanik stabilite sağlar ve maliyet hususlarını dengeler. Farklı çekirdek malzemelerinin kullanılması, SMSG sistemlerinin verimliliği ve rüzgâr üretimindeki genel performans üzerinde önemli bir etkiye sahiptir. Bu nedenle bu çalışma, rüzgâr türbini uygulamalarında çeşitli çekirdek malzemeleri kullanan PMSG sistemleri için karşılaştırmalı bir performans analizi sunmaktadır. Tasarım ve analiz metodolojisi ANSYS/MAXWELL simülasyon yazılımına dayanmaktadır. Önerilen rüzgâr türbini modeli 380 V, 50 Hz ve 24 HP çıkış gücünde tasarlanmıştır. Çalışma, silikon çelik, amorf çelik ve ferrit malzemeler gibi çeşitli çekirdek malzemeleri kullanan PMSG sistemlerinin performans özelliklerini araştırıyor. Tasarım aşamasında, ANSYS Maxwell kullanılarak çekirdek malzemeleri karşılaştırmak için Sonlu Elemanlar Analizi (FEA) gerçekleştirilir. Sonuçlar, farklı çekirdek malzemeleri kullanan tasarım yaklaşımının etkinliğini ve doğruluğunu göstermektedir. Sonuçlar, SMSG'ye dayalı rüzgâr enerjisi sistemlerinin verimliliğini ve sürdürülebilirliğini artırmak için en iyi çekirdek malzemelerin seçimine rehberlik etmeye yardımcı olmaktadır.

Comparative Performance Analysis of PMSGs Using Various Core Materials for Wind Turbine Application

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ABSTRACT

Permanent Magnet Synchronous Generator (PMSG) cores play an important role in determining the performance of wind power. Core materials of PMSGs influence magnetic flux density, minimize losses, facilitate heat dissipation, ensure mechanical stability, and balance cost considerations. The use of different core materials has a significant impact on PMSG systems efficiency and overall performance in wind generation. Therefore, this study provides a comparative performance analysis for PMSG systems using diverse core materials in wind turbine applications. The design and analysis methodology is based on ANSYS/MAXWELL simulation software. The proposed model for a wind turbine is designed with 380 V, 50 Hz, and 24 HP output power. The study investigates the performance characteristics of PMSG systems utilizing various core materials such as silicon steel, amorphous steel, and ferrite materials. During the design phase, the Finite Element Analysis (FEA) is performed to compare core materials using ANSYS Maxwell. The results demonstrate the effectiveness and accuracy of the design approach using different core materials. The results help guide the selection of the best core materials to improve the efficiency and sustainability of wind energy systems based on PMSG.

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1.Introduction

The harnessing of wind energy through wind turbines has emerged as a vital contributor to renewable energy generation worldwide. At the heart of these wind turbines lies the generator, a crucial component responsible for converting mechanical energy from the wind into electrical energy. Among the various generator technologies employed in wind turbines, the Permanent Magnet Synchronous Generator (PMSG) has gained significant attention due to its numerous advantages and suitability for wind energy applications. PMSGs utilize permanent magnets to create the magnetic field necessary for generating electricity, eliminating the need for a separate excitation system, such as brushes and slip rings, found in other generator types. This inherent simplicity results in reduced maintenance requirements, enhanced reliability, and improved efficiency, making PMSGs particularly well-suited for remote or offshore wind farm installations where accessibility and maintenance can be challenging (Abdelateef Mostafa et al., 2023). In addition to their operational advantages, PMSGs offer superior power density, allowing for more compact and lightweight designs compared to traditional generators. This characteristic is especially advantageous in wind turbine applications where space and weight constraints are critical factors in turbine design and installation. Furthermore, the direct-drive configuration, commonly employed with PMSGs, eliminates the need for a gearbox, thereby reducing mechanical complexity, noise, and maintenance costs while improving overall system efficiency. Despite these advantages, the design and optimization of PMSGs for wind turbine applications present unique challenges, particularly concerning the selection of core materials, winding configurations, and control strategies to maximize efficiency, reliability, and power output.

Numerous investigations have been conducted within the realm of Permanent Magnet Synchronous Generator (PMSG) for wind turbine application. It is compared and evaluated two distinct configurations of micro-grid-connected wind turbines with Permanent Magnet Synchronous Generators (PMSGs). In the first setup, the wind turbine, PV panels, and batteries are linked to a rectifier, filter-boost converter, and DC bus. In contrast, the second setup separates PV panels and batteries, connecting them to an inverter, while the wind turbine directly connects to 3-phase AC through a back-to-back converter and step-down transformer. Analysis of simulation results reveals that while the first design boasts superior power quality with reduced voltage harmonics, the second design excels in supporting multiple households owing to the higher efficiencies of the inverter and transformer (Tazi et al., 2020). It is introduced an Improved Magnetic Circuit (IMC) model for enhancing a Five-Phase Permanent Magnet Synchronous Generator (FP-PMSG) for wind power applications. By merging Finite Element Method (FEM) with the IMC model, rapid outcomes are attained. The model refines FP-PMSG parameters like leakage fluxes, core and rotor materials, and saturation effects, employing a winding function for armature reaction flux computation. Examination encompasses various sleeve and core materials, optimizing dimensional parameters. Notably, reducing air-gap flux leads to diminished voltage and cogging torque, thereby reducing torque ripple (Kumar et al., 2020a). The other study is conducted a design and assess a Novel Dual Stator Pseudo-Pole Five Phase Permanent Magnet Synchronous Generator (NDSPPFP-PMSG) tailored for wind power utilization. This innovative generator incorporates dual stators and two sets of five-phase windings, resulting in improved power density and fault tolerance. Its uniqueness stems from the creation of eight magnetic poles using just four magnet poles on each rotor surface. The outcomes demonstrate a higher power density achieved by the proposed generator (Kumar et al., 2020b). It is examined various techniques for maximizing power extraction and compares the dynamic performance between Permanent Magnet Synchronous Generators (PMSG) and Permanent Magnet Vernier Generators (PMVG). An innovative approach, termed current augmented Open-Transition Control (OTC), is introduced to decrease inertia and enhance dynamic performance. PMVG demonstrates a 0.505% enhancement in power extraction efficiency compared to PMSG under typical OTC control conditions. Additionally, the study conducts comprehensive analyses of design, volume, weight, and cost comparisons between PMVG and PMSG (Palanimuthu et al., 2022). It is presented a comparative study on PMSG performance, exploring various factors such as the type of permanent magnet, environmental conditions like rotor speed, and design and geometrical parameters including rotor length, number of poles, and stator slots. The investigation utilizes the Finite Element Method (FEM), recognized as a robust tool for PMSG study and design. The study findings reveal that both efficiency and power output of the system rise as the rotor length increases. However, efficiency declines when the rotor length surpasses that of the stator. Consequently, the optimal rotor length is determined to be 65mm (Mellah and Hemsas, 2013). It is evaluated the performance under varying wind speeds and fault scenarios. particle swarm optimizer (PSO)performs well in wind speed changes, while gray wolf optimizer (GWO)and WOA excel in symmetrical fault scenarios. GWO demonstrates superior performance in symmetrical faults compared to whale optimizer algorithm (WOA). MATLAB/Simulink simulations validate the effectiveness of the proposed GWO technique and Braking chopper (BC) in improving PMSG dynamic performance (Mahmoud et al., 2020). A new system with a grid-side converter (GSC) and a machine-side converter (MSC) for a Permanent Magnet Synchronous Generator (PMSG), employing a three-level Neutral Point Clamped (NPC) setup and fuzzy Proportional-Integral (PI) control is introduced. It examines the PMSG's performance under varying loads and finds that with the NPC configuration, the Total Harmonic Distortion (THD) of the electrical grid voltage is approximately 1.45%. The study concludes that the proposed model is stable even when subjected to changing loads, based on thorough analysis. (Gencer, 2018). Two primary challenges encountered in direct-grid coupled Permanent Magnet Synchronous Generators (PMSGs) are discussed. It is proposed the optimizing slot/pole combinations to address the MPPT limitation and analyze reactive power variation for designing high-power Factor (PF) machines across diverse power outputs. Analytical insights highlight the advantages of fixed-speed systems across different wind speeds and capacity factors (Bakbak et al., 2022). The authors aim to enhance the rotor design parameters of a 4000 rpm PMSG. They focus on optimizing factors such as embrace, offset, outer diameter, and magnet thickness to ensure that the magnetic flux density distribution and flux density on stator teeth and stator yoke remain within desired limits while maximizing efficiency. The findings reveal that efficiency is optimized, and magnetic distributions are maintained within suitable bounds (Perin et al., 2024). It is explored the utilization of Series Dynamic Braking Resistor (SDBR) and Bridge fault current limiter (BFCL) to enhance the Low Voltage Ride Through (LVRT) capability of PMSG wind turbines. It evaluates and contrasts the effectiveness of both methods on the PMSG under severe balanced fault conditions. The results indicate that while the BFCL, despite its complex structure, enhances the fault ride-through capability of PMSG wind farms, the simpler SDBR topology performs differently (Okedu, 2023). It is presented a 1.5 kW inner rotor permanent magnet synchronous generator, featuring surface-mounted magnets. To investigate the influence of different magnet materials on machine performance, SmCo24, SmCo28, and NdFe35 magnets were analyzed in the same reference machine. Results indicate that NdFe35 magnets yield the highest efficiency and air gap flux density. However, it's noted that NdFe35 magnets also exhibit higher cogging torque compared to the other magnet types. (Özmen and Onat, 2021).

When the literature study is examined, it is seen that PMSGs used in wind turbines play an important role in renewable energy production and contribute to the growth in the wind energy sector. Efficiency and performance increases of PMSGs have become an important issue. In this article, a different path is followed to increase the efficiency of PMSGs in wind turbine applications. The main objectives of this study are explained as follows:

- To conduct a comparative performance analysis of Permanent Magnet Synchronous Generators (PMSGs) utilizing diverse core materials within the context of wind turbine applications.
- To perform a comparative evaluation of core materials through Finite Element Analysis (FEA) within the ANSYS Maxwell environment.
- To investigate the performance characteristics, including power, and losses, of PMSG systems employing various core materials such as silicon steel, amorphous steel, and ferrite materials.
- To validate the efficacy of the design approach using outcomes derived from ANSYS Maxwell simulations.
- To provide valuable insights and recommendations to facilitate informed decision-making in selecting optimal core materials, thereby enhancing the performance and sustainability of PMSG-based wind energy systems.

2. Material and Method

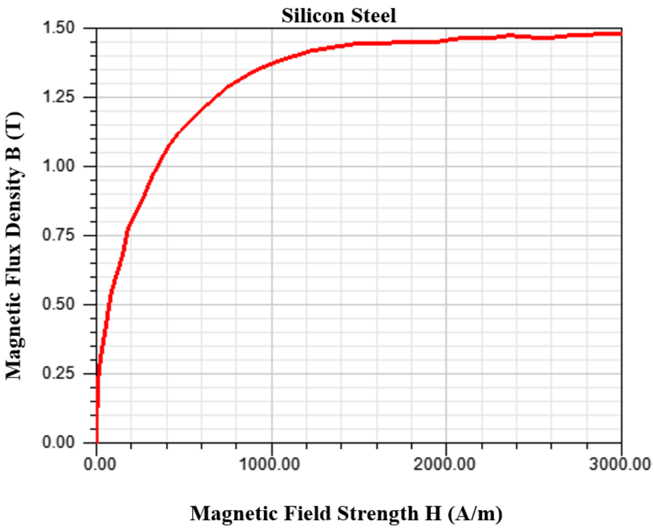
Different core materials have different magnetic properties. A core material with a high magnetic saturation point can provide higher magnetic flux density and therefore higher efficiency. Additionally, a material with low magnetic losses minimizes losses in the energy conversion process and therefore increases overall efficiency. Additionally, the core material also affects the mechanical durability of the generator. A material that does not have sufficient mechanical strength may be damaged when faced with vibrations and mechanical stresses, which can negatively affect the performance and life of the generator. As a result, the correct selection of the core material is critical for long-term reliability and sustainability, as well as improving the efficiency of the PMSG. Therefore, great attention should be paid to core material selection in PMSG design and optimization. Various core materials commonly used in Permanent Magnet Synchronous Generators (PMSGs) were considered for this comparative analysis. These are silicon steel, amorphous steel, ferrite materials, and other emerging materials. Selection criteria for core materials included factors such as magnetic properties, mechanical strength, thermal conductivity, and cost-effectiveness.

In this study, a wind turbine model is established with specifications including 380 V, 50 Hz, and 24 HP output power. These specifications are chosen to represent typical operating conditions for wind turbine applications. The comparative analysis focused on evaluating the performance of PMSG systems using different core materials. These are silicon steel, an amorphous metal alloy, and a ferrite material. Silicon steel is also known as electrical steel or silicon iron, this material is widely utilized in machine cores due to its high magnetic permeability and low core losses. It helps minimize eddy current losses, making it ideal for high-efficiency machine designs. Amorphous metal alloys exhibit extremely low core losses due to their non-crystalline structure. They offer superior magnetic properties compared to traditional silicon steel, making them suitable for applications where minimizing losses is critical (Zhang et al., 2023). Ferrite materials including ferrite ceramic and soft ferrite, are commonly used in lower-cost machines and applications requiring moderate magnetic performance. While they may not offer the same level of efficiency as silicon steel or amorphous alloys, they provide good performance in applications with lower power requirements.

The most common ferrite core material used for Permanent Magnet Synchronous Generators (PMSGs) is manganese-zinc (MnZn) ferrite. This type of ferrite is widely used in electrical and electronic applications due to its relatively high permeability and low cost compared to other ferrite materials. MnZn ferrite cores offer good magnetic properties, thermal stability, and resistance to demagnetization, making them suitable for use in PMSGs and other electromagnetic devices (Thakur et al., 2020).

The most efficient type of silicon steel core material for a Permanent Magnet Synchronous Generator (PMSG) typically falls within the category of high-permeability, low-loss electrical steels. Among these, grain-oriented silicon steel (GOSS) is often considered one of the most efficient materials for PMSG cores. Grain-oriented silicon steel is specifically engineered to exhibit superior magnetic properties in the direction of grain orientation, resulting in reduced core losses and improved efficiency (Li et al., 2022). It is commonly used in high-efficiency electrical machines such as transformers and generators, including PMSGs, where minimizing losses is crucial for maximizing energy conversion efficiency. Additionally, advanced grades of grain-oriented silicon steel with optimized magnetic properties and reduced losses are continuously being developed by manufacturers to further enhance the efficiency of PMSGs and other electrical devices. Ultimately, selecting the most efficient silicon steel core type material for a PMSG involves considering factors such as specific application requirements, desired performance characteristics, and cost considerations. Consulting with manufacturers and conducting thorough analyses help determine the most suitable material for a given PMSG application.

The B-H curve, also known as the magnetization curve or hysteresis loop, of the core material plays a crucial role in determining the performance of a PMSG. The B-H curve provides information about the magnetic properties of the core material, including its magnetic permeability, saturation flux density, and coercivity. These properties directly influence the ability of the core to channel and concentrate magnetic flux, which is essential for efficient energy conversion in the generator. The design methodology emphasizes a comparative evaluation of core materials through Finite Element Analysis (FEA) conducted within the ANSYS Maxwell software. The analysis assesses the performance of the designed PMSG across various core materials with distinct characteristics. Figure 1 presents the B-H curve characteristic of PMSG core materials used in FEA analysis.



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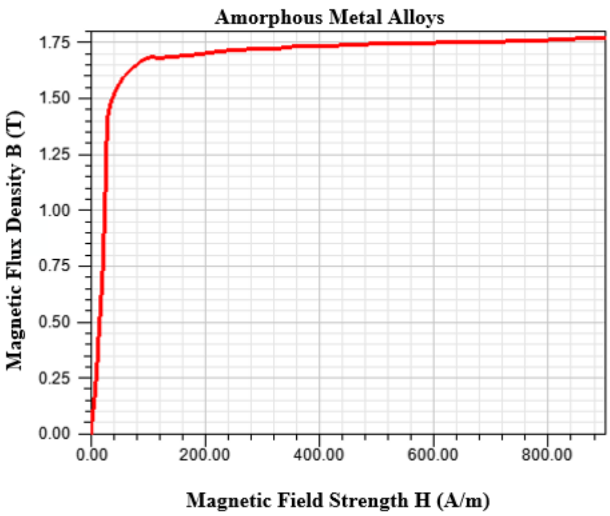

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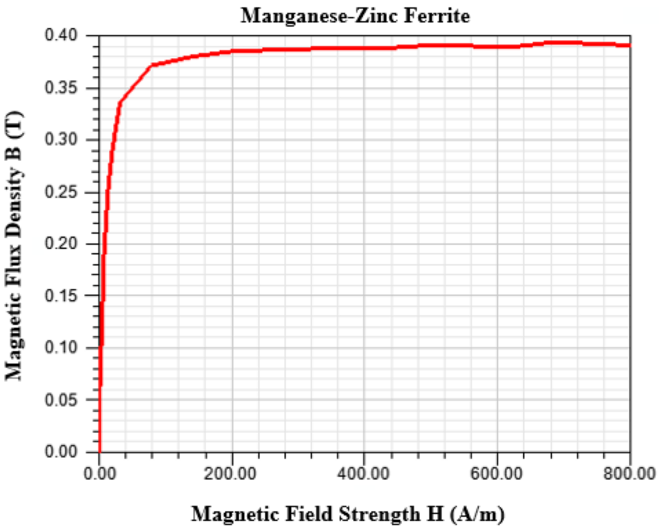

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Figure 1. B-H curve characteristic of PMSG core materials a) silicon steel b) amorphous metal alloy c) manganese-zinc ferrite

The core loss model is a mathematical representation or empirical model used to predict the core losses in magnetic materials, such as those used in transformers, inductors, motors, and other electromagnetic devices. Core losses occur due to hysteresis and eddy current losses in the magnetic core material when subjected to alternating magnetic fields. There are various core loss models used depending on the specific characteristics of the magnetic material and the operating conditions. The values of mass density, conductivity, thickness, and Poisson's ratio are used to occur the core loss model. Table 1 presents the core loss characteristics of the used stator core for PMSG.

Table 1. Core loss characteristics of the used stator core for PMSG

Core Materials	**Silicon Steel**	**Amorphous Metal Alloy**	**Manganese-Zinc Ferrite**
Mass density (g/cm^3)	7.65	7.2	5.3
Thickness (mm)	0.35	0.25	0.2
Thermal Conductivity (W/(m·K))	28	30	5
Specific Resistance (μΩ·m)	0.48	1.3	0.57
Magneto-striction λ10/400 (x10^{-6})	0.8	27	7.8
Poisson's ratio	0.32	0.35	0.33

The ANSYS Maxwell program serves as a valuable aid in designing and assessing the performance of both stator and rotor geometries through RMxprt. Various factors come into play during the design process, including the diameters of the stator and rotor, the number of slots, the length of the iron core, the choice of insulation material, winding configurations, the overall size of the PMSG, and the type of material used. In general, the diameter of the machine significantly influences its torque and speed characteristics. Larger diameters tend to generate more torque but at lower speeds, while smaller diameters yield higher speeds with less torque. Adjustments in machine size are necessary as flux density increases, which can affect machine performance and size. However, exceeding the rated flux density can lead to magnetic core saturation, resulting in overheating and potential machine failure. Therefore, careful consideration must be given to cooling requirements when determining the machine's diameter. To mitigate overheating issues and maintain operating temperature limits, lengthening the machine is often necessary. This entails balancing factors such as operating temperature, wire size, torque, and speed, which involves a trade-off between machine length and diameter. Additionally, the design of the machine is heavily influenced by its intended application, with different diameters and lengths requiring specific material considerations. Proper selection of materials and geometric characteristics, such as core dimensions and winding configurations, plays a crucial role in enhancing generator efficiency. This study primarily focuses on identifying the most suitable material for manufacturing a PMSG tailored for wind power applications. The cross-sectional view of the PMSG is illustrated in Figure 2, and detailed specifications are provided in Table 2.

Table 2. Characteristics structure of the permanent magnet alternator

Variables	Features
Power rating	24HP
Voltage	380V
Speed	120 rpm
Frequency	50 Hz
Nominal Power Factor	0.8
Poles	50
Slots	48 mm
Stator outer diameter	500 mm
Stator inner diameter	424 mm
Rotor inner diameter	422 mm
Inner Size of the Rotor	399 mm
Number of winding layers	2
Stator winding type	Whole-coiled
Number of Conductors	26
Total Net Weight	114.525 kg

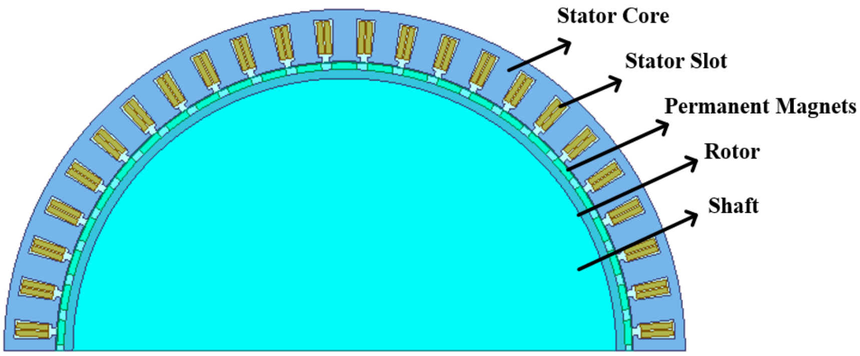


Figure 2. Cross-sectional view of the proposed PMSG.

The mathematical modeling of the proposed PMSG design utilizes direct quadrature equations. To facilitate analysis, expressions for voltages, currents, power, torque, flux, and inductance, as shown in Equations 1 to 6, have been transformed into direct quadrature (d_q) frames (Gencer, 2016).

$$\varphi_{sd} = L_d . i_{sd} + \varphi_m \tag{1}$$

$$\varphi_{sq} = L_q . i_{sq} \tag{2}$$

$$V_{sd} = R_s . i_{sd} + \frac{d\varphi_{sd}}{dt} - w_e . \varphi_{sq} \tag{3}$$

$$V_{sq} = R_s . i_{sq} + \frac{d\varphi_{sq}}{dt} - w_e . \varphi_{sd} \tag{4}$$

$$P_e = \frac{3}{2}(V_{sd} . i_{sd} + V_{sq} . i_{sq}) \tag{5}$$

$$T_e = \frac{3}{2} p_p (i_q . i_d (L_d - L_q) + \varphi_m . i_q \tag{6}$$

These equations feature symbols such as V_{sd} and V_{sq} representing stator voltage in the direct-quadrature (d_q) axis, i_{sd} and i_{sq} indicating stator currents in the d_q axis, and φ_{sd} and φ_{sq} representing stator fluxes in the d_q axis. Additionally, L_d and L_q denote the d_q axis inductances, R_s represents stator winding resistance, and ω signifies the angular speed of the alternator. Moreover, Equation 7 illustrates the direct proportionality between the stator's inner diameter and length and the magnetic flux.

$$\phi_g = B_{av} \times (\frac{\pi \times D_{si} \times L_s}{p}) \tag{7}$$

In this context, the symbol Φ_g represents magnetic flux, while D_s denotes the inner dimension of the stator, and Ls signifies the stator's length (Arumugam et al., 2017).

This study employs the ANSYS/Maxwell program to model and comprehensively analyze a more efficient wind turbine alternator. Utilizing the Finite Element Method (FEM), this program addresses engineering challenges about heat conduction, fluid mechanics, and electrical and magnetic fields. FEM is renowned for its effectiveness in solving electromagnetic field problems. Initially, the problem is subdivided into smaller substructures termed finite elements, a process known as meshing. These substructures are interconnected via nodes and elements. The desired solution is achieved through the interpolation of values at these nodes. Following the completion of the design phase, mesh analysis is conducted on the stator, rotor, and shaft of the PMSG. A computer program is utilized to execute these tasks, employing Maxwell's equations to address design challenges in electrical machinery. These equations, derived from Ampere's law, Faraday's law of induction, Gauss' law for magnetism, and Gauss' law, form the foundation for solving electromagnetic field problems. They offer a superior approach to tackling such challenges. Below are Maxwell's four fundamental equations (Yavuzdeger et al., 2021).

$$\nabla x E = -\frac{\partial B}{\partial t} \tag{8}$$

$$\nabla x H = J + \frac{\partial D}{\partial t} \tag{9}$$

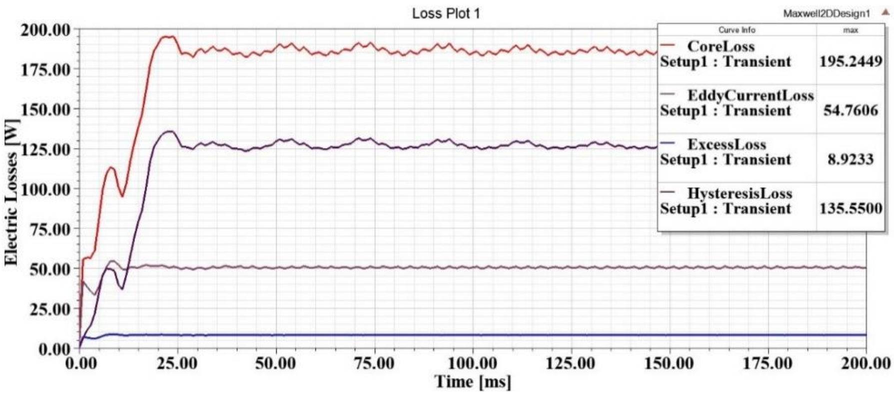
$$\nabla . B = 0 \tag{10}$$

$$\nabla x D = \rho \tag{11}$$

Equation 8, known as Maxwell's law, illustrates Faraday's induction principle, stating that changes in magnetic flux density over time within a surface area induce an electric field with opposite polarity surrounding that area. Equation 9 reveals that electric currents and time-varying electric flux are proportional to the magnitude of the magnetic field surrounding an object. Equation 10 indicates that the total magnetic flux entering a closed surface equals the total flux exiting it. Lastly, Equation 11 asserts that the electric flux through a closed surface area equals the charge density within that area. These equations serve as the foundation for electromagnetic analysis in ANSYS/Maxwell software when examining electric machines.

3. Results and Discussions

This section entails conducting finite element analysis (FEA) utilizing ANSYS software to explore material considerations crucial for the design of a 25 HP PMSG. Three different types of materials are evaluated for the core and winding design of a three-phase PMSG to determine the most suitable options. The selection of materials is guided by the characteristics of their respective B-H and B-P curves. Typically, soft magnetic materials are preferred for stator cores to optimize the efficiency, power factor, and torque of the PMSG. The properties of silicon steel are high magnetic permeability, low core losses, good magnetic saturation, and controlled grain orientation. Compared to amorphous metal alloys, silicon steel typically has higher core losses but is more cost-effective. Silicon steel has lower magnetic permeability compared to ferrite, but it offers lower core losses and higher magnetic saturation. It is a crystalline material, whereas amorphous metal alloys have a non-crystalline atomic structure, resulting in different magnetic properties. Amorphous metal alloys present low core losses, high magnetic permeability, and reduced magnetostriction. Ferrite cores offer high electrical resistivity, low magnetic permeability, and stability over a wide temperature range. Ferrite materials have lower magnetic permeability and higher electrical resistivity compared to silicon steel and amorphous metal alloys. The PMSG undergoes electric performance testing using the ANSYS/Maxwell program to assess its performance. Figure 3 illustrates the core losses incurred by the PMSG during testing.



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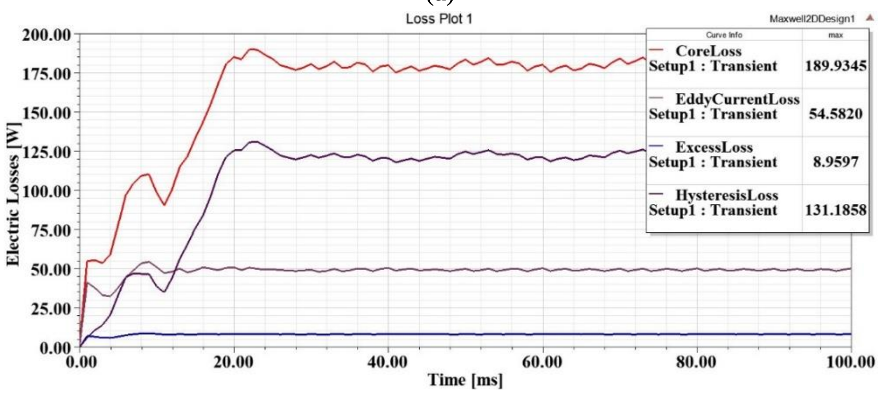

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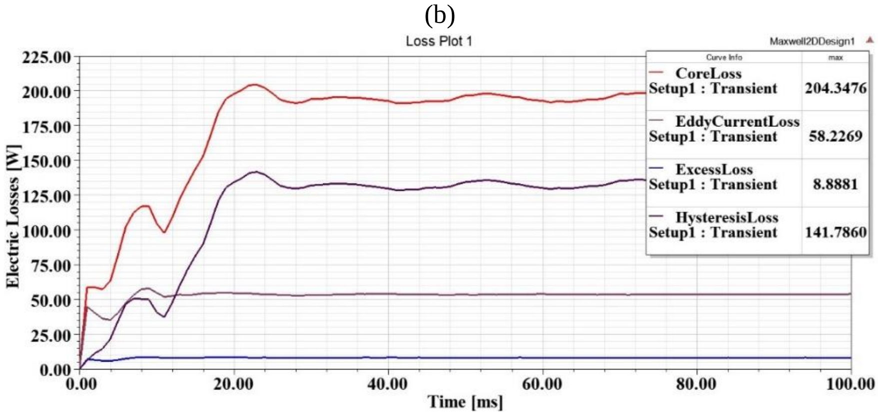

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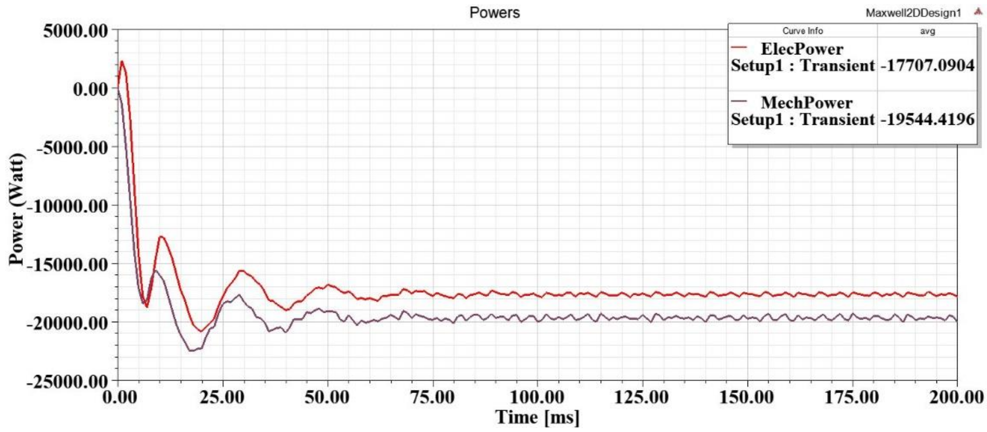
Figure 3. Core loss analyses of designed PMSG a) silicon steel core type b) amorphous metal alloys core type c) manganese-zinc ferrite core type

The choice of stator core material impacts various performance parameters of the PMSG, including its efficiency characteristics, and overall reliability. Figure 4 presents the electric and mechanical power of the PMSGs with various stator core types.



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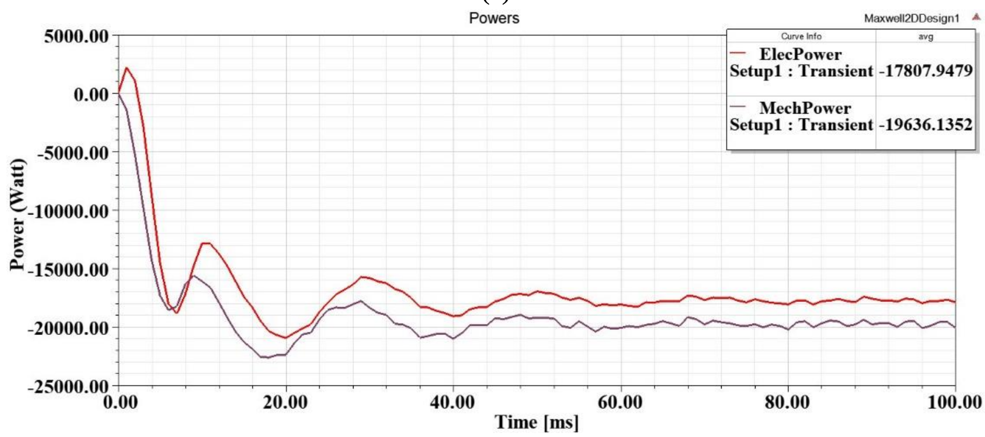

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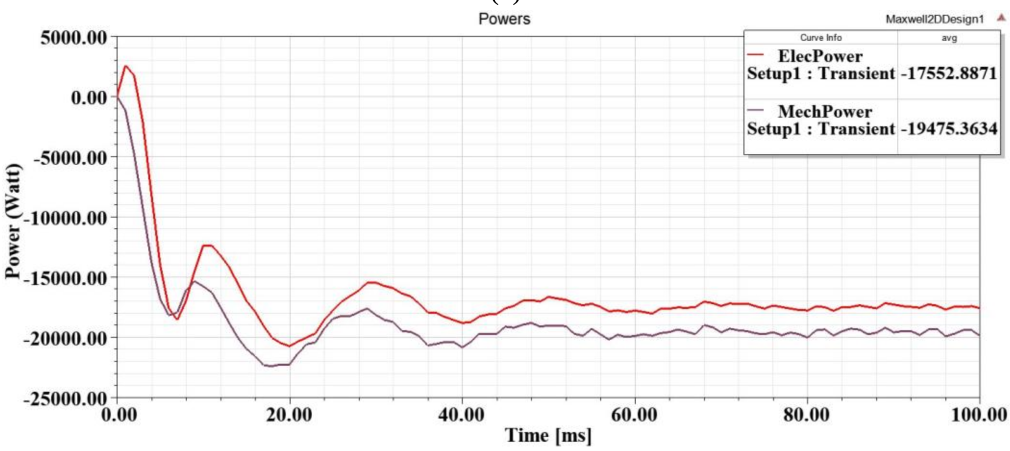

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Figure 4. Electric and mechanical power of the PMSGs a) silicon steel core type b) amorphous metal alloys core type c) manganese-zinc ferrite core type

It is observed the core losses in the analysis results. Other losses were neglected to analyze the effective efficiency of the stator cores. As a result of the loss analysis, the performance analysis of the PMSGs with silicon steel, amorphous metal alloys, and manganese-zinc ferrite is presented in the power analysis given in Figure 4. Amorphous metal alloys offer lower core losses compared to silicon steel and ferrite materials, making them highly efficient for wind power applications. The analysis results present that Amorphous metal alloys have a non-crystalline atomic structure, which contributes to their good magnetic properties and low core losses. The ferrite materials have higher core losses than amorphous metal alloys and silicon steel.

4. Conclusion

Accurate design and careful material selection are pivotal in generators that deliver high performance while remaining cost-effective. This research delves into the impact of diverse core materials on Permanent Magnet Synchronous Generators (PMSGs) and explores strategies for enhancing their efficiency through a materials-oriented approach. Through detailed case studies conducted via ANSYS software, the optimal pairing of core and winding materials is scrutinized with the goal of efficiency enhancement. The outcomes of these case studies are meticulously compared against predetermined PMSG parameters and scrutinized utilizing ANSYS Maxwell 2D software tools.

In this study, the examination of loss analysis yielded insights into the performance of PMSGs employing different core materials, including silicon steel, amorphous metal alloys, and manganese-zinc ferrite. Notably, it is observed that amorphous metal alloys exhibit superior efficiency due to their significantly lower core losses compared to silicon steel and ferrite materials. Conversely, ferrite materials demonstrate higher core losses when compared to both amorphous metal alloys and silicon steel, highlighting the importance of material selection in optimizing PMSG performance.

Conflict of Interest Declaration

The author has no conflicts of interest to declare.

Researchers' Contribution Rate Declaration Summary

The author declares that he has contributed 100% to the article.

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