

etic composite materials to fabricate the stator core offers greater design flexibility, but the lower permeability and saturation flux density limit the ability to achieve high output torque [13,14]. Research has been conducted to maximize the advantages of both materials. A study on a permanent magnet claw-pole motor with a double-stator structure utilized both soft magnetic composite and electrical steel. The stator yoke was constructed from electrical steel, while the soft magnetic composite was applied to the claw-pole stator teeth, and the performance of various rotor structures and hybrid core designs was compared [15]. In another study, a soft magnetic composite was applied to the stator teeth and shoe in a claw-pole transverse-flux machine. Based on this configuration, the characteristics of a model using a newly developed SL-soft magnetic composite material were compared and analyzed against those of a model using a conventional soft magnetic composite [16]. Lastly, another study focused on optimizing rotor permanent magnets to reduce torque ripple while simultaneously utilizing both soft magnetic composite and electrical steel in the stator core design. By adjusting the rotor arc width ratio, the study aimed to effectively minimize torque ripple [17]. This paper proposes a structure that maximizes the advantages of both materials by applying a soft magnetic composite to areas of the stator requiring design flexibility and electrical steel to the central region of the stator core while maintaining the same shape and size of the permanent magnets. Through this approach, we propose a cladding core structure that effectively leverages the properties of both materials, resulting in higher torque at low speeds compared to using only soft magnetic composite material, by performing a finite element method (FEM) analysis.

2. Materials and Methods

Axial flux motors generate torque in the same manner as conventional synchronous motors, where multi-phase current is applied to the windings placed in the stator, and torque is generated through interaction with the magnetic flux from the field magnet. In radial flux motors, the area of the air gap where current and magnetic flux interact is defined by both the rotor radius and the motor length, whereas in axial flux motors, the air gap area is defined solely by the rotor radius. The rotational force generated in an axial flux motor can be expressed by Lorentz's force law, as shown in (1) [18].

I is the applied current, B_{airgap} is the air gap flux density, and $A(r)$ is a sheet of uniform surface current density, where $\vec{r} = A(r) d\vec{S}$, $d\vec{r}$ is the radial distance at the sheet of uniform surface current density, dS is the surface component, and B_{airgap} is the vector of the normal component of the magnetic flux density in the air gap. An axial flux-type

motor provides a B_{airgap} value that is practically independent of the radius component. The tangential force acting on the core can be calculated using the Ampere's equation.

$$\vec{F} = I \left(d\vec{r} \times \vec{B} \right) = A(r) (d\vec{S} \times \vec{B}_{airgap}) \quad (1)$$

A sheet of uniform surface current density is also a function of the radius, so the max value of the line current density is determined using (2). The number of the phase is m , the number of poles is p , the number of turns is N , and the pole pitch is $\tau(r)$ and expressed as $\pi r/p$.

$$A(r) = \frac{m}{2\pi} \frac{2NI}{p\tau(r)} \quad (2)$$

To account for the shape of the air gap, the air gap flux density factor (α_k) can be incorporated, as shown in (3). The air gap flux density factor (α_k) is defined as the ratio of the average air gap flux density (B_{avg}) and the max air gap flux density (B_{max}).

$$\alpha_k = \frac{B_{avg}}{B_{max}} \quad (3)$$

$$B_{max}$$

The magnitude of the resulting torque is given by (4), where k_ω represents the winding factor. Assuming the magnetic flux density meets the current perpendicularly, they are considered independently in the calculation. The B_{airgap} value is expressed as $\alpha k B_{max}$, and the motor has a circular shape dS , expressed as $2\pi r dr$.

$$\begin{aligned} dT &= r dF = r [k_\omega A(r) B_{airgap} dS] \\ &= 2\pi \alpha k B_{max} A(r) k_\omega r^2 dr = 2\alpha k B_{max} m l N k_\omega r dr \end{aligned} \quad (4)$$

Equation (5) can be derived by integrating (4) over the range from the inner radius of the motor ($D_{in}/2$) to the outer radius of the motor ($D_{out}/2$) because the actual diameter of an AFPM motor is determined by the difference between the outer and inner diameters.

$$T = \int_{D_{in}/2}^{D_{out}/2} 2\alpha k B_{max} m l N k_\omega r dr \quad (5)$$

This is expressed as (6).

$$T = \frac{1}{4} \alpha_k m l N k_\omega B_{max} (D_{out}^2 - D_{in}^2) \quad (6)$$

By using the ratio of the inner to outer radius ($k_d = D_{in}/D_{out}$), it can be expressed as (7).

$$T = \frac{1}{4} \alpha_k m l N k_\omega B_{max} D_{out}^2 (1 - k_d^2) \quad (7)$$

The output torque of an axial flux motor is determined by the motor's diameter, flux density, number of turns, current, and number of phases. In particular, the motor's outer diameter and the difference between the outer and inner diameters (k_d) have a significant impact on the torque, and as the flux density and current increase, the torque also increases.

Additionally, the armature flux density ($B_{F.M}$) and the field flux density (B_A) are defined. As shown in (8), the air gap flux density consists of the saturation flux density of both the field magnet and the armature.

$$B_{avg} = B_{F.M} + B_A \quad (8)$$

$\phi_{F.M}$ is defined as the armature flux, $A_{F.M}$ is the armature core area, $R_{F.M}$ is the armature core reluctance, $l_{F.M}$ is the armature core length, and $\mu_{F.M}$ is the permeability of the core. The armature flux, as expressed in (9), is represented as the flux density over the area through which the flux passes.

$$B_{F.M} = \frac{\phi_{F.M}}{A_{F.M}} \quad (9)$$

As shown in (10), it can be observed that the core permeability and saturation flux density values contribute significantly.

$$\phi_{F.M} = \frac{B_{F.M} l_{F.M}}{\mu_{F.M} R_{F.M}} \quad (10)$$

Unlike radial flux motors, which laminate electrical steel of identical shapes in the axial direction, as shown in Figure 1a, axial flux motors laminate electrical steel with non-uniform shapes in the radial direction, as illustrated in Figure 1b. Additionally, altering the shape of the

stator core to reduce torque ripple or improve efficiency can be extremely challenging, or even impossible, due to the complex lamination manufacturing techniques required. To overcome these manufacturing limitations, extensive research has been conducted on using soft magnetic composite materials, which have high formability, for stator cores, as shown in Figure 1c [19]. Soft magnetic composite materials are designed to suppress eddy current generation by combining thermosetting resins that inhibit electron movement with materials of low electrical conductivity [20]. This material works by coating the surface of iron powder particles with a thin insulating layer, which blocks potential conductive paths within the matrix and creates insulation barriers between layers, preventing the easy formation of eddy current loops. Due to these material properties, soft magnetic composite materials offer high formability, enabling the production of complex core shapes [21]. Additionally, the powder-based composition of soft magnetic composite materials helps reduce eddy current losses at high speeds, as the penetration depth decreases due to the skin effect. However, cores made from soft magnetic composites have randomly aligned particles and contain pores, unlike electrical steel, which increases electrical resistance and makes it difficult for current to follow a consistent path. As a result, the current flow within the core is disrupted, leading to higher eddy currents at low speeds [22,23]. Furthermore, during the powder compaction process used to manufacture the core, the material's inherent properties can cause core breakage. Despite its high stiffness, the material has relatively low strength, necessitating precise manufacturing techniques [24,25].

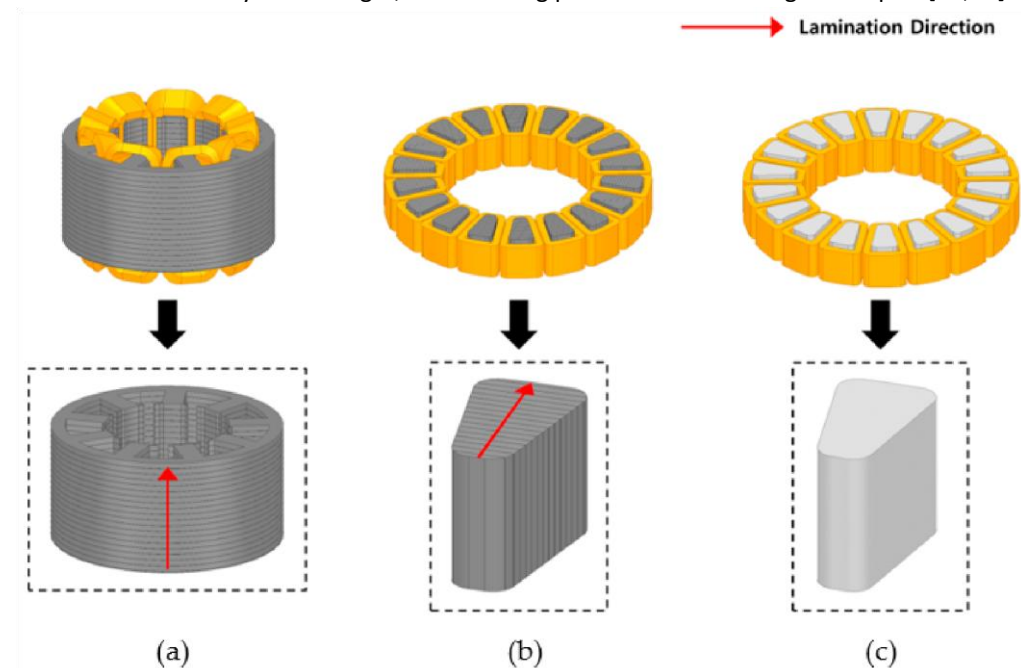


Figure 1. Lamination direction depending on motor: (a) radial flux motor lamination with Si steel; (b) axial flux motor lamination with Si steel; (c) axial flux motor lamination with soft magnetic composite.

Figure 2 shows the structure of the axial flux motor used in this study. The motor consists of a stator, a rotor, permanent magnets, and coils, with the flux generated by the rotor moving parallel to the rotation axis [26]. Due to this flux flow, axial flux motors generally have an unstable structure that creates attractive forces between the stator and the rotor, which can lead to an uneven air gap formation [27]. To reduce the magnetic imbalance between the stator and the rotor, a structure with two rotors and one stator was used. Table 1 presents the specifications of the baseline model. To minimize vibration and noise, a 16-pole, 18-slot configuration was adopted [28–30]. The outer and inner diameters of the motor were set to 200 [mm] and 150 [mm], respectively, with a stack length of 64.8 [mm]. Additionally, to ensure accurate comparison, the number of turns and current were kept identical. Since soft magnetic composite materials are manufactured through powder

compaction, they require careful handling to avoid external impact. Therefore, a soft magnetic composite material (Hoganas 500 1P, 600 MPa) with tensile stress and strength similar to electrical steel (27PNX1350F) was selected.

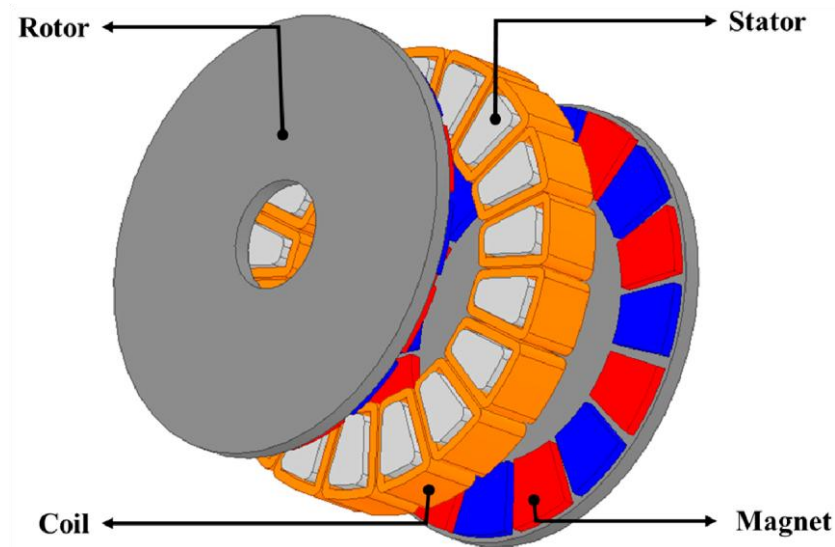


Figure 2. Structure of AFM.

Table 1. Axial flux-type motor model specifications.

Parameter	Unit	Single Soft Magnetic Composite Core	Single Electrical Steel Core
Pole/Slot	-	16/18	16/18
Outer/Inner diameter	mm	200/125	200/125
Axial Length	mm	64.8	64.8
Input Current	Arms	24.3	24.3
Turns	-	49	49
Material	-	Hoganas 500 1P, 600 MPa	27PNX1350F

Figure 3 presents the speed–torque performance comparison data when silicon steel and soft magnetic composite materials were applied as the stator core in an axial flux motor. When the same current was applied, the model with electrical steel as the stator core generated 75.09 [Nm] of torque and 14.36 [W] of iron loss at 800 [r/min]. At the maximum speed of 1600 [r/min], it produced 36.32 [Nm] of torque and 33.83 [W] of iron loss. On the other hand, when soft magnetic composite material was used as the stator core, it generated 68.49 [Nm] of torque and 52.28 [W] of iron loss at 800 [r/min], and 33.34 [Nm] of torque and 114.61 [W] of iron loss at 1600 [r/min]. As observed from the analyzed output torque and loss comparison data, applying silicon steel resulted in higher torque and lower iron loss compared to using a soft magnetic composite. This indicates that silicon steel can offer higher efficiency.

As shown in Figure 4, when the same external magnetic field was applied, the soft magnetic composite material (Hoganas 500, 1P, 600 MPa) had lower flux density and permeability compared to electrical steel (27PNX1350F). Additionally, due to its material properties, it exhibited relatively higher iron loss at lower frequencies. For these reasons, electrical steel is generally used as the core material for motor stators, enabling superior output torque. As previously mentioned, various manufacturing methods have been developed to apply electrical steel, with its excellent magnetic properties, to the stator of axial flux motors, including tightly folding the steel in strip form or producing it in a roll form. However, these manufacturing methods are limited in their ability to accommodate detailed shape designs aimed at reducing torque ripple, and they also have drawbacks in terms of manufacturing quality, such as tearing at the corners of the stator core. This paper proposes a cladding core technology that maximizes the utilization of flux crossing the air gap to increase output torque. In this approach, the outer part of the stator core, which has a

complex and irregular shape, uses a soft magnetic composite material with high formability, while the central part of the stator core employs laminated electrical steel with a symmetrical shape that is easier to manufacture.

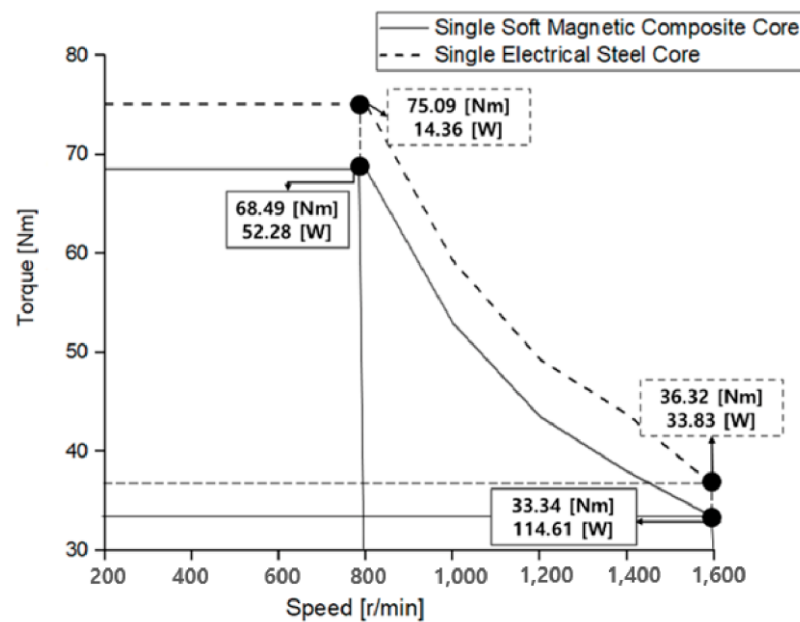


Figure 3. Characteristic curves for each material.

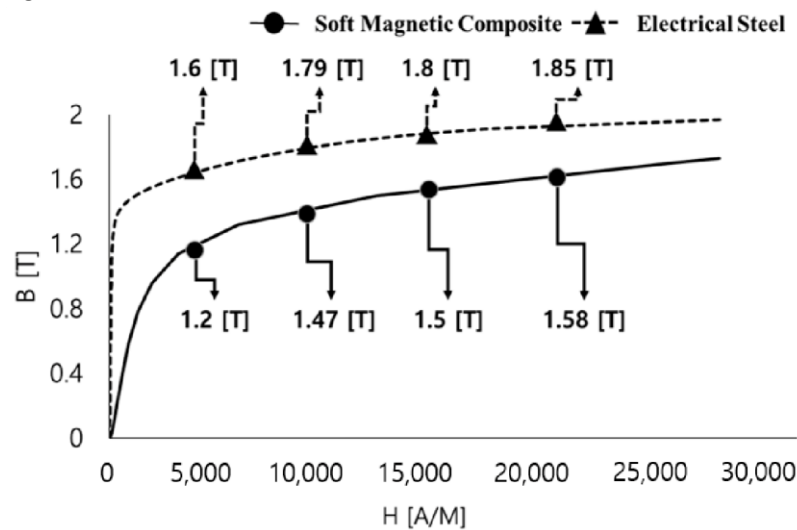


Figure 4. Characteristic curves for each of the materials.

3. Performance Analysis of AFPM with Cladding Core

When applying electrical steel, which has limited formability, the stator core may be designed with an I-type core, as shown in Figure 5a, rather than the Fan-type core in Figure 5b. However, as seen in Figure 6, this design results in lower performance compared to a model that uses a Fan-type core, which better maximizes the flux crossing the air gap. Therefore, the stator core should use a Fan-type core that can fully utilize the air gap flux.

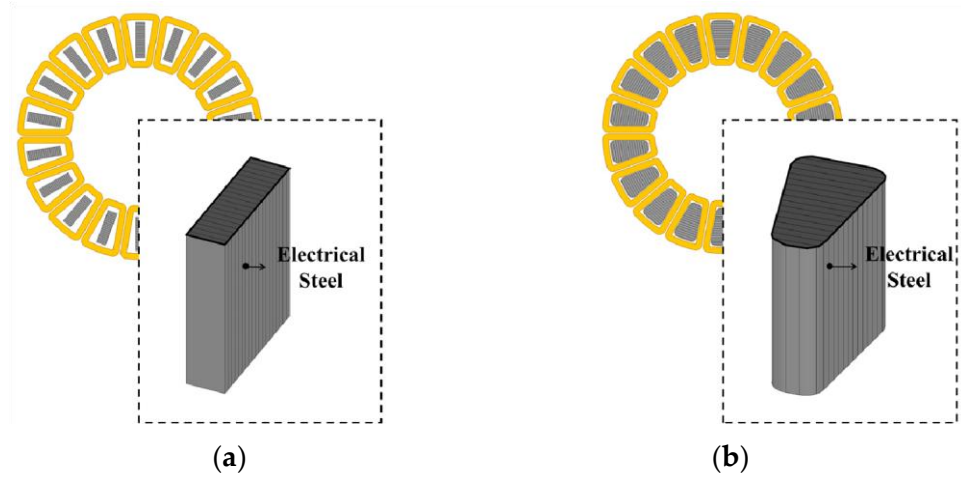


Figure 5. AFM core structure: (a) I-type core; (b) Fan-type core.

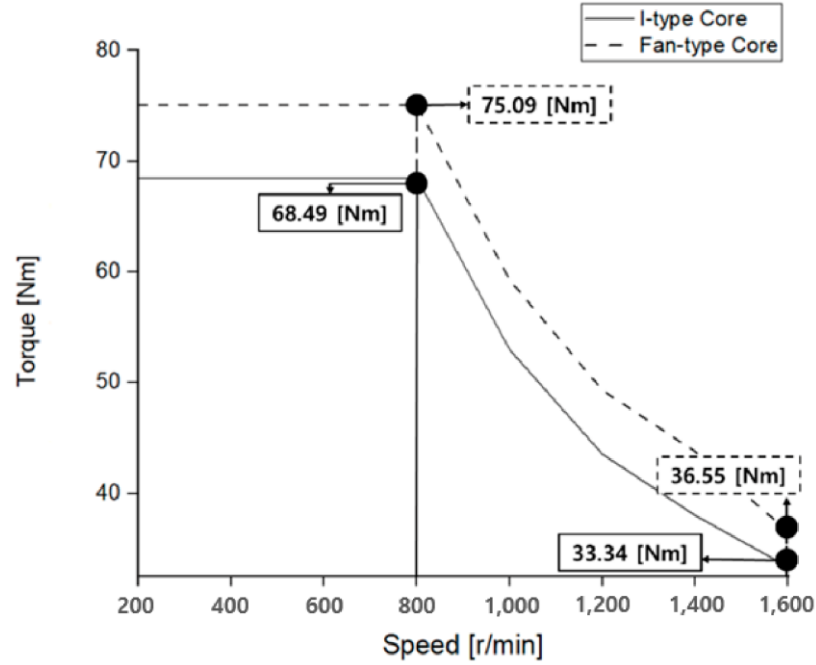


Figure 6. Characteristic curves for each core type.

$\phi_{E.S}$ represents the flux in the electrical steel, and ϕ_{smc} represents the flux in the soft magnetic composite material. When applying the cladding core proposed in this paper, $\phi_{F.M}$ is expressed as the sum of the flux in the electrical steel and the flux in the soft magnetic composite, as shown in (11).

$$\phi_{F.M} = \phi_{E.S} + \phi_{smc} \quad (11)$$

$B_{E.S}$ is the flux density of the electrical steel, $\mu_{E.S}$ represents the permeability of the electrical steel, $R_{E.S}$ is the reluctance of the electrical steel, and $l_{E.S}$ is the length of electrical steel. Similarly, B_{smc} is the flux density of the soft magnetic composite, μ_{smc} represents the permeability of the soft magnetic composite, R_{smc} is the reluctance of the soft magnetic composite, and l_{smc} is the soft magnetic composite. As shown in (12), by using two different materials, the flux in each material is determined in proportion to the flux density and the length of the electric steel and soft magnetic composite, and it varies inversely with the permeability and flux reluctance of each material.

$$\phi_{F.M} = \frac{B_{E.S} I_{E.S}}{\mu_{E.S} R_{E.S}} + \frac{B_{smc} I_{smc}}{\mu_{smc} R_{smc}} \quad (12)$$

This affects the average flux density in (8), ultimately leading to changes in torque. Figure 7 shows the flux density saturation under the same size, number of turns, and load conditions as in Table 1. Figure 7a illustrates the flux density saturation in a core with a single soft magnetic composite material, while Figure 7b shows the flux density saturation in a core with cladding. Electrical steel has a higher permeability than soft magnetic composite material, allowing it to concentrate flux more efficiently, resulting in relatively lower leakage flux. Therefore, as seen in Figure 7, more flux flows through the high-permeability electrical steel. As shown in Figure 7b, even when the outer part of the electrical steel becomes saturated, the surrounding soft magnetic composite material helps minimize leakage, allowing the flux to continue flowing through the outer region of the core.

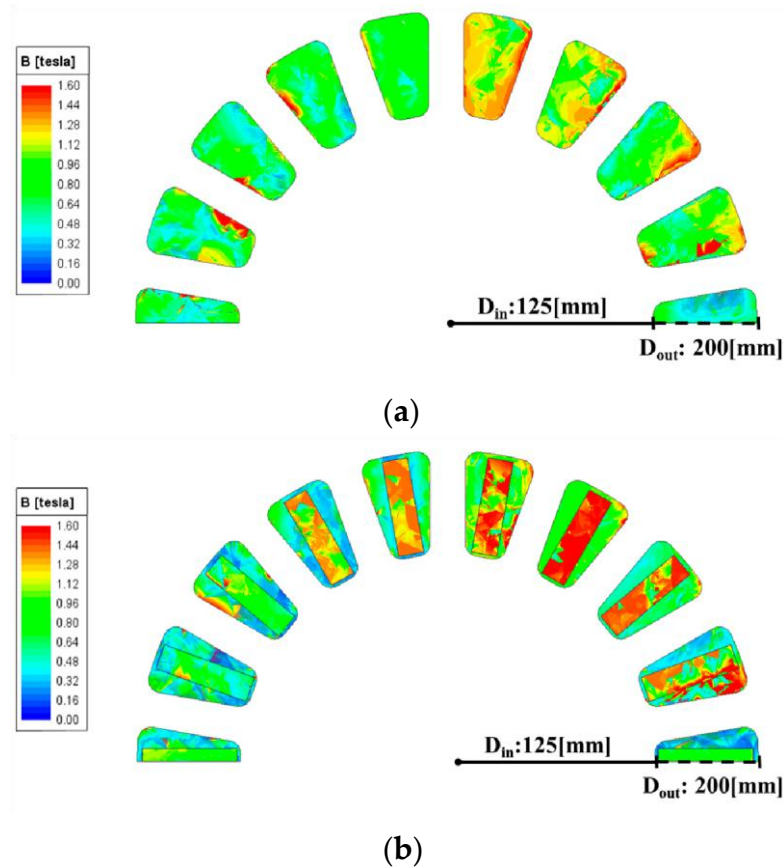


Figure 7. Magnetic flux density saturation of the core: (a) single soft magnet composite core; (b) cladding core (I-type).

Additionally, Figure 8 shows a per-unit (P.U.) graph of the armature flux density and iron losses based on the proportion of electrical steel and the soft magnetic composite material used in the cladding core. The flux density is determined based on the maximum saturation flux density of the soft magnetic composite material and electrical steel. The maximum iron loss value at the base speed of 200 [Hz] was also considered. As the proportion of electrical steel approaches 1, the armature flux density increases, resulting in higher torque and minimal iron losses. Conversely, as the proportion of the soft magnetic composite material approaches 1, the armature flux density decreases, leading to lower torque and maximum iron losses.

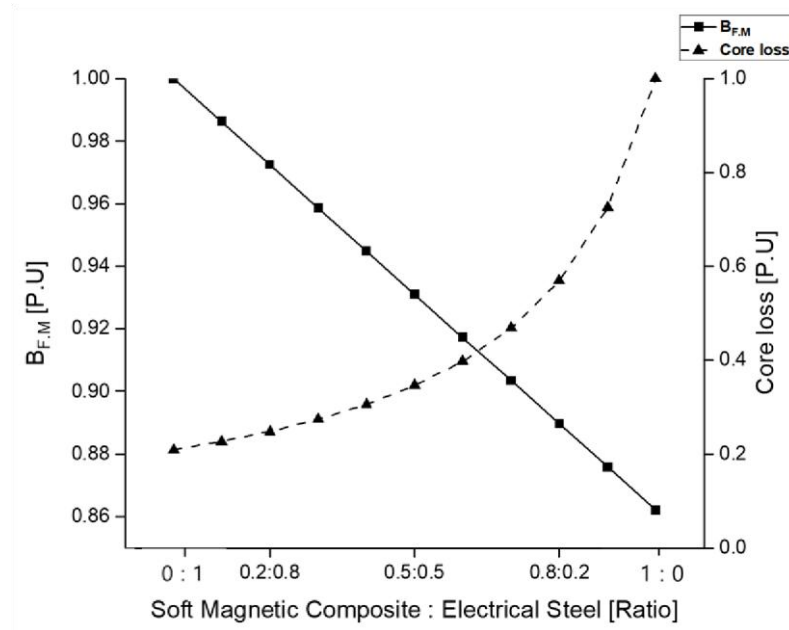


Figure 8. Comparison of the magnetic flux density and core loss according to the proportion of material; as this proportion approaches 1, the armature flux density decreases, leading to lower torque and maximum iron losses.

P_{loss} is the total core iron loss, P_{hys} is the total hysteresis loss, P_{eddy} is the total eddy current loss, and P_{exc} is the total excess loss. As shown in (13), P_{loss} consists of hysteresis loss, eddy current loss, and excess loss.

$$P_{loss} = P_{hys} + P_{eddy} + P_{exc} \quad (13)$$

$\eta_{E.S}$ is the hysteresis constant of the electrical steel, f is the frequency, and η_{smc} is the hysteresis constant of the soft magnetic composite. As shown in (14), P_{hys} expressed as the sum of the hysteresis loss of electrical steel and the soft magnetic composite. The hysteresis loss in the electrical steel is expressed as $\eta_{E.S} f B_{E.S}^2$ and is proportional to the square of the flux density. Additionally, the hysteresis loss in the soft magnetic composite is represented by $\eta_{smc} f B_{smc}^{1.75}$ and is proportional to the 1.75th power of the flux density.

$$P_{hys} = \eta_{E.S} f B_{E.S}^2 + \eta_{smc} f B_{smc}^{1.75} \quad (14)$$

$k_{e,E.S}$ is the eddy current loss coefficient of the electrical steel, $\rho_{E.S}$ is the electrical resistivity of the electrical steel, $k_{e,smc}$ is the eddy current loss coefficient of the soft magnetic composite, and ρ_{smc} is the electrical resistivity of the soft magnetic composite. As shown in (15), P_{eddy} is expressed as the sum of the eddy current loss of electrical steel and the soft magnetic composite. The eddy current loss in electrical steel is determined by $k_{e,E.S}$, $B_{E.S}$, f , and $\rho_{E.S}$, and it is proportional to the square of f and $B_{E.S}$ while inversely proportional to the electrical resistivity. Similarly, the eddy current loss in the soft magnetic composite is influenced by $k_{e,smc}$, B_{smc} , f , and ρ_{smc} .

$$P_{eddy} = \frac{k_{e,E.S} f^2 B_{E.S}^2}{\rho_{E.S}} + \frac{k_{e,smc} f^2 B_{smc}^2}{\rho_{smc}} \quad (15)$$

$P_{exc,E.S}$ is the excess loss in the electrical steel, and $P_{exc,smc}$ is the excess loss in the soft magnetic composite. As shown (16), P_{exc} refers to additional energy losses that cannot be

explained by hysteresis loss or eddy current loss. It can be expressed as the sum of $P_{exc,E.S}$ and $P_{exc,smc}$.

$$P_{exc} = P_{exc,E.S} + P_{exc,smc} \quad (16)$$

Since the cladding core uses both electrical steel and soft magnetic composite material simultaneously, it results in lower iron losses at low speeds compared to axial flux motors that use a single soft magnetic composite. In other words, by utilizing the properties of both electrical steel and a soft magnetic composite to increase the flux density across the entire stator core, this structure provides the advantage of increased output torque while reducing iron losses. Therefore, it is necessary to analyze the effect by minimizing the number of layers of electrical steel plates inserted into the center of the core.

In this study, to investigate the minimal multilayer structure, the output torque was analyzed by applying I-type and T-type stator core structures. Additionally, since the thickness of the electrical steel inserted in the core's center cannot be increased indefinitely, the soft magnetic composite material applied to the outer part of the core must not be too thin, as this could lead to core saturation and flux leakage. To prevent this, the thickness of the soft magnetic composite material was set to 1 [mm].

Figure 9 illustrates the I-type stator core structure. The design variables for the I-type stator core include the width (W_i) and thickness (T_i) of the electrical steel, and these were selected for analysis. Additionally, if the outer thickness of the core with the applied soft magnetic composite material becomes oversaturated, flux leakage occurs, leading to a reduction in torque. As shown in Figure 10, when T_i varied from 2 [mm] to 8 [mm], the torque increased from 62.51 [Nm] to 70.41 [Nm], representing a 12.63 [%] increase, and the iron losses decreased from 44.06 [W] to 27.6 [W], representing a 37.35 [%] reduction. Figure 11 shows the results of the analysis of the characteristics with varying $Width_i$. Based on the previously analyzed optimal T_i length of 8 [mm], W_i varied from 5 [mm] to 30 [mm]. The torque increased from 65.21 [Nm] to 69 [Nm], showing a 9.5 [%] increase, and the iron losses decreased from 50.01 [W] to 46.07 [W], representing a 9.48 [%] reduction. This analysis shows that, for the I-type stator, changes in the thickness of the electrical steel inserted into the core's center have a greater impact on torque than changes in width. Additionally, it was observed that increasing the amount of electrical steel reduced iron losses. Therefore, when the I-type stator cladding core structure had a T_i of 8 [mm] and a W_i of 30 [mm], the torque increased by 3.23 [%] to 70.41 [Nm], and iron losses decreased by 45.94 [%] to 27.6 [W] compared to a motor using a single soft magnetic composite material in an axial flux configuration, improving the overall characteristics.

Next, to examine the minimal multilayer cladding core structure, a T-type structure was proposed and analyzed, as shown in Figure 12. Although it is possible to set a larger number of stages, we limited it to a simple structure, centrally laminated electrical steel output torque comparison model, which is an advantage of cladding core technology. To analyze the characteristics of the T-type two-layer cladding core structure with a central laminated electrical steel core, the optimized design value of $T_{T1} = 8$ [mm] from the previous I-type cladding core study was selected. To implement the two-layer structure, the design variables W_{T1} , W_{T2} , and T_{T2} were adjusted, and the lengths were modified within the range that maximized the utilization of the cladding core. The Fan-type core had a structure that narrowed toward the center and gradually widened toward the outer region. As shown in Table 2, as W_{T2} increased, T_{T2} decreased, based on the same outer thickness of the core. These were categorized into different cases, and Figure 13 shows the results for each case. The torque increased by 4.09 [%], from 71.47 [Nm] to 74.39 [Nm], while the iron losses decreased by 6.88 [%], from 25.47 [W] to 23.71 [W]. This indicates that as the area of the electrical steel used increases, the torque increases, and the iron losses decrease. As a result, in Case 2, where T_{T1} and W_{T1} were 8 [mm] and 16 [mm], and T_{T2} and W_{T2} were 16 [mm] and 14 [mm], respectively, the torque increased by 8.61 [%] to 74.39 [Nm], and the iron losses decreased by 54.65 [%] to 23.71 [W] compared to when a single soft magnetic composite core was applied in an axial flux motor.

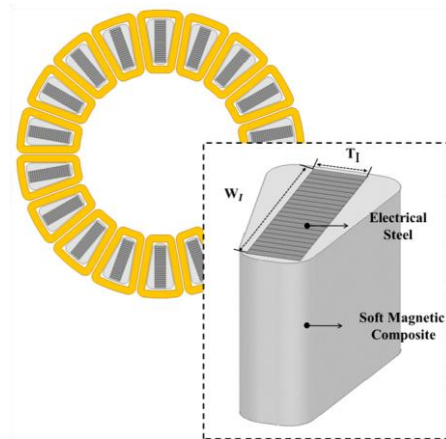


Figure 9. Cladding core (I-type) structure.

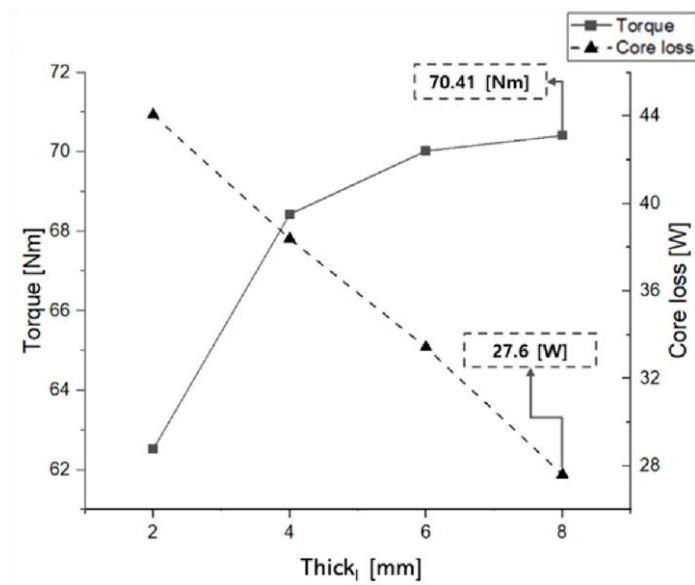


Figure 10. Characteristics according to the T_l of cladding core (I-type).

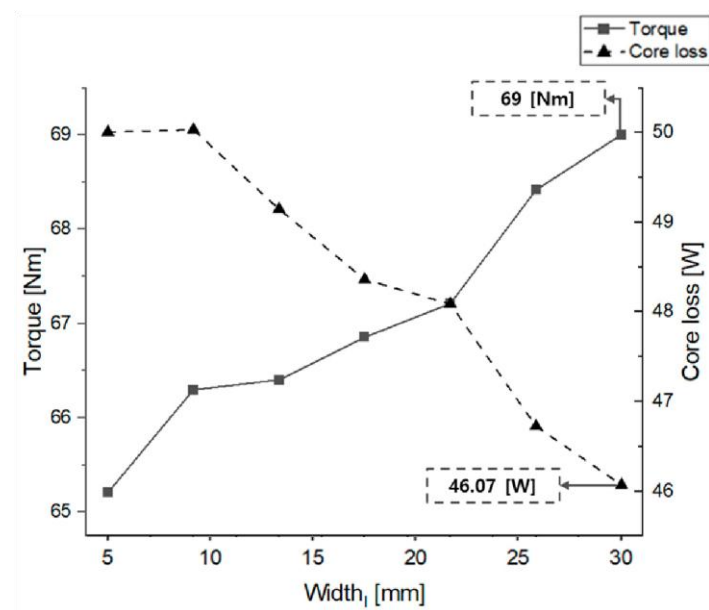


Figure 11. Characteristics according to the w_l of cladding core (I-type).

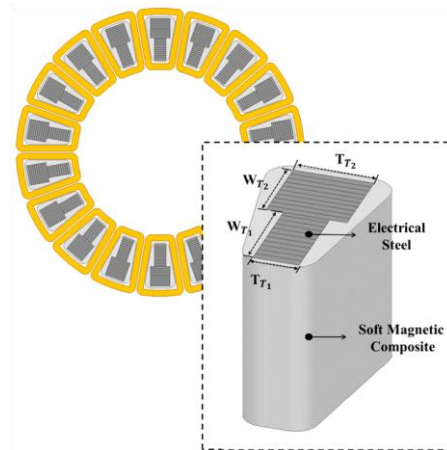


Figure 12. Cladding core (T-type) structure.

Table 2. The cladding core (T-type)'s case for analysis.

Case	W_{T1} [mm]	W_{T2} [mm]	T_{T1} [mm]	T_{T2} [mm]
1	20	10	8	17
2	16	14	8	16
3	12	18	8	14
4	8	22	8	13
5	4	26	8	11

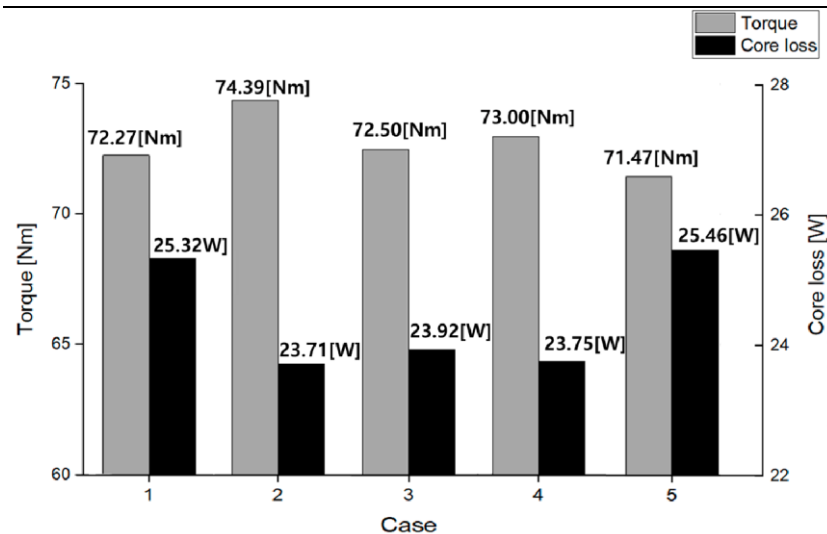


Figure 13. Characteristics according to the case of cladding core (T-type).

Figure 14 shows the efficiency map of an axial flux motor with a core made of soft magnetic composite material, while Figures 15 and 16 present the efficiency maps for I-type and T-type cladding cores. When the cladding core was applied, it was observed that iron losses decreased, and torque increased in the low-speed region compared to the motor with a single soft magnetic composite core. As a result, it was observed that the area with 90% efficiency was larger compared to when a single soft magnetic composite material was applied to the core. Figure 17 shows the magnetic flux density vector for the core with a single soft magnetic composite and for the cladding core (I-type and T-type). It can be observed that flux is concentrated in the center of the cladding core, specifically in the central region where electrical steel is applied. Under the same load conditions, the fact that more flux is concentrated in the cladding core indicates that the proportion of flux leakage into the air gap from the soft magnetic composite material applied to the outer part of the core is reduced, with more flux being directed into the central region where

the electrical steel is applied. This suggests that flux leakage is reduced compared to a core using a single soft magnetic composite material. Therefore, the cladding core structure more effectively reduces flux leakage compared to the structure using only soft magnetic composite material. Finally, Figure 18 and Table 3 show the characteristics of models using a single electrical steel core, a single soft magnetic composite core, and a cladding core. When the cladding core is applied under the same size and load conditions, the flux is concentrated in the center of the core, resulting in increased torque compared to the core using a single soft magnetic composite material. Additionally, the flux density is more evenly distributed between the center and outer regions of the core, reducing torque ripple. The axial flux motor with the I-type cladding core generated approximately 3.23 [%] more torque than the motor with a single soft magnetic composite core, producing 70.41 [Nm] of torque and achieving an efficiency of 94.04 [%], representing an improvement of 1.44 [%]. The magnetic field distribution between the stator and rotor becomes more uniform, reducing torque ripple by 2.18 [%] to a final value of 2.88 [%]. Furthermore, the axial flux motor with the T-type cladding core generated 8.61 [%] more torque, producing 74.39 [Nm] of torque, with an efficiency improvement of 3.5 [%] to reach 96.1 [%], and torque ripple was reduced by 2.79 [%], achieving a value of 2.27 [%]. In conclusion, based on the findings described above, the application of the cladding core shows a tendency to increase output torque. Furthermore, it demonstrates advantages such as reduced torque ripple and overall improved efficiency across the operating range.

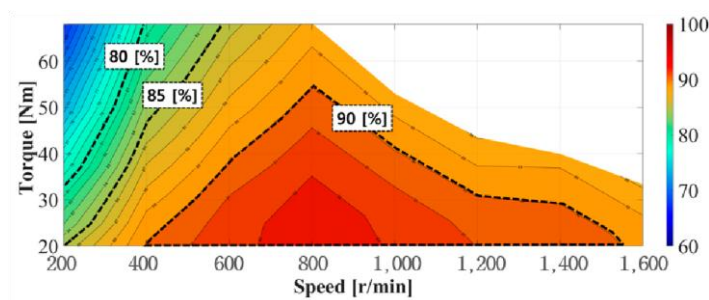


Figure 14. Efficiency map of the single soft magnetic composite core.

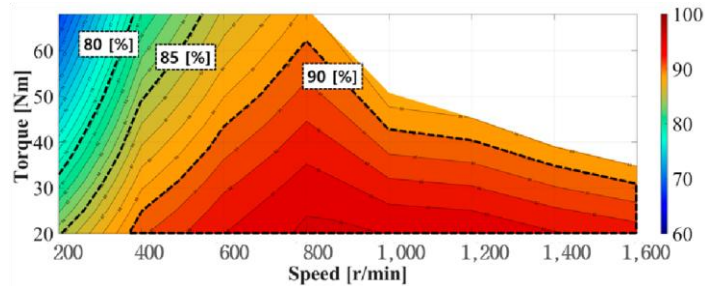


Figure 15. Efficiency map of cladding core (I-type).

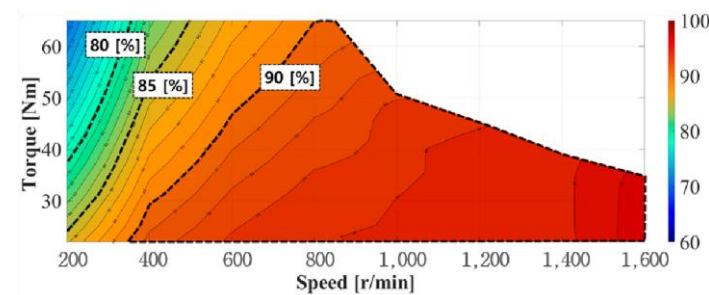


Figure 16. Efficiency map of cladding core (T-type).

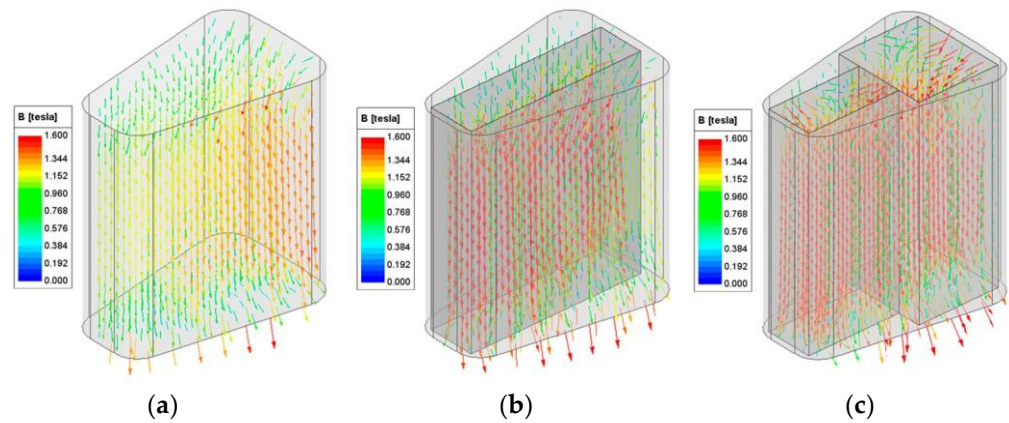


Figure 17. Magnetic flux density vector of the core: (a) single soft magnet composite core; (b) cladding core (I-type); (c) cladding core (T-type).

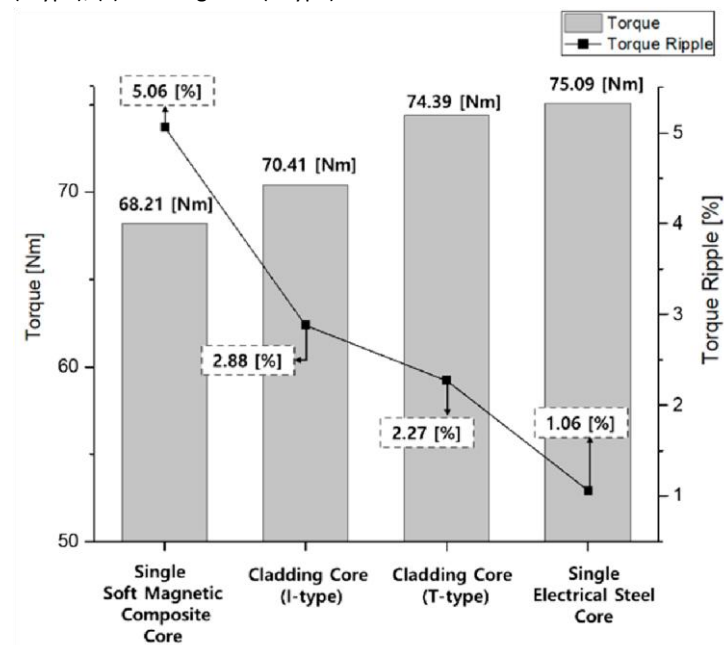


Figure 18. Comparative analysis of characteristics of the proposed model.

Table 3. Comparison of specifications for single soft magnetic composite core model and cladding core model.

Parameter	Unit	Single Soft Magnetic Composite Core	Cladding Core (I-Type)	Cladding Core (T-Type)
Outer/Inner diameter	mm	200/125	200/125	200/125
Axial Length	mm	64.8	64.8	64.8
Input Current	A _{rms}	24.3	24.3	24.3
Turns	-	49	49	49
Material	-	27PNX1350F	27PNX1350F Hoganas 500 1P, 600 MPa	27PNX1350F Hoganas 500 1P, 600 MPa
Torque	Nm	68.21	70.41	74.39
Torque Ripple	%	5.06	2.88	2.27

Efficiency	%	92.6	94.04	96.1
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4. Conclusions

As a solution to enhance the output torque of axial flux motors using a single soft magnetic composite material, this paper proposes a cladding core structure, by performing finite element method (FEM) analysis. When soft magnetic composite materials with high formability are applied to axial flux motors, the flux density generated under the same external magnetic field is lower compared to electrical steel due to the material's properties, resulting in lower output performance. To solve this issue, this paper proposes a structure that reduces flux leakage from the outer part of the stator core to the air gap and concentrates the flux toward the center of the stator core, thereby increasing the overall flux density and boosting output torque. This structure applies soft magnetic composite material to the irregularly shaped, asymmetrical outer part of the stator, while the regular, symmetrical center of the stator core is formed with electrical steel, creating a cladding core structure. As a result, the flux was evenly distributed throughout the stator core, leading to increased output torque and reduced torque ripple. Additionally, while soft magnetic composite materials tend to generate high iron losses at low speeds, the application of the cladding core reduced the amount of soft magnetic composite material used, thereby decreasing iron losses and improving efficiency. Therefore, to enhance the output torque of axial flux motors using soft magnetic composite materials, it would be appropriate to apply the T-type cladding core structure proposed in this paper. However, further research is needed on the manufacturing and mechanical design of axial flux motors for high-speed operation. To apply the cladding core proposed in this paper to high-speed applications, additional studies on material properties and manufacturing techniques will be necessary.

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