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Effect of Coil Diameter on the Performance of Interior and Embedded Permanent Magnet for Double-stator Generator

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ABSTRACT

The permanent magnet synchronous motor (PMSM) intended for low-speed, high-torque applications generally possesses a substantial physical size, and the internal space of the permanent magnet rotor is frequently underutilized. The rising electrical demands in electric machines have necessitated enhancements in power density, especially in double-stator systems featuring interior and embedded permanent magnets. Nevertheless, research on motors employing copper coils of differing sizes is restricted. This paper analyses the performance of an interior and embedded permanent magnet double-stator generator using JMAG software by varying the coil diameter, establishing an inverse proportionality between coil diameter and the number of turns per slot. Performance analysis under different loads and speeds showed that a 1.0 mm coil diameter achieved the highest average power (293W) at 2 ohms for speeds of 200 rpm and 1662 W at 1 ohms for 800 rpm. Larger diameters did not guarantee higher output; 0.75 mm and 1.0 mm were the best performers. A 1.0 mm coil also exhibited the best power efficiency (56%–75%) across all speeds, outperforming 0.5 mm (below 55% efficiency) and 1.5 mm (efficiency above 73% but with a steep slope in load resistance variation).

Keywords: Electrical power, PMSM, power efficiency, speed

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INTRODUCTION

Permanent Magnet Synchronous Machines (PMSMs) have attracted significant attention due to their efficiency, power density, and

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precise control capabilities (Krause et al., 2013; Lin et al., 2013; Mehrjou et al., 2017). They excel in regulating various parameters such as speed, torque, and position with high accuracy and responsiveness. PMSMs achieve this by directly converting mechanical energy into electrical energy through the shaft, eliminating the need for a gearbox and thereby improving efficiency (Rahman et al., 2010; Wang, 2008; Wu et al., 2009; Yasa & Mese, 2014). Gearboxes are prone to noise production, increased energy losses, and frequent maintenance requirements, leading to significant periods of inactivity.

The performance of PMSMs can be evaluated based on their structure and parameter design. They can be classified into three types based on stator and rotor numbers: single-stator single-rotor (Gieras et al., 2008), double-stator single-rotor (Chau et al., 2006; Liu et al., 2008; Feng et al., 2004; Gul et al., 2020; Norhisam et al., 2009; Wang et al., 2015; Zhang et al., 2020), and single-stator double-rotor (Zheng et al., 2013). The single-stator PMSMs require a significant number of poles and slots to generate more power. However, this approach can lead to unutilized space in the middle of the rotor. To address this issue, maintaining the size of the single-stator and adding another stator in the middle of the rotor can result in higher generated power. This is due to reduced magnetic flux leakages that flow in the direction of the shaft. This concept is supported by Feng et al. (2004), who conducted a performance analysis of a double-stator starter generator. Their study demonstrated that double-stator machines outperform single-stator ones. This is primarily attributed to the larger output torque of the armature winding in series, which acts as a motor at low speeds, and the ability to alter the two stator windings' relative positions when operating as a generator.

Zhang et al. (2020) demonstrated that double-stator PMSMs offer higher torque density, starting torque, and electric machine utilization compared to traditional single-stator machines. In contrast, the maximum output of a single-stator inner rotor permanent magnet motor is only 65.9% of that of a double-statordouble-stator PMSM, indicating that the former is underutilized, acting primarily as rotor support. Li (2022) investigated a wind turbine power generation system using a double-rotor machine configuration, which showed benefits such as reduced harmonic generation, lower costs, and improved reliability compared to traditional PMSGs. However, the mechanical complexity of double-rotor machines, requiring two separate shafts (a constant speed shaft for the inner rotor and a variable speed shaft for the outer rotor), led to their exclusion from this study.

Regarding the permanent magnet rotor structure, the researchers (Chau et al., 2006; Liu et al., 2008; Feng et al., 2004; Gieras et al., 2008; Gul et al., 2020; Li, 2022; Norhisam et al., 2009; Wang et al., 2015; Zhang et al., 2020) mostly utilized surface-mounted PMSMs, except for reference (Zheng et al., 2013), which employed an interior-mounted PMSM. Wu et al. (2022) explored various rotor structures for double-stator PMSMs, highlighting that surface-mounted permanent magnets only produce electromagnetic torque due to a closer-to-sine-wave air gap flux density waveform, with the d-axis and q-axis being the same. In contrast, interior permanent magnets can produce electromagnetic and reluctance torque because of a flat-top air gap flux density waveform, resulting in different d-axis and q-axis properties. Asgari and Mirsalim (2019) noted that surface-mounted permanent magnets can pose mechanical challenges, as they are more susceptible to dislodging at high perimeter speeds. Consequently, interior and embedded permanent magnet double-stator PMSMs were favored due to their high power density, efficiency, and reduced risk of permanent magnet dislodgement.

Several design parameters can enhance the performance of PMSMs, including the diameter of the copper coil. Qiu et al. (2024) observed that decreasing the number of turns or increasing the copper coil size in a PMSM results in non-linear growth in magnetic density, with local regions exceeding 2T. They also noted that eddy current density and loss vary synchronously in a V-shaped curve with changes in the number of turns. The eddy current loss is minimized at 26 turns and increases by 2 times with a 23% reduction in turns. Therefore, determining the suitable coil size is crucial to maximizing PMSM performance. However, a comparison of various copper sizes for an interior and embedded permanent magnet double-stator PMSM has not yet been presented.

This research investigates the impact of coil diameter on the performance of an interior and embedded permanent magnet double-stator PMSM. An S-shaped permanent magnet is utilized, as it has shown superior performance compared to U-shaped and V-shaped permanent magnets. The coil diameter varies from 0.5 mm to 1.5 mm, and the number of turns is calculated based on it. The performance of the interior and embedded permanent magnet double-stator PMSM is analyzed in terms of generated power using a two-dimensional finite element method.

STRUCTURAL CONFIGURATION AND DESIGN SPECIFICATION

Traditional PMSMs consist of a single stationary and rotating part, leading to lower generated power due to the unutilized space in the middle of the rotor. In contrast, double-stator generators feature two stationary parts and a rotating part, enabling full space utilization and increased power generation as shown in Figure 1. Neodymium iron boron (NdFeB) permanent magnets are chosen for their straightforward construction, low operating costs, and high-power efficiency. Two sizes are employed: 16 mm × 6 mm for embedded permanent magnets and 6 mm × 3 mm for interior permanent magnets. The 16 mm × 6 mm magnets are classified as embedded permanent magnets because one surface faces the air gap, while the 6 mm × 3 mm magnets are categorized as interior permanent magnets because none of their surfaces face the air gap, and the permanent magnet arrangement resembles the shape of a capital “S”. The three-phase PMSM is designed with 45 slots and 30 poles. The specification of the designed PMSM is shown in Table 1.

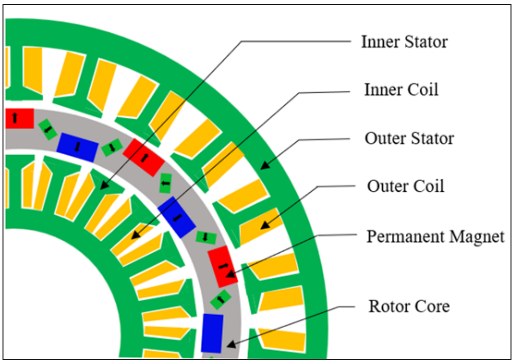


Figure 1. Structure of the designed PMSM

Table 1
Design specification of the designed PMSM

Design Parameter	Value
Inner Diameter [mm]	175
Outer Diameter [mm]	300
Airgap [mm]	3
Slots Number	45
Poles Number	30
Magnet Material	NdFeB
Rotor Core and Stator Material	50H800

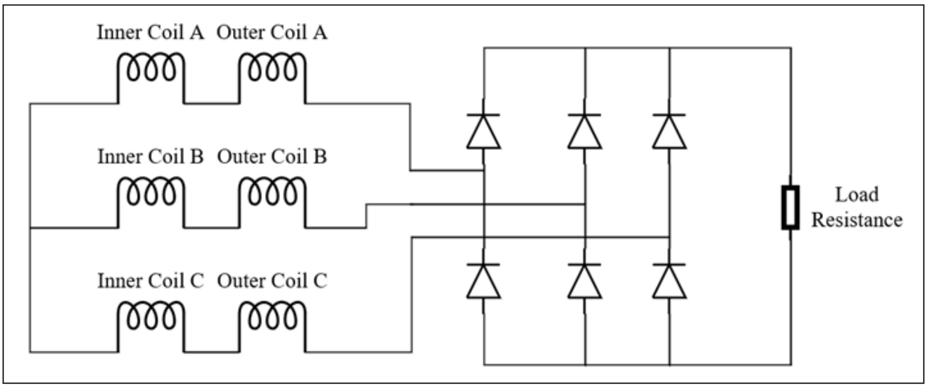


Figure 2. Coil connection of the proposed PMSM

The proposed PMSM consists of an inner coil for the inner stator and an outer coil for the outer stator. Each stator phase has 15 slots, making a total of 45 slots for the complete stator. Each coil is connected in series with the others, and the inner coil and outer coil are also connected in series for each phase, as illustrated in Figure 2. The output of each phase is then connected to a three-phase rectifier to convert the alternating current (AC) to direct current (DC). After the AC to DC conversion, a load resistor is connected and varied from 0.1 ohms to 30 ohms to observe the average power produced by the proposed PMSM.

EVALUATION METHOD

JMAG is a finite element analysis software tailored for the simulation and analysis of electrical machines. It enables the modeling of various operating conditions and facilitates the optimization of designs to enhance performance, efficiency, and reliability. The two-dimensional finite element method is enough to observe the performance of the PMSM, as its accuracy is less than 10% compared to the three-dimensional finite element method, and simulation can be done in minimal time. The diameter of the copper coil is inversely proportional to the number of turns in each slot and also depends on the coil space of the inner and outer stator. The relationship of the coil diameter with the number of turns and coil space is represented in Equation 1:

$$N = \frac{A_{winding}}{A_{coil}} \times C_{coefficient} \quad [1]$$

where N represents the number of turns, $A_{winding}$ represents the area of winding space in the stator, A_{coil} represents the area of the copper coil, and $C_{coefficient}$ represents the coil coefficient.

To validate the simulation and experimental results, the proposed PMSM was fabricated and assembled according to Figure 3, and the validation results are presented in Figure 4. The model numbers of the equipment used in the experiments are as follows: The motor controller is HPC300 72300, the DC motor is HPM05KW-12-PZ, and the torque sensor is TRB-10K. The fabricated PMSM uses a 1 mm coil diameter for validation, with the coil resistance for each phase measured at 1.04 ohms using an LCR meter (model LCR-8110G). The graph in Figure 4 shows the percentage differences in generated power between the simulation and experimental data, with a difference of 12%. This indicates that the disparities between the simulation and experimental results are relatively minor, suggesting that the simulation results are trustworthy and applicable.

Therefore, the fundamental design parameters are maintained constant, including the number of slots and poles, the size of the proposed PMSM, the air gap, and the permanent

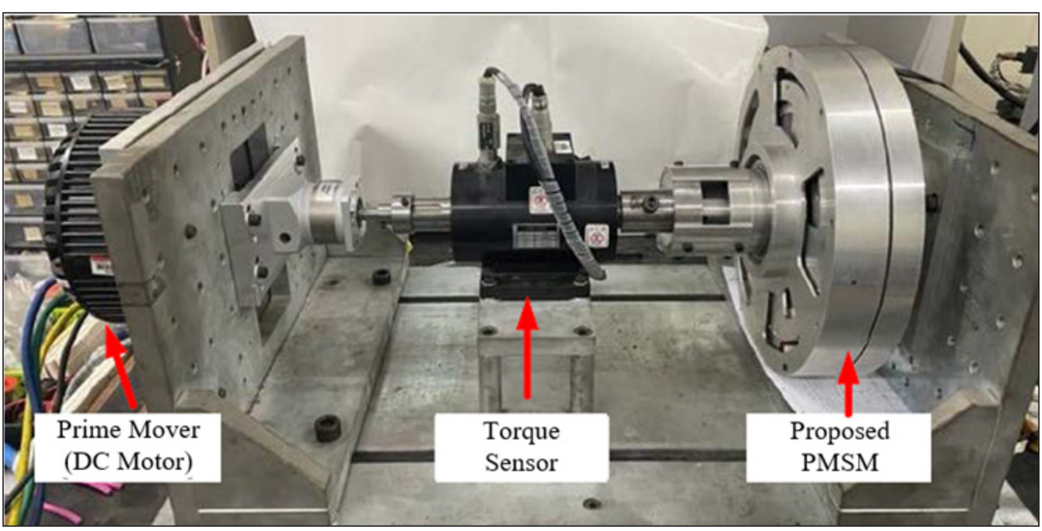


Figure 3. Experimental setup of the proposed PMSM

magnet. The number of turns for the inner and outer stators varies depending on the coil diameter, which ranges from 0.5 mm to 2.0 mm. The specific number of turns for each stator is presented in Table 2. The table indicates that the inner stator has fewer turns than the outer stator due to the limited winding space. Additionally, the number of turns decreases for each stator as the coil diameter increases.

The data includes electrical power measurements and total losses, which were obtained using JMAG-designer software. The average power and power losses represent the electrical power and losses that the proposed generator produces for each load resistance. The maximum average power is the peak power obtained from the graph, as in Figure 5. The efficiency of the power is calculated based on Equation 2:

$$E_{power}\ (\%) = \frac{P_{max}}{P_{losses} + P_{max}} \times 100 \qquad [2]$$

where E_{power} represents the power efficiency, P_{max} represents the maximum average power, and P_{losses} represents the power losses for the proposed generator.

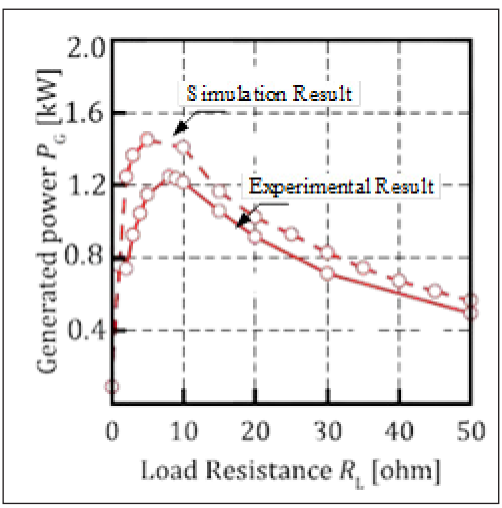


Figure 4. Validation result of proposed PMSM

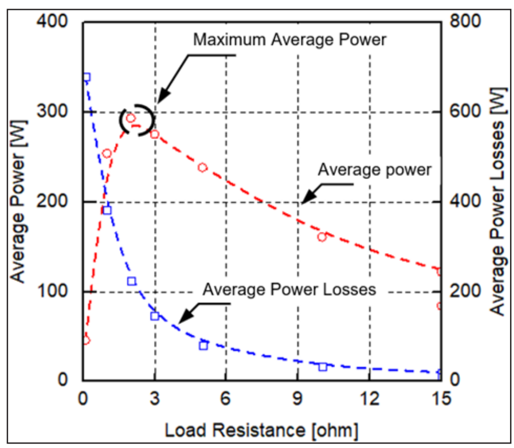


Figure 5. Data evaluation

POWER CHARACTERISTICS FOR DIFFERENT COIL DIAMETERS

Load Variation

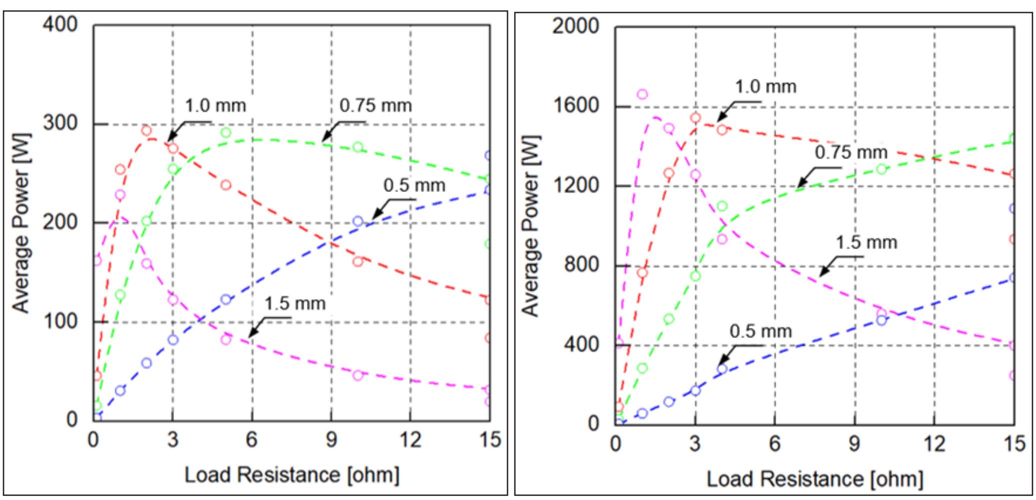
The performance of the proposed PMSM is evaluated based on the generated power produced by the PMSM for different loads

Table 2
Number of turns for each coil diameter

Coil Diameter [mm]	Number of Turns	
	Inner Stator	Outer Stator
0.5	52	79
0.75	23	35
1.00	13	20
1.50	6	9
2.0	3	5

and speeds. The load resistance was varied from 0.1 ohms to 30 ohms to observe the effect of coil diameter on the performance of the proposed PMSM. The maximum average power and the load resistance at which the maximum power occurs are recorded and analyzed. Figure 6 illustrates the load variation analysis, with the load resistance on the X-axis and the average power on the Y-axis for speeds of 200 and 800 rpm.

Based on the analysis for speeds of 200 rpm and 800 rpm, the highest average power is achieved with a coil diameter of 1.0 mm for 200 rpm, which is 293W at a load resistance of 2 ohms and 1662W with a coil diameter of 1.5 mm at a load resistance of 1 ohm for 800 rpm. Even though the coil diameter of 1.5 mm shows the highest average power at 800 rpm, the slope gradient drastically drops, yielding 800W at a load resistance of 6 ohms. In contrast, the average power for a coil diameter of 1.0 mm does not drop drastically, to 1500 W at a load resistance of 6 ohms. The results indicate that a larger coil diameter does not necessarily result in higher power output, nor guarantees a lower gradient of the average power slope. Based on the load resistance analysis, the best coil diameters were determined to be 1.0 mm, as they produce more power while maintaining a low gradient of the slope.



(a) Speed of 200 RPM (b) Speed of 800 RPM

Figure 6. Load variation

Power Efficiency

Power efficiency is crucial for minimizing energy wastage in each coil diameter. Figure 7 illustrates the total power versus speed graph, where the total power comprises the average power and power losses. Analyzing the graph for a coil diameter of 0.5 mm reveals that the power losses generated by the proposed PMSM are nearly equal to the average power at every speed. For instance, at 300 rpm, the power losses amount to 421 W, while the average power is 464 W. This indicates that a coil diameter of 0.5 mm is unsuitable for the proposed PMSM, as it results in losses comparable to the average power output. In contrast, for coil diameters of 1.0 mm and 1.5 mm, the average power at 800 rpm is 1545 W and 1662 W, respectively, with corresponding power losses of 896 W and 600 W. This suggests that these diameters are more favorable, as they yield higher average power outputs compared to the power losses incurred.

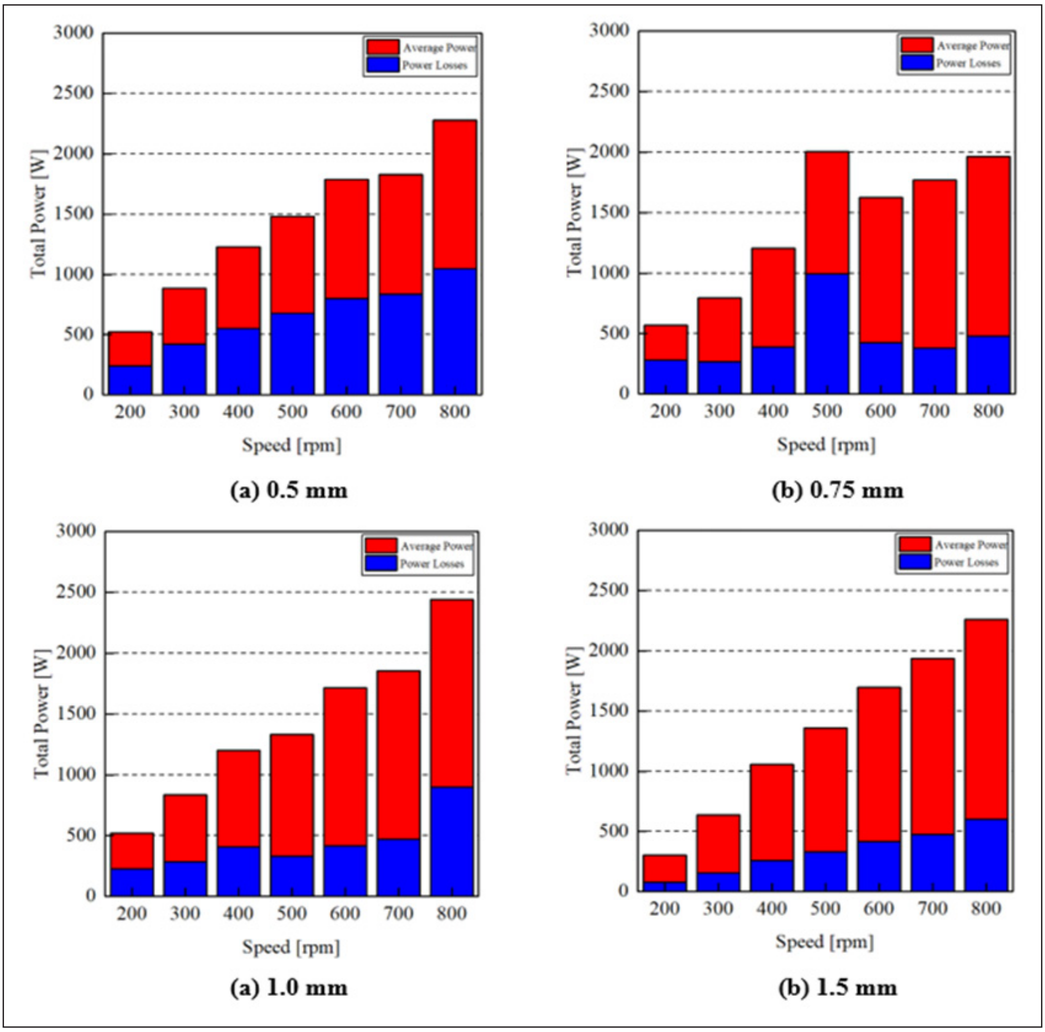


Figure 7. Average power and power losses for each coil diameter

Table 3 shows the power efficiency, which is one of the analyses to observe the performance of the proposed PMSM when varying the coil diameter. The lowest efficient coil diameter is 0.5 mm because it is achieved below 55% for every speed of the proposed

PMSM. Even though 1.5 mm reached 73% and above, it has a drawback: the slope of the graph was very steep when varying the load resistance. The coil diameter of 1.0 mm can be considered the best-performing size because the power efficiency is more than 55% for every speed, ranging from 56% to 75%.

Table 3
Power efficiency for each coil diameter

Speed (rpm)	Power Efficiency (%)			
	0.5 mm	**0.75 mm**	**1.0 mm**	**1.5 mm**
200	53.8	51.0	56.6	75.0
300	52.4	66.7	65.9	75.6
400	55.2	67.7	66.4	75.7
500	54.4	50.5	75.4	75.8
600	55.2	73.7	75.7	75.6
700	54.3	78.5	74.8	75.5
800	54.0	75.5	63.3	73.5

CONCLUSION

The study was conducted using JMAG software and focused on analyzing the performance of a permanent magnet synchronous motor (PMSM) by varying the coil diameter. The relationship between the coil diameter, number of turns, and coil space in the stator was established, indicating an inverse proportionality between the coil diameter and the number of turns per slot. The study maintained constant fundamental design parameters, such as the number of slots and poles, PMSM size, air gap, and permanent magnet properties. The number of inner and outer stator turns varied based on the coil diameter, ranging from 0.5 mm to 1.5 mm. Performance evaluation was conducted by analyzing the generated power under different loads and speeds. The analysis showed that a coil diameter of 1.0 mm achieved the highest average power (293W) at a load resistance of 2 ohms for speeds of 200 rpm and 1662 W at a load resistance of 1 ohms for 800 rpm. Larger coil diameters did not necessarily result in higher power output, and the best-performing coil diameters were found to be 0.75 mm and 1.0 mm, producing more power while maintaining a low gradient of the average power slope. Power efficiency analysis showed that a coil diameter of 1.0 mm performed the best, with power efficiency ranging from 56% to 75% for all speeds, compared to 0.5 mm, which consistently achieved below 55% efficiency, and 1.5 mm, which had efficiency above 73% but exhibited a steep slope in the graph when varying the load resistance.

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