



# Performance Comparison of BLDC Machines in Flywheel Applications: Hybrid vs. Conventional Magnet Arrays

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## Abstract

The incorporation of rare-earth magnets in permanent magnet machines significantly improves torque characteristics and power density, enabling the development of more compact and efficient electric machines. However, their high cost and limited availability pose considerable challenges, particularly in electric vehicle applications, where these magnets account for a substantial portion of production expenses.

To address this issue, this study introduces a composite magnet array as a cost-effective alternative. By employing a hybrid configuration of rare-earth and ferrite magnets, manufacturing costs can be reduced while preserving essential performance attributes such as torque enhancement and minimized torque ripple. The research focuses on an external rotor brushless DC (BLDC) machine designed for flywheel applications, analyzing the magnetic field distribution in the air gap using the proposed hybrid magnet array.

The performance of this configuration is evaluated through finite element analysis (FEA) and compared with conventional magnet arrangements. Key performance metrics—including torque characteristics, eddy current losses, and magnet costs—are assessed to establish an optimal balance between efficiency, performance, and cost-effectiveness.

**Keywords:** Direct current brushless machine, eddy current losses, Hybrid magnet array, torque ripple.

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## 1. INTRODUCTION

The growing demand for high-efficiency and cost-effective electric machines has spurred significant advancements in permanent magnet (PM) motor design. In particular, brushless direct current (BLDC) machines with external rotors have attracted considerable attention due to their high torque density, compact size, and exceptional reliability. These advantages make them especially well-suited for applications such as flywheel energy storage systems (FESS), electric vehicles (EVs), drones, and industrial automation [1]–[3].

Despite their performance advantages, PM machines that depend on rare-earth magnets face significant challenges due to the high cost and supply chain instability of materials like neodymium-iron-boron (NdFeB). The rising price volatility of rare-earth elements has driven extensive research into alternative magnet configurations that preserve efficiency while lowering material costs [4]–[7]. A promising solution is the integration of hybrid magnet arrays, which combine low-cost ferrite magnets with rare-earth magnets to achieve an optimal balance between performance and affordability.

Previous studies have investigated various strategies to improve the efficiency and cost-effectiveness of PM

motors. For example, reference [3] proposed the use of a Halbach magnet array to achieve a more sinusoidal air gap flux density, enhance magnetic performance, and reduce eddy current losses in BLDC machines. However, this approach also led to higher construction costs. Similarly, reference [4] examined hybrid permanent magnet materials (HPMM) in a permanent magnet machine, demonstrating that reducing magnet volume could lower cogging torque and improve the total harmonic distortion (THD) of the induced voltage in the stator winding. Furthermore, reference [5] introduced an external rotor interior permanent magnet synchronous machine (IPMSM) that incorporated both ferrite and rare-earth magnets, successfully reducing magnet costs while simultaneously enhancing torque characteristics.

This paper addresses these challenges by proposing a hybrid magnet configuration for an external rotor BLDC machine, integrating ferrite and NdFeB magnets to achieve a cost-effective, high-performance solution. The proposed design is analyzed through finite element analysis (FEA) to evaluate key performance metrics, including:

- Electromotive force (EMF) waveform quality and harmonic distortion
- Electromagnetic torque characteristics and ripple reduction

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- Eddy current losses and thermal considerations
- Overall cost reduction of magnet materials

TABLE. 1. Designed Machine Parameters

Parameters	Symbol	Value
Number of Poles	$p$	8
Number of Slots	$Q$	6
Outer Radius of Outer Rotor (mm)	$R_o$	91.5
Inner Radius of Outer Rotor (mm)	$R_r$	79
Magnet Thickness (mm)	$h_m$	6.3
Machine Length (mm)	$L_m$	39
Outer Radius of Inner Rotor (mm)	$R_{so}$	63
Inner Radius of Inner Rotor (mm)	$R_{si}$	53
Residual Flux Density of NdFeB Magnet (T)	$B_r(NdFeB)$	1.1
Residual Flux Density of Ferrite Magnet (T)	$B_r(FeS)$	0.24

The results demonstrate that the hybrid magnet configuration significantly enhances the sinusoidal nature of the back-EMF waveform, reducing total harmonic distortion (THD) by 67% compared to the conventional design. Additionally, torque ripple and eddy current losses are reduced by 60% and 40%, respectively, while achieving a 14% reduction in magnet material costs.

These findings provide valuable insights into the feasibility of hybrid magnet designs for high-speed applications such as FESS and electric propulsion systems. This approach presents a promising pathway toward cost-effective and high-efficiency BLDC motor solutions, facilitating broader adoption in industrial and energy storage applications.

Furthermore, a detailed cost-performance analysis reveals that the proposed configuration:

- Achieves a 14% reduction in magnet cost for the same output torque
- Delivers 16% higher average torque compared to a conventional design with the same magnet cost
- Demonstrates a significant reduction in total harmonic distortion (THD) of the induced EMF, improving output waveform quality.

## 2. The structure of the investigated machines

In Fig. 1, the cross-section of a traditional iron-free stator BLDC permanent magnet machine is shown. This configuration consists of an iron rotor, an iron-free stator winding, and magnets mounted on the outer rotor. In flywheel applications, brushless machines require an external rotor back iron to increase system inertia. The analyzed machine features eight poles (magnets) and six winding branches. Fig. 2 illustrates the cross-section of the same machine but with a combined magnet configuration. In this design, one-third of the rare-earth magnets have been replaced with ferrite magnets. Each pole consists of three distinct magnets: two ferrite magnets on the sides and a neodymium-Fe-B (NdFeB) magnet in the center. This hybrid configuration strategically reduces the dependency

on expensive rare-earth materials while maintaining the machine's efficiency and performance.

The combined magnet structure takes advantage of the difference in residual magnetic flux density between ferrite and NdFeB magnets, leading to a more sinusoidal flux distribution in the air gap. While the segmentation of magnets presents slight challenges in alignment and retention within the rotor, the trade-off results in a substantial reduction in magnet costs. This design effectively balances performance and affordability. An initial design is introduced in [3] and in this paper, the main dimensions are the same as the initial design. The dimensional specifications of the machines analyzed in this study are summarized in Table 1, providing detailed parameters for a comprehensive performance comparison.

## 3. Comparison of Traditional and Hybrid Magnet Machine

The evaluation is conducted based on four key factors: electromotive force (EMF), electromagnetic torque, eddy current losses, and magnet cost. Each parameter is carefully assessed to provide a holistic understanding of the machine's efficiency and cost-effectiveness.

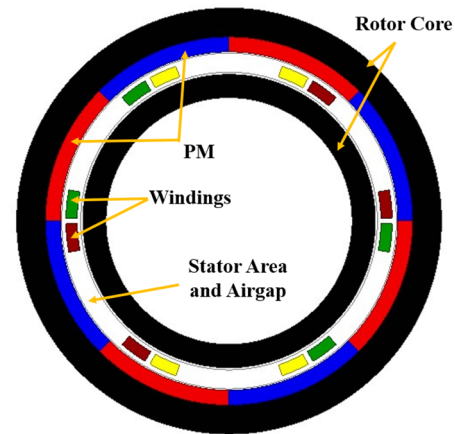


Fig. 1. Cross-section of stator ironless BLDC machine with traditional magnet array

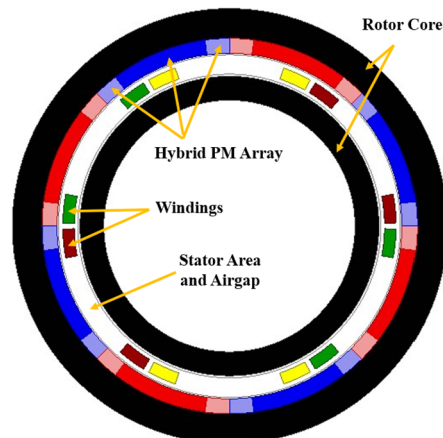


Fig. 2. Cross section of stator ironless BLDC machine with hybrid magnet array

### 3.1. Back-EMF Comparison

The EMF induced in the stator windings is analyzed using finite element analysis (FEA) for both the traditional and hybrid magnet configurations. This evaluation highlights the impact of the combined magnet arrangement on machine performance, particularly in achieving a more sinusoidal EMF waveform. The analysis is performed under no-load conditions, with zero current in the windings, and at a nominal rotational speed of 40,000 rpm. Each coil consists of five turns of winding. The magnetic flux distribution and magnetic flux density distribution for both machine configurations are compared in Figs. 3 to 5.

Fig. 3 illustrates the distribution of the magnetic vector potential ( $A$ ) in both conventional and hybrid machines. As observed, the maximum value of  $A$  in the hybrid machine is approximately 54% lower compared to that in the conventional machine, particularly in the back iron and stator stacks from a magnetic perspective. Figs. 4 and 5 illustrate the magnetic flux density distribution in conventional and hybrid machines, respectively. The difference is significant, with the maximum flux density in the conventional machine being approximately 65% higher than in the hybrid machine. As a result, the hybrid machine experiences reduced core loss, and the magnetic saturation present in the conventional machine is completely eliminated. This reduction in saturation not only minimizes magnetic losses but also contributes to a more linear torque-current relationship in the hybrid machine.

The waveform of the induced EMF for both machine configurations is depicted in Fig. 6. The results show that the amplitude of the induced EMF in each phase is approximately 104 volts for the traditional machine and slightly lower at 102 volts for the machine with the combined magnet. However, the induced EMF waveform in the hybrid magnet machine is significantly closer to a sinusoidal shape.

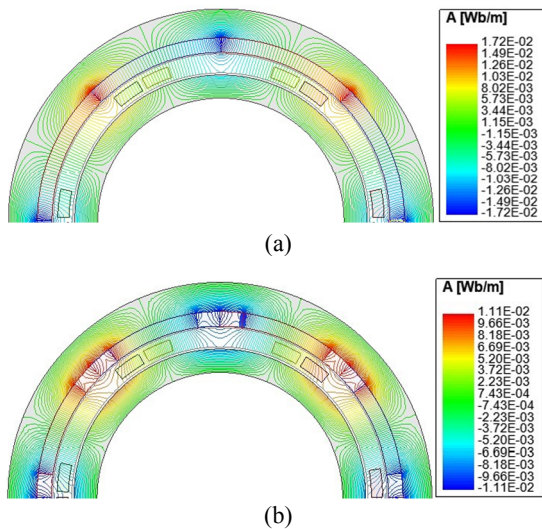


Fig. 3. Magnetic vector potential distribution in designed machines (a) traditional machine (b) machine with Hybrid magnet

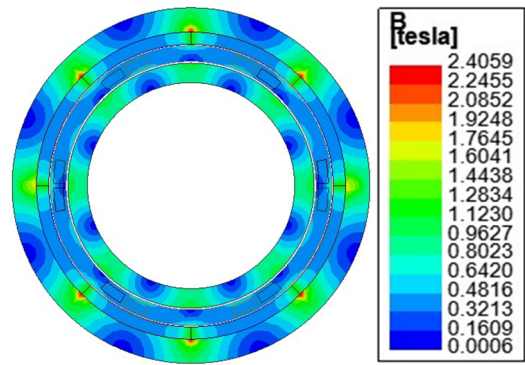


Fig. 4. Cross section of ironless BLDC external rotor machine with traditional magnet array

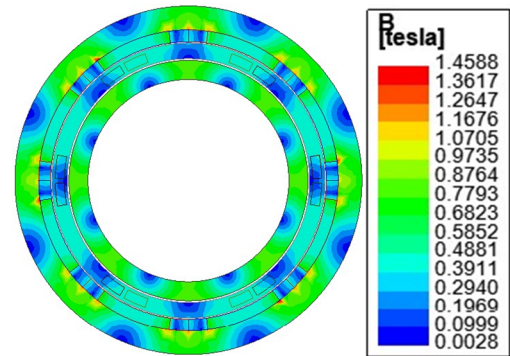


Fig. 5. Cross section of ironless external rotor BLDC machine with hybrid magnet array

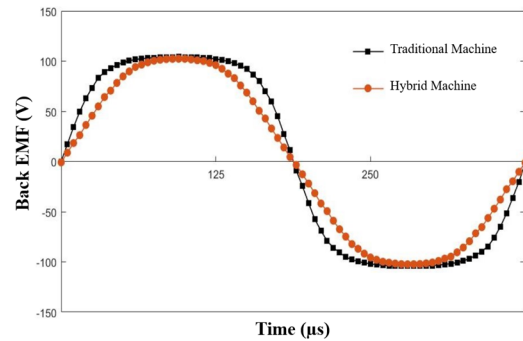


Fig. 6. Induced EMF waveform in each phase of designed machines

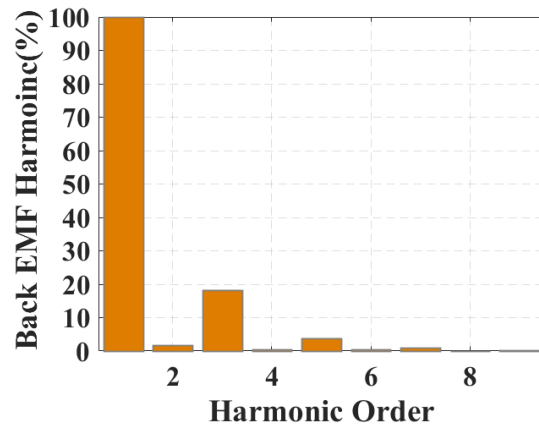


Fig. 7. Harmonic spectrum of no-load BEMF of conventional machine

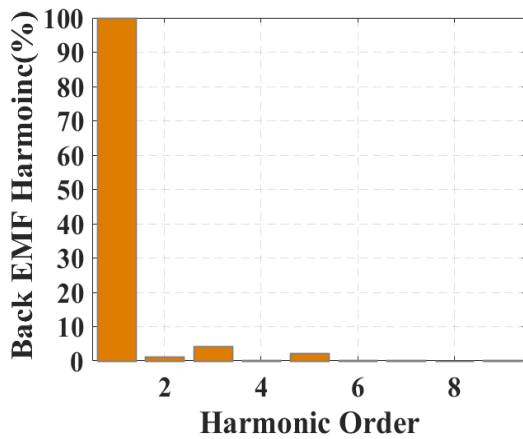


Fig. 8. Harmonic spectrum of no-load BEMF of hybrid machine

This improvement is reflected in the total harmonic distortion (THD) of the induced EMF, which is reduced from 30.8% in the traditional machine to 10.1% in the hybrid magnet machine. This substantial enhancement in waveform quality contributes to smoother and more efficient machine operation.

Figs. 7 and 8 present the harmonic spectrum of the no-load BEMF phase voltage for both conventional and hybrid machines. As observed, the fundamental harmonic in the hybrid machine is more dominant than in the conventional one. Quantitatively, the 3<sup>rd</sup> harmonic component in the conventional motor accounts for approximately 18.35% of the fundamental harmonic value, whereas in the hybrid machine, this value is significantly reduced to about 4.35%, indicating a substantial improvement. Consequently, the BEMF waveform of the hybrid machine is much closer to a pure sinusoidal shape.

### 3.2. Torque Characteristic Comparison

As previously mentioned, ironless BLDC machines are predominantly used in Flywheel Energy Storage Systems (FESS). In these systems, the electric machine typically operates in three distinct modes [3]:

#### 1. Charging Mode (Motor Mode):

In this mode, the machine functions as a motor, converting electrical energy into mechanical energy to accelerate the flywheel and store energy.

#### 2. Unloaded Mode (No-Load Mode):

During this mode, the flywheel spins freely with minimal energy exchange, maintaining its rotational speed with only minor losses due to friction and other factors.

#### 3. Discharging Mode (Generator Mode):

In this mode, the machine operates as a generator, converting the mechanical energy stored in the flywheel back into electrical energy for use in external systems.

These modes highlight the versatility and importance of BLDC machines in efficiently managing energy within FESS applications.

In this study, the electromagnetic torque of both machine configurations was analyzed and compared in discharge

mode (generator mode). To ensure identical operating conditions, the phase current in both machines was set to 20 A during generator operation, providing a fair basis for evaluating torque characteristics and performance differences.

The induced electromagnetic torque for both the traditional and hybrid magnet configurations was calculated using finite element analysis. As shown in Fig. 9, the induced torque in the traditional machine is approximately 1.07 Nm, while the average induced torque in the combined magnet machine is 0.83 Nm. As expected, the lower flux density in the hybrid magnet machine results in reduced torque compared to the traditional machine. However, the more sinusoidal flux distribution in the air gap of the.

Ironless permanent magnet machines inherently exhibit minimal cogging torque due to the absence of iron in the stator, which is a highly desirable characteristic. However, torque fluctuations still occur, and minimizing these fluctuations is crucial for improving performance and efficiency.

To ensure a fair comparison, the ratio of ripple torque to average torque was evaluated for both machines. This ratio was found to be 0.21 for the traditional machine and 0.09 for the machine with the hybrid magnet configuration. These results demonstrate that the ripple torque ratio in the hybrid magnet machine is approximately 60% lower than that of the traditional machine, highlighting the improved performance and smoother operation achieved with the combined magnet design.

### 3.3. PM Eddy Current Loss Comparison

In ironless BLDC machines, the absence of a stator core eliminates hysteresis losses, leaving the machine's losses primarily composed of two components: **copper losses** and **eddy current losses** in the magnets and rotor iron [1]. Eddy current losses are exclusively caused by the armature reaction, which generates eddy currents in these materials [3].

Addressing and minimizing losses is essential for enhancing the efficiency and performance of the machine. In this study, eddy current losses in the magnets were calculated with a winding current of 20 A. To improve accuracy, losses were calculated separately for each individual magnet piece and then summed to determine the total losses. Fig. 10 presents the eddy current losses in the magnets for both machine configurations, showing a significant reduction in the machine with the hybrid magnet arrangement.

Additionally, Fig. 11 illustrates that the average eddy current loss in the hybrid magnet machine is nearly 40% lower than in the traditional machine. This reduction in eddy current losses contributes to the improved efficiency of the hybrid magnet configuration.

### 3.4. PM Cost Comparison

The cost of electric machine components is a major factor influencing their commercial viability, particularly in

applications such as electric vehicles and Flywheel Energy Storage Systems (FESS). FESS offer advantages such as high efficiency, long lifespan, and zero emissions. However, they currently face high investment costs, estimated at approximately \$5000/kWh [2].

It is important to note that FESS is not limited to electric vehicle applications; they are also used in the space industry, distributed generation, power grid stabilization, and various other energy storage solutions [1]. As demand for energy storage continues to grow, reducing the cost of FESS while maintaining performance and efficiency remains a critical challenge for widespread adoption.

In permanent magnet machines, the cost of rare-earth magnets constitutes a significant portion of the overall production cost [5]. Currently, neodymium (NdFeB) magnets cost approximately \$70 per kilogram, while ferrite magnets cost around \$4 per kilogram [8].

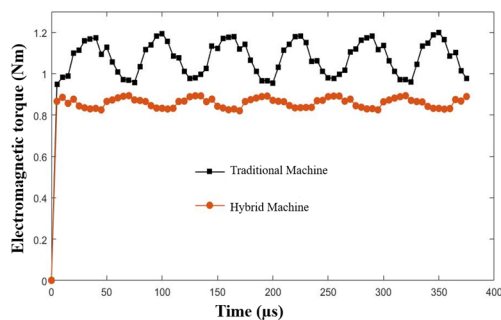


Fig. 9. Electromagnetic torque waveform in each phase of designed machines

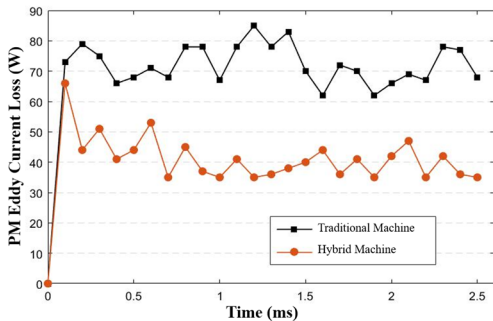


Fig. 10. PM Eddy Current Loss waveform in each phase of designed machines

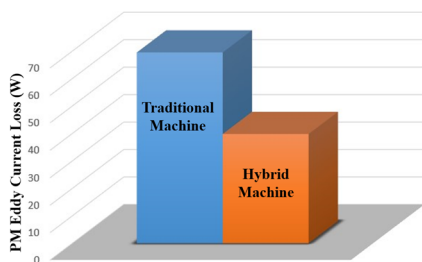


Fig. 11. PM Eddy Current Loss waveform in each phase of designed machines

Table 2 compares the magnet costs in both the traditional and hybrid magnet machines. Despite having the same total magnet cost, the hybrid magnet machine delivers an average torque that is approximately 16% higher than that of the

traditional machine. This represents a notable improvement in torque performance, making the hybrid magnet machine a more cost-effective solution for achieving higher efficiency.

TABLE. 2. Designed Machine Parameters

	NdFeB Magnet Weight (kg)	Ferrite Magnet Weight (kg)	Total Magnet Cost (\$)	Average Torque to Magnet Cost Ratio (Nm/\$)
Traditional Machine	0.866	-	66.8	0.0157
Hybrid Machine	0.577	0.191	45.4	0.0183

#### 4. CONCLUSIONS

This study explored a method to reduce the manufacturing cost of an external rotor BLDC machine by using a hybrid magnet array that combines neodymium and ferrite magnets. The analysis demonstrated that the air gap magnetic flux density in the hybrid magnet configuration was more sinusoidal. While the induced EMF in the hybrid magnet machine was 1.5% lower than in the traditional machine, the Total Harmonic Distortion (THD) was significantly reduced by 67%, indicating that the EMF waveform in the hybrid magnet machine was much closer to a pure sine wave.

Additionally, ripple torque and eddy current losses were reduced by 60% and 40%, respectively, in the hybrid magnet machine compared to the traditional design. Furthermore, for the same average torque, the hybrid magnet configuration reduced magnet costs by 14%.

In conclusion, this study demonstrates that employing a hybrid magnet array not only reduces construction costs but also enhances key performance metrics such as total harmonic distortion (THD), ripple torque, and eddy current losses, ultimately improving the machine's overall quality and efficiency. Future research should integrate mechanical and thermal considerations alongside magnetic factors to ensure the reliability of the proposed design.

#### REFERENCES

- [1] K. Liu, X. Fu, M. Lin, and L. Tai, "AC copper losses analysis of the ironless brushless DC motor used in a flywheel energy storage system," *IEEE Trans. Appl. Supercond.*, vol. 26, no. 7, pp. 1–5, 2016.
- [2] A. A. K. Arani, H. Karami, G. B. Gharehpetian, and M. S. A. Hejazi, "Review of Flywheel Energy Storage Systems structures and applications in power systems and microgrids," *Renew. Sustain. Energy Rev.*, vol. 69, pp. 9–18, 2017.
- [3] K. Liu, M. Yin, W. Hua, Z. Ma, M. Lin, and Y. Kong, "Design and analysis of Halbach ironless flywheel BLDC motor/generators," *IEEE Trans. Magn.*, vol. 54, no. 11, pp. 1–5, 2018.
- [4] Q. Chen, G. Liu, W. Zhao, M. Shao, and Z. Liu, "Design and analysis of the new high-reliability motors with hybrid permanent magnet material," *IEEE Trans. Magn.*, vol. 50, no. 12, pp. 1–10, 2014.
- [5] D. Yu, X. Huang, X. Zhang, J. Zhang, Q. Lu, and Y. Fang, "Optimal design of outer rotor interior permanent magnet synchronous machine with hybrid permanent magnet," *IEEE Trans. Appl. Supercond.*, vol. 29, no. 2, pp. 1–5, 2019.
- [6] Jeong, C.L., Kim, Y.K. and Hur, J., 2019. Optimized design of PMSM with hybrid-type permanent magnet for improving

- performance and reliability. IEEE Transactions on Industry Applications, 55(5), pp.4692-4701.
- [7] Wu, W., Li, D. and Wang, W., 2024, October. Design and Analysis of an Outer Rotor Hybrid Excitation Permanent Magnet Motor with Consideration of PM Combination Relationships. In International Conference of Electrical, Electronic and Networked Energy Systems (pp. 335-342).
- [8] Magnet shop, "Magnet Basics FAQs," magnetshop.com, para. 13, 2020. [Online]. Available: <https://www.magnetshop.com/resources/magnet-basics.html>. [Accessed: Aug. 15, 2021]