Tuijin Jishu/Journal of Propulsion Technology
ISSN: 1001-4055
Vol. 44 No.6 (2023)

A FEA Study of the Optimal Magnetic Material for IPMSM Design in EV Applications

Rahul Desai[1], Rajesh Holmukhe[1], Diksha Chopade[1], Rupali Ambekar[1], Nilesh Pangare[1], Raviraj Kadam[1], Parag Chaudhari[2], Mohan Pare[3], and Hrishikesh Mehta[3]

[1]Department of Electrical Engineering, Bharati Vidyapeeth (Deemed to be University) College of Engineering, Pune 411 048, Maharashtra, India

[2]Defense Research and Development Establishment (DRDO), India

[3]Research & Development, Aethertec Innovative Solutions, Pune, India

Abstract: -Electric vehicles (EVs) are becoming increasingly popular, and the demand for efficient and powerful motors is growing. Interior Permanent Magnet Synchronous Motors (IPMSMs) are a promising choice for EV propulsion, but the efficiency of an IPMSM is highly dependent on the magnetic material used. This paper presents a comprehensive study of the magnetic material selection for IPMSM design in EV applications. Using Finite Element Analysis (FEA) and ANSYS Maxwell software, a 3kW, 48V IPMSM employing diverse magnetic materials was evaluated. The motor's performance was scrutinized across various operating speeds, and the results showed that the optimal magnetic material for this application is NdFe30. The findings of this study provide valuable insights into the factors that affect the efficiency of IPMSMs. The results also demonstrate the effectiveness of FEA for evaluating the performance of IPMSMs under different operating conditions.

Keywords: *IPMSM, FEA, ANSYS Maxwell, EV, NdFe30, SmCo28, N32EZ*

1. Introduction

The advent of electric vehicles (EVs) heralds a paradigm shift with far-reaching ramifications across energy, environment, and transportation landscapes. EVs wield the potential to not only redefine high-tech advancements and economic growth but also serve as a potent countermeasure against global air pollution. By virtue of their unique attributes, EVs offer a sustainable, well-rounded energy alternative characterized by efficiency and ecological stewardship.

Within the domain of EV propulsion, Permanent Magnet Synchronous Motors (PMSMs) stand out as a linchpin, permeating various sectors including traction, automotive, robotics, and aerospace. Distinguished by their heightened power density and lower moment of inertia, PMSMs have surged to the forefront of high-performance drive systems, particularly in the electric vehicle domain. Of these, Interior Permanent Magnet Synchronous Motors (IPMSMs) have garnered prominence owing to their salient advantages:

- Saliency: IPMSMs exploit inductance differentials between the stator and rotor, contributing to enhanced operational efficiency.
- Robust Architecture: The durable design of IPMSMs enables seamless operation at elevated speeds, aligning with the demands of modern electric vehicles.
- Versatile Field Weakening: IPMSMs exhibit effective field weakening capabilities, facilitating smooth operation across a wide speed spectrum.

This paper embarks on a meticulous exploration of IPMSM design intricacies, centering on the pivotal role of magnetic material selection and subsequent Finite Element Analysis (FEA) through ANSYS Maxwell software. The aim is to unveil the optimal magnetic material for achieving maximal efficiency within the IPMSM framework, bolstering its viability for electric vehicle applications.

Research on designing a highly efficient PMSM for EV application has picked up pace only until recently as the demand for the motor has risen manifold times. In [1], a performance comparison for three operating speeds of an IPMSM of 3 kW, 48 V for EV applications using finite element analysis (FEA) is provided. FEA is a computational approach used to solve engineering and physics issues. It may be used to solve issues involving complex geometry, loadings, and material characteristics.

In FEA, we need to know how a complicated item behaves physically to forecast its performance and behaviour. A rotor structure, which comprises of a core with a bridge that is required to preserve the rotor assembly's stiffness, as well as a rotor assembly made by cross laminating segment-type rotor cores, which is required to reduce leakage flux and improve torque density is suggested [2]. A new technique based on the design of experiments for conducting FEA is proposed to overcome the time-consuming design approach of conventional FEA while a 3-D FEA is reported to handle complex mid-frequency behaviour of the PMSM considering its iron core [3, 4]. A support vector regression-based supervised machine learning algorithm is utilized to optimize the design of a 6-slot, 34-pole consequent pole six-phase PMSM [5]. In ANSYS Maxwell, a 2-D transient finite-element method (FEM) model for a 15 kW PMSM is created, and a vector control circuit model is created in ANSYS Simplorer using lookup table approach [6]. A study investigating maximum slot occupation (MSO) coil to generate high torque density with reduced efficiency is proposed in [7, 8]. Various optimization algorithms for the design of PMSM like hybrid differential evolution algorithm, genetic algorithm (GA), differential evolution (DE), response surface methodology (RSM), grid search (GS), particle swarm optimization (PSO), mesh adaptive direct search (MADS), Taguchi method and response surface method have been explored by the researchers in last few years utilizing FEA [9-17]. Various control algorithms to improve the efficiency of the IPMSM design have been proposed [18-21]. Fractional slot concentrated winding for IPMSM have been considered as well [22, 23]. Various rotor shapes for design optimization of IPMSM have been considered in [24-26]. Real-world driving cycles have been considered for the design of PMSM based electric drive train model in [27]. A comparison of motors including IPMSM, induction and switched reluctance motor suggests definite advantages of IPMSM motors over other motors [28]. A high-speed low-noise topology for EVs has been proposed in [29] while rare earth magnet-free motors have been studied in [30].

Magnets play a crucial part in many gadgets; thus, it is critical to enhancing their characteristics. Materials based on rare earth metals and transition metals are receiving a lot of interest right now. Permanent magnets with high magnetic characteristics may be made using these materials. Magnets have varied magnetic and mechanical characteristics, as well as different corrosion resistance, depending on the technology. The study of the effect of different magnetic materials on the efficiency and torque generation of an IPMSM has not been widely covered in the literature. This paper analyzes three common types of magnetic materials used for the construction of the IPMSM rotor. The performance in terms of efficiency and torque generated of the IPMSM is verified by FEA using ANSYS Maxwell software.

This paper makes the following contributions:

- It provides a comprehensive study of the effect of different magnetic materials on the efficiency and torque generation of an IPMSM.
- It uses FEA to simulate the performance of the motor under different operating conditions.
- It identifies NdFe30 as the optimal magnetic material for IPMSM design in EV applications.

This paper is organized as follows. Section 2 provides background information on IPMSMs and magnetic materials. Section 3 describes the FEA methodology used in this study. Section 4 presents the results of our simulations. Section 5 discusses the implications of our findings.

2. Construction of a PMSM and its design procedure

The PMSM's construction details are given below.

2.1 Permanent Magnet (PM) Structure

Despite the PMSM's excellent efficiency and power density, the PMSM's development is hampered by the prohibitively costly PM material. As a result, it is critical to utilize fewer PMs to save money without losing motor performance.

The usage of PMs can be increased by adjusting the form of the PMs. The shape of PM, on the other hand, is directly connected to the electromagnetic performance of motors, particularly the cogging torque (T_{cog}), maximum torque (T_{max}), and PM eddy losses (PPM).

The total PM volume V_m required for this PMSM can be estimated by [1]

$$V_m = C_v \cdot (P_{in}/f B_r H_c) \quad (1)$$

where,

V_m= PM volume

C_v = coefficient (ranged from 0.54 to 3.1 with a typical value of 2), P_{in} = input power,

f = input frequency,

H_c = PM coercivity, and

B_r= PM remanence.

In this study, an interior PMSM is designed using different magnetic materials for FEA analysis.

2.2 Airgap length

In the motor, energy conversion takes place in the airgap. Its size and shape have a significant impact on motor performance, as well as on vibration and noise levels. Due to road conditions, the airgap flux density of the same pole position changes typically for the EV with a PMSM. As a result, an adequate air gap length is required to assure energy conversion capacity while simultaneously lowering radial electromagnetic force and preserving motor stability.

The electromagnetic force operating on the rotor in a PMSM may be split into radial and tangential electromagnetic forces theoretically. The armature generates torque and operates as a result of the tangential force. The motor core deforms due to the radial force. The variation of the radial electromagnetic force causes the motor to vibrate, resulting in motor vibration and noise. The radial and tangential electromagnetic force (f_r and f_θ) of the unit area can be represented as according to Maxwell stress tensor theory in the air gap of the PMSM [1].

$$\begin{cases} f_r = (B_r^2 - B_\theta^2)/2\mu_0 \\ f_\theta = B_r B_\theta / 2\mu_0 \end{cases} \quad (2)$$

Where B_r is the radial air gap flux density, $B_\theta$the tangential air gap flux density, $\mu_0$the magnetic permeability of air. According to (2), B_θ will not only reduce the output tangent force but also cause the rotor radial force.

2.3 Stator Structure

The stator slot sizes, yoke thickness, and tooth width are the primary characteristics to consider while optimizing the stator construction. The yoke thickness and tooth width will change when the stator slot size changes as long as the stator outer diameter, inner diameter, and the number of slots is known. As a result, only the stator slot size is used as an optimization parameter in this study.

2.4 Design procedure

The design procedure for the simulation of PMSM using ANSYS Maxwell is as follows:

1.Define the design requirements. This includes the desired power, torque, and speed output, as well as the minimum volume, temperature rise, and efficiency.

2.Create a preliminary design. This can be done using a variety of tools, such as CAD software or hand calculations.

3.Analyze the preliminary design using ANSYS Maxwell. This will help to identify any potential problems with the design.

4.Revise the design as needed. This may involve making changes to the geometry, material properties, or operating conditions.

5.Repeat steps 3 and 4 until the design meets the desired requirement.

The flowchart in Figure 1 provides a visual representation of the design procedure.

It is important to note that the design procedure is an iterative process. This means that the design will be revised multiple times as new information is gathered and as the design is analyzed using ANSYS Maxwell. The goal is to arrive at a design that meets the desired requirements and optimizes the performance of the PMSM.

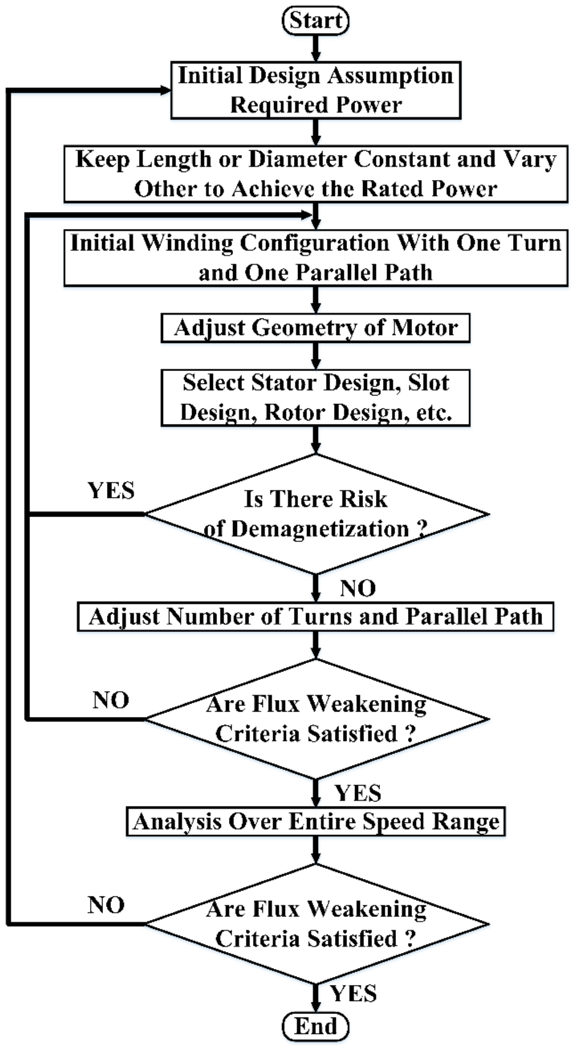

Figure 1.Flowchart for Design Procedure in ANSYS Maxwell

3.Finite Element Analysis of 3kW, 48V PMSM for EV

The PMSM selected for analysis is intended for applications such as 6-seater e-rickshaw, go-cart or light motor vehicle application. The parameters used for the ANSYS simulation are shown in Table 1.

Table 1. Parameters of 3kW, 48V PMSM

Sr. No.	Parameter	Value
1	Rated Output Power (kW)	3
2	Rated Voltage (V)	48
3	Number of Poles	8
4	Frequency (Hz)	200
5	Type of PMSM	IPMSM
6	Type of Source	Sine
7	Operating Temperature (C)	75

As an outcome of the design procedure, the optimal dimensions of the PMSM obtained from Ansys Maxwell as shown in Table 2. As shown in the table, the dimensions of the motor are kept the same for all simulations while the magnetic materials are changed. Commonly used neodymium-iron-boron (NdFe30), Shin-Etsu rare-earth magnet (N32EZ) and Samarium Cobalt (SmCo28) type magnets are used for comparison. Based on the major design parameters and material, the main dimension of the motor may be estimated in advance. The motor is then modelled and the dimensional parameters are optimized using ANSYS Maxwell.

Table 2. Parameters of 3kW, 48V IPMSM

Sr. No.	Dimensions	Design
1	Stator (OD)	120 mm
2	Stator (ID)	70 mm
3	Stack Length	74 mm
4	No. of Stator Slots	24
5	Turns/Phase	9
6	No. of Poles	8
7	Magnet Grades for Comparison	a. NdFe30 b. N32EZ c. SmCo28
8	Air Gap	1.5 mm
9	Slot Area	124.223 mm2
10	Cu. Weight	1.7 kg
11	Thickness of magnet	3.5 mm
12	Number of Conductors per Slot	11
13	Number of Wires per Conductor	6
14	Stator Slot Fill Factor (%)	75
15	Inner Diameter (mm)	20
16	Width of Magnet (mm)	18

The selected permanent magnet material properties are tabulated as shown in Table 3. It can be seen that the materials have closely matching properties. However, their impact on performance can be seen changing drastically in results shown later.

Table 3. Permanent Magnet Data

Magnetic material / Parameter	NdFe30	ShinEtsu N32EZ	SmCo28
Residual Flux Density (Tesla)	1.1	0.97	1.07

Coercive Force (kA/m)	838	748.12	820
Maximum Energy Density (kJ/m^3)	230.45	181.10	219.35
Relative Recoil Permeability	1.0446	1.03	1.03842
Demagnetized Flux Density (Tesla)	0	0	0
Recoil Residual Flux Density (Tesla)	1.1	0.97	1.07
Recoil Coercive Force (kA/m)	838	748.12	820

The simulated IPMSM in ANSYS Maxwell is shown in Figure 2. Different parts of the designed motor are highlighted in the figure.

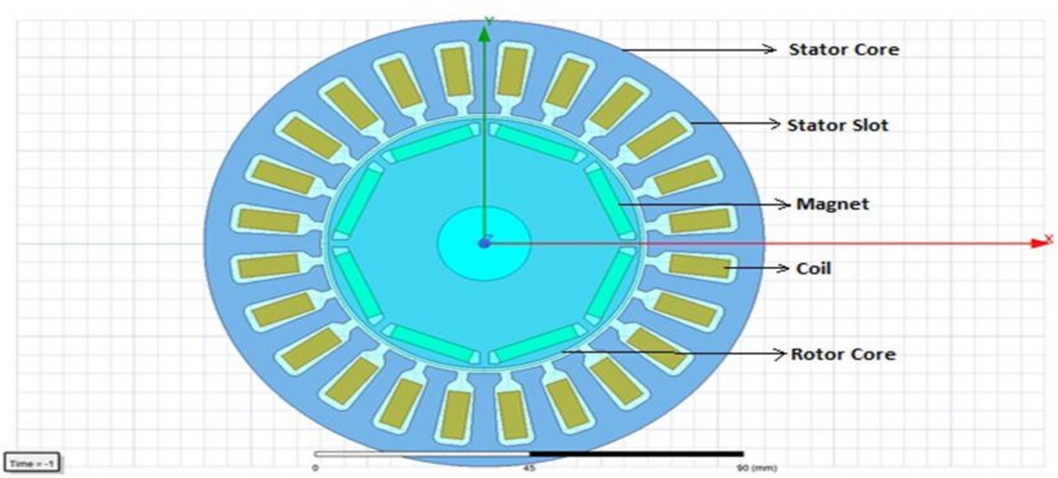

Figure 2. Simulated interior PMSM using ANSYS Maxwell

3.1Flux-Density Distribution

Figure 3 shows the flux density distribution and Figure 4 shows the field strength of NdFe30 magnet-based IPMSM by using FEA. Because of the improved size of PMs, the flux density of the designed motor is 4% greater than the initial motor design assumptions. Furthermore, due to the appropriate selection of stator slot size, the flux density in the tooth and yoke of the stator is in relative balance. The designed motor has a greater flux density than the initially assumed parameters for the motor, implying that the designed motor's torque output capability has been enhanced while the PMs are used at the same level as the initial assumptions.

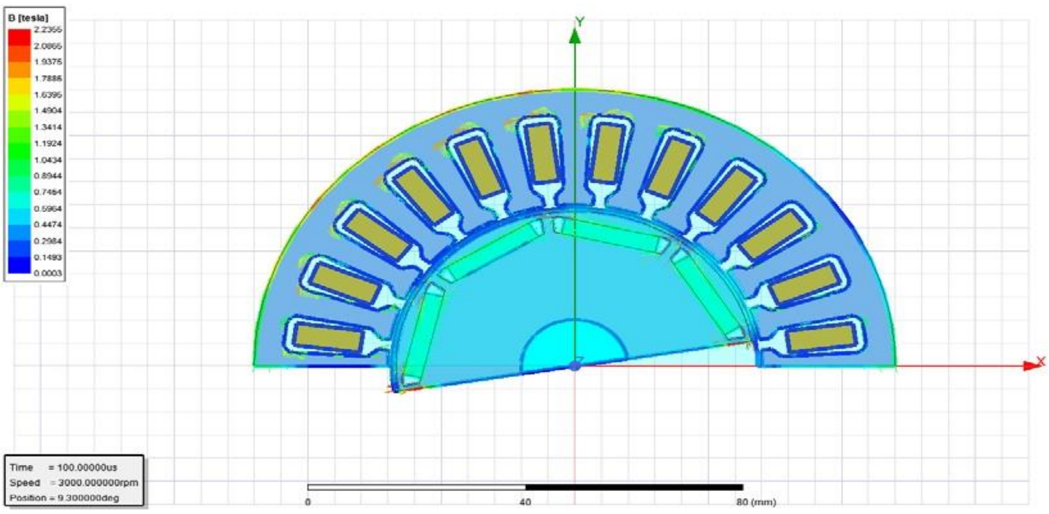

Figure 3. Flux Density Vector Map of IPMSM using ANSYS Maxwell

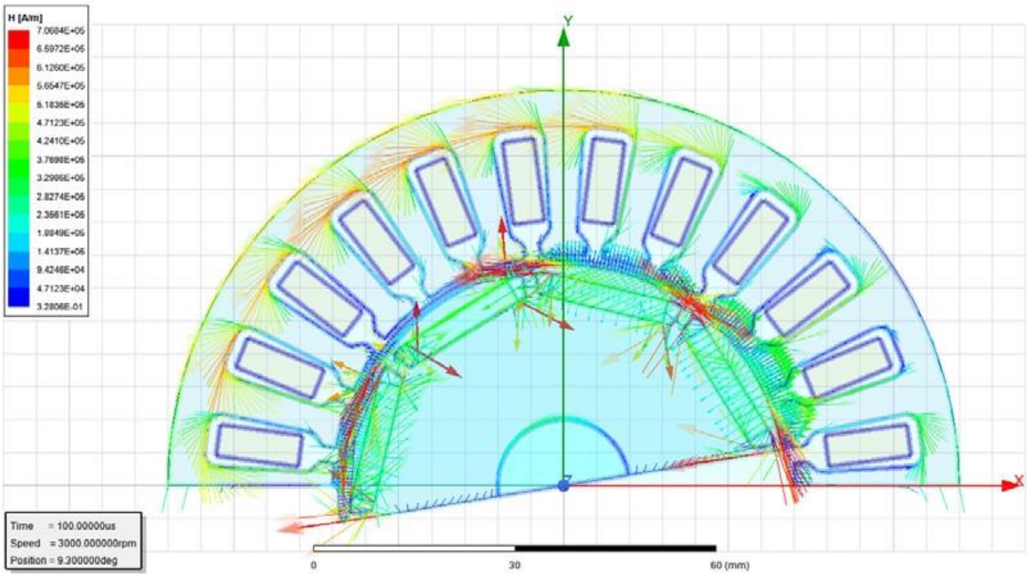

Figure 4. Field Strength Vector Map of IPMSM using ANSYS Maxwell

3.2 Performance of the IMPSM with different magnets

To verify the torque capability of the designed motor, the expected torque was noted at 3000 rpm as predicted by the FEA method. Along with the rated torque, efficiency, output power and other performance-related parameters are tabulated in Table 4.

Table 4. Performance of IPMSM using various magnetic materials for its rotor

Magnetic material / Parameter	NdFe30	ShinEtsu N32EZ	SmCo28
Rated Torque (N.m)	9.55	9.549	9.549
Cogging Torque (N.m)	4.97e-13	2.408e-13	3.09e-13
No-Load Input Power (W)	57.34	52.61	51.387
Torque Angle (degree)	47.39	69.078	53.922
Armature Copper Weight (kg)	1.712	1.594	1.631
Permanent Magnet Weight (kg)	0.281	0.289	0.309
Armature Core Steel Weight (kg)	2.479	2.479	2.479
Rotor Core Steel Weight (kg)	1.451	1.451	1.451
Total Net Weight (kg)	5.925	5.814	5.871
Maximum Line Induced Voltage (V)	58.943	61.253	63.295
Root-Mean-Square Line Current (A)	41.861	43.907	41.067
Input Power (W)	3187.99	3293.44	3221.97
Total Loss (W)	187.767	293.356	221.923
Output Power (W)	3000.23	3000.09	3000.05
Efficiency (%)	94.11	91.09	93.11
Maximum output power (W)	5228.65	3639.9	4510.03

As shown in Table 4, for different magnets, the power consumption differs. NdFe30 gives the highest efficiency of 94.11% and gives 15 - 45% more maximum torque output as compared with other magnets, however, also increases the net weight of the motor. Other parameters have small differences, as the air resistance and friction resistance are negligible in the simulation process.

3.3 Performance of the IPMSM at different operating points

ANSYS Maxwell simulation is extended to design the motor for various operating points. The selection of IPMSM for EV applications is based on design trials for certain operating points depending on below rated, rated, or overrated motor speed. Tables 5, 6, and 7 illustrate the results of the testing of the IPMSM with different operating points for various magnetic materials.

Table 5. Performance of NdFe30 at different operating points

Operating Points	Speed (RPM)	Torque Produced (Nm)	Max. Output Power (kW)	Efficiency (%)
Below Rated RPM	1500	14.14	2.22	75.07
Rated RPM	3000	9.55	5.2	94.11
Above Rated RPM	4000	7.16	6.76	95.6

Table 6. Performance of N32EZ at different operating points

Operating Points	Speed (RPM)	Torque Produced (Nm)	Power (kW)	Efficiency (%)
Below Rated RPM	1500	9.83	1.5	74.37
Rated RPM	3000	9.55	3.63	93.11
Above Rated RPM	4000	7.16	5.06	92.74

Table 7. Performance of SmCo28 at different operating points

Operating Points	Speed (RPM)	Torque Produced (Nm)	Power (kW)	Efficiency (%)
Below Rated RPM	1500	12.92	2.03	74.69
Rated RPM	3000	9.55	4.5	91.09
Above Rated RPM	4000	7.16	6.5	95.4

It can be noted from Tables 5, 6 and 7 that the results are consistent with the results for rated RPM. In any case, the performance of the NdFe30 magnet is better than other types of magnets by at least 15%. Hence, it is recommended for the design of IPMSM for electric vehicle applications.

4. Conclusion

The results of this study show that the use of NdFe30 magnets in IPMSMs for electric vehicles can significantly improve efficiency and torque output. This suggests that NdFe30 magnets are a promising option for the design of future electric vehicles. However, further research is needed to optimize the design of NdFe30 magnets for electric vehicles. This research could focus on improving the efficiency of NdFe30 magnets, reducing their cost, and increasing their availability.

The implications of these findings for the design of electric vehicles are significant. The improved efficiency of NdFe30 magnets could help to extend the range of electric vehicles, while the increased torque could help to ensure that they have the power they need to accelerate and climb hills. This could make electric vehicles more attractive to consumers and help to accelerate the adoption of electric vehicles.

The limitations of this study should also be acknowledged. The study was conducted using FEA, which is a powerful tool for simulating the performance of electric motors. However, FEA results are not always perfectly accurate, so further testing is needed to confirm the findings of this study. Additionally, the study only considered a single application, so it is not clear how the findings would generalize to other applications.

Despite these limitations, the findings of this study provide valuable insights into the potential of NdFe30 magnets for electric vehicles. Further research is needed to optimize the design of NdFe30 magnets for electric vehicles, but the potential benefits of using these magnets are significant.

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