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Comparative of Permanent Magnet Motors Based on Rotor Topologies and Magnet Types

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Finite Element Method (FEM).

A B S T R A C T

This research examines slotless permanent magnet synchronous machines (PMSMs) with surface-mounted (SPM) and in-plane-mounted (IPM) topologies using NdFeB and ferrite magnets. To ensure a fair comparison, the original and equivalent surface areas of the magnets were calculated, as shown in Table 4 for neodymium, iron, and boron magnets, and for ferrite. Finite element analysis (FEM) confirmed equal flux per pole. Parametric evaluations of the number of poles, magnet thickness, air gap length, pole-to-pitch ratio, splitting ratio, and shaft material were performed using ANSYS 2D Maxwell, with validation using MATLAB. The results demonstrate that while NdFeB provides higher flux density, optimized ferrite designs achieve lower flux density with fewer harmonics, with equal flux in both cases, highlighting ferrite as a promising and low-cost alternative. These results give an explanation for the effects of rotor parameters in slotless machines and lay the foundation for future studies incorporating slots and windings.

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1. Introduction

Permanent magnet synchronous machines (PMSMs) have become widely used in various advanced applications, such as electric vehicles, robotics, and drones, due to their high efficiency, small size, and precise control.[1-5] However, their overall performance is strongly influenced by the choice of magnet material and rotor topology.[6-8] NdFeB magnets offer high flux density and compact designs, but they are expensive and resource limited. Ferrite magnets are more affordable and abundant, but have a lower flux density.[9-12] Interestingly, ferrite's low flux density helps keep the magnetic circuit from saturating, resulting in a sinusoidal air gap flux and a lower back electromotive force with less harmonic distortion compared to NdFeB in the same design.[11-16]

Rotor topology and design parameters including the number of poles, magnet thickness, air gap length, pole to pitch arc ratio, splitting ratio, and shaft material play a major role in machine performance. A previous study [17]addressed these factors, but it only addressed one type of rare earth magnet and did not address harmonic behavior. This work expands the scope of the research and analysis by examining both NdFeB and ferrite magnets under the same equivalent flow conditions in slotless SPM and IPM machines. Using ANSYS 2D Maxwell FEM simulation and MATLAB for validation using Fast Fourier Transform, the study systematically evaluates the effect of rotor parameters on the air gap flux density and its harmonic content, with the goal of providing clear design insights for future PMSM development.

2.1 Proposed Rotor Model of PMSM

This study examines two different types of slotless permanent magnet synchronous motors : a surface-mounted magnet (SPM) motor and an interior-magnet (IPM) motor. Both models are simulated using ANSYS Maxwell software, using the same stator geometry and boundary conditions as described in [17] Alternatively, The only difference lie in the type of magnet material (NdFeB versus ferrite) used and the corresponding adjustments to the motor dimensions.. Figure 1 illustrates the geometry of both proposed models. The parameters for the proposed model are shown in Table 1.

Table 1. Parameters of PMSM [17]

Parameter	SPM	IPM
Stator outer diameter (mm)	270	270
Stator bore diameter (mm)	135	135
Air-gap length (mm)	0.5	0.5
Shaft diameter (mm)	20	20
Magnet length (mm)	5	-

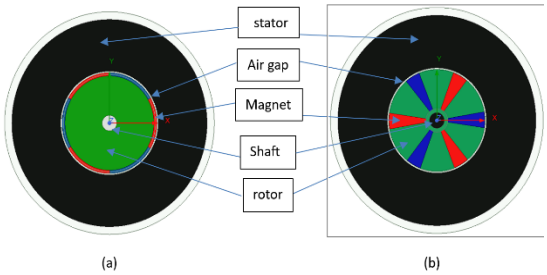


Fig. 1. PMSM motor geometriesv (a) SPM (b) IPM**.** [17]

2.2 Equivalent Magnet Surface Area Calculation

To ensure a fair comparison between rareearth (NdFeB) and Ferrite permanent magnets, the equivalence is established based on the generated magnetic flux in the air gap. Since the airgap length and magnet thickness are kept constant, the adjustment is made through the surface area of the magnet. The magnetic flux produced by a permanent magnet can be expressed by a one-number equation for the flux:

$$\Phi = Br * Am \tag{1}$$

where Φ is the magnetic flux, Br is the remanent flux density of the magnet material, and Am is the surface area of the magnet exposed to the air gap.

By equating the flux of NdFeB and ferrite magnets, the following relationship was obtained:

$$Br,N * A,N = Br,F * A,F \tag{2}$$

Where Br.N is the remanent flux density of NdFeB and Br.F is the remanent flux density of ferrite

A,N is the surface area of the NdFeB magnet

A,F is the surface area of the ferrite magnet

which leads to:

$$A,F = A,N * (Br,N/Br,F) \tag{3}$$

Equation (3) indicates that, due to the lower residual flux density of ferrite magnets, a larger surface area is required to achieve the same air-gap flux density predicted when used NdFeB magnets[18] In practice, this resulted in modifying the stator diameter while maintaining constant magnet thickness, air-gap length, and splitting ratio. Table 2 summarizes the original dimensions for the proposed geometry equipped with Neodymium magnet and the new dimensions when using Ferrite magnet instead.

Table 2. Adjusted dimensions for NdFeB and ferrite slot less PMSM

Magnet type	**Nd, Br=1.2T**		**Fe, Br=0.41T**	
Parameter	**SPM**	**IPM**	**SPM**	**IPM**
Stator outer diameter (mm)	270	270	744	744
Stator bore diameter (mm)	135	135	372	372
Magnet length (mm)	5	-	5	-
Air-gap length (mm)	0.5	0.5	0.5	0.5

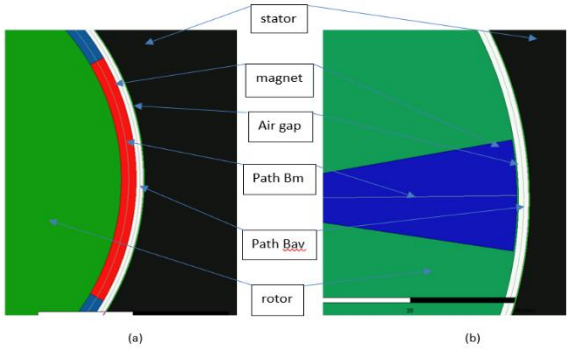


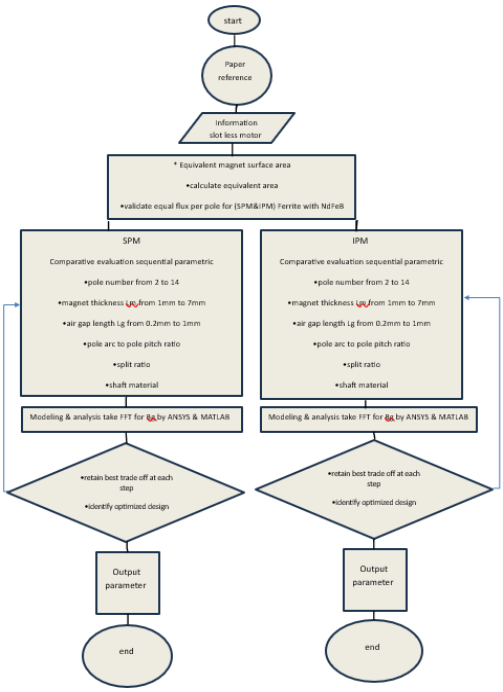
Fig. 2. PMSM motor geometriesv (a) SPM (b) IPM

2.3 PMSMs Comparative Study

This study systematically compared slotless PMSMs using NdFeB and ferrite magnets under equivalent flux conditions. Both the flux density magnitude and its harmonic content in the air gap were evaluated to highlight the trade-offs between high-performance rare-earth and low-cost ferrite options. A sequential parametric analysis was carried out by varying pole number, magnet thickness, air-gap length, pole-arc to pole-pitch ratio, split ratio, and shaft material. At each stage, the design that offered the best compromise maximum flux density with minimal harmonic distortion was retained before proceeding to the next parameter. This iterative approach ensured the identification of optimized machine parameters for both magnet types. The steps covered are illustrated in the flowchart below.

Table 3. Magnetic flux results

Magnet type	Neodymium, **Br=1.2T**		**Ferrite, Br=0.41T**	
Parameter	**SPM**	**IPM**	**SPM**	**IPM**
Flux per pole(wb/m)	0.0682	0.00354	0.0683	0.00357



3. Results and Discussion

3.1 Validation of Equivalent Magnet Surface Area

Before conducting the parametric analysis, the equivalent magnet surface area was calculated for the ferrite magnets to ensure they produced the same magnetic flux as the NdFeB-based design. Simulation results confirmed that both configurations generated approximately equal flux per pole, demonstrating the accuracy of the theoretical calculations and justifying their use as a basis for subsequent comparisons, as shown in Table (3).

3.2 Effect of Poles Number on Bg

For the SPM configuration, increasing the pole number from 6 to 10 significantly modified the air-gap flux density waveform. Higher pole counts increased the fundamental flux density but introduced additional harmonic content. Similarly, for the IPM motor, increasing the pole number from 8 to 10 improved flux density distribution but also shifted the harmonic spectrum.[19, 20] The trade-off highlights the need to balance flux enhancement with harmonic suppression when selecting the pole number.

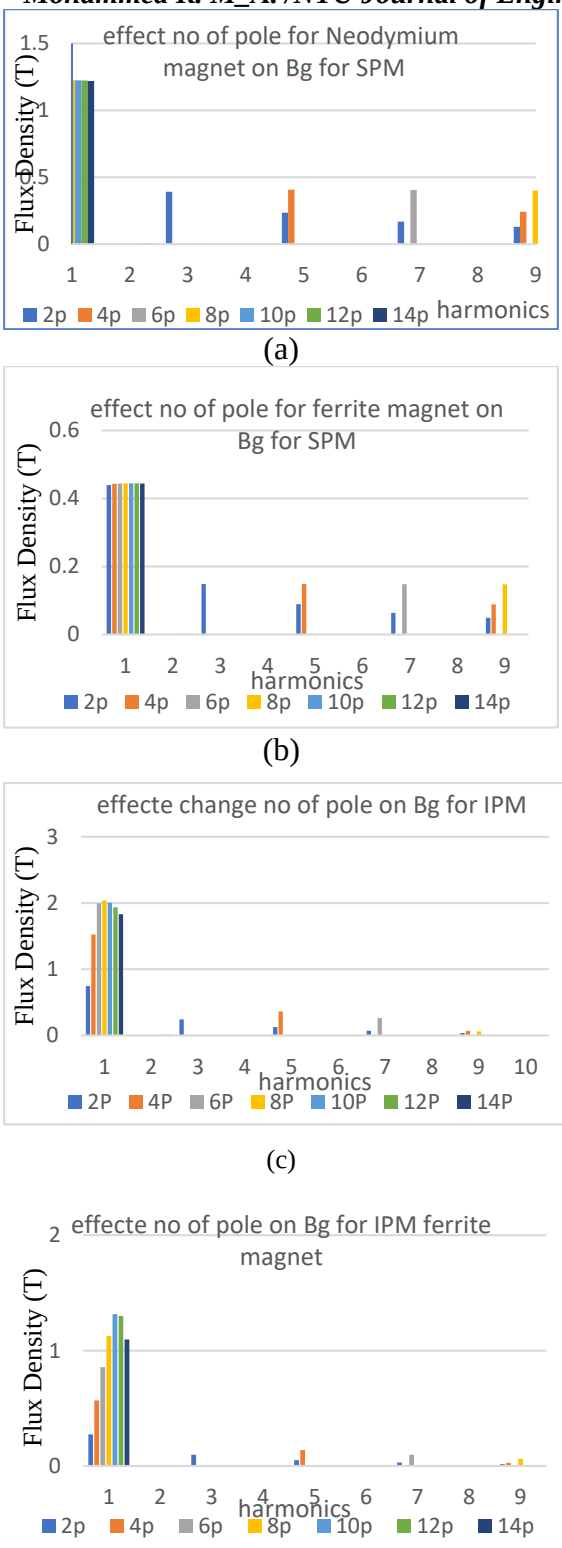


Fig. 3. Effect no of poles on Bg for (a) SPM,N (b) SPM,F (c) IPM,N (d) IPM,F

3.3. Effect of Magnet Thickness on Bg

The simulation results for the SPM motor indicated that the magnet thickness significantly affects the air gap flux density. While increasing the thickness improves the flux density,[21-23] this improvement diminishes beyond a certain point; for example, at a thickness of 4 mm, only a slight further increase was achieved. as shown in Fig. 4 Furthermore, increasing the magnet thickness raises manufacturing costs and introduces mechanical risks, such as detachment at high speeds.[24-26] Some design guidelines suggest that the magnet thickness should not exceed ten times the air gap.[27] Therefore, the optimal thickness must balance electromagnetic performance, cost, and mechanical reliability.[28]

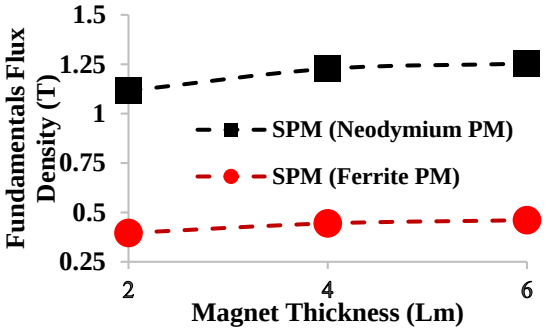


Fig. 4. effect of Magnet Thickness on Bg

3.4. Effect of Pole-arc to Pole-pitch Ratio (α) on Bg

Figure 5 Shows the representation of the pole arc and pole pitch of the proposed PMSMs geometry. Furthermore Fig. (6) and Fig.(7) illustrate its effect on the predicted flux density waveforms for the SPM and IPM motors, respectively. In the SPM motor, the variation of the pole arc to pole pitch ratio has a little impact on the peak flux density;.[22, 29, 30] Inn Figure 5, the best performance was achieved with $\alpha = 0.7$ for NdFeB and $\alpha = 0.9$ for ferrite, where harmonic distortion are minimized.

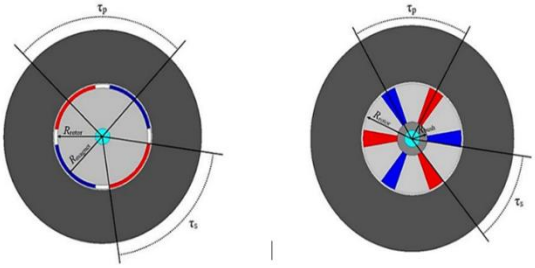


Fig. 5. presents the influence of the pole-arc to pole-pitch ratio α on the rotor geometry,[17]

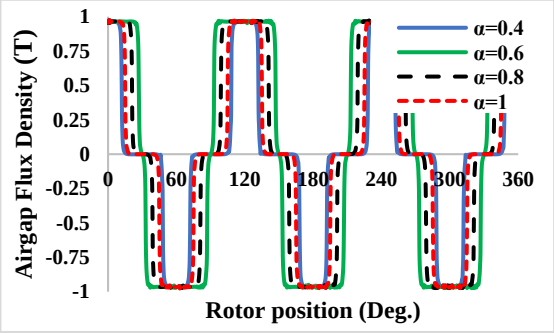
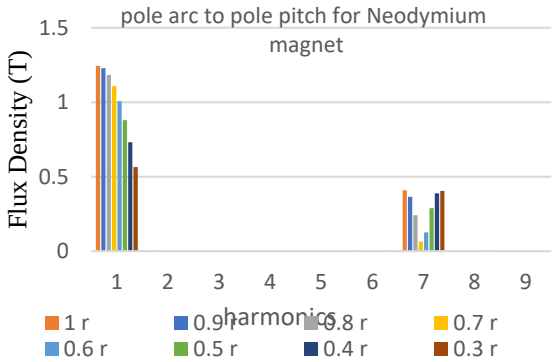
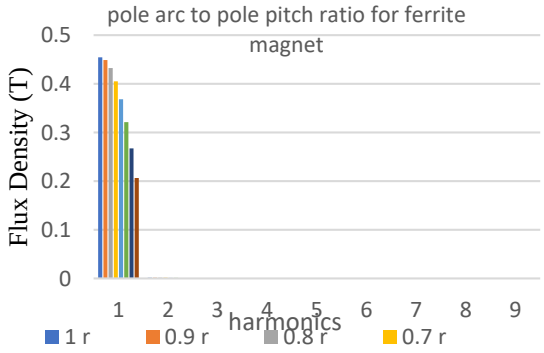


Fig. 6. (a)Variation of airgap flux density for SPM Neodymium with the pole arc to pole pitch ratio



(b) FFT form Bg for SPM NdFeB



(C) FFT form Bg for SPM ferrite

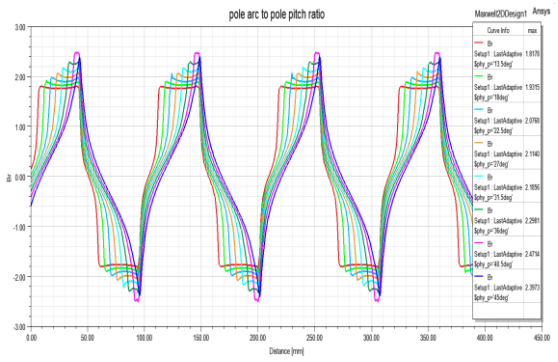
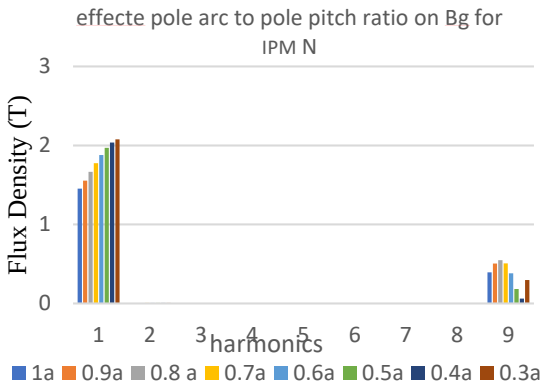
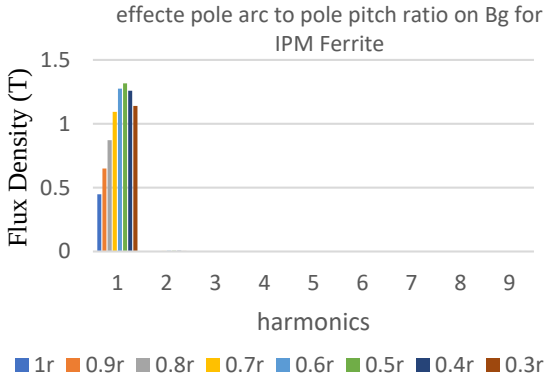


Fig.7.(a).Variation of airgap flux density for IPM Neodymium with the pole arc to pole pitch ratio



(b) FFT form Bg for IPM NdFeB



(c) FFT form Bg for IPM ferrite

In contrast, the IPM motor displayed a distinct trend. The pole-arc to pole pitch ratio strongly influenced the peak flux density, with an inverse relationship,larger ratios resulted in lower peak values. Moreover, this parameter has a pronounced effect on magnet volume and thus on cost.[31,32] As illustrated in Fig. 6, the optimal ratios are identified as (0.4) for NdFeB and (0.5) for ferrite, which yielded the strongest fundamental flux component with the least harmonic distortion.

3.5. Effect of Air-gap Length on Bg

Reducing the air gap length increases magnetic flux density and improves torque, but it also imposes higher manufacturing requirements and increases the level of undesirable harmonics. Conversely, increasing the air gap length leads to a decrease in magnetic flux density and efficiency.[33, 34] A value of 0.5 mm has been found to provide the optimal balance for both SPM and IPM motors. Furthermore, for IPM motors, we observe almost no harmonics at this air gap value, as shown in Fig. 8. This value ensures sufficient magnetic flux density for high torque while maintaining mechanical stability and avoiding saturation, and it represents a practical choice from a manufacturing precision standpoint.

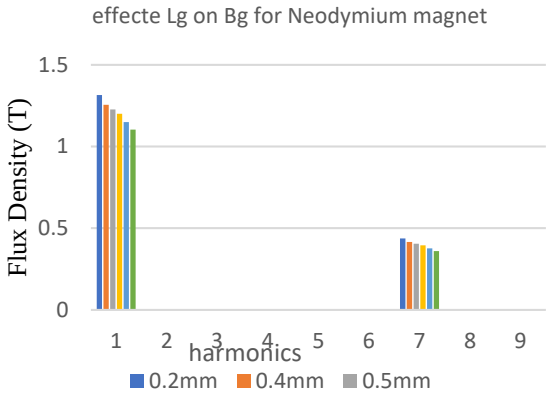
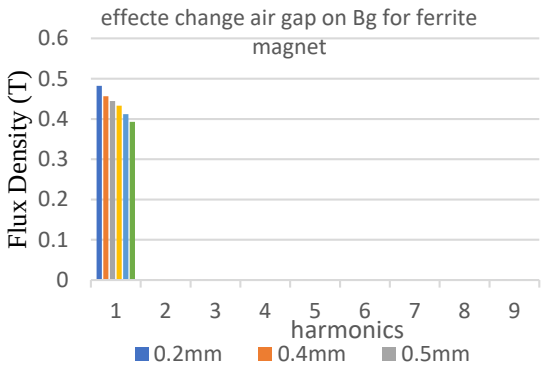
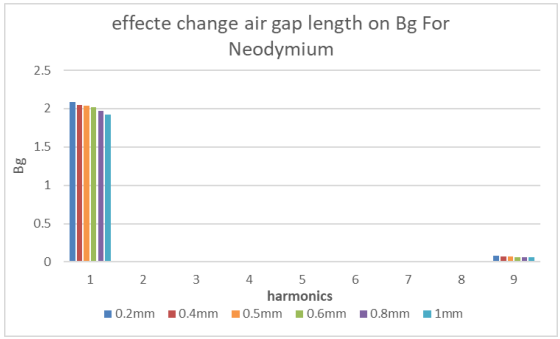


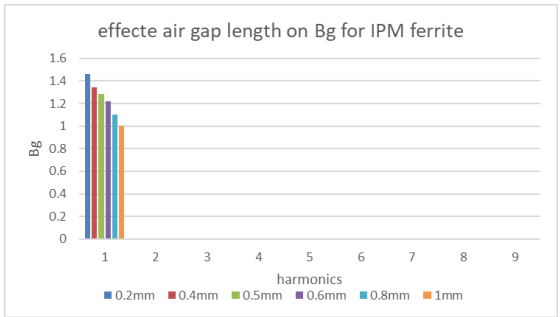
Fig.8.(a) FFT form Bg for SPM NdFeB



(b).FFT form Bg for SPM Ferrite



(c) .FFT form Bg for IPM NdFeB



(d).FFT form Bg for IPM Ferrite

3.6. Effect of Split Ratio on Bg

The split ratio is defined as the ratio of the inner diameter of the stator to its outer diameter, as shown in the equation(4) below and Fig. 9.

$$SR = \frac{in\ stator}{outer\ stator} \qquad (4)$$

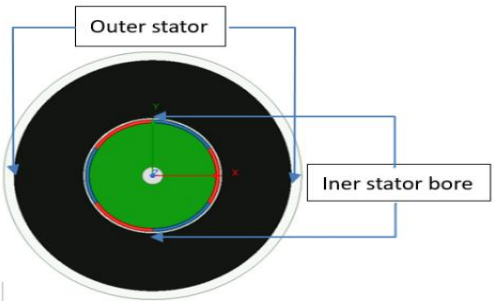


Fig.9. Split Ratio PMSM

After testing various values of this ratio, it was found that it does not affect the air gap flux density or its harmonic spectrum. However, it plays a critical role in other aspects of machine performance. Specifically, it affects core losses and heat dissipation, as well as torque, efficiency, and size. This ratio also affects the stator slot geometry. Previous studies have indicated that the optimum range for this ratio lies between 0.6 and 0.7 for slot-wound machines, as this range provides an ideal balance between efficiency, torque production, and minimizing losses and heat dissipation.[35-37] as illustrated in Figure (10).

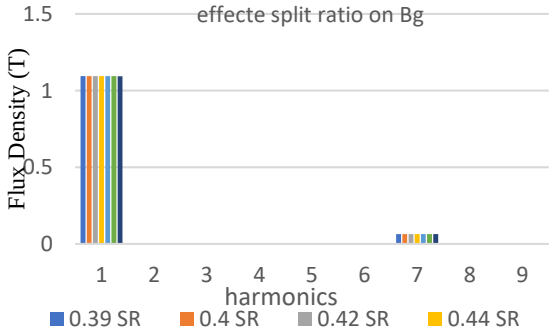
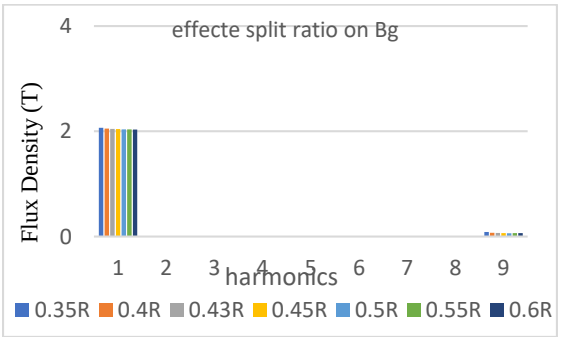


Fig.10.(a) effect split ratio on Bg for SPM



(b) effect split ratio on Bg for IPM

3.7. Effect of Shaft Material on Bg

A study of the shaft material effect showed that the shaft material type does not affect the magnetic flux density in the air gap of surface permanent magnet (SPM) machines, due to the shaft's distance from the flux path, unlike in internal permanent magnet (IPM) machines where the shaft is close to the flux path [17, 38, 39], as illustrated in Fig. 11.

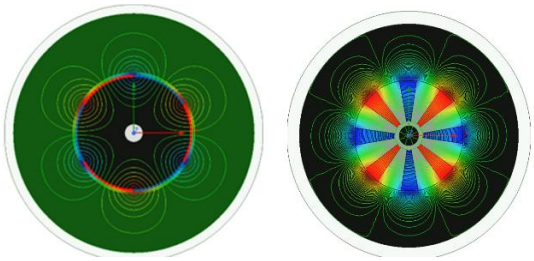


Fig.11. Effect of Shaft Material on Bg for (a)SPM& (b)IPM

Non-magnetic shaft maintained the flux in the air gap, while magnetic shaft created leakage paths that reduced the effective flux. As shown in Figure 12,

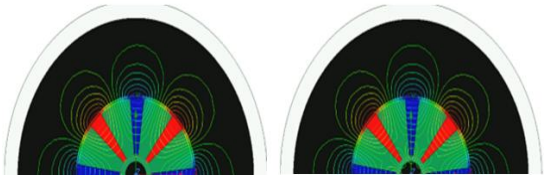
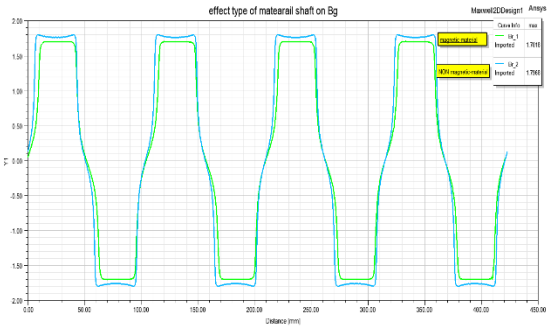


Fig. 12. (a) Nonmagnetic material shaft (b)magnetic material shaft



(c) Effect of Shaft Material on wave form Bg for IPM

this confirms that non-magnetic shaft are the best choice for achieving optimal performance.

3.8. Optimal Configuration

By sequentially optimizing each parameter to its best value, improved designs were achieved for both NdFeB and ferrite motors. As shown in Table [4], despite the lower remanence of ferrite, careful selection of the parameters yielded competitive flux densities with acceptable harmonic levels, making ferrite a practical and cost-effective alternative.

Table 4. Optimal parameters of the proposed SPM and IPM geometry.

Magnet type	**N, Br=1.2T**		**F, Br=0.41T**	
Parameter	**SPM**	**IPM**	**SPM**	**IPM**
Number of pole	6	8	10	10
Pole Arc to Pole Pitch Ratio	0.7	0.4	0.9	0.5
Split ratio	0.6	0.6	0.6	0.6
Bg1	1.1	2.05	0.45	1.31
Stator outer diameter (mm)	225	225	620	620
Stator bore diameter (mm)	135	135	372	372
Magnet length (mm)	5	-	5	-
Air-gap length (mm)	0.5	0.5	0.5	0.5

4. Conclusion

This research investigated a comparative study of slotless permanent magnet synchronous machines (PMSMs), both surface-mounted (SPM) and internal-mounted (IPM), using NdFeB and ferrite magnets.To ensure that the comparison is fair, the equivalent magnet surface area was found so that both types of magnets create the same amount of flux per pole. After this change, the NdFeB stator had an inner diameter of 135 mm, and the ferrite stator had an inner diameter of 372 mm. Finite element simulations showed that the resulting flux values were the same. Thereafter, a systematic parametric analysis was done on important rotor parameters, such as the number of poles, magnet thickness, air gap length, pole arc-to-pitch ratio, splitting ratio, and shaft material, to see how they affect air gap flux density and harmonic behavior. Performing the analysis on a slotless motor allowed the study of the effects of rotor parameters in isolation, without interference from the effects of opening and winding, making the effects more apparent. The results confirmed that NdFeB magnets, because of their high retention ratio, provide higher flux density, while improved ferrite-based designs achieve competitive performance with lower harmonic distortion, making ferrite a practical and cost-effective alternative. Future work is to further refine the obtained parameters, taking into account the effects of notches and coils, to complement the evaluation of combined electromagnetic and mechanical effects under more practical operating conditions.

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Author Contributions

Mohammed K. Contributed to software development, validation, formal analysis, investigation, resources, data curation, preparation of the original draft, manuscript review and editing, and visualization.
Ahmed J. contributed to supervision, project administration, and manuscript review and editing.
Abdullah K. contributed to conceptualization, methodology, and manuscript review and editing.
All authors have read and approved the final version of the manuscript.

Competing Interests

The authors declare there are no competing interests.

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