Study the dynamic performance of PM machines for different rotor topologies

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ABSTRACT

For hybrid and electric vehicle drive-train (automotive applications) achieving high torque and efficiency at a wide range of operating conditions can be considered an important matter. Therefore, precise structure optimization of the permanent magnet synchronous machines (PMSMs) is recommended. Consequently, the effect of the main leading design parameters (such as PM arrangement, magnet thickness, pole arc to pole pitch ratio, airgap length as well as the effect of shaft material) for a different number of rotor poles configuration of PMSM can achieve optimum design results in electric motors with economical cost and excellent performance. This paper submits a comparative analysis of different rotor topologies of (PMSM). Moreover, the dynamic performances of the suggested rotor geometry topologies are investigated based on investigation of finite element analysis (FEA). The analysis offers a piece of complete information about the magnetic flux distribution and magnetic flux density over the motor geometry. Gained results from the analysis are used to give a decision for the selection of a suitable PMSM design.

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1. INTRODUCTION

Compared with other types of electrical machines, permanent magnet synchronous machines (PMSM) have high torque density, high power density, small losses, simple structure for the rotor, and then high efficiency and reliability which gain its great popularity and a contender for various industrial application and domestic appliance [1]–[4]. Accordingly, the use of high-energy magnets as a source of excitation such as rare earth plays an important effect on the dynamic performance of the machines.

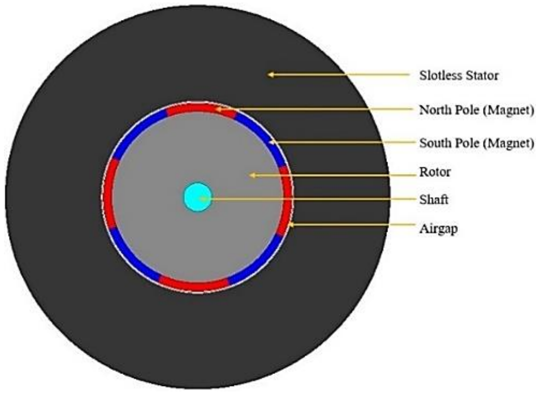
In the last years, a revolution in the software for modelling a complex structure had developed which allows for simulation and optimize the parameters of electric machine design previous to manufacture. These methods are based e.g., on the finite element method (FEM), which is currently considered the best widespread method in the engineering design of electrical machines [5]–[11]. Internal permanent magnets (IPM) which comprise rotors with inserted magnets are becoming more attention for better PM utilization and are widespread with the machine of constant power compared with the surface-mounted permanent magnet (SPM). It has a wide-ranging speed and torque, high power, and efficiency, and is lightweight [12]. The dynamic operation of IPM is directly controlled by the topologies and shape of the rotor part. This topology can be enhanced by optimizing the geometry of the rotor [13]. Moreover, some types of IPM with different structure and location of magnets with arc shape and flux barriers in the rotor leads to variate values of the average torque of the motor [7], [14], [15]. The characteristics of the permanent magnet in the rotor (PM), magnet dimensions, and shape as well as air gap length have an important effect in determining the efficiency of the PMSM [16], [17]. Recently many researchers focus their works on studying the rotor structure variations to modify the most important parameters that affect the dynamic operation of permanent magnet motors [18]‒[21]. It investigates the optimization of airgap shape, rotor pole numbers, and stator configuration which improve the airgap flux and reduce torque ripples. SPM machines with a small length of the airgap in the d-axis direction with increasing airgap length in the q-axis direction will reduce the value of ripple torque which enhances the steady state operation [22]‒[24]. The inset IPM pole shape is considered by modifying the dimensions of the pole shape (length, width, and pole embrace) to obtain a criterion for the design rules based on the variation of the ratio of airgap length in both d-q directions [25]. This optimization improves the developed torque and efficiency of the motor. In addition, the back emf and cogging torque are improved [8]. A small hole is created on the rotor core near the airgap to control the direction of the magnetic flux. It produces an altered direction for the reluctance path which decrease the ripple torque of the IPM. These modifications are implemented using FEM [26].

On the other hand, analytical methods can also be used to model the modifications on PM pole shapes of different types (SPM, IPM, single and multi-layer-type IPM) machines to validate the results obtained from FEMs [9], [27], [28]. The steel materials of the stator and rotor have a great effect on the flux variation, eddy current, and hysteresis losses which affect the efficiency of the electric machines. Therefore, the selection of some right ferromagnetic and PM materials will provide sufficient performance for the magnetic parameters [29]. It is found that the construction material used in motors which are applied in the high-rotation speed of machine are faced with high operational frequencies of energy supply source, which reduce the efficiency of the motor due to increasing occurs in both core losses components (hysteresis-eddy current losses). These losses can be reduced by a correct choice of the steel type having low properties of core loss. While the generated eddy currents can be reduced by laminated rotor and stator cores [30], [31]. Airgap flux density (B_g) is one of the main factors affected by the performance of the machines and characteristics, therefore enhancing the achievable value of (B_g) can achieve high torque and power density as well as qualifies the machines to be desirable for different speed applications when the field weakening is required such as electric and hybrid vehicles [32], [33]. In addition, the mechanical structure of the rotor is considered an important part of electrical machines therefore it should be built with a construction that provides a harmless operation during high rotational speed. Essentially, choosing a suitable position for the magnets is crucial for the choice of correct rotor topology. To reduce the effect of the centrifugal forces, internal permanent magnet rotors (IPM) are the suitable selection although that (SPM) can also be used for high-speed motors [34], [35]. However, the configuration and distribution of the magnet in the rotor as well as the thickness are considered one of the most important leading design parameters alongside the airgap length and should be analyzed and optimized in the initial steps [36]‒[39].

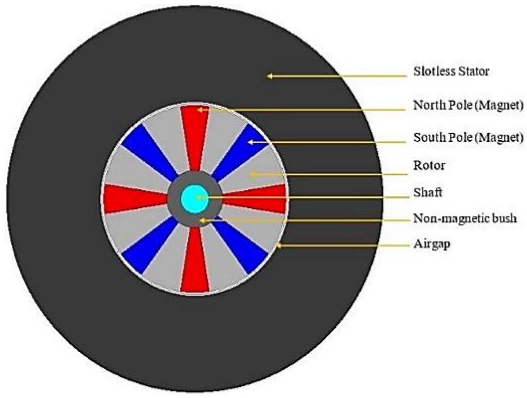
This paper presents the FE model for computing the magnetic field produced in slot less PM motors. The model considers the effect of flux distribution in the stator and rotor regions. The modelling of the slot less effect has a vital effect on the leading design parameters used for the design of these specific types of machines.

2. PROPOSED ROTOR TOPOLOGIES

Two types of rotors (IPM and SPM) are assumed with different geometries and dimensions of the magnets. For a rational comparison of the motor performance, some design parameters of the two types are given in Table 1. This paper focuses on the assembly and design of a PMSM by considering two types of rotor magnets with different topologies. The two types of PM motors are assumed slot less to cancel the effect of stator slots (slotting effect) on rotor poles' magnetic flux. Figure 1 shows the structure of the two categories of rotor-mounted PM machine geometry adopted in this paper (a) SPM and (b) IPM. In the SPM machine, the magnet is supplied with rare earth material and fixed on the rotor surface and adjacent to the airgap flux with radial magnetization. Therefore, it has an interesting feature such as less magnet leakage flux. For the ideal case, the maximum value of the airgap flux density should equal approximately the value of magnetic flux density (B_m). In an IPM machine, the flux is produced by two adjacent PMs and concentrated in the airgap area (A_g). Therefore, the generated airgap flux density can be higher than SPM machines. However, the main disadvantage of IPM machines is the leakage flux specifically around the bottom of PMs near the shaft. Therefore, a non-magnetic bush is fixed over the shaft to reduce the value of the leakage flux [40].



(a)



(b)

Figure 1. Geometries of PMSM: (a) SPM and (b) IPM

Table 1. Parameters of PMSM

Parameters	SPM	IPM
Stator outer diameter (mm)	270	270
Stator bore diameter (mm)	135	135
Rotor outer diameter (mm)	125	57.12
Airgap length (mm)	0.5	0.5
No. of poles	8	8
Shaft diameter (mm)	20	20

3. RESULTS AND DISCUSSION

This section investigates the effect of the main leading design parameters on the achieved values of the airgap flux density of PM machines. Moreover, the machines parameter such as magnet thickness, pole arc to pole pitch ratio, airgap length as well as inner to outer diameter ratio of the rotor besides the effect of shaft materials on the leakage flux are analyzed using 2D Maxwell Ansys-R1 for the two PMSM geometries mentioned above.

3.1. Influence of the variation of magnet thickness and pole arc to pole pitch ratio on the airgap flux density

3.1.1. For SPM machines

Figure 2 depicts the variation of the airgap flux density at different magnet thicknesses. It can be noticed that the thickness of the magnet of SPM machines has an important effect on the value of B_g [41]. Consequently, as the thickness increases the value of B_g will increase as investigated from (1) and (2) respectively which are derived based on Ampere and Gauss' law. However, when the thickness approaches about (4-5 mm), the value of B_g will keep to a fixed value which is about (0.9 T). Where B_r, A_g, A_m, L_g, L_m, and μ_r are remanence of the magnet in tesla, the cross-section area of the airgap, the cross-section area of the magnet, airgap length, magnet length, and relative recoil permeability of the magnet respectively.

$$B_g = \frac{B_r}{\left(\frac{A_g}{A_m} + \mu_r \frac{L_g}{L_m}\right)} \tag{1}$$

For SPM machines $(A_g \cong A_m)$

$$B_g = \frac{B_r}{\left(1 + \mu_r \frac{L_g}{L_m}\right)} \tag{2}$$

3.1.2. For IPM machines

The ratio of pole arc to pole pitch (α) for the IPM geometry proposed in this paper has a direct effect on the magnet thickness. In other words, as (α) increases that means the thickness of the magnet will increase and vice versa. This can be clearly illustrated in Figure 3 and obtained in (3) [42], [43]. In contrast, the variation of the pole arc to pole pitch ratio (α) has no effect on the magnet thickness as well as the value of the airgap flux density for SPM geometry as shown in Figure 4. Figure 5 clarifies the pole arc (τ_s) and pole pitch (τ_p) schematic map (a) SPM and (b) IPM selected geometries. The fundamental value of the airgap flux density (B_1) is predicted as shown in (4) [43].

$$B_g = \frac{B_r}{\left(\frac{A_g}{A_m} + \mu_r \frac{2L_g}{L_m}\right)} \quad (3)$$

$$B_1 = \frac{4}{\pi} B_g \sin\left(\alpha \frac{\pi}{2}\right) \quad (4)$$

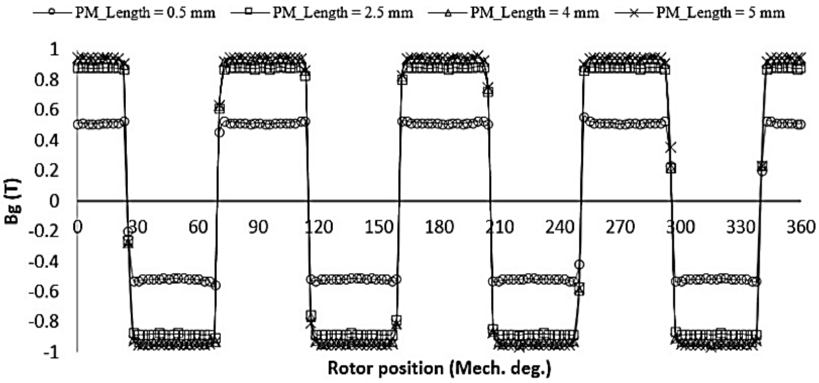


Figure 2. Variation of airgap flux density for SPM at different magnet thickness

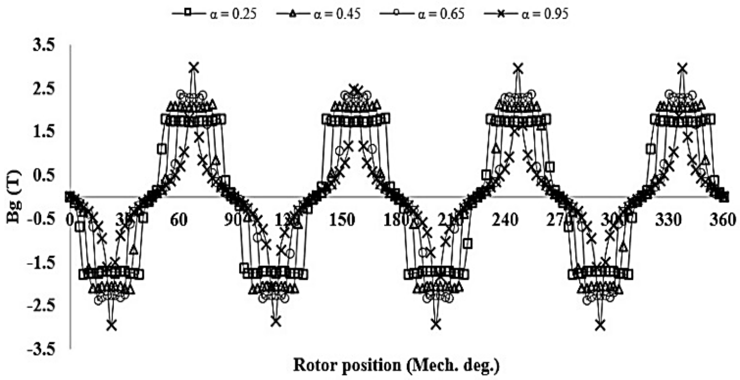


Figure 3. Variation of airgap flux density for IPM at different magnet thickness

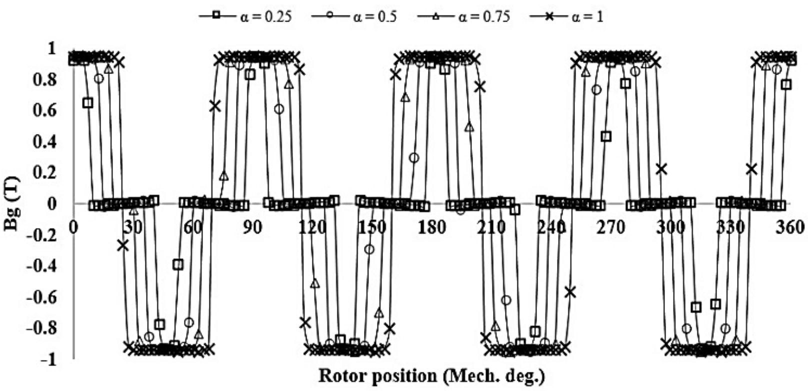


Figure 4. Variation of airgap flux density for SPM at different pole arc to pole pitch ratio (α)

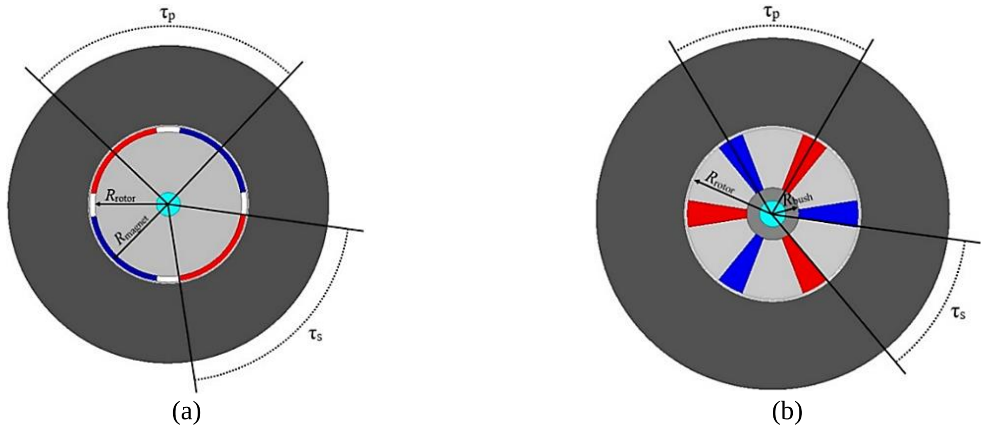


Figure 5. Pole arc (τ_s) and pole pitch (τ_p), schematic map for (a) SPM and (b) IPM geometries

3.2. Influence of the variation of airgap length on the airgap flux density

3.2.1. For SPM Machines

Figure 6 illustrates the variation of the airgap flux density (B_g) at different airgap lengths (L_g) for the proposed SPM geometry. It can be noticed that the value of (B_g) is inversely proportional to the airgap length. However, the maximum value of the airgap flux density doesn't exceed (1 T) while for IPM machines the value of (B_g) will be doubled as can be seen in Figure 7, this belongs to the geometrical position of the magnets through which a higher value of flux concentration can be achieved.

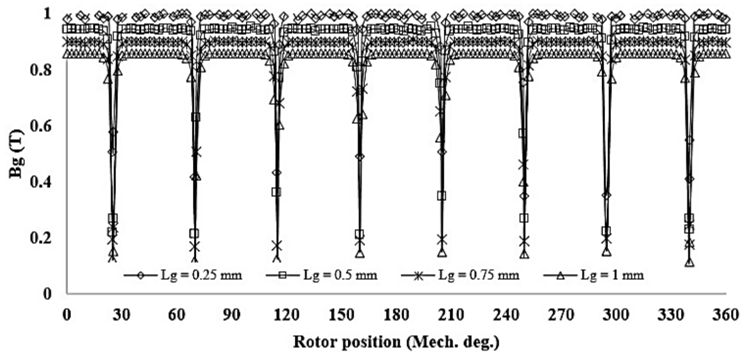


Figure 6. Variation of the airgap flux density for SPM at different airgap lengths

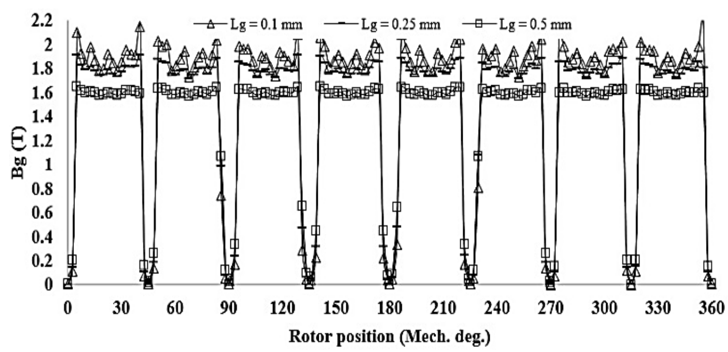


Figure 7. Variation of the airgap flux density at different airgap length

3.2.2. For IPM machines

The variation of the airgap flux density (B_g) at different airgap lengths (L_g) for IPM geometry is depicted in Figure 7. As for SPM machines, the airgap flux density is reduced as the airgap length increase. Therefore, this has a great effect on the magnetic characteristics of the proposed machines. Consequently, the influence of airgap length is very important and should be considered seriously and accurately in the initial step of PM machines design since the magnetic inductance for the air is very low and the ability of the magnetic flux line to across the airgap is very sensitive to the airgap length and this will reduce the magnetic flux captured by the stator winding as well as increase the leakage flux which is an undesirable feature for the machines.

3.3. Influence of the magnetic characteristics of the shaft material on the airgap flux density

In addition to the above-mentioned factors which have a great effect on the magnetic characteristics of the PM machines, the material of the shaft has also a noticeable effect on the generated airgap flux density (B_g) for both SPM and IPM machines. The material of the shaft can be either magnetic characteristics such as ferromagnetic material like steel, or non-magnetic characteristics such as aluminum and stainless steel.

3.3.1. For SPM machines

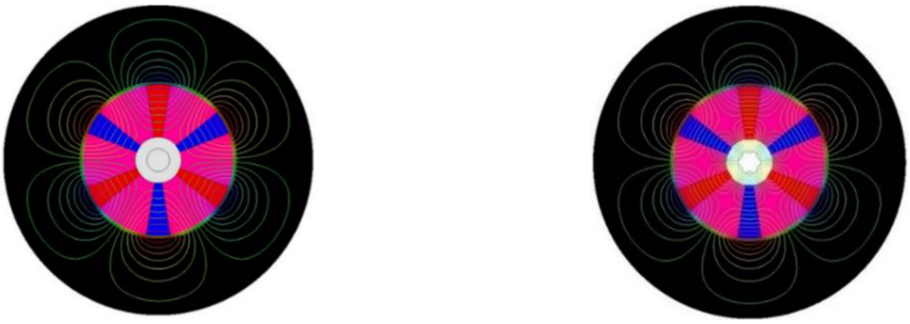
Due to the position of the magnetic pole pairs which are away from the shaft, the material of the shaft has no observable influence on the value of the airgap flux density although the material of the shaft has magnetic or non-magnetic characteristics. This can be observed as shown in Figure 8, which illustrates the magnetic flux lines distribution for a different number of poles (a) 4-poles, and (b) 8 poles.

(a) (b)

Figure 8. Flux lines distribution for SPM machines: (a) 4-poles and (b) 8 poles

3.3.2. For IPM machines

The influence of the shaft material on the value of the airgap flux density can be obviously noted for this type of machine. In another word, due to the position of the magnet near the edge of the shaft, there will be flux leakages at that point and the value of the leakage flux can be observed and predicted clearly as illustrated in Figure 9. When a non-magnetic material for the shat is used the value of the leakage flux at the rear of the magnet and around the shaft region will be very few and almost non-existent as shown in Figure 9(a). However, the leakage flux line can be intense and huge in the same region when a ferromagnetic magnetic for the shaft is chosen as shown in Figure 9(b). Consequently, the effect of the shaft material has an important effect and should be considered as a part of the leading parameters in the design and implementation of this type of PM machine since it has a direct effect on the value of the predicted airgap flux density as shown in Figure 10.



(a) (b)

Figure 9. Flux lines distribution for IPM machines, (a) non-magnetic-material and (b) magnetic-material

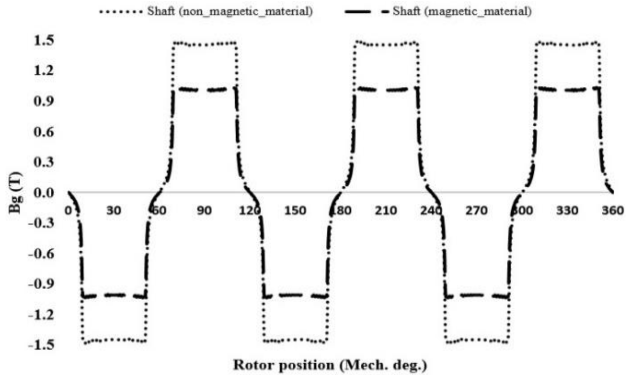


Figure 10. Variation of the airgap flux density for IPM at different shaft materials

4. CONCLUSION

In this paper, the investigation of the effect of the main leading design parameters of two PM geometry is illustrated. In another word, the variation of the airgap flux density for two geometries of a rotor mounted PM machines surface mounted and inner rotor PM machines (SPM & IPM) respectively for a different number of rotor poles and slotless stator is analyzed taking into account the initial design parameters such as magnet thickness, pole arc to pole pitch ratio, airgap length as well as the effect of shaft material. In comparison between the SPM and IPM machines, the predicted results concluded that:

The value of the airgap flux density is inversely proportional to the airgap length. Therefore, the influence of airgap length is very important and should be considered seriously and accurately in the initial step of both types of PM machines to achieve optimum design results in electric motors with economical cost and excellent performance. It can be noticed that for IPM a higher airgap flux density can be achieved compared with SPM with a ratio of about (1:2 for the same airgap length), this belongs to the geometrical position of the magnets through which a higher value of flux concentration can be achieved.

For SPM three is no observable variation of (B_g) as pole arc to pitch ratio (α) changes, however, the effect of (α) can be noticed and considered for IPM geometry since the thickness of the magnet is changed leading to the produced value of the concentrated flux will be higher (about 1.5 Tesla at (α) = 0.25 for IPM comparing with 1 Tesla for SPM for the same pole arc to pitch ratio).

The material of the shaft (magnetic or non-magnetic) has no observable influence on the value of the airgap flux density for SPM machines. In contrast, it has a noticeable effect on the generated airgap flux density (B_g) for IPM machines. Meanwhile, the position of the magnet away from or near to the edge of the shaft affects the value of the leakage flux and then has a considerable effect on the value of the predicted airgap flux density.

Consequently, the conducted analysis offers a piece of complete information about the magnetic flux distribution and magnetic flux density over the motor geometry. As an initial step, gained results from the analysis are considered very important and recommended prediction used to give a decision for the selection of a suitable design of PMSM and to optimize the performance of the machines to be a good contender for different applications.

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