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Material and Magnetization Effect on Permanent Magnet Motor Design

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Abstract: Permanent Magnet (PM) motor materials affect on their developed torque, torque pulsation and other performances. However, the performance sensitivity to the material changes by material and motor types (SFPM, Inset, IPM, Buried ...). Usually, PM motor designers optimize the motor based on motor dimensions and topology and less on material selection. However, material has significant effect on motor performances. Choosing high quality and expensive material does not always guarantee to improve torque quality and quantity. This study analyzes the performance sensitivity versus material magnetic characteristics for SFPM and IPM motors. Moreover, the optimum material based on developed average torque is presented. Then, we analyze PM magnetization effect on air gap magnetic flux density.

Key words: Machine design, material effect, magnetization effect

INTRODUCTION

Permanent Magnet Synchronous Motors (PMSM) have high efficiency, because of using Permanent Magnet (PM) materials as the source of mmf (or magnetic flux). There are two major types of PM motors which are Surface Mounted PM (SFPM) and Interior PM (IPM) motors. Recently, interior permanent magnet synchronous motor is increasingly used in home applications and hybrid electric vehicles.

SFPM motors have simpler rotor structure and better speed and position controllability.

Moreover, as shown in Fig. 1, their torque pulsation is less than that of IPM, since their magnetic field distribution is closer to the sinusoidal form. However, their maximum possible speed is lower than that of IPM due to centrifugal force which is applied to the magnets. IPM motors have higher torque density, compare to SFPM, due to two available torque components, which are electromagnetic (mutual) and reluctance torque. The electromagnetic torque is produced by interaction between the rotor magnetic field and the stator's windings mmf (or current). This is the most part of the IPM motor developed torque. On the other hand, the reluctant torque is produced due to different d and q axis reluctances (Rd and R q). However, IPM motor has higher torque pulsation compare to SFPM, due to: space harmonics in air gap flux distribution produced by PMs (Fig. 2) and fluctuation of reluctance torque. In PM motors, magnetic flux experiences air-gap, stator, rotor and magnets reluctances. These reluctances affect the average developed torque and torque pulsation. Different electric motors show different sensitivity versus material change. Quantitative analysis of these sensitivities helps the machine design procedure, significantly. Nowadays due to advances in technology, magnetic materials with high saturation flux density (Bmax) and high permeability (μ) are available. However, these materials are still expensive. In future, we may have magnetic material with higher Bmax and μ. Using these high quality magnetic materials needs economical analysis. The question is that how much using these advanced materials can improve the motor performances.

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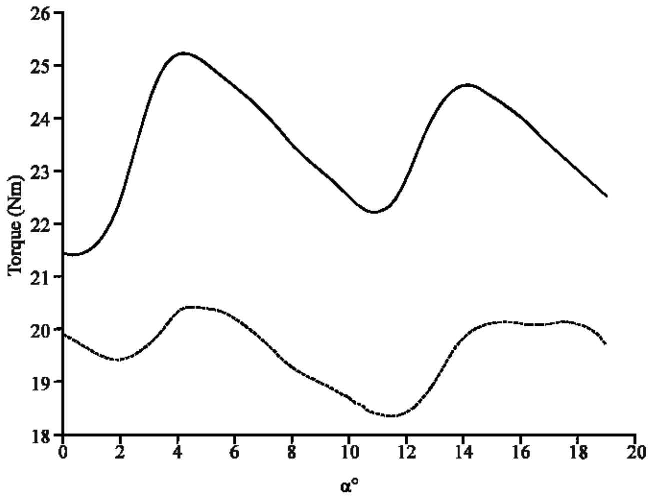


Fig. 1: Torque of IPM (−) and SFPM motors(- -)

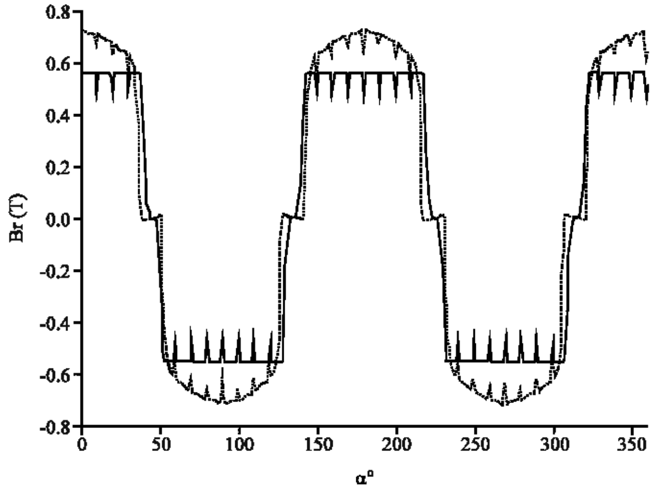


Fig. 2: Radial components of magnetic flux density of SFPM (- -) and IPM (−) motors

In this study, first briefly present on magnetic material characteristics. Then, we analyze material effect on PM motors. Finally, we analyze the effect of PM material magnetization form (radial, parallel) on SFPM and IPM motors.

MAGNETIZATION PHENOMENA OF MAGNETIC MATERIALS

In the magnetic materials, orbiting electrons of each individual atom can be considered as a current loop in a winding. Without an external magnetic field H, the orbiting atoms electrons are randomly disposed and the material does not show any resultant magnetic flux. The presence of external magnetic field influences the orbit of the individual atom and creates magnetic dipole moment m. The direction of the magnetic dipole is perpendicular to the loop plain in the direction of a right hand screw. For example, if the equivalent current loop of the orbiting atom electrons is located in the x-y plane and orbiting in the clockwise direction, the current loop moment is defined as:

$$m = \pi r^2 \, I a_Z \tag{1}$$

Where:
r = Orbit radius of the orbiting electron
I = Equivalent current of the orbiting electron

The vector potential of such an orbiting electron is:

$$A(x,y,z) = \frac{\mu_0 I}{4\pi} \oint_c \frac{dI}{R_1} \tag{2}$$

where, R1 is the distance of (x, y, z) point with any point of the electron orbit.

An overall representation of the magnetic dipole moments of a finite body (material), which is so called magnetic polarization vector M, can be obtained by multiplying ma_m by the number of atoms per unit of volume N

$$M = Nm \tag{3}$$

By calculation and integration of the magnetization effect of all atoms we have (lipo)

$$A = \frac{\mu_0}{4\pi} \oint_S \frac{M \times a_n}{R} dS + \frac{\mu_0}{4\pi} \int_V \left(\frac{1}{R}\right) \nabla \times M(x,y,z) dV \tag{4}$$

Comparing this expression of the vector potential with that for true current, we can interpret the term $M \times a_n$ as an equivalent surface polarization current J_{ms}. In the same way, the curl of magnetization vector $\nabla \times M$ can be interpreted as an equivalent volumetric polarization current J_m. Therefore, we have:

$$A = \frac{\mu_0}{4\pi} \left(\oint_S \frac{J_{ms}}{R} dS + \int_V \frac{J_m}{R} dV \right) \tag{5}$$

Comparing the above equation with :

$$\nabla \times B = \mu_0 \, J \tag{6}$$

it can concluded that:

$$\nabla \times B = \mu_0 \, (J + J_m) \tag{7}$$

Since:

$$\nabla \times M = J_m \tag{8}$$

Comparing the above to Eq. 7 concludes:

$$\nabla\times\left(\frac{B}{\mu_0}-M\right)=J \tag{9}$$

where, J is the surface current density of the external (true current). Therefore, comparing the above equation with:

$$\nabla\times H=J \tag{10}$$

We have:

$$H=\frac{B}{\mu_0}-M \tag{11}$$

Or:

$$B=\mu_0\,(H+M)=\mu_0 H+\mu_0 M \tag{12}$$

In other words, the magnetization phenomena can be represented by magnetic permeability. By comparing the above equation with

$$B=\mu H=\mu_r\,\mu_0\,H \tag{13}$$

Concludes:

$$\mu=\frac{\mu_0}{1-(\frac{\mu_0 M}{B})} \tag{14}$$

Theoretically, It's not possible to determine a specific limit for saturation B(T) and μ in materials. So, advance in material science may discover new materials with higher quality than one of existing materials. In continue, we go ahead considering this fact and use some of materials characteristics that there are not yet but they may be made in the future.

SENSITIVITY OF SFPM MOTOR TORQUE TO THE STATOR AND ROTOR MATERIALS

Until now, some works have been done on material effect on electric motor losses (Anayi *et al*., 2003; Yagisawa *et al*., 2007; Toda *et al*., 2005) and on mechanical characteristics of electric motors (Zhilinski and Zozulya, 1977). In addition, some researches have been done to improve utilizing the material used in electric motors and to get the better motor characteristics (e.g., more average torque), (Nethe *et al*., 2002). Figure 3 shows B-H curve of nine different materials (Ideal material is No. 10 and not shown). First we analyze the torque sensitivity to the stator core material. In this analysis, is chosen ideal soft magnetic material (that is: material with $\mu\cong\infty$) for rotor, change the stator material and compute the developed torque, which is shown in Fig. 4. The results concludes that using high permeability (high quality)

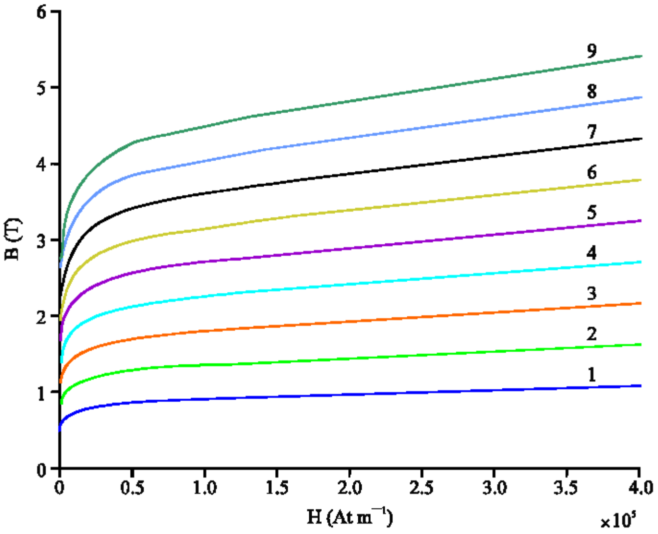


Fig. 3: B-H curve of different materials (existing or coming in the future), number 10 is ideal material

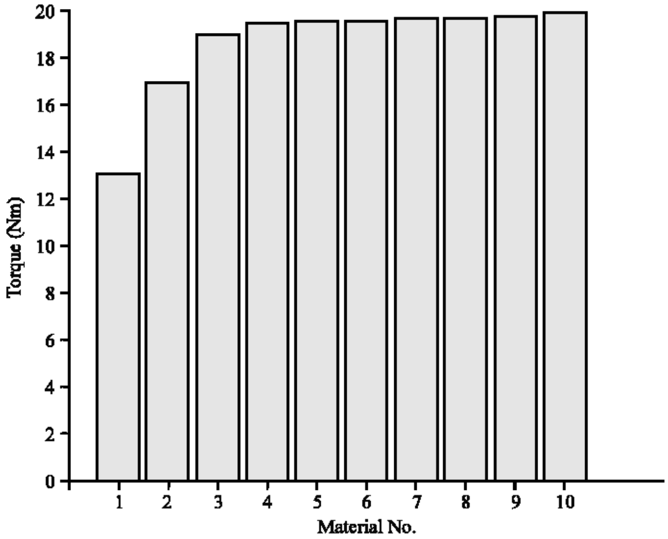


Fig. 4: Average torque of SFPM motor with constant rotor (ideal) and variable stator materials

materials cause very little (less than 2.42%) increase in the developed torque. In other words, the SFPM motor developed torque show little sensitivity to the stator material quality.

In the second stage, we analyze the torque sensitivity to the rotor core material. In this stage, we chose ideal soft magnetic material (that is $\mu \cong \infty$) for stator, change the rotor material and compute the developed torque, which is shown in Fig. 5. In this stage, the results concludes that using high permeability (high quality) materials cause extremely little (less than 0.46%) increase in the developed torque. In other words, the SFPM motor developed torque show

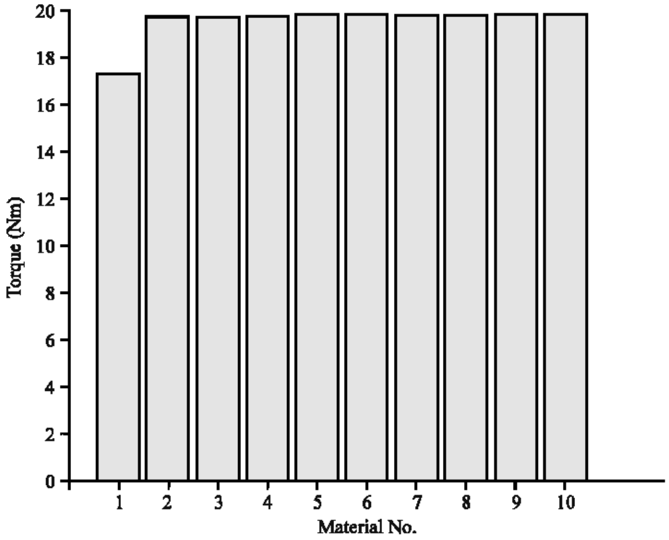


Fig. 5: Average torque of SFPM motor with constant stator (ideal) and variable rotor materials

extremely little sensitivity to the material quality. Comparing the result of these two stages shows that SFPM developed torque sensitivity to the rotor material is even much smaller than that of stator material.

The above two analysis clearly conclude that conventional magnetic material used in stator and rotor cores of SFPM are very proper. In other words, using higher permeability (number nine) material have extremely little effect (less than 2%) on the motor developed torque and therefore has no economic reason.

SENSITIVITY OF IPM MOTOR TORQUE TO THE STATOR AND ROTOR MATERIALS

The sensitivity analysis of IPM motor to the core material is very different to that of SFPM and have unexpected conclusion. As known, IPM motor needs flux-barrier or air-bridges between the adjacent rotor magnets with opposite polarity. Otherwise, the produced magnetic flux of the magnets will be shorted in the rotor and does not pass stator and armature. Ideal air-bridge must start from the magnet edge and continued till rotor surface, which separate the core above the magnet from the rest of the rotor. However, to keep the rotor integrity against centrifugal force, we must keep minimum thickness of the core between the air-bridge and rotor surface which is called critical plane. Otherwise, the rotor takes into parts at high or even medium speed. Due to the above mentioned special rotor structure of IPM, choosing very high permeability (high quality) material cause more flux to be shorted via critical planes (Fig. 6). Therefore, less magnetic flux enters the air-gap which causes less developed torque. In Fig. 7 flux entering the air-gap is depicted versus material number. Therefore, using rotor core material with low permeability causes more percentage of the rotor flux to enter the air-gap. On the other hand, the electromagnetic developed force distribution at each point of rotor and stator surface is represented Maxwell stress tensor as:

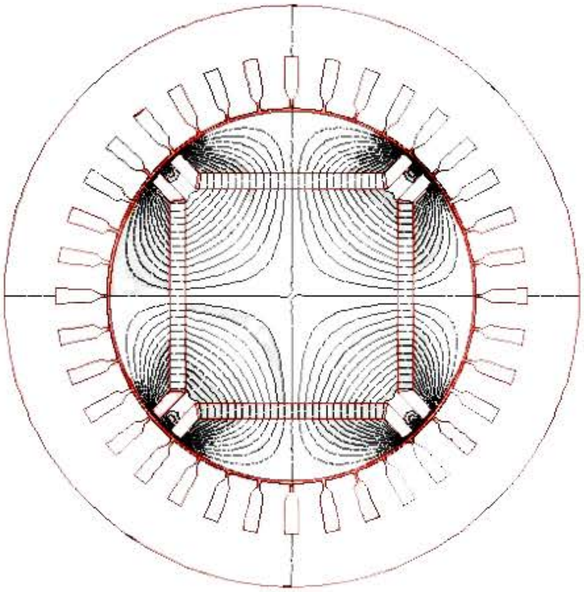


Fig. 6: Magnetic flux lines of IPM motor with high quality rotor material

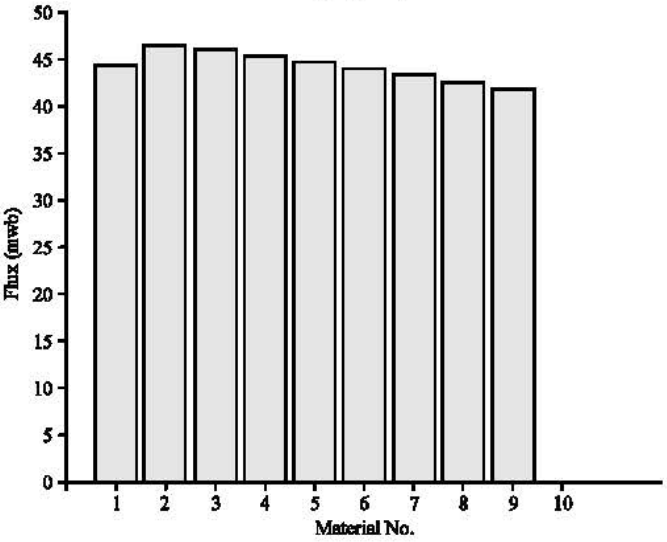


Fig. 7: Permanent magnets magnetic flux entering the air-gap

$$F(x,y,z) = \upsilon_0 Z R^2 \Delta\theta \sum B_r B_\theta \tag{15}$$

$$\upsilon_0 = \frac{1}{\mu_0}$$

Z = Motor length
R = Radius to middle of air-gap

$\Delta\theta = \frac{2\pi}{n}$, n = Number of node pair used to calculated the torque

Br = Radial component of magnetic field density

Bθ = Tan gential component of magnetic field density

Choosing low permeability material for rotor cause more magnetic field intensity to drop on rotor core body and decrease the developed torque. Therefore, there exists an optimum quality (optimum permeability) to achieve maximum motor developed torque. In fact, high permeability material does not decrease the air-gap magnetic flux directly. The real problem is that such a material facilitates the shorted flux in the critical region. Therefore, if we can have high permeability material with very high mechanical strength, we can make the critical plane narrower to decrease the shorted flux and increased the average torque.

EFFECT OF RADIAL OR PARALLEL MAGNETIZED MAGNET IN SFPM MOTOR

In SFPM motor, magnetizing orientation (radial or parallel) of the magnet affects the air gap flux density, as shown in Fig. 8. It seems that in SFPM motor changing the magnetic flux distribution around air-gap can be shaped by two methods. The first method is to change the air-gap flux direction using magnetizing orientation of the magnets. But this method is not practical, since the flux lines departing the magnet surface intend to pass through the shortest path to enter the stator surface. Therefore, magnetization orientation of the magnets does not affect the flux direction out of the magnet surface.

The second method (to shape the magnetic flux distribution) is to choose the magnitude of magnetic flux as a function of space angle θ. This can be done by magnetizing orientation and magnet shaping.

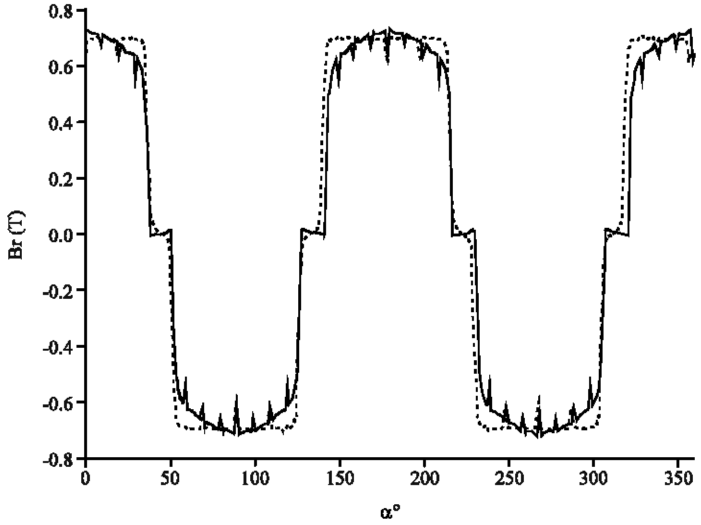


Fig. 8: Magnetic flux density of SFPM motor with radial magnetization (--) parallel magnetization (–)

MATHEMATICAL ANALYSIS OF RADIAL AND PARALLEL MAGNETIZATION

Figure 9a shows equivalent electric circuit of SFPM motor in no load conditions considering the ideal material for rotor and stator. Figure 9b shows schematic of magnet of SFPM motors.

- With radial magnetization

$$L_{av} = L_1$$

$$A_{av} = \frac{A_1 + A_2}{2}$$

$$\varphi_{rad} = \frac{\dfrac{L_1}{\mu(\frac{A_1 + A_2}{2})l_e}}{\dfrac{L_1}{\mu(\frac{A_1 + A_2}{2})l_e} + \dfrac{g}{\mu l_e A_1}} B_r l_e (\frac{A_1 + A_2}{2}) = \frac{L_1}{L_1 + \dfrac{g}{A_1}(\frac{A_1 + A_2}{2})} B_r l_e (\frac{A_1 + A_2}{2})$$

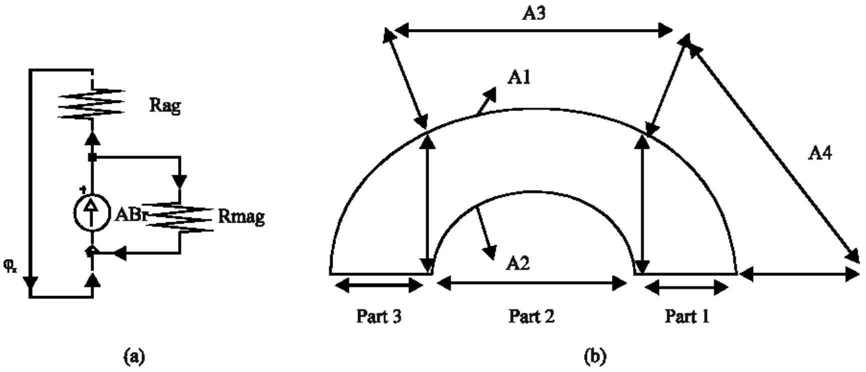
- With parallel magnetization

$$L_{av} = \frac{L_1 + L_2}{2}$$

$$A_{av} = \frac{A_2 + A_3}{2}$$

Flux produced by magnet of part 2 is:

$$\varphi_{P2} = \frac{\dfrac{(L_1 + L_2)/2}{\mu l_e (A_2 + A_3)/2}}{\dfrac{(L_1 + L_2)/2}{\mu l_e (A_2 + A_3)/2} + \dfrac{g}{\mu l_e A_3}} B_r l_e (\frac{A_2 + A_3}{2}) = \frac{L_1 + L_2}{L_1 + L_2 + g(A_2 + A_3)/A_3} B_r l_e (\frac{A_2 + A_3}{2})$$



(a) (b)

Fig. 9: (a) Equivalent circuit of magnetic system, (b) Schematic of one SFPM motor magnet, Br = Bresidual, A = Magnet area, Rmag = Magnet reluctance, Rag = Air-gap reluctance, φ_x = Flux entering the air-gap, A_x: Arc length, g: Air gap length

Flux produced by magnet of part 1 and part 3 is:

$$\varphi_{p1,3} = \frac{\dfrac{L_2/2}{\mu L_1 l_e}}{\dfrac{L_2/2}{\mu L_1 l_e + \dfrac{g}{\mu A_4 l_e}}} B_r l_e L_1 = \frac{L_2/2}{L_2/2 + \dfrac{gL_1}{A_4}} B_r l_e L_1$$

Total flux produced by PM is:

$$\varphi_{pt} = \varphi_{P2} + 2\varphi_{P1,3}$$

$$\frac{\varphi_{rad}}{\varphi_{par}} = \frac{L_1((A_1+A_2)/2)(L_1+L_2+g(A_2+A_3)/A_3)(L_2/2+gL_1/A_4)}{(L_1+g(A_1+A_2)/2)[(L_1+L_2)(L_2/2+gL_1/A_4)(A_2+A_3)/2+2(L_1L_2/2)(L_1+L_2+g(A_2+A_3)/A_3)]}$$

For the following SFPM motor dimensions (with two poles), the above ratio (the ratio of flux produced by radial and parallel magnet) is equal 1.01 (This ratio changes by permanent magnet dimensions). This ratio shows using parallel magnetization helps to have a semi-sinusoidal magnetic field density but 1% less magnetic flux in the air-gap. So, in parallel and radial magnetization with given dimensions, the flux entering the air gap is nearly equal, but their space harmonics are not the same.

EFFECT OF RADIAL OR PARALLEL MAGNETIZED MAGNET IN IPM MOTOR

In IPM motor, magnetizing orientation (radial or parallel) of the magnet affects the air gap flux density at each point. This fact can be observed in the FEM result as shown in Fig. 10. However as can be shown in Fig. 10, magnetizing orientation of the magnet does not affect the magnetic flux distribution around the air gap. This can be explained by the following facts:

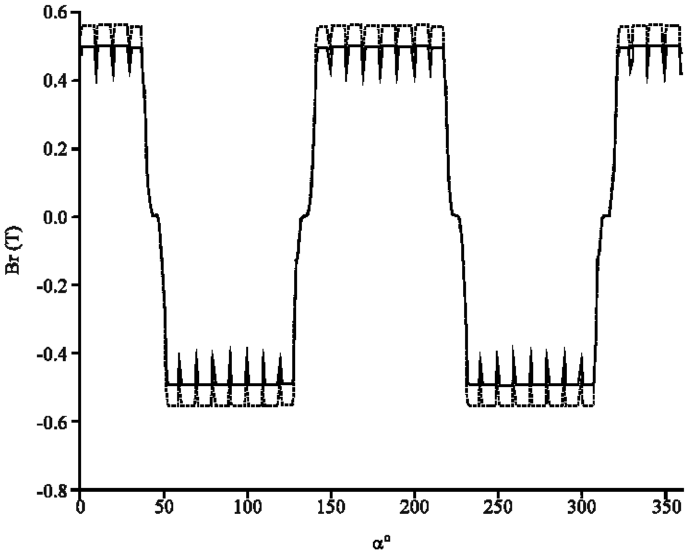


Fig. 10: Magnetic flux density of IPM motor with parallel magnetization (--) and radial magnetization(−)

- The iron core above the magnet determines the flux path, due to its very large permeability compare to air-bridges. So, the flux lines are led to pass the iron core above the magnet
- The border of a magnet and an iron core, the flux enters at normal direction to the iron, but it may change its direction inside iron, radically
- The shortest path for every magnetic flux above the magnet is the one closest to a radial path

The above facts cause the magnetic flux to be distributed almost equally at the rotor edge. On the other words, at no-load the IPM flux line distribution is very similar to that of an ideal SFPM motor with radial magnetization. Therefore, the magnet shaping methods can not make sinusoidal magnetic flux distribution in the air-gap. These methods may only increase the average mutual torque but does not improve this torque quality. However, they may slightly improve the quality of the reluctance torque (Lipo, 2004).

CONCLUSION

This study analyzes the effect of PM magnetization orientation and the core materials on the air-gap flux distribution and developed torque of SFPM and IPM motors. It shows that the air-gap flux distribution of SFPM motors Br (θ) can be shaped using the magnetization orientation (Parallel, radial ...). This shaping is not directly due to the magnetization orientation. In fact, the magnetizing orientation cause the magnet to produces different air-gap magnetic flux density at each space angle θ, which can be expressed by mathematical equation. However, in IPM motor due to Iron core above the magnet, the magnetic flux density Br (θ) is uniform and radial above the pole arcs and zero above the air-bridges. Therefore, the magnetization orientation affects uniformly the magnitude of the whole air-gap flux density waveform Br (θ). In other words, the magnetizing orientation has almost no effect on the shape of air-gap flux distribution. This concludes that the magnets orientation and in the same way the magnet shaping have negligible effect on air gap flux distribution shape and the motor torque quality. This study also shows that average developed torque of SFPM motors is more sensitive to the stator material quality than that of the rotor. Moreover, the higher quality of the future materials (which are expected also to be more expensive) affects negligibly the SFPM average torque. On the other hand, in IPM motors, due to their special rotor structure, using high quality material for rotor causes more magnetic flux to be shorted above the air-bridges. Therefore, air-gap flux density and average torque decreases, unexpectedly. However, higher quality material increases the magnetic flux due to the stator currents and the motor reluctance torque. Therefore, by balancing the above two opposite effect, we can determine the optimal material for the rotor, can be determined.

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