Sizing of Permanent Magnets in Improvingthe design of Permanent Magnet Synchronous Reluctance Motor

D.Vimalakeerthy, Dr.S.Thangavel, N.Sridhar

Abstract— A During the past few decades, AC motor drives have gradually replaced the DC drives because of high performance and low cost in variable speed applications. Induction motor is not an ideal machine for many applications due to its relatively low efficiency and difficulties associated with controlling torque. In particular, modern field oriented control of such machines requires the use of a position sensor in the torque loop. In recent year synchronous reluctance motor, have become much popular and are used as standard industrial drive. Permanent magnet (PM) motor is generally accepted as the ideal motor in that, the machine has the highest efficiency, easier controllability and the smallest frame size of all AC motors. An improved design of permanent magnet synchronous reluctance motor is presented and the effect of sizing of permanent magnet in the improved design is analyzed.

Index Terms— Permanent Magnet, Synchronous Reluctance Motor Design and sizing of magnets.

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1 INTRODUCTION

Permanent Magnet Synchronous Reluctance Motor is one among the family of brushless AC machines. In recent years PMSRM is experiencing a growing interest in variable speed applications. It is due to the low cost construction, flux weakening capability, improved torque, etc. PMSRMs are preferred due to their quiet operation due to generation of ripple free smooth torque. PMSRMs have significantly replaced Induction Motors particularly in variable speed industry applications. Development of a machine topology suitable for current industry need with maximum saliency, power factor and high efficiency still continues to be a goal of electrical machine researchers. The purpose of this paper is to analyze various effects of sizing of permanent magnet in the improved design of PMSRM.The proposed design involves the insertion of permanent magnet into the rotor flux barriers[5]. Finite element analysis on a transversally laminated PMSRM is performed to investigate the effect of different rotor parameters on the motor performance in terms of output torque and saliency ratio[6]. In order to increase the efficiency of motor, certain amount of magnet is used which improves saliency ratio[7]. This also results in adding magnetic torque to overall output torque. Much effort has been put on the design of the PMSRM rotor geometry in order to have a more efficient PMSRM drive. More refinements in the design of the PMSRM rotor geometry have been possible through the numerical magnetic analysis by use of finite element analysis. Geometry of the rotor is designed to be suitable for magnetizing of the ferrite. Magnetization is performed after manufacturing of the motor through its stator windings which makes the design very cost effective.

2 ANALYSIS

In principle, the PMSRM is similar to the traditional salient pole synchronous motor. Improvement of rotor design started with the construction of simple salient pole rotor as shown in figure 1.

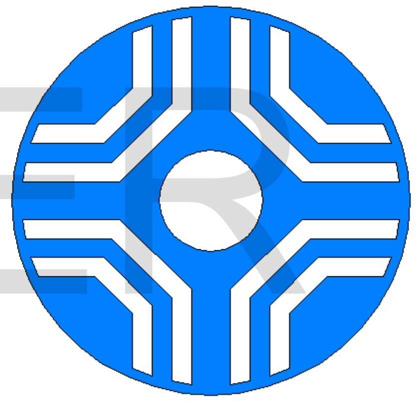

Figure 1. Four-pole transversally-laminated rotor design.

Following to that rotor with segmental construction was introduced. Later axially laminated rotor was introduced. These machines in terms of saliency ratio failed and their performance was well below the performance of equivalent Induction Motor. An axially laminated rotor can present a high-anisotropy and provide a very high unsaturated saliency ratio [19]. The next generation of transversally laminated rotor attracted the interest of using Synchronous Reluctance Motors. Figure 1 shows a conventional 4-pole transversally laminated rotor with two flux barriers per pole. This type of rotor is also called as Multiple flux barrier rotor. Transversally laminated rotor has some advantages including suitability for rotor skewing and easy for mass production. Moreover, the transversally laminated type of rotor can be optimized by proper design, in order to minimize the airgap harmonics and their effect on torque ripple. This is obtained by both the proper shaping of the various flux-barriers and the proper choice of their access points at the airgap.
In this paper only the rotor is constructed with salient poles. The stator inner surface is cylindrical and typically retains

many of the benefits of variable reluctance motors and at the same time eliminates its several disadvantages. In this case, it was necessary that the PMSRMs include a squirrel cage on the rotor to provide the starting torque. Otherwise, the rotor could not accelerate and synchronize with the supplying network. The squirrel cage was also needed as a damper winding in order to maintain synchronism under sudden load torques.

Flux barriers are used to form a difference in saliency between the polar axis(d-axis) and inter polar axis(q-axis). In this case the generated torque has a large torque pulsation. This leads to substantial speed oscillations. Also the starting torque produced is an inductive torque and it results in continuous operation as induction motor rather than synchronous motor. These problems are very detrimental to the application which demanded precise speed control. Moreover, ratio of the d axis inductance over q axis inductance (saliency ratio) of such machines could not exceed much more than 2:1. Because of the low saliency ratio, frame size of this motor was larger than an equivalent induction motor. Nonetheless, such machines were used for many years and continued to be manufactured. However, they have been largely replaced by permanent magnet synchronous reluctance motors in recent applications.

Developments in machine design and power electronics allowed the machine designers to remove the starting cage from the rotor and achieve a better performance by using field oriented (vector) control. In vector controlled drives, two crucial parameters are namely (i)difference of d and q axes inductances (Ld-Lq) and (ii)the ratio of these two inductances (Ld/Lq) [16]. A variety of vector controlled strategies have been analyzed and it turns out that the best performance for all of them is obtained if these two parameters are made as large as possible. In order to fulfill this requirement, the rotor should be designed for maximum Ld and minimum Lq. Several attempts have been made on the design of the PMSRM rotor and the evolution of the rotor configurations [5, 7] is an effort to accomplish this goal. Use of other materials such as composite powder metal rather than iron has been considered as an alternative for the rotor manufacturing. By use of this type of materials, geometry of the rotor can be more flexible and manufacturing becomes easier. Inserting magnet in the rotor flux barriers is an efficient way to improve the performance of the motor [20] which changes the synchronous reluctance motor (SRM) to PMSRM. The purpose of this paper is to design and implement an efficient AC drive using a permanent magnet assisted SRM with high reliability, adequate performance for high volume production.

3. ROTOR GEOMETRY

Adding the proper quantity of permanent magnets into the PMSRM rotor core is another way to improve the operating performance of this motor. In this case, the motor is similar to an interior permanent magnet (IPM) motor. However, the amount of permanent magnets used and the permanent magnet flux-linkages are smaller with respect to the conventional IPM. Thus, the proposed motor can be called a Permanent Magnet Synchronous Reluctance Motor (PMSRM). Permanent Magnets can be mounted in the rotor core of the axially or transversally laminated structure The polarity of magnets is chosen such that they counteract the q-axis flux of the SRM at rated load. Regardless of the different choice of d, q axes, in principle, the PMSRM seems nothing more than a particular case of interior permanent magnet motor (IPM). However, a substantial difference is the high anisotropy rotor structure of PMSRM and as a result, low value of the PM flux. The amount of PM flux is quite lower than the amount of rated flux. In contrast, in the usual IPM the most flux comes from the magnets and the flux produced by stator currents is considered as an unwanted reaction flux. In practice, because of the above mentioned difference between PMSRM and IPM machines, they have different suitability to the large flux-weakening ranges.

The rotor geometry can be obtained to meet the desired criteria and manufacturing limits such as minimum width of ribs and number of flux barriers[21]. As it was mentioned before, to improve the efficiency of the motor some Ferrite magnets are placed in the rotor [9]. One of the features considered in the design of this motor is the magnetization of the ferrites using stator windings. This feature will cause a reduction in cost and ease of manufacturing [10]. To do so, the geometry of the rotor has been changed slightly to make it suitable for this purpose. Figure 2 shows the same rotor with modified flux barriers and permanent magnets inside the core.

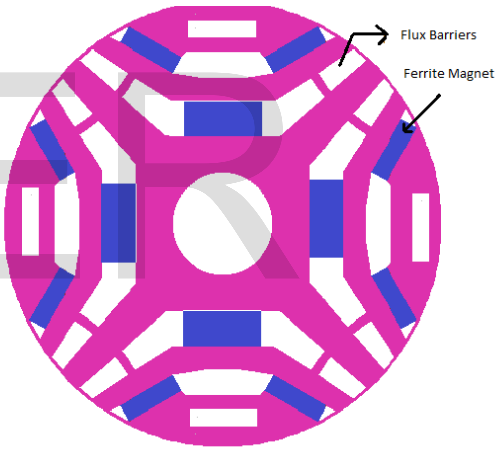

Figure 2. Proposed PMSRM

The amount of the ferrite placed in the rotor core is limited by the geometry of the rotor and also the material cost. The magnetization of the ferrites is done through the stator windings. To do so, rotor q-axes is placed along the axis of the phase R. Then an avalanche current is applied to the star-connected stator winding while phase Y and B are connected in parallel. This current can be obtained by discharging a capacitor in stator windings. In this case current is going though the phase R and coming out from phase Y and B. Therefore, the stator flux vector is along with the phase R axis. It results in magnetizing the ferrite in a symmetric way.

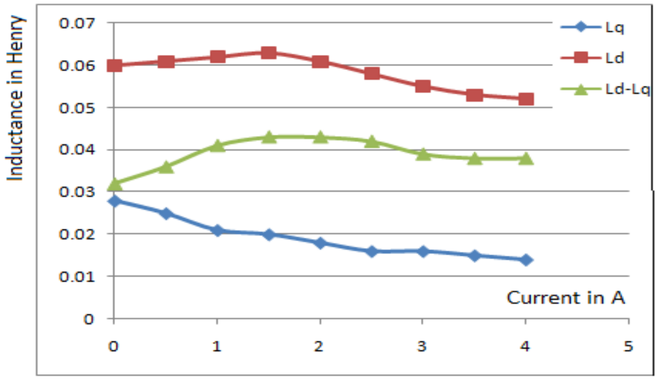

Figure 3. Calculated d-q axes inductances

To calculate the d-q axes inductances, 3-phase stator flux is measured while rotor is placed on d- direction and on q-direction. Using the Park transformation, d and q axes fluxes can be obtained for different amount of stator current amplitude. Using the measured fluxes[11], d and q axes inductances can be calculated by use of winding information[20]. Figure 3 shows the calculated d-q axes inductances. As it can be inferred by inserting magnets in the rotor, the inductance ratio and their difference have increased which implies increase of power factor and torque density of the motor. Moreover, improvement of the motor performance due to the permanent magnets placed in the rotor core is investigated by studying their effect on developed torque and the d and q inductances. An insulation ratio of 0.4-0.6 should be selected to maximize the developed torque. Location of the flux barriers plays an important role in the torque ripple however, it does not affect the average torque significantly. Minimum air-gap length is limited by the mechanical manufacturing limits.

The amount of permanent magnets used in the motor is limited by the cost and flux barrier shapes. In order to reduce the manufacturing cost, one of the design criteria is to achieve a rotor geometry that is suitable for magnetizing the ferromagnetic materials (such as Ferrite) placed in the rotor core. Ferrite is placed in the rotor core first and then is magnetized using the stator winding. Simulation and preliminary experimental results are presented to support the validity of the proposed procedure.

4 SIZING OF PERMANENT

Industrial permanent magnet synchronous reluctance motors may have a low pull-out torque. This is because common industrial PMSRMs have buried magnets in the rotor. Buried magnets usually produced higher direct-axis inductance which results in a low pull-out torque. However, the buried magnet construction is mechanically favourable, since simple rectangular magnets can be used. The buried magnets are also well protected electromagnetically and mechanically. In case of short circuit, the protection offered by this buried magnet is good, as the surrounding iron, diverts the flux to pass the magnets. Thus the magnetic field strength may not exceed the demagnetizing value.

Also it is much easier to manufacture rotor pole surfaces to required shapes that result in a sinusoidal air-gap flux density distribution. With an adequate design the torque ripple generated in the machine is also minimized. Earlier, surface-magnet constructions are used especially in low-speed industrial machines. Here simple gluing of the magnets is adequate for attaching the magnets due to low rotor peripheral speed. The major drawback in a surface magnet construction is the need for curved magnets to obtain a smooth air-gap. Using surface magnets, the armature reaction is small, and problems might arise if the field weakening is to be utilized. With industrial motors, however, this is rarely the case. Owing to relatively high price of the rare-earth magnets, the amount of the PM material selected carefully to compromise both technological and economical aspect. Thus most of PM machine prefers thin magnets. With magnets mounted on the flux barriers of the rotor, the consumption of the PM material is lesser. It also has the advantage that the leakage flux of the magnets is lower and secondly, reduced value of quadrature magnetizing inductance effectively decreases the armature reaction. This leads to a decreased pole angle and an increased torque.

The problem with surface magnets, especially in difficult environments, the possibility of small ferromagnetic particles like iron dust and the moisture to enter the rotor is more. When the NdFeB magnets are exposed to hydrogen (water), the phenomenon called white corrosion occurs, and the PM material is converted to white powder and losses its properties. In proposed PMSRM the permanent magnets are inserted in the flux barriers and are protected against moisture and rust.

High performance of a PMSRM is possible by using a large amount of PM material on the rotor. In practice, most of the industrial motors operate continuously, where both overloading capability and the fast torque response is essential. One of the most important designs is low manufacturing costs. As the price of the NdFeB magnets in particular is relatively high, it is always preferred to use lesser PM material in industrial machines. For reducing the size of the PM the thickness of the magnets are decreased. On decreasing the thickness, MMF of the magnets also decreases.

$$\theta_{PM} = H_c l_{PM} \qquad (1)$$

where,

H_c is the magnet coercive field strength and

l_{PM} is the magnet thickness.

Obviously, the thickness of the permanent magnets is large when compared to the length of the physical air-gap, and thus the total reluctance of the flux path is mainly caused by the permanent magnets. The air-gap magnetic flux Φ_g created by the magnets can be expressed as:

$$\Phi_g = \frac{\theta_{PM}}{R_{PM} + R_\delta + R_{Fe}} = \frac{H_c l_{PM}}{\dfrac{l_{PM}}{\mu_{r\,PM}\,\mu_0 L' w_{PM}} + R_\delta + R_{Fe}} \qquad (2)$$

where,

R_{PM}	is the reluctance of the magnet,
R_δ	is the air-gap reluctance,
R_{Fe}	is the iron reluctance,
μ_{rPM}	is the magnet relative permeability,
μ_0	is the vacuum permeability, and

w_{PM} is the magnet width.

Air-gap reluctance between the magnets and the stator can be calculated from

$$R_\delta = \frac{\delta_{eff}}{\mu_0 L \tau_P} \quad (3)$$

where,

δ_{eff} is the effective air-gap length (excluding the magnets) and τ_p is the pole-pitch.

However, because of lesser magnet width than the pole-pitch, the air-gap reluctance between the stator and the permanent magnets is higher than the value given by Equation (1.3). The reluctance of the iron is usually very small when compared to that of the air-gap or the magnets, unless the flux path saturates heavily. As the reluctance of the magnets decreases with the thickness, the air-gap flux and consequently the air-gap flux density, will slightly decrease because, the iron path and air-gap reluctances remain approximately constant. However, there is a knee-point, where if the thickness of the magnet is further decreased, the flux density collapses. This is illustrated in Figure 4. The air-gap flux density B_δ can be calculated

$$B_\delta = \frac{\phi_g}{\alpha \tau_P} \quad (4)$$

where,

α is the coefficient that represents arithmetic average of the flux distribution in one pole area and ϕ_g is the air-gap flux.

In case of a surface magnet machine that has a constant air-gap length, the coefficient can be assumed to be the ratio of the width of the magnets to the pole-pitch. But for the embedded magnets with sinusoidal air-gap flux distribution, it can be approximated to be 2/π.

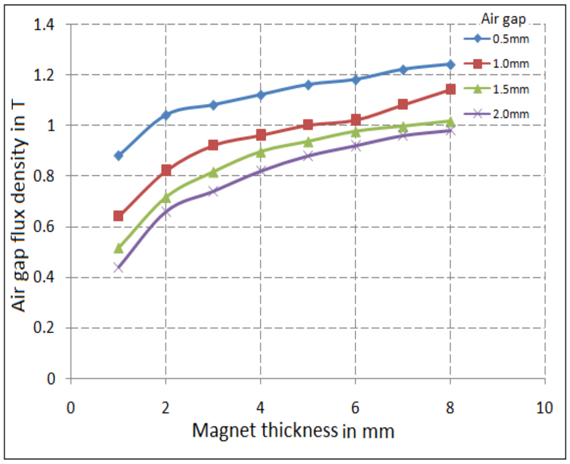

Figure 4 Variation of air-gap flux density with respect to air-gap length

The air-gap flux density as a function of the magnet thickness at four different effective air-gap lengths is shown in Figure 4. The values are obtained based on the analytical equations shown above. Since the exact PM material of the motor was not known, the values of 2mm to 12mm thickness of NdFeB magnets were used in the calculation. The coercive field strength of this material is 830kA/m, and the relative permeability 1.1. The physical air-gap length of the motor was 0.5 mm. Effective air-gap excluding the magnet thickness can thus be estimated to be nearer to 1.0 mm. The value of air-gap reluctance used in Figure 4 was estimated using Equation (1.3), and therefore the flux density values can be slightly lower in reality.

The effect of the magnet thickness is selected to be relatively small on the flux density, with the exception of the smallest values of magnet thicknesses. Values are analytically calculated with the above presented equations. The thickness of the magnets could be reduced from 8 mm to 4 mm, without significantly decreasing the air-gap flux density of the motor. By reducing the thickness of the magnets from 10 mm to 3 mm decreases the air- gap flux density only by 0.1 T. To compensate this drop in air-gap flux density, only 10 % higher stator current is required to produce the same torque. This is the reason why industrial motors have a minimum amount of the magnetic material in the rotor. The same value of torque production capability can also be achieved by slightly increasing the amount of the copper and the current rating of the machine. Use of decreased PM material will slightly decrease the back-EMF E_{back} .

$$E_{back} = \frac{\xi_1 N_s \omega \Phi_g}{\sqrt{2}} \quad (5)$$

where,

ξ_1 is the fundamental winding factor,
N_s is the number of turns and
ω is the electrical angular frequency.

Though air-gap flux density and the back-EMF are mildly affected, decreasing the magnet thickness has a substantial effect on the direct-axis magnetizing inductance L_{md}. It is given by:

$$L_{md} = \frac{m_p}{2}\frac{4}{\pi}\alpha\mu_0 \frac{1}{2p}\frac{\tau_p}{\left(\delta_{eff} + l_{PM}\right)} L'\left(\xi_1 N_s\right)^2 \quad (6)$$

where,

m_p is the phase number,
α is the arithmetic average of the flux density distribution in one pole area,
τ_p is the pole-pitch,
δ_{eff} is the effective air-gap length (excluding the magnets),
L' is the stack electromagnetic length,
ξ_1 is the fundamental winding factor, and
N_s is the number turns.

The inductances thus behave in a similar manner to the air-gap flux density as a function of the magnet thickness shown in Figure 5. The effective air-gap includes the increase in air-gap length due to slotting and saturation of the iron. The effect of the slotting can be taken into account by multiplying the physical air-gap δ_p with the Carter's coefficient K_c

$$\delta' = K_c \delta_p \qquad (7)$$

where,

δ' is the average electric air-gap length.

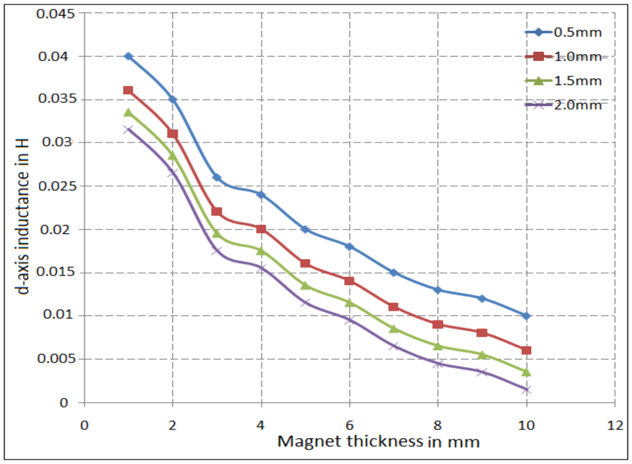

Figure 5. Pull-out torques as a function of the magnet thickness of the PMSRM

Due to the saturation of iron, air-gap is further electromagnetically increased and the effective air-gap δ_{eff} includes both of these phenomena. It is observed that when the thickness of the magnets decreases, the value of back-EMF decreases as per Equation (1.5), which results in increasing direct axis inductance given by Equation (1.6). Because of this the torque production capability of the PMSRM decreases, which means that the pull-out torque decreases, and the rated torque is obtained at a higher load angle. In practice if the load angle is higher, the torque stiffness of the motor is degraded and results in reduction of dynamic stability. The pull-out torques and *d*-axis synchronous inductances are plotted as a function of the magnet thickness for four different air-gaps are shown in Figure 6.

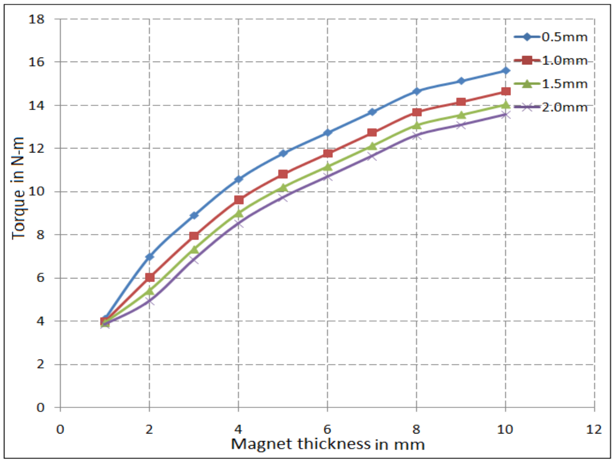

Figure 6. Pull-out torques as a function of the magnet thickness of the PMSRM

By introducing rare-earth magnets in the rotor, a high air-gap flux density and a high torque can be obtained. On increasing the thickness of the magnets, the direct-axis inductance rapidly decreases. A low value of L_d will provide a low value of the load angle during rated operation and a high pull-out torque. Also when the thickness of the magnets is increased, the amount of the leakage flux term in the synchronous inductance becomes more. This emphasizes the necessity for leakage minimization design with thick magnets. On using thicker magnets, the effective value of air-gap becomes smaller, which facilitate to increase the air-gap length for increasing the mechanical strength. On the other side, use of thinner magnets, the effect of the air-gap is more dominating, and should be reduced as small as possible. Further, by increasing the length of the air-gap, the *d*-axis inductance can be decreased, but the torque production capability would deteriorate, as more and more MMF in the air-gap is required.

5. CONCLUSION

A new design in the rotor of the Permanent Magnet Synchronous Reluctance Motor is proposed. With respect to the conventional Synchronous Reluctance Motor, this motor offers better torque capabilities. . In this paper Finite Element Method is used to obtain the inductance. Effects of the magnets on d-q inductances were studied. A comparison between inductances of Synchronous Reluctance Motor and PMSRM was performed. It has been shown that the proposed PMSRM substantially improves the performance due to modified rotor geometry. Computer simulation and the experimental result for the PMSRM show the effectiveness of the proposed method. Computer simulation results for the PMSRM show the effectiveness of the proposed method.

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BIOGRAPHY

D. Vimalakeerthy, was born in Tamil Nadu, India. He received B.E degree in Electrical and Electronics Engineering and M.E degree in Power Electronics and Drives. His research interest is Design improvement of Synchronous Reluctance Motor and Finite Element Analysis.