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Permanent Magnet Synchronous Reluctance Motor Design Enhancement Using Finite Element Method

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Abstract*—A Synchronous motors and conventional induction motors are preferred as the most common drive for industrial and civil applications due to their simple construction and robustness. But they are not suitable when the application requires variable speed regulation. In such cases high torque, high efficiency, and simple controllability are often desired. Permanent Magnet Synchronous Reluctance Motor "PMSRM" has gained interest due to several factors like reduced cost, ability to operate at near zero speed even at full load and flux weakening capability for spindle and traction applications. As the high field strength of neodymium-iron-boron (NdFeB) magnets become commercially available with affordable prices, PMSRMs are receiving increasing attention due to their high speed, high power density and high efficiency. A modified design in the location of permanent magnets in the flux barriers of PMSRM is proposed and its results are validated to improve the performance. Finite Element Method (FEM) is used to analyze the design parameters.

***Index Items* — Permanent Magnet, Synchronous Reluctance Motor Design and Finite Element Method.**

I. INTRODUCTION

Permanent Magnet Synchronous Reluctance Motor is one among the family of brushless AC machines. In recent year 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 provide a novel design for PMSRM. One large drawback to Permanent Magnet (PM) machines is the torque ripple that is inherent to their design. This ripple is parasitic, and can lead to mechanical vibration, acoustic noise, and problems in drive systems, all of which lower efficiency. One of the main contributors to this torque ripple is a phenomenon known as cogging torque [1]. A method of optimal magnetic arc is used to reduce cogging torque [2]. The design of stator of the machine is kept unaltered where the rotor construction is modified for its improved performance [3] [4]. 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. This paper presents an improved rotor design and a better method to eliminate the cogging torque. This design needs to be done through the magnetic analysis and by use of numerical methods [18]. 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.

II. 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. Following to that rotor with segmental construction was introduced. Later axially laminated rotor was introduced. These machines in terms of saliency ratio failed and in their performance of equivalent Induction Motor.

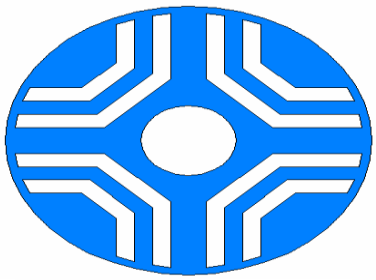

Fig 1. Four-Pole Transversally-Laminated Rotor Design

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 rotors. Transversally laminated rotor

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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 air gap 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 air gap. 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.

III. MATHEMATICAL MODEL OF PMSRM

A 2-pole synchronous reluctance motor is shown in Figure 2. It has 3-phase stator winding and a salient rotor.

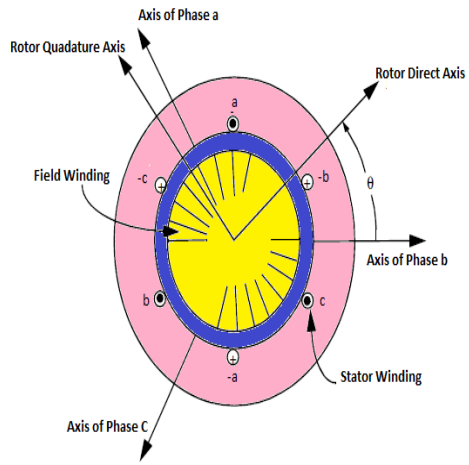

Fig 2. Synchronous Reluctance Motor

The stator windings are identical windings and displaced 120° from each other with *Ns* equivalent turns and resistance of r_s. It is usually assumed that windings of PMSRM are distributed sinusoidally. Since the stator winding of the synchronous reluctance motor is sinusoidally distributed, flux harmonics in the air gap contribute an additional term to the stator leakage inductance. Hence, the equations which present the behavior of the synchronous reluctance machine can be obtained from the conventional equations of a conventional wound field synchronous machine. in PMSRM, the excitation field winding does not exist, hence eliminating both the field winding and damper winding equations from Park's equations. Thus the basis for the d-q equations for a synchronous reluctance motor can be obtained as follows:

$$v_d = r_s i_{ds} + \frac{d\lambda_{ds}}{dt} - \omega_r \lambda_{qs} \qquad \text{----------} \qquad (1)$$

$$v_q = r_s i_{qs} + \frac{d\lambda_{qs}}{dt} + \omega_r \lambda_{ds} \qquad \text{----------} \qquad (2)$$

Where

$$\lambda_{ds} = L_{ls} i_{ds} + L_{md} i_{ds} = L_{ds} i_{ds} \qquad \text{----------} \qquad (3)$$

$$\lambda_{qs} = L_{ls} i_{qs} + L_{mq} i_{qs} = L_{qs} i_{qs} \qquad \text{----------} \qquad (4)$$

Here L_{ls} , L_{md} and L_{mq} are the stator leakage inductance, direct axis magnetizing inductance and quadrature axis magnetizing inductance, respectively. The quantity r_s are the stator resistance per phase. i_{ds} and i_{qs} represent the direct axis current and quadrature axis current respectively. The electromagnetic torque is identical to that of synchronous motor given by

$$T_e = \frac{3}{2}\frac{P}{2}(\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds}) \qquad \text{----------} \qquad (5)$$

The angular relationship between the stator voltage vector and the d-q is shown in Figure 3

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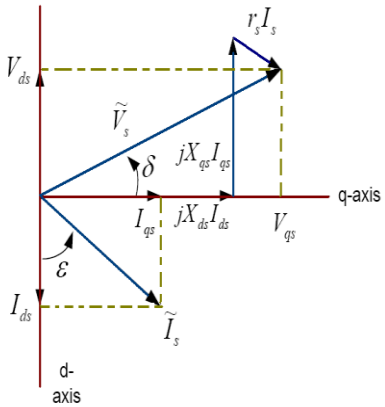

Fig 3.Phasor Diagram for PMSRM

In phasor notation:

$$\tilde{V}_s = r_s \tilde{I}_s + jX_{ds}\tilde{I}_{ds} + jX_{qs}\tilde{I}_{qs} \qquad \text{----------} \qquad (6)$$

Here X_{ds} and X_{qs} are the direct axis reactance and quadrature axis reactance and V_s is the stator voltage. The value of currents can be obtained in terms of steady state voltage as

$$I_{ds} = \frac{\omega_e L_{qs} V_{qs} + r_s V_{ds}}{r_s^2 + \omega_e^2 L_{ds} L_{qs}} \qquad \text{----------} \qquad (7)$$

$$I_{qs} = -\frac{\omega_e L_{ds} V_{ds} + r_s V_{qs}}{r_s^2 + \omega_e^2 L_{ds} L_{qs}} \qquad \text{----------} \qquad (8)$$

Neglecting stator resistance

$$I_{ds} = \frac{V_{qs}}{\omega_e L_{ds}} \quad \text{and} \qquad \text{----------} \qquad (9)$$

$$I_{qs} = -\frac{V_{ds}}{\omega_e L_{qs}} \qquad \text{----------} \qquad (10)$$

Where I_{ds} and I_{qs} are the direct axis current and quadrature axis current respectively.

IV. FINITE ELEMENT ANALYSIS

Assumption of magnetic flux path is the main limitation of the magnetic circuit method. The lengths and cross-sectional areas of all the paths must be known. Normally the paths are assumed to consist of straight lines, which is erroneous to some extent. To calculate the effects of flux fringing, saturation and leakage flux usually empirical correction factors are used. Nowadays, the motor designers are often involved with the new design concepts for which the flux paths and empirical factors are unknown. Even if the design is a newer version of a well-understood older design concept, there is a great need for accurately determining the effects of geometric changes and saturation on the motor efficiency and other parameters related to the magnetic field. The finite element analysis can be made readily available in the form of computer software called Maxwell® [8]. The software requires no assumption of flux paths or related empirical factors. This is an important advantage. This software can accurately calculate magnetic field and the related motor design parameter for motors of complicated geometry, with saturation and/or permanent magnets, with significant armature reaction, and with or without eddy currents. The variables investigated here are the width and location of the flux barriers. The design of parameters is carried out using Two-dimensional finite element method, 2D-FEM. The PMSRM rotor structure must be designed in such a way that it is possible to achieve the maximum torque per current ratio. The calculation method used to evaluate the torque takes into account the effect of cross saturation between the d- and q-axis inductances, but the effect of the iron losses on torque production is ignored. More refinements in the design of the PMSRM rotor geometry have been possible through the numerical magnetic analysis by use of finite element software Maxwell®. However, the finite-element analysis must be used to consider the nonlinear magnetic behaviors of the materials which play a key role whenever overload performance prediction is essential**.** Finite element analysis is based on energy conversion. For electric motor the conservation of energy equation is given by Maxwell's equation

$$-\int \bar{E}\,\bar{J}\,dv = \int \bar{H}\,\frac{\partial}{\partial t}\,dv \qquad \text{----------} \qquad (11)$$

Stored magnetic energy is equal to input electrical energy for lossless devices. Variation techniques such as finite element analysis obtain solution to field problem by minimizing the energy function. Minimization of the magnetic energy functional over a set of finite elements leads to a matrix equation that can be solved throughout the mesh. Figure 4 shows the coordinate system for planar problems, along with part of a typical finite element mesh.

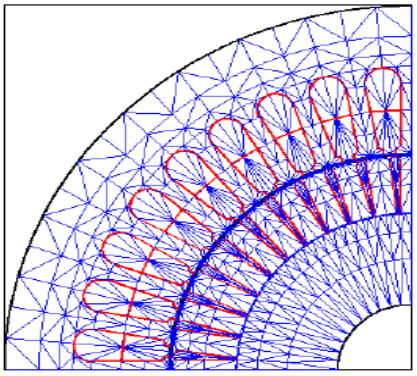

Fig 4 Typical Triangular Finite Elements

The entire planar mesh may represent, for example, the stator and rotor laminations and air gap of a motor. The analyzed device must be subdivided into triangles or quadrilaterals called finite elements. Each of these elements has three or four vertices called grid point. Given the motor geometry, this mesh can be automatically generated in the software for the best solution accuracy. In such two-dimensional problems, *J* and *A* are assumed to be directed out of or into the page. Here J is the magnetic field intensity and A is the vector magnetic potential. Within each

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triangular finite element A is assumed to vary linearly according to:

$$A = \sum_{k=l,m,n} \frac{A_k}{2\Delta}(d_k + e_k X + f_k Y) \quad \text{----------} \quad (12)$$

Where Δ is the triangle area.

Once the matrix equation has been assembled and A constrains have been enforced, solution for A at the unconstrained grid points may proceed. If the permeability μ, is known throughout the region, then the solution can be obtained directly by Gauss-Jordan elimination.

V. DESIGN SYNTHESIS

A. *Reducing Cogging Toque*

One of the disadvantages of Permanent Motor is their cogging torque. Several techniques [14][15] have been developed to reduce the cogging torque. Cogging torque is defined as the torque ripple generated by the interaction of the rotor magnetic flux and the angular variations in the stator magnetic reluctance. Therefore, no stator excitation is associated with cogging torque production [2]. Because of stator slotting, the reluctance of the air gap is not constant. Cogging torque can be represented by

$$T_{cog} = -\frac{1}{2}\phi_g^2 \frac{dR}{d\theta} \quad \text{----------} \quad (13)$$

Where ϕ_g the air gap flux and R is is the air gap reluctance [1]. This supports the idea that cogging torque is the interaction between the magnets (the source of the air gap flux since cogging torque is considered with an unexcited stator) and the stator teeth (the source of the varying air gap reluctance). The air gap reluctance *d, q* Axes superimposed onto a three phase two pole PM motor varies periodically, thus causing the cogging torque to be periodic [14]. Because of this periodicity, cogging torque can be expressed in Fourier series as follows:

$$T_{cog} = \sum_{k=1}^{\infty} T_{mk} \sin(mk\theta) \quad \text{----------} \quad (14)$$

Where *m* is the least common multiple of the number of stator slots (*Ns*) and the number of poles (*Np*), *k* is an integer, and T_{mk} is a Fourier coefficient. It is seen that the cogging torque has *m* periods per mechanical revolution of the rotor and has a direct relationship to the number of slots and poles. The torque produced by a synchronous reluctance motor is dependent on the stator current and the difference between the *d, q* axis inductance created by the rotor saliency is given by

$$T_r = \frac{3}{2}\frac{N_p}{2}(L_d - L_q)i_s^2 \frac{\sin(2\partial)}{2} \quad \text{--------} \quad (15)$$

Magnets are set into the flux barriers and a modified rotor is created and the total torque is the sum of the torque created by the magnets and the torque created by the rotor saliency

$$T_t = \frac{3}{2}\frac{N_p}{2}\left(\lambda_{af} i_s \sin\partial + (L_d - L_q)i_s^2 \frac{\sin(2\partial)}{2}\right) \text{ - (16)}$$

To theoretically eliminate cogging torque via machine design one must examine the equations which define it. From inspection of (13), it is seen that cogging torque can be eliminated by forcing either the air gap flux, ϕ_g , or the rate of change of the air gap reluctance, *dR/dθ*, to be zero. Making ϕ_g zero is not possible since the air gap flux is needed for the alignment and reluctance torque components which drive the Motor. Therefore, cogging torque can be cancelled by forcing the air gap reluctance to be constant with respect to rotor position. In practice, however, cogging torque can not actually be eliminated, but it can be greatly reduced [14]. Examination of equation (14) reveals that cogging torque can be represented as a Fourier series. So it is a summation of harmonic sinusoids. In traditional machines with no cogging torque reduction design techniques, the rotor magnets have an additive effect when contributing to cogging torque because each magnet has the same relative position with respect to the stator slots [2]. The torque from each magnet is in phase with the others, and thus the harmonic components of each are added. By designing a machine so the cogging effects from the magnets are out of phase with each other, one can eliminate some of the harmonics, thus reducing cogging torque. it is a well established fact that the magnet pole-arc can have a large effect on the amplitude of cogging torque [12]. There exists an optimum value for pole-arc that minimizes cogging and can be found using

$$\alpha_m = \frac{n+\nu}{N_{sm}} < 1, 0 < \nu < 1 \quad \text{----------} \quad (17)$$

Where α_m is the ratio of pole-arc to pole-pitch, *n* is an integer, *Nsm* is the number of slots per pole, and ν is the parameter that is varied to minimize cogging [15]. For a given value of *n*, there exist *i* values of ν that will minimize the ith *harmonic* of the cogging torque. Finding the proper values of ν is not trivial and requires the use of finite element analysis. The back EMF, shown in Figure 5 was increased since the magnet arc was also increased, thus raising the amount of flux linking the stator and rotor. The rate of change of the air gap flux density caused by the magnet edges as one moves from one magnet pole to the next contributes to cogging torque [1].

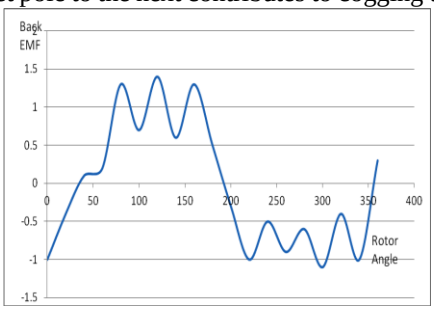

Fig 5. Back EMF of Optimal Magnetic ARC Design

With conventional magnet shapes, the transition from magnet to non-magnet is immediate, and therefore the rate of change is very high. By so shaping the magnets the magnet thickness is smaller near the magnet edges the transition from

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rotor material or air (for inset or surface machines, respectively) to magnet is more gradual, thus reducing the rate of change of the air gap flux density and the cogging torque [4].

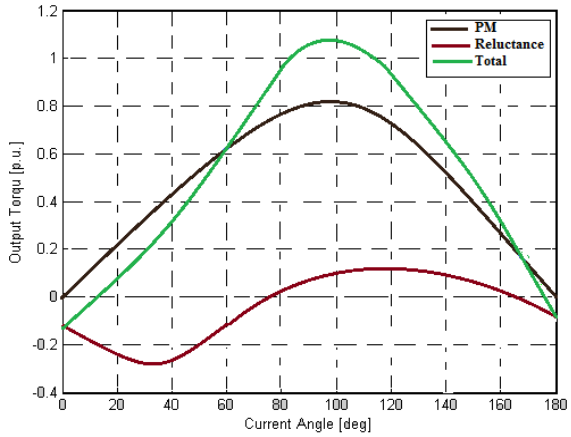

Fig 6. Full Load Torque of Optimal Magnetic Arc Design

Finite Element Analysis has the ability to utilize a rotating air gap feature, which allowed solutions that required motion to be solved without redrawing the geometry for each rotor position. When using the rotating air gap feature, however, great care had to be taken in the meshing of the gap. In order to minimize the influence of finite element numerical residual errors due to the meshing, the mesh at the air gap needed be the same for every time step. This was achieved with the use of an air gap with three layers: (1) from the rotor outer diameter to the moving air gap, (2) the moving air gap itself, and (3) the region from the air gap to the stator inner diameter [13]. The size of the mesh elements in the air gap needed to be made so that the nodes of one time step would overlap the nodes of the next time step. For example if a rotor is moving at a rate of 1± per second and the problem is to solved every 0.5 seconds, the nodes of the air gap mesh should be exactly 0.5± apart since the rotating portion of the machine is moving 0.5± every time step. As shown in figure 6 a reduction in the cogging torque decreased the full load ripple.

B. 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] as shown in Figure 7. 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 7 shows the same rotor with modified flux barriers and permanent magnets inside the core. The amount of the ferrite placed in the rotor core is limited by the geometry of the rotor.

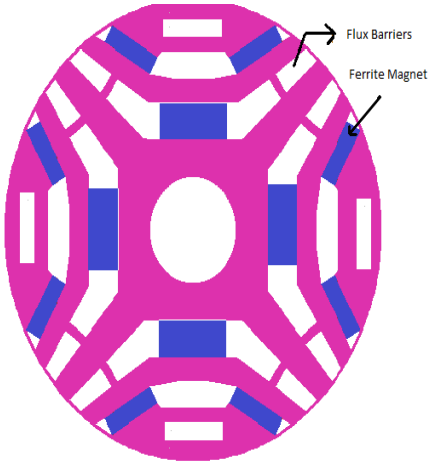

Fig 7. Proposed PMSRM

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. 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 8 shows the calculated d-q axes inductances. The effects of inserted magnets on the d-q inductances and their difference and ratio can be seen by comparing the inductances [[17] of the SRM without PMs in rotor core in Figure 9 and 10.

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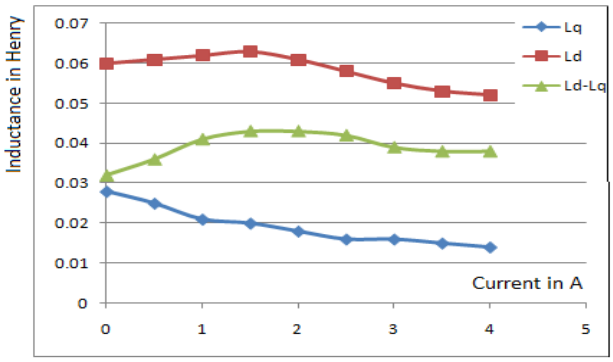

Fig 8. Calculated D-Q Axes Inductances

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 [22].

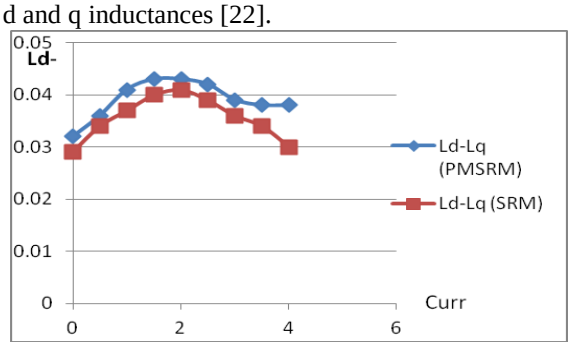

Fig 9. Ld-Lq Vs Current of SRM & PMSRM

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 [23]. 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.

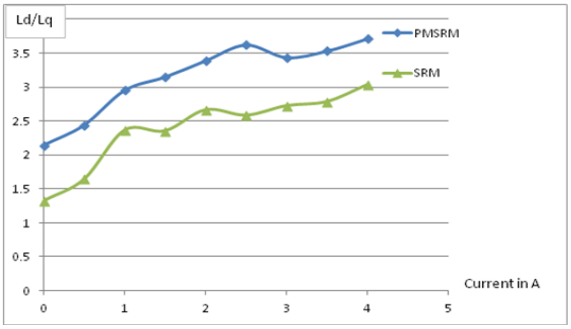

Fig 10. Saliency Ratio of SRM & PMSRM

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.

VI. 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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