ISSN: 2319-5967
ISO 9001:2008 Certified
International Journal of Engineering Science and Innovative Technology (IJESIT)
Volume 2, Issue 1, January 2013

Novel Design of Permanent Magnet Synchronous Reluctance Motor using Finite Element Method

D. Vimalakeerthy* Dr.N. Kanagaraj** and Dr.M.Y.Sanavullah***
*AVS Engineering College, Salem, Tamilnadu
**K.S.Rangasamy College of Engineering, Tiruchengodu, Tamilnadu
***V.M.K.V Engineering College, Salem

Abstract*— In recent years permanent magnet motors are replacing conventional motors like Induction motor and Synchronous motors. It is because of the face that conventional motors are not suitable where the applications require speed regulation. In most applications high torque, high efficiency, and simple controllability are required. Permanent Magnet Synchronous Reluctance Motors are preferred due to several factors like reduced cost, ability to operate at desired speed and flux weakening capability for medical and traction applications. In recent days, high field strength neodymium-iron-boron (NdFeB) magnets become commercially available with affordable prices, Also PMSRMs are proved to have high speed, high power density and high efficiency. A new design of PMSRM is proposed here. 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. To analyze the design parameters Finite Element Analysis is used.

Index Terms— **Permanent Magnet, Synchronous Reluctance Motor Design and Finite Element Analysis.**

I. INTRODUCTION

Permanent Magnet Synchronous Reluctance Motors are receiving much attention due to their high speed, power density and efficiency characteristics [1]. PMSRMs are preferred due to the following advantages [2].

- They have lower inertia compared with ordinary induction motors. Therefore their torque to inertia is higher.
- They have small rotor losses and so their efficiency is high.
- They require no external excitation.
- Since rotor losses are less, heating is also less. This improves the performance of the motor
- Consequently the PMSRM is smaller in size and lesser in weight. It is ideal for small size applications.

Modified rotor configurations, and the commercial availability of high field strength neodymium-iron-boron (NdFeB) magnets have reduced the cost of such machines to a level where they can now provide a significant performance improvement particularly in variable speed applications. Unfortunately, manufacturers of such machines provide very little information for drive designers wishing to implement high performance torque control. PMSRM has high efficiency and torque because the motor can utilize both magnetic and reluctance torque due to the magnetic saliency. These motors are widely used for electric household appliances and electric vehicles. For the optimum design, several papers have been reported on the analysis of the permanent magnet motors based on Finite Element Method (FEM). Most of the papers [3][4] however, discussed static characteristics such as motor torque and flux distribution. For the dynamic analysis, some papers have reported about an electrical equivalent circuit [5] [6]. Advanced high speed salient-pole synchronous machine uses vector control in the synchronously rotating reference frame to actively vary the d-axis armature current as a function of loading and speed. Such operation, commonly referred to as 'flux weakening', allows for higher speed, torque, and efficiency levels when compared with conventional control [7]. Proper implementation of flux weakening control requires the knowledge of synchronous machine parameters. The most common parameters required for the implementation of such advanced control algorithms are the classical simplified model parameters:

Ld - the direct axis self- inductance
Lq - the quadrature axis self- inductance and
□ mag- the permanent magnet flux linkage.

Prior knowledge of the previously mentioned parameters, and the number of pole pair's p, allows for the implementation of torque control. The required parameters determine the linearized representation for the d-axis

ISSN: 2319-5967
ISO 9001:2008 Certified
International Journal of Engineering Science and Innovative Technology (IJESIT)
Volume 2, Issue 1, January 2013
reactance Xd, q-axis reactance Xq, and permanent magnet excited voltage Eo. The non-linearity of certain types of salient-pole synchronous machines has made it difficult to apply these control rules.

II. LOCATION OF PERMANENT MAGNETS

PMSRMs are now very popular in a wide variety of industrial applications. Majority of PMSRMs are constructed with the permanent magnets mounted on the periphery of the rotor core. Such motors are called Surface Permanent Magnet Synchronous Motors (SPMSM) [2]. When permanent magnets are buried inside the rotor core the motor not only provides mechanical ruggedness but also opens a possibility of increasing its torque capability. By designing a rotor magnetic circuit such that the inductance varies as a function of rotor angle, the reluctance torque can be produced in addition to the mutual reaction torque of synchronous motors. This class of Interior Permanent Magnet Synchronous Motors (IPMSM) can be considered as the combination of Reluctance Synchronous motor and the permanent magnet Synchronous Motor. It is now very popular in industrial and military applications by providing high power density and high efficiency compared to other types of motors. The proposed design called Permanent Magnet Synchronous Reluctance Motor involves embedding of permanent magnets in the flux barriers of the rotor. Figure 1 shows different location of permanent magnets in rotor.

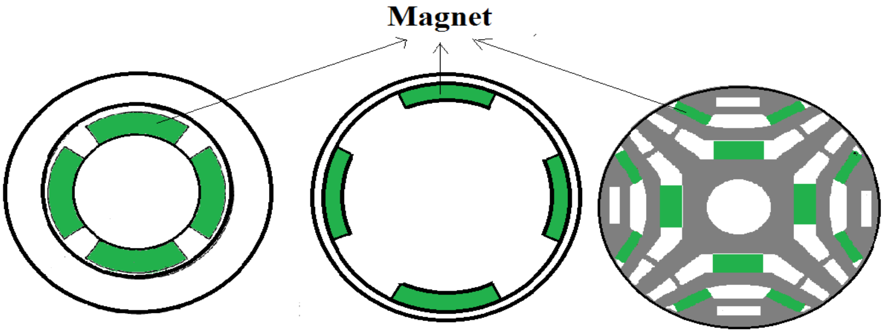

Fig 1. Different Locations of Permanent Magnets in Rotor

III. ANALYSIS OF PMSRM

A 4-pole synchronous reluctance motor is shown in Figure 2. It has 3-phase stator winding and a salient rotor. The stator windings are identical and displaced 120° from each other. 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 winding does not exist. Hence, eliminating both the field winding and damper winding equations from Park's equations, the basis for the d-q equations for a Synchronous Reluctance Motor can be obtained. These d-q equations express the behavior of the physical stator and rotor currents in a reference frame which is rotating with the rotor of the machine in much the same manner as for a wound field synchronous machine (rotor reference frame). These voltages form a constant amplitude rotating vector in the d-q plane. When the rotor rotates at the same angular velocity as the angular velocity of the rotating voltage vector, (modified by the number of pole pairs), the voltage vector appears to be stationary with respect to the rotor reference frame.

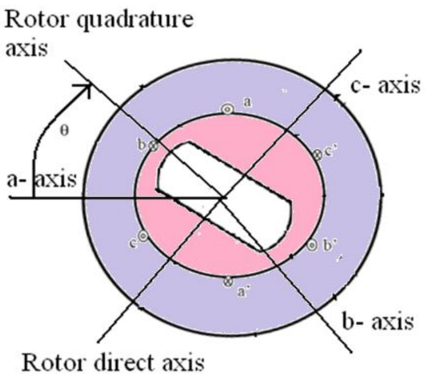

Fig 2. Four pole Synchronous Reluctance Motor

ISSN: 2319-5967
ISO 9001:2008 Certified
International Journal of Engineering Science and Innovative Technology (IJESIT)
Volume 2, Issue 1, January 2013
In this case, the angular relationship between the stator voltage vector and the d-q axes as the two components are described as

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

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

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 Lls , L_{md} and L_{mq} are the stator leakage inductance, direct axis magnetizing inductance and quadrature axis magnetizing inductance, respectively. The quantity r_s is the stator resistance per phase. The electromagnetic torque is identical to that of Synchronous Machine given by

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

Here T_e is the electromagnetic torque and P is number of poles.
The angular relationship between the stator voltage vector and the d-q axis is shown in Figure 3.

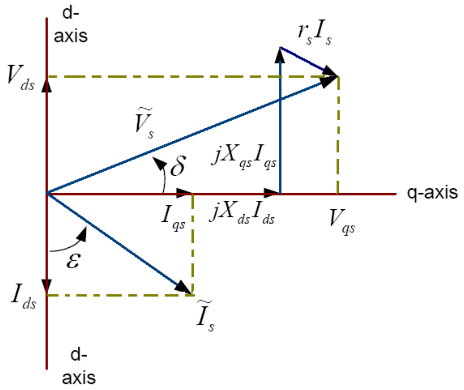

Fig 3. Phasor diagram for Synchronous Reluctance Machine

In phasor notation:

$$V_s = r_s I_s + jX_{ds} I_{ds} + jX_{qs} I_{qs} \qquad \text{------------} \qquad (6)$$

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

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

Here ω_e is the angular velocity of the rotating reference frame.

IV. DETERMINATION OF ROTOR PARAMETERS

It is apparent from the discussion in earlier works, that the advantages of a PMSRM is highly dependent upon the saliency ratio Ld/Lq[8]. Four pole configuration of Figure2 is considered. Specifically, the rotor is assumed to be constructed of "packets" of thin laminations. These packets of steel are assumed to be separated by a suitable

ISSN: 2319-5967
ISO 9001:2008 Certified
International Journal of Engineering Science and Innovative Technology (IJESIT)
Volume 2, Issue 1, January 2013
insulator, plastic laminate or epoxy-like material. All of the lamination segments are assumed to be equally spaced. Also, the machine is assumed to have 24 slots (2 slots/pole/phase) with a tooth width over tooth pitch ratio of 0.54. The sum of "$n(W_{iron}+W_{ins})$" is chosen so as to always equal to be the width of one stator to limit pulsating fluxes in the stator teeth.

$$K_w = W_{ins} / W_{iron} \qquad \text{------------} \quad (10)$$

Where W_{ins} and W_{iron} represent the width of insulation and width of iron. Clearly, when Kw=0, the rotor is assumed to be completely made of iron, (i.e. no saliency). When Kw=1 the rotor is constructed of lamination segments in which the air space and lamination segments are equal. The values of d axis inductance and q axis inductances are given in table

Table 1.Experimental values of Ld and Lq inductances of PMSRM

I (A)	L_q(H)	L_d(H)	L_d-L_q (H)	L_d/L_q
0	0.028	0.06	0.032	2.14
0.5	0.025	0.061	0.036	2.44
1	0.021	0.062	0.041	2.95
1.5	0.02	0.063	0.043	3.15
2	0.018	0.061	0.043	3.38
2.5	0.016	0.058	0.042	3.62
3	0.016	0.055	0.039	3.43
3.5	0.015	0.053	0.038	3.53
4	0.014	0.052	0.038	3.71

Figure 4 shows the d axis and q axis inductance for different values of current. From the graph it is clear that the value of d axis inductance is greater than the value of q axis inductance.

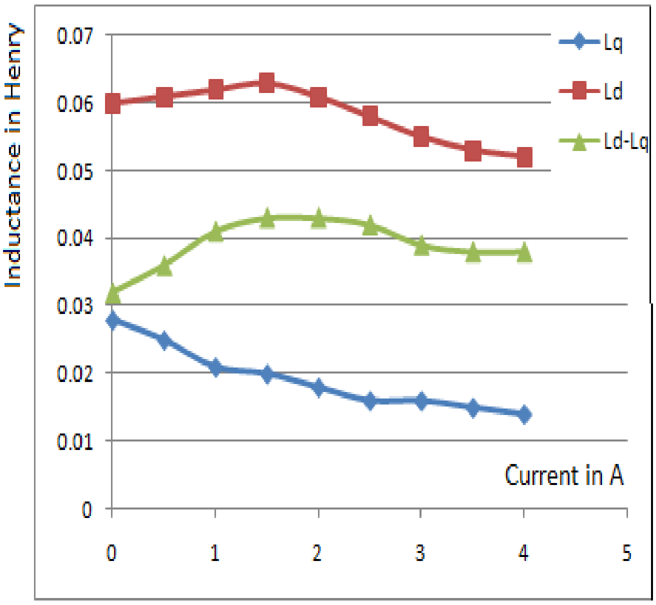

Fig 4. Calculated d-q axes inductances

Various parameters required for the analysis of PMSRM are determined using the routine shown in Figure 5.

ISSN: 2319-5967
ISO 9001:2008 Certified
International Journal of Engineering Science and Innovative Technology (IJESIT)
Volume 2, Issue 1, January 2013

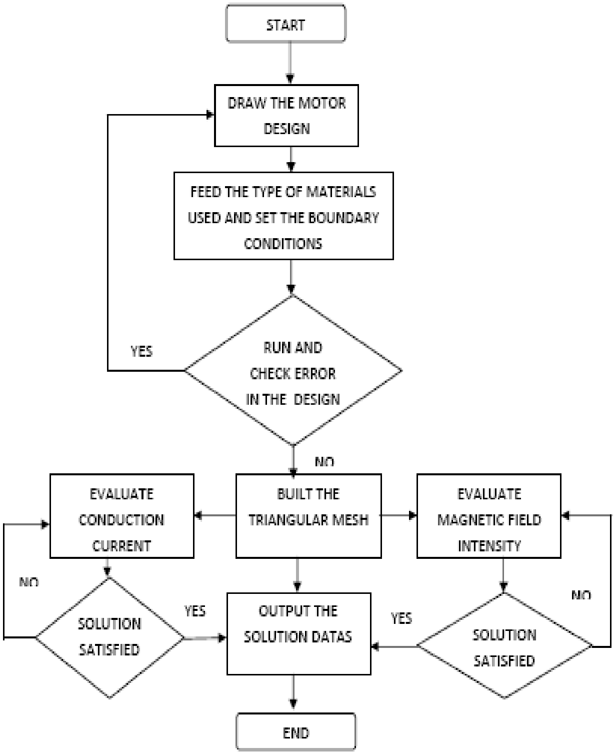

Fig 5. Flow chart of Finite Element Analysis to estimate parameters of PMSRM

V. DESIGN SYNTHESIS

A. Stator Geometry

The design of stator of the machine is kept unaltered where the rotor construction is modified for its improved performance. 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. The overall view of the motor is as shown in the figure 6.

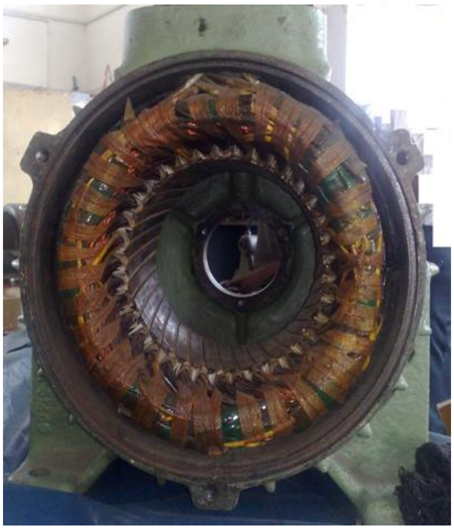

Fig 6. Experimental Stator of PMSRM

ISSN: 2319-5967
ISO 9001:2008 Certified
International Journal of Engineering Science and Innovative Technology (IJESIT)
Volume 2, Issue 1, January 2013

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 [16]. In this case, the motor is similar to an Interior Permanent Magnet (IPM) Motor [9]. 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 it counteracts 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 IPMSM. However, a substantial difference is the high anisotropy rotor structure of PMSRM results in low value of the permanent magnet flux. The amount of permanent magnet 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 IPMSM 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. As it was mentioned before, to improve the efficiency of the motor some Ferrite magnets are placed in the rotor 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][13]. Figure 8 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 and also the material cost. The d- axis inductance L_{ds} and q-axis inductances Lqs, are known to depend on the air gap flux. Ferrite, ceramic magnets and Neodymium-Iron-Boron materials are well known materials used in PM motors. The flux density of the magnets changes significantly by variation of temperature. The variation of the flux density affects the d- and q-axis inductances and also directly affects the output torque [11].

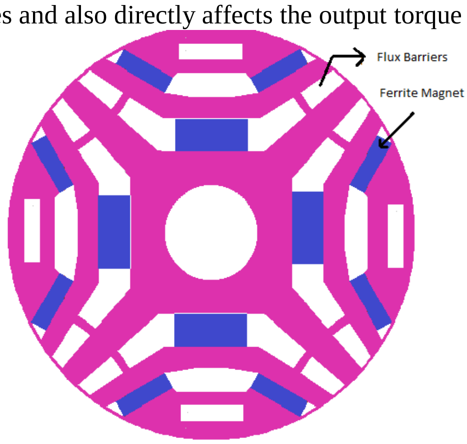

Fig 7. Proposed PMSRM

VI. FLUX DENSITY WITH RESPECT TO ROTOR ANGLE

Since the rotor of PMSRM follows the flux, the position of rotor and fluxes are changed together and it is possible to extract the rotor position by detecting of flux position. Therefore in this method the rotor position is estimated using flux linkage. In this approach, torque (T_e), speed ($\square_r$) and flux linkage phase angle (ρ_s), in both transient and steady states, is calculated by using the estimated stator flux linkage (ψ_s), and its components ($\psi_{\square}\square$,$\psi_{\square}\square$) in stationary reference frame. The equations of these calculations are shown in the following equations.

$$T_e = \frac{3}{2} p(\Psi_\alpha i_\beta - \Psi_\beta i_\alpha) \text{------------} \quad (11)$$

$$\Psi_s = \sqrt{(\Psi_\alpha^2 + \Psi_\beta^2)} \quad \text{------------} \quad (12)$$

$$\Psi_\alpha = \int (v_\alpha - R_a i_a) dt \quad \text{------------} \quad (13)$$

$$\Psi_\beta = \int (v_\beta - R_a i_\beta) dt \quad \text{------------} \quad (14)$$

ISSN: 2319-5967
ISO 9001:2008 Certified
International Journal of Engineering Science and Innovative Technology (IJESIT)
Volume 2, Issue 1, January 2013

$$\rho_s = \tan^{-1}\left(\frac{\Psi_\beta}{\Psi_\alpha}\right) \qquad \text{------------} \quad (15)$$

The value of flux density in air gap with respect to different rotor angle is shown in figure 8.

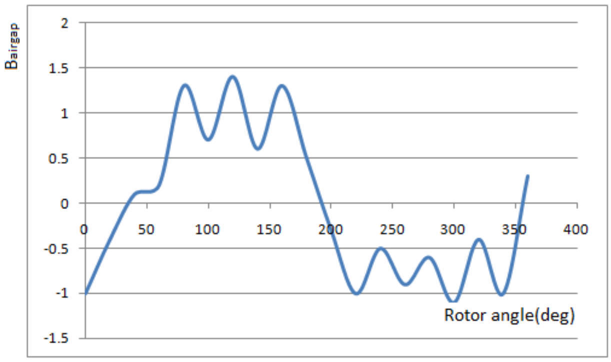

Fig 8. Rotor Phase Angle Detection

The total resulting torque is the summation of reluctance torque and permanent magnet torque. The values of overall torque of the SRM, surface mounted – PMSRM(SM-PMSRM) and PMSRM are shown graphically in figure 9.

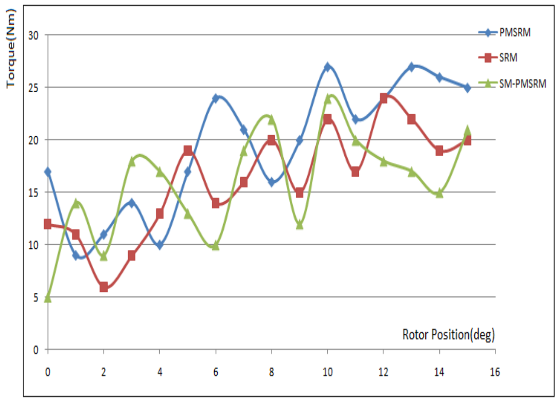

Fig 9. Comparison of Reluctance Torque Using FEA

Also the values of reluctance torque, permanent magnet torque and the resulting torque are calculated for the proposed PMSRM and shown graphically in the figure10.

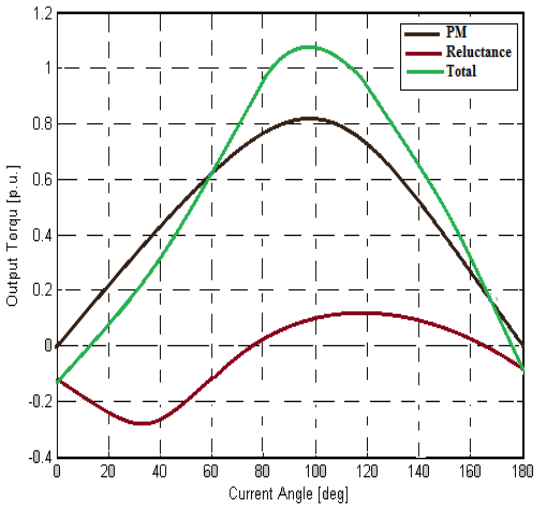

Fig 10. Output Torque with different current Angles

ISSN: 2319-5967
ISO 9001:2008 Certified
International Journal of Engineering Science and Innovative Technology (IJESIT)
Volume 2, Issue 1, January 2013

VII. CONCLUSION

A novel design of Permanent Magnet Synchronous Reluctance Motor is proposed. It is analyzed that, with respect to the conventional Synchronous Reluctance Machine, this motor offers better torque capabilities and power factors. .Finite Element Method is used to obtain the inductance and motor parameters. Various Effects of the permanent magnets on d-q inductances were studied. A comparison between torques of Synchronous Reluctance Motor, Surface mounted PMSRM and PMSRM was performed. It results show that the proposed PMSRM substantially improve the efficiency due to modified rotor geometry. Simulation results and the extensive experimental results for the PMSRM show the effectiveness of the proposed method.

REFERENCES

[1] T. Ohnishi and N. Takahashi, "Optimal design of efficient IPM motor using finite element method," IEEE Trans. Magn., vol. 36, no. 5, pp. 3537–3539, 2000.

[2] N. Bianchi, S. Bolognani, "Interior PM synchronous motor for high performance applications", Proceedings of Power Conversion Conference, vol. 1, pp. 148-153, April 2002.

[3] D. J. Sim, D. H. Cho, J. S. Chun, H. K. Jung, and T. K. Chung, "Efficiency optimization of interior permanent magnet synchronous motor using generic algorithms," IEEE Trans. Magn., vol. 33, no. 2, pp. 1880–1883, 1997.

[4] M. Kondo, K. Kondo, Y. Fujishima, S.Shinji,"Rotor design of " Rotor design of Permanent Magnet Synchronous Motor for Railway Vehicle", IEEJ Trans.IA, vol. 124, no.12, 2004.

[5] T. M. Jahns, G. B. Kliman, and T. W. Neumann, "Interior permanent magnet synchronous motors for adjustable-speed drives," IEEE Trans. Ind. Applicant., vol. 22, no. 4, pp. 738–747, 1986.

[6] G. H. Kang, J. P. Hong, G. T. Kim, and J.W. Park, "Improved parameter modeling of interior permanent magnet synchronous motor based on finite element analysis," IEEE Trans. Magn., vol. 36, no. 4, pp. 1867–1870, 2000.

[7] S. Morimoto, M. Sanada, Y. Takeda, "Performance of PM assisted synchronous reluctance motor for high efficiency and wide constant power operation," IEEE Transactions on Industry Applications, vol. 37, no. 5, pp. 1234-1240, September/October 2001.

[8] B. V. Litvinov and O. B. Davydenko, "A Synchronous Reluctance Motor with a Laminated Rotor" ISSN 1068-3712, Russian Electrical Engineering, 2009, Vol. 80, No. 1, pp. 29–32. © Allerton Press, Inc., 2009.

[9] Li Liu, Wenxin Liu and David A. Cartes ,"Permanent Magnet Synchronous Motor Parameter Identification using Particle Swarm Optimization", International Journal of Computational Intelligence Research. ISSN 0973-1873 Vol.4, No., pp.211–218, 2 (2008).

[10] A.Kiyoumarsi, M.R.Hassanzadeh and M. Moallem, "A New Analytical Method on Interior Permanent Magnet Synchronous Motors", Scientica Iranica, vol. 13, No.4, pp. 364-372, October 2006.

[11] Tsuyoshi Hanamoto, Ahmad Ghaderi, Muneto Harada, Teruo Tsuji, "Sensor less speed control of synchronous reluctance motor using a novel flux estimator based on Recursive Fourier Transformation," icit, pp.1-6, 2009 IEEE International Conference on Industrial Technology, 2009

[12] Thierry Lubin,Hubert Razik, and Abderrezak Rezzoug, "On-line efficiency optimization of a synchronous reluctance motor" Electric Power Systems Research Volume 77, Issues 5-6, Pages 484-493, April 2007.

[13] B. Singh, B.P. Singh, and S. Dwivedi, "A review of sensor reduction techniques in permanent magnet synchronous motor drives," 10.2316/Journal.203.2009.1.203-3714, (203) International Journal of Power and Energy Systems - 2009.

[14] R. Lateb, N. Takorabet, F. Meibody-Tabar, A. Mirzaian, J. Enon, and A. Sarribouette, "Performances comparison of induction motors and surface mounted PM motor for POD marine propulsion", in Conf. Rec. IEEE-IAS Annu.Meeting. 2005.

[15] Albert W.-J. Hsue, M.-T. Yan,"Comparison on linear synchronous motors and conventional rotary motors driven Wire-EDM processes", Technology, Volumes, Pages 478-485, 1 October 2007

[16] D.Vimalakeerthy and Dr.M.Y.Sanavullah ,"An Improved Design of Permanent Magnet Synchronous Reluctance Motor using Finite Element Method", CiiT International Journal of Programmable Device Circuits and Systems, Vol. 1, No 5, August 2009.

[17] Khan K, Haghbin S and Leksell, "Design and Performance analysis of permanent magnet assisted synchronous reluctance motor for an integrated charger application", International Conference of Electrical Machines, 06 to 08 September 2010.

ISSN: 2319-5967
ISO 9001:2008 Certified
International Journal of Engineering Science and Innovative Technology (IJESIT)
Volume 2, Issue 1, January 2013

AUTHOR BIOGRAPHY

Mr. 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. Currently he is working as an Assistant Professor at AVS Engineering College, Salem and pursuing his PhD in Anna University, Coimbatore. His research interest is Design improvement of Synchronous Reluctance Motor and Finite Element Analysis.

Dr.N. Kanagaraj was born in Tamil Nadu, India. He is working as Professor and Director of Electrical Engineering Department in KSR College of Engineering, Tiruchengode. His Area of specialization is Fuzzy logic controller; Microcontroller based system and Embedded System.

Dr.M.Y.Sanavullah,, was born in Tamil Nadu, India. He received B.E degree in Electrical and Electronics Engineering and M.Sc Engineering in Power System Engineering. He received the Ph.D., degree in High Voltage Engineering. He worked as lecturer for 16 years, as Assistant Professor for 10 Years and Principal for 10 years. Currently he is working as a Professor and Dean in the Department of Electrical and Electronics Engineering, VM.K.V Engineering College, Salem. His research interests are High Voltage Engineering and Finite Element Analysis.