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Performance Evaluation of PMSG for Aircraft Applications

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Abstract

In this paper, the 68W/20V permanent magnet synchronous generator for aircraft application is discussed at the speed of 9000rpm. The electromagnetic and thermal analyses of the machine are carried out using the software of finite element analysis (FEA). Finally, the overall performance such as Electromagnetic flux, voltage, current and Temperature of the analytically designed machine is compared with the results obtained from simulation and hardware analysis

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Keywords: Aircraft; Multi stage generator system; Finite Element method; Electromagnetic and Thermal Analysis.

1. INTRODUCTION

The Indian aircraft project is now called the Light Combat Aircraft (LCA) in order to create an identity distinct from the Light Weight Fighter concept. In the early 1980s, India, knowing well that the Mig-21s, Mig-23s, and a variety of other aging Russian fighters composing a vast percentage of their air power would soon grow obsolete, decided to produce a new fighter to replace the MiG-21 "Fishbeds" legacy. The new aircraft would be of

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indigenous design, and its development would fall under the care of India's own Aeronautics Limited. The aircraft that would spawn from the program was designated the Light Combat Aircraft and it would be one of the worlds lightest, yet most capable dedicated multi-role aircraft of all time [1] – [2].

In LCA, 30 – 60 kVA generator provided electrical power supply for all electrical loads. If this power system fails, the backup power supply supports and is called integrated generator system (IGS) providing power supply for emergency loads such as cabin lighting, food preparation, gunshot and cockpit, etc. This IGS consists of 3 electrical generators, namely permanent magnet synchronous generator (PMSG), Brushless synchronous generator (also called Main exciter) and Synchronous generator(also called main generator)being mounted on single shaft which is driven by aircraft engine gear box. The basic structure of IGS is shown in Figure 1 [3].The major problem in aircrafts to fix in this IGS is the available space in aircraft, which is just140 mm. Also aircraft engine rotating speed lies between 7000 rpm and 24000 rpm. So, it does not provide any external cooling arrangements at this dimension for high speed operations. Due to these reasons, much heat is produced in the main generator.

Normally, PMSG is one of the machines used in the multi stage generator system for aircraft power supply. The main advantage of this machine is to eliminate slip rings & brushes. Also it has the advantages of high power density and better heat dissipation capability. Due to its self excitation capability, high PF & efficient operation is possible and the machine has the capability of overloading & handling full load at a very low speed operation [4] – [7]. During high speed operation, the Interior Permanent Magnet Synchronous Machine (IPSM) produces high torque [8]. The permanent magnets are made up of Neodium-Iron-Boron (NdFeB), Samarium Cobalt (SmCo) and Alnico [9]. NdFeB has high remanent magnetization and Energy product. SmCo has better thermal characteristics. Since NdFeB is a non radioactive material, it is suitable for both civil and military applications. But its thermal characteristics is poor when compared to SmCo. So it is not suitable for high speed operation.

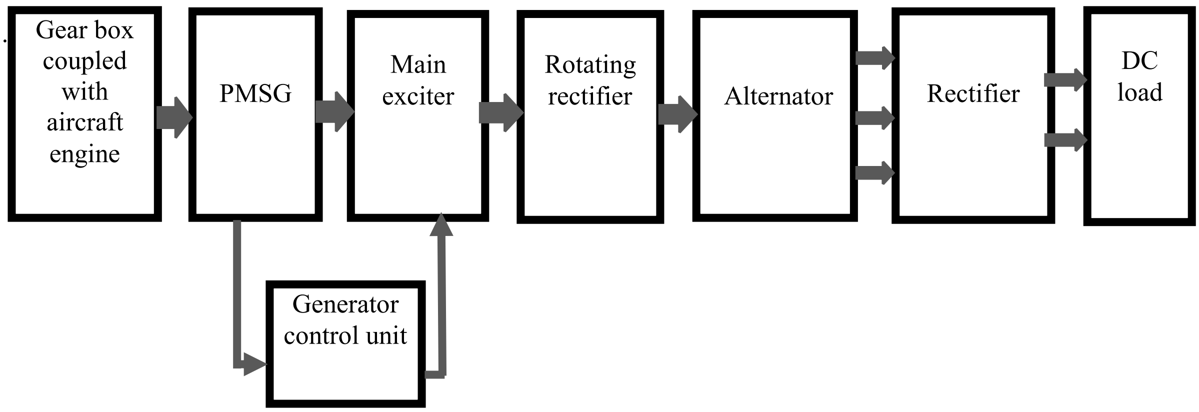

Fig.1 Basic Structure of IGS system

The above literature does not deal with PMSG operating to a specific dimension, speed and power rating. This work proposes the PMSG for aircraft applications with required dimension and high speed operations. The simulation analysis & prototype model of 68W PMSG are presented. The organization of the paper is as follows: section II deals with the design & model description of the PMSG. The simulation results of the proposed generator are given in section III. The experimental results are presented in section IV. The work is concluded in section V.

2. DESIGN AND MODEL DESCRIPTION OF PMSG

The basic mathematical expressions used for PMSG is given below based on [10].

The RMS value of the fundamental component of the phase excitation voltage in PMSG is given by

$$E_{ph1} = 4.44\, f\, N_{ph}\, K_{w1}\, \Phi_{PM} \qquad (1)$$

Where f, N_{ph} and K_{w1} are the electrical frequency of the generator, number of winding turns per phase and the fundamental harmonic winding factor respectively. Also Φ_{PM} stands for the flux per pole due to the magnet.

The torque developed in the machine is

$$T_e = 3/2p\,[\,\lambda\, i_q + (L_d - L_q)\, i_d\, i_q\,] \quad (2)$$

Where p is the number of poles, L_d and L_q are d axis and q axis inductances respectively and λ is the amplitude of the flux induced by the permanent magnets of the rotor in the stator phases.

Percentage of Armature Reaction MMF is given by

$$\text{MMF} = \frac{3\, I_{ph} \sin(\cos pf) N_{tc}}{2 * path * p} \quad (3)$$

Where I_{ph} is the phase current in amps, N_{tc} and N_{cp} are the number of turns per coil and number of coils per pole respectively and path is the number of parallel paths.

The state vector form of the stator voltage equation is

$$V_{abc} = R_s I^S_{abc} + d\,\lambda^S_{abc}/dt \quad (4)$$

Where Rs is the stator winding resistance per phase, I_{abc} is the stator phase current, V_{abc} is the stator phase voltage and λ_{abc} is the Flux linkage.

Based on the reference frame theory, stator voltage equations in dq synchronous reference frame are

$$V^S_d = R_s i^S_d + d\lambda^S_d/dt - \omega_e \lambda^S_d \quad (5)$$

$$V^S_q = R_s i^S_q + d\lambda^S_q/dt + \omega_e \lambda^S_q \quad (6)$$

Where V^S_d and V^S_q are the dq axis stator voltages, i^S_d and i^S_q are the dq axis stator currents, λ^S_d and λ^S_q are the dq axis stator Flux linkages, Rs is stator resistance and ω_e is the electrical speed in rad/s.

Flux linkage equations are

$$\lambda^S_d = L_d i^S_d + \lambda_m \quad (7)$$

$$\lambda^S_q = L_q i^S_q \quad (8)$$

Where L_d and Lq are dq axis inductances and λ_m is the permanent magnet Flux linkage.

Total mass of the machine in Kg is given by

$$M_{tot} = M_{ts} + M_{cs} + M_{ir} + M_{sr} + M_m + M_{con} \quad (9)$$

Where M_{ts} is Mass of the stator teeth in kg, M_{cs} is Mass of the stator core in kg, M_{ir} is Mass of the rotor iron in kg, M_{sr} is Mass of the rotor shaft, M_m is Mass of the magnet in kg and M_{con} = Mass of the conductor in kg.

Total loss of the machine in watts is calculated as

$$L_{tot} = L_{cop} + L_{core} + L_{teeth} + L_{fri} \quad (10)$$

where L_{cop} isThree phase copper loss in watts, L_{core} is Core loss in watts, L_{teeth} = Stator teeth loss in watts and L_{fri} is Frictional & windage loss in watts.

The theoretical design of the generator is carried out by standard design equation available in [11] – [12] and RMxprt software tool. Based on this the theoretical design values listed in the following table 1.

Table 1: Design Parameters

Parameter	Value
Rated Power, (W)	68
Rated DC Voltage, V_{dc} (V)	20
Phase Current, I_{ph} (A)	3.53
Stator Outer Diameter, ods (mm)	108
Rotor Outer Diameter, odr (mm)	78.6

Length of the Air gap, L_g (mm)	0.7
Speed, N (rpm)	9000
Number of Slots, S	9
Number of Poles, P	8
Power Factor	0.88
Total Losses, (W)	21.25
Temperature, (^oC)	30
Efficiency, (%)	85.6

3. FINITE ELEMENT ANALYSIS OF PMSG

Finite element analysis is an effective simulation tool for analyzing complicated structure with non-linear elements. Normally electromagnetic analysis of the electrical machines is carried out using finite element software like SPEED, FLUX, MagNet, Motor Solve, etc. These tools act as intermediator between analytical calculation and prototype model for the purpose of reduced cost and improved performance. In this analysis simulation work was carried out using MagNet software which is used to see the visual effect of flux linkage, flux density, voltage, current and ohmic losses.

3.1 Magnetic Analysis

Software used to solve this problem is MagNet 7. This is used to carry out electromagnetic analysis of a generator. MagNet software coming under Finite element analysis package and this software developed Infolytica Corporation. Boundary used in this problem is closed boundary, so problem formulation is based on vector potential with magneto dynamic computations. Also Number of nodes is 43367, Number of edges is 128595 and Number of faces is 101331. The FEM based 2D design of voltage on no load condition is shown in Figure.3.

In the preprocessor step the generator was designed based on analytical design values. After the design completion, machine stator and rotor core were filled with hiperco 50A(cobalt iron alloy) steel and windings were filled with copper material. In this problem the size of the meshes is 2 mm for entire generator includes stator and rotor. Also the shape of mesh is triangular, because it will give accurate result when compared to other mesh shapes. If the size of mesh is reduced below 2 mm, the overlap will occur between meshes and not able to get output properly. The calculation time of the generator can be increased by increasing number steps fixed in the software. The number of steps fixed to solve this problem is 10.

The developed PMSG will provide power to the main exciter field windings and the Generator Control Unit (GCU) electronics. In the preprocessor step the generator was designed based on analytical design values. The PMSG has 9 stator slots and 8 rotor poles with concentric winding at the stator and the rotor uses the ferrite permanent magnets. The PMG is designed to supply a power of 68 W, 20 V DC at 9000 rpm to meet the requirements of the main exciter stator field. The magnets are mounted in such a way that the leakage flux is minimized and the working flux is maximized. Vanadium Cobalt Steel is used for stator/rotor laminations with 0.35 mm thickness. The simulation model of the proposed generator cross sectional view of PMSG is shown in the Figure 2.

In the post-processor analysis, the magnetic flux distribution of the machine is obtained and this flux distribution is shown at no load condition in the Figure 2. In that Figure, the flux density is uniformly distributed within the core of the machine. The maximum value of the flux density is 2.72 Wb/m^2 at 9000 rpm and these values are approximately equal to the theoretical designed values. The maximum flux density is concentrated on the edges of the poles. From this flux plots, the leakage of flux is very less.

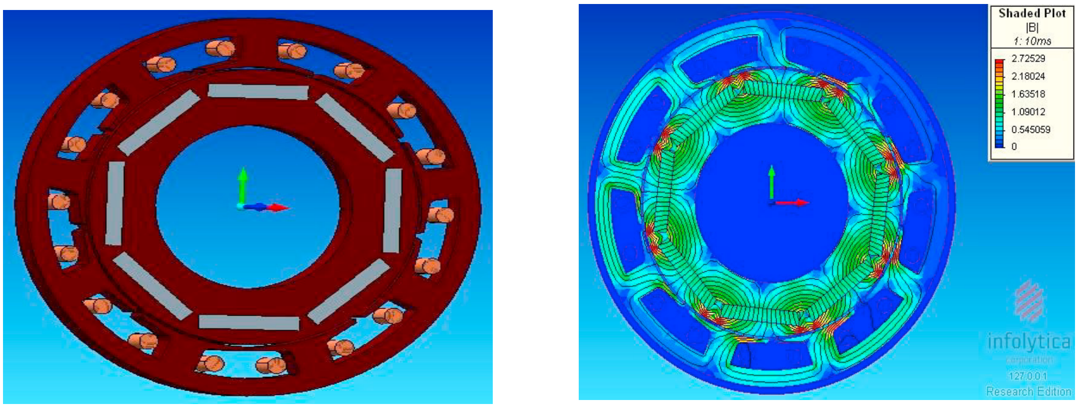

Fig. 2 Cross Sectional View of PMSG and Magnetic Flux Distribution during no load

The voltage waveform of the unloaded PMSG at 9000 rpm is shown in the Figure 3. From the waveform, it is observed that the induced voltage is sinusoidal and the maximum voltage at no load condition is 17.28 V at 9000 rpm and this value is approximately equal to the theoretically designed values. In Figure 3, the flux linkages in all the 3 phases at no load condition are purely sinusoidal. The maximum value of flux linkage is 0.0037 Wb

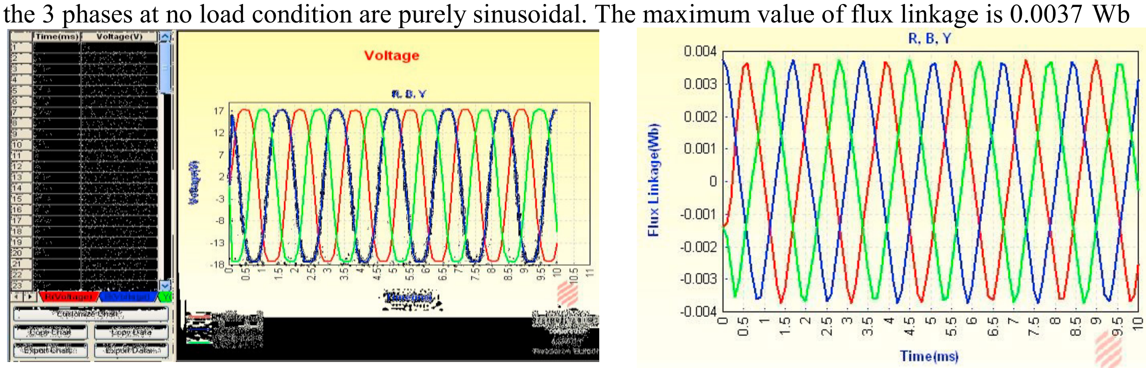

Fig. 3 Voltage on no load condition at 9000rpm and Flux Linkages in All 3Phases

As shown in Figure 4, when a machine is connected to a 3.5 Ω resistive load through a diode rectifier circuit, we get dc voltage and dc current. The maximum dc voltage that is obtained across the load is 20.040 V as shown in Figure 5. The maximum dc current that is obtained through the load is 3.5 A at 9000 rpm as shown in Figure 5. These values are approximately equal to the theoretical values mentioned in the design table.

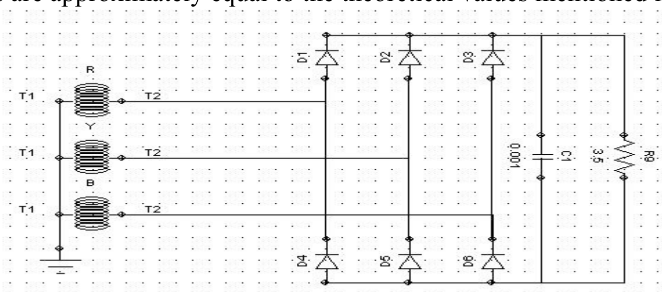

Fig. 4 Machine connected with Resistive load

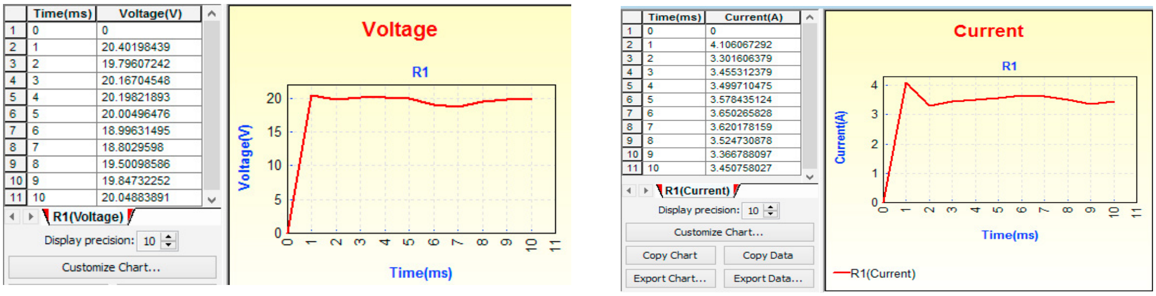

Fig. 5 DC voltage and DC current during load condition at 9000rpm

3.2 Thermal Analysis

The overall thermal analysis of the machine is carried out using the ThremNet software. This analysis is used to evaluate the overall temperature generated and total heat flow in the machine and find out the main sources of heat.

In this section, the designed machine using the MagNet software is directly implemented or coupled with the ThermNet software. Figure 6 shows the total heat formation of the machine at 9000 rpm and the maximum temperature is 27.76°C. From the Figure 6 we conclude that the temperature is high at conductors. The total heat flow in the machine at 9000 rpm is shown in the Figure 6.

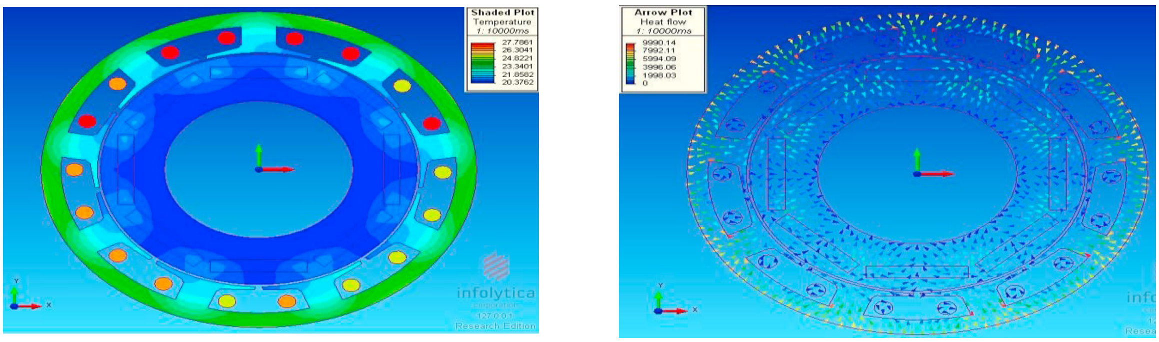

Fig. 6 Temperature and Total Heat flow at 9000rpm

4. Hardware Results

The proto type model of the 68 W / 9 slots / 8 poles PMSG is shown in the Figure 7. It consists of induction generator, PMSG mechanical coupling and resistive load. Here induction generator act as prime mover rotating at 1500 rpm and mechanical coupling provide 6:1 speed ratio.

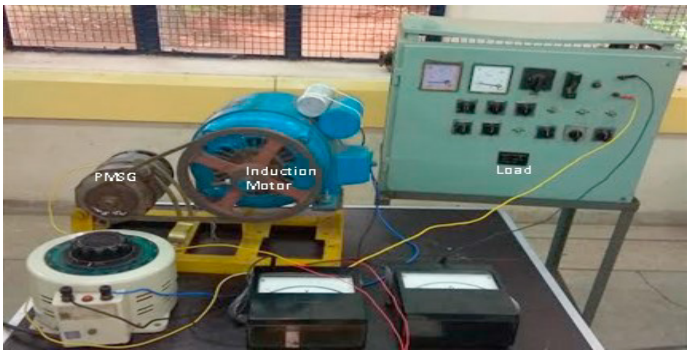

Fig. 7 Prototype Model of PMSG

The output voltage and current characteristics of the PMSG is shown in the Figure 8. From the waveform it is observed that the voltage is slightly reduces when load increases similarly current curve keeps on increasing when load increasing.

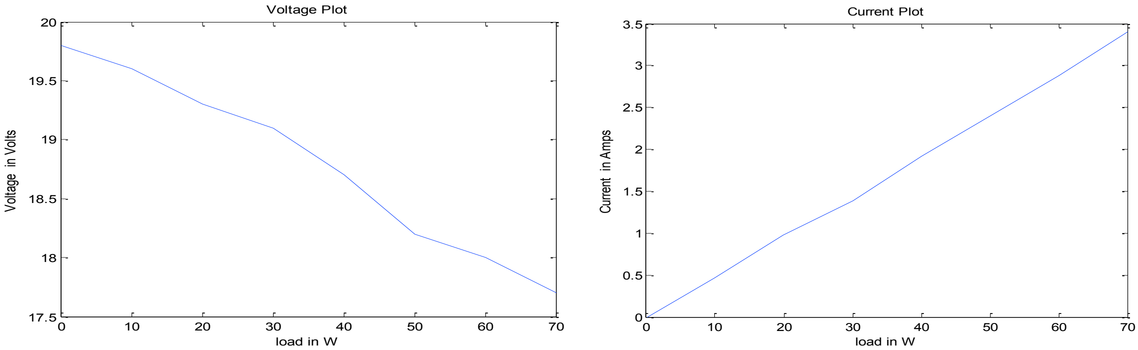

Fig.8 Load voltage and Current

The temperature of the generator is measured by temperature indicator in various parts of the generator. The thermal plots of the PMSG are shown in the Figure 9. These plots drawn between temperature VS load and temperature VS speed. It is observed that the temperature value not crosses more than 32°C full load condition and 9000 rpm. The maximum temperature is concentrated at stator core and conductors.

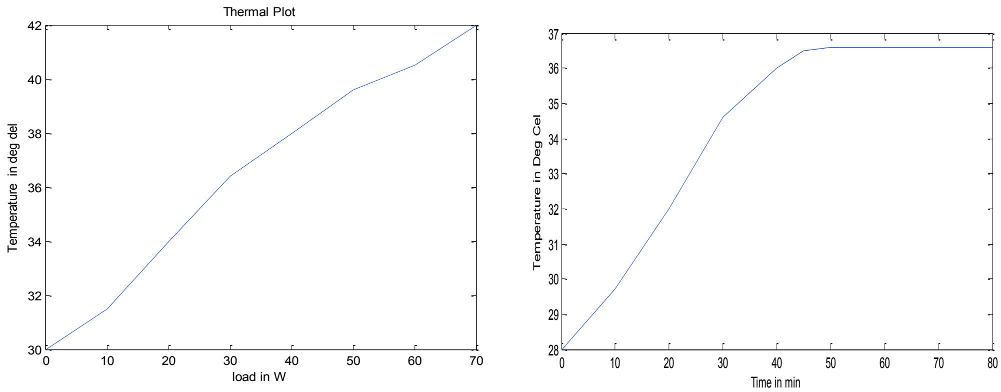

Fig.9 Temperature Plot

The overall performance of PMSG is compared with simulation and hardware results and it is given in the following Table 2.

Table 2: Performance Comparison of PMSG

Parameter	**Simulation**	**Hardware**
Voltage in V	20.040	19.7
Current in A	3.5	3.42
Temperature in °C	27.28	32

From the above table it is conclude that the performance of the PMSG is good for both simulation analysis and experimental validation at high speed operation with required dimension.

V. CONCLUSION

In this paper, a 68W/20V PMSG is designed and simulated at the speed of 9000rpm for multi stage generator system which provides Efficient and safe operation of the Aircrafts. The Electromagnetic field analysis of the PMSG machine is analyzed to determine its electromagnetic flux, voltage and current using MagNet software. The temperature and heat flow of the machine is obtained by thermal analysis using ThermNet software. After the analyses, the results have shown that the overall performance of the PMSG is better and efficient at high speed conditions. This kind of efficient generator is most commonly used in Aircraft, Marine industries and fly wheel energy storage applications.

The performance of the inverted permanent magnet synchronous generator for aircraft application will be studied in the future.

REFERENCES

1. https://en.wikipedia.org/wiki/HAL_Tejas
2. http://www.tejas.gov.in/
3. Deepak Arumugam, Premalatha Logamani and Santha Karuppiah, 'Design and Implementation of claw pole alternator for Aircraft Application', *The Applied Computational Electromagnetics Society Journal*, vol.31, no.5, pp. 582-590, 2016
4. Ajay Kumar, Sanjay Marwaha and Amarpal Singh, Anupama Marwaha, 'Performance investigation of a permanent magnet generator', *Simulation Modeling Practice and Theory* Vol.17, pp. 1548-1554, 2009.
5. Rahul Singh, Vinit Chandray Roy and C.K.Dwivedi, 'Speed control of permanent magnet synchronous motor drive using an inverter', *International Journal of Electrical and Electronics Engineering*, Vol. 1, pp. 2231-5284, 2012
6. Mohammad S Widyan and Rolf E Hanitsh, 'High power density radial flux permanent magnet sinusoidal three phase three slot four pole electrical generator', *Electrical power and Energy systems,* Vol. 43, pp. 1221-1227, 2012.
7. Guannan Duan, Haifeng Wang, Hui Guo and Guobiao Gu, 'Direct drive permanent magnet wind generator design and electromagnetic field finite element analysis', *IEEE transactions on applied superconductivity*, Vol. 20, pp. 1883-1887, 2010.
8. Jae Woo Jung, Byeong Hwa Lee, Do Jin Kim, Jung Pyo Hong, Jae Young Kim, Seong Min Jeon and Do-Hoon Song, 'Mechanical stress reduction of rotor core of interior permanent magnet synchronous generator', *IEEE Transactions on Magnetics,* Vol. 48, pp. 911-914, 2012.
9. Sandra Eriksson, Andreas Solum, Mats Leijon and Hans Bernhoff, 'Simulations and experiments on a 12 kiloWatts direct driven PM synchronous generator for wind power', *Renewable Energy*, Vol. 33, pp. 674-681, 2008.
10. Paul C.Krause, Oleg Wasynczuk and Scott D.Sudhoff, 'Analysis of Electrical Machines & drive systems', Wiley Interscience publications, second edition.
11. Sawhney. A.K, "Course in Electrical Machine design,"
12. Dhanpat rai & sons publications, Sixth edition, 2006.
13. J.R.Hendershot and T.J.E.Miller, 'Design of Brushless Permanent-Magnet Machines', Motor Design Books LLC; Second Edition edition, 2010.