Simplified Design of Permanent Magnet Synchronous Generator for Gas Turbine Application

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Abstract—**There is a need for simple design strategies for designing high speed PMSG with less weight and high efficiency. There is a lot of scope for further improving the design and performance by integrating the results from magnetic, thermal and vibration analysis. In this paper a simplified analytical design for the given specifications is done. Two dimensional finite element analysis using MagNet software is considered for investigating the design. The flux parameters are compared to validate the design obtained using analytical method. A simplified model is designed for thermal analysis to validate the rating of the machine designed. A simple thermal analysis of the machine circuit is performed and the results are validated using MATLAB / SIMULINK Software.**

***Index Terms*—Six Phase PMSG, analytical design, FEM, Thermal analysis**

I. NOMENCLATURE

bts -tooth width
D -inner stator diameter
Dr - rotor diameter
Drc- rotor core diameter
Dy-outer stator diameter
f - frequency
hss-slot height
hsy -stator yoke height
ks - stacking factor
lu-useful length of stator core
Lc -stack length
Lp -inductance /phase
Mm -magnet mass
Mtot -total mass
Mts -stator teeth mass
Pcu -copper loss
Pcs -core loss
Pfri-mechanical loss
Pout - output power
Pte-loss in teeth
Ptot - total loss
Pp - parallel path
Rs - resistance per phase
S-Number of slots
Vts- stator teeth volume
Xl- reactance /phase
Xsl -slot reactance
Xel -end leakage reactance
Zs-impedance /phase
α-magnet angle
Mcs -stator core mass
Mcon-conductor mass
Mcr-rotor core mass
α1-Heat transfer co-efficient of stator yoke back
λfe-Conductivity of iron
δ -air gap length

II. INTRODUCTION

Gas turbine applications require relatively light weight and highly efficient generation units. The permanent magnet synchronous generator (PMSG) has the advantage of high efficiency, relatively light weight, simple mechanical construction and absence of moving contacts. PMSG has higher efficiency, power factor and reasonable power converter costs when compared to the switched reluctance generators or induction generators.

High-speed permanent magnet machines have high power-to-weight ratio, smaller size, and higher efficiency compared to the induction machines which make them a preferred choice for aircraft and marine applications that use gas turbines for the mechanical input [19].General electrical and magnetic sizing of high speed PMSG for various power ranges and tip speeds, rotor capability and cooling system performance have been analyzed in [1], [5]. Designs offering reductions in both weight and volume provide flexibility to naval and aerospace applications since power, weight, and volume are integral parts of the design and construction processes [13],[20].The main disadvantages of the permanent magnet rotor type is the complexity of the rotor and the poor temperature tolerance of the magnets [17]. Electromagnetic and thermal approaches to design a high specification electrical machine are presented in [6].A comprehensive design using simple techniques is attempted by analyzing basic thermal models in [2] and FEM analysis approaches in [9].

A design is attempted in this paper for a customized PMSG for high speed gas turbine military application with the maximum radius of 150mm, weighing about 5Kg, subjected to the operating temperature range of -55 to 120 degree centigrade and constant voltage for a varying speed range from 70% to 100% with the rating of 5 kW and 30000 rpm. A symmetrical six phase PMSG is considered to provide a constant DC output for the application as shown in Figure 1. The multiphase machines are designed for functioning in autonomic systems, like electric energy generation in wind systems, electric traction, alternators, and exciters in electric propulsion submersible systems [4], [10]. Compared to their three-phase counterparts, the six phase machines have lower torque pulsation, higher power density and multi-control

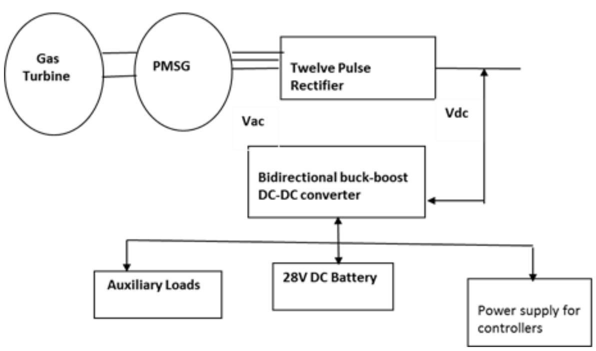

Figure1.Block diagram of PMSG application

freedom [12],[15]. The use of permanent magnet multiphase generators in marine current turbines is highlighted for their fault-tolerance capability [18].The power is split across a higher number of phases in six phase high power drives. This reduces the per-phase inverter rating, making possible the use of most competitive IGBTs in high power drives with a two level topology [7]. The effect of phase shifts between the two 3-phase systems affects the machine losses as well as the space harmonic patterns [14].The comparison of flux density spectrum in the air gap for three and six phase shows that the six phase machine successfully reduces the fifth and seventh harmonics and even the slot harmonics [23].

III. ANALYTICAL DESIGN

The following section focuses on the design of the surface-mounted permanent magnet motor. It is a simple permanent magnet machine design using basic relations of machine design [22]. The radial-flux generator with surface-mounted magnets is shown in Figure 2.

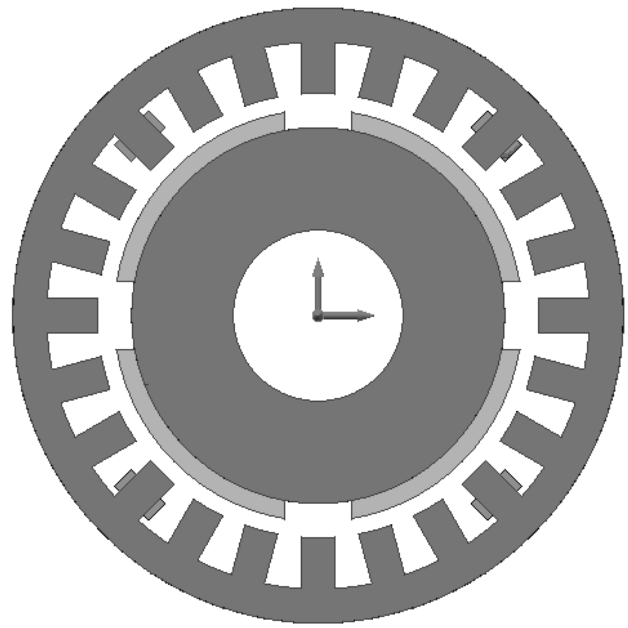

Figure 2. Surface mounted rotor

A. STATOR CONFIGURATION

Specific considerations are needed in designing stator core, winding, and the choice of rotor structure for high speed PMSG [8], [16]. Six phase machines are generally analyzed as two sets of three phase windings that are displaced 30 degrees in space. The PMSG is modeled as a symmetrical six phase stator with each winding having 60 degree displacement in space. The advantage of the single star point is that there is an improved fault tolerance, when compared to the isolated double star arrangement. The stator network can also be directly interconnected with the converter network and the rest of the electrical system.

The dimensions of the stator are obtained from basic relations like the inner diameter of the stator

$$D = D_y - 2(h_{ss} + h_{sy}) \quad (1)$$

where Dy is the outer diameter of the stator, hss is the slot height and hsy is the stator yoke height.

The winding parameters are calculated as follows:

The reactance X1 is calculated from Xsl, the slot reactance and Xel, the end leakage reactance. The reactance per phase

$$X1=(Xsl+Xe1)/ Pp^{2} \quad (2)$$

The impedance $Zs=\sqrt{(Rs^2+X1^2)}$ (3)

The inductance per phase is calculated from the reactance per phase as

$$Lp=X1/(2\pi f) \quad (4)$$

where f is the frequency.

B. ROTOR CONFIGURATION

Permanent-magnet excitation is chosen as it gives an efficient generator in which the pole pitch can be made small, leading to a light core and low end-winding losses. The magnet material preferred is Neodymium Iron-Boron (NdFeB). It has high remnant flux density and lower price compared to Samarium Cobalt (SmCo). The radial-flux design allows a simple generator structure, good utilization of the active materials, and small diameter since the stator can be long and construction is easy with a slotted stator. The air gap can more easily be made small in a radial flux machine than in an axial-flux machine, which leads to a low amount of permanent magnet material. The surface permanent magnet rotors are capable of producing slightly more torque for the given rotor external diameter, length and permanent magnet weight [11].

The dimensions of rotor and magnet are obtained based on the following relations:

The outer diameter of the rotor

$$Dr=D-2\delta \quad (5)$$

where δ is the air gap length.

The diameter of the rotor core is calculated from the outer diameter and height of the magnet hm

$$Drc=Dr-2hm \quad (6)$$

The area of magnet

$$Am= [(Dr-hm) (\pi \alpha Lc)] / 180 P \quad (7)$$

where α is the pole magnet angle and Lc is the stack length.

C. MASS AND LOSS CALCULATIONS

The mass of each machine part is calculated from the volume and the density of the materials used. The volume of stator teeth is

$$Vts = bts\ hss\ Lc\ ks \quad (8)$$

Mass of stator teeth ,$Mts=\rho_{Fe} Vts$ (9)

The total mass Mtot is given by

$$Mtot=Mts + Mcs + Mcr + Mm + Mcon \quad (10)$$

The copper loss for the six phase winding is given by

$$Pcu=6\ Iph1^2Rs \quad (11)$$

Friction and windage losses, Pfri are considered to be 2.5% of output).

Total losses is given by

$$Ptot = Pcu + Pcs + Pte +Pfri \quad (12)$$

Power input, Pin= Ptot + Pout (13)

Efficiency, η= Pout / Pin (14)

The geometric parameters are given in Table 1 and the performance parameters are given in the Table 2.

Table 1.
GEOMETRIC PARAMETERS

Parameters	
Poles	4
Outer Diameter of Stator, Dy(mm)	147
Slots	24
Inner Diameter of Rotor, Drc(mm)	70
Height of Magnet, hm (mm)	3
Magnet Arc, α (degrees)	120

Table 2.
PERFORMANCE PARAMETERS

Parameter	Value	Parameter	Value
Frequency, f (Hz)	1000	Resistance per phase, Rs(Ω)	0.0014
Voltage/phase, Eph (V)	14	Reactance,X1(Ω)	0.037
Current/Phase, Iph, (A)	70.05	Mass of Stator Core, Mcs (kg)	2.33
Terminal Voltage, Vt, (V)	12.88	Mass of Rotor,Mcr(kg)	2.19
Total mass, Mtot(kg)	6.59	Mass of Magnet, Mm (kg)	0.29
Efficiency, η (%)	85.84	Mass of Conductor, Mcon(kg)	0.48
Core Loss, Pfe(W)	578.4	Copper loss,Pcu(W)	40.29
Teeth Loss, Pteeth (W)	177.81	Fric., Win., Fan Losses, Pfri(W)	51.42

The B-H curve considered in the analysis for the NdFeB magnet is shown in Figure 3. The load characteristics are shown in Figure 4. It is found from the load characteristics that for a 10% variation in speed there is a maximum voltage variation of 9.25%. The machine is required to provide constant voltage for increase/decrease of 1000 rpm for which the variation of voltage is 3%. It is hence possible to design a simple chopper based controller to further improve the regulation.

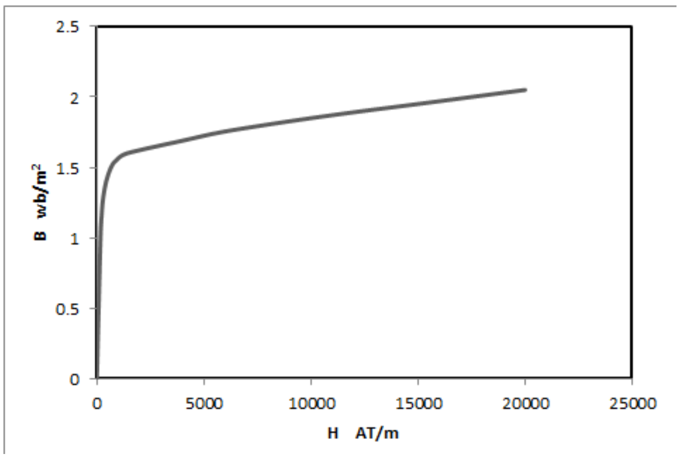

Figure 3. B-H Curve considered for analysis

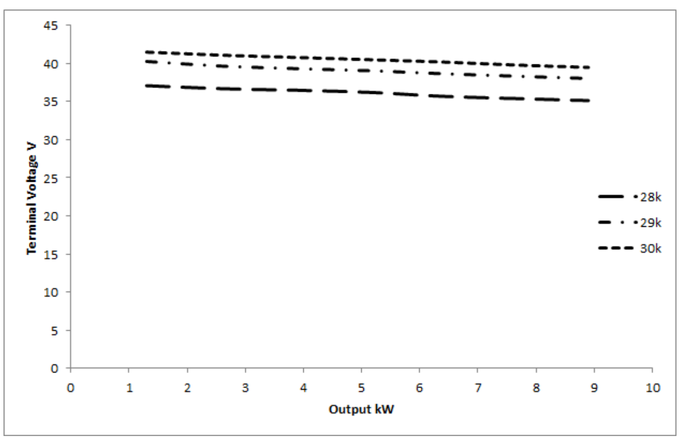

Figure 4. Load Characteristics for various speed range

IV. FINITE ELEMENT ANALYSIS

The design values obtained analytically are used for the modeling of the machine in MagNet software to get static 2D analysis. The solid 2D model of the four poles, twenty four slots PMSG in the polar and inter polar axis is shown in Figure 5 and Figure 6. In the MagNet software, the finite element mesh is created before the model is solved. The flux density values are obtained after running the Newton Raphson and conjugate gradient steps from the shaded field. The values of the flux densities obtained from analytical design and FEM analysis are given in Table 3. The analytical values obtained for the selected dimensions and the output based on the finite element method are nearly equal with a maximum variation of 20 to 30% due to the nonlinear characteristics which are not accounted for in the analytical design. The flux density values are within the magnetic limits of the material.

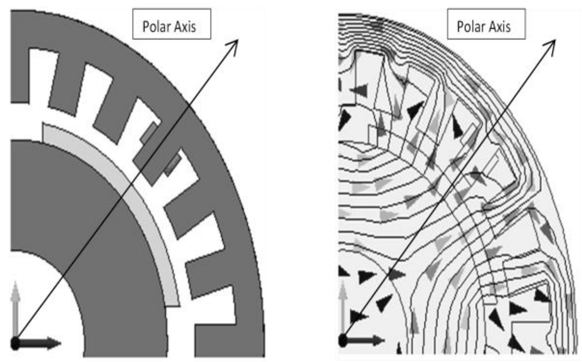

Figure 5.Solid 2D model and flux field view of 4 poles, 24 slots PMSG across polar axis

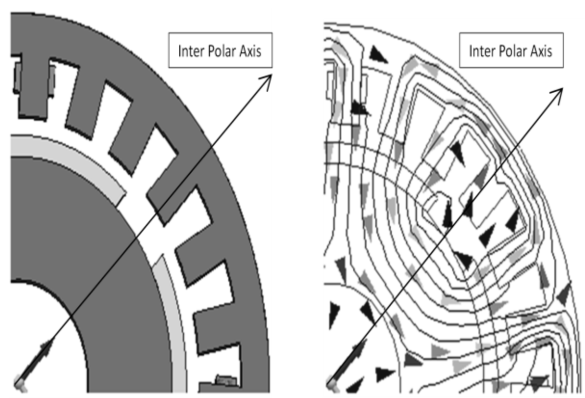

Figure 6. Solid 2D model and flux field view of 4 poles, 24 slots PMSG across inter-polar axis

Table 3.
COMPARISON WITH FEM VALUES

Flux Density [T]	Analytical Values	FEM Values	Magnetic Limits
Air gap Bg	0.443	0.52	1.2
Stator core Bcs	0.877	0.94	1.5
Stator teeth Bts	1.184	1.43	2.0
Rotor core Bcr	1.172	1.26	1.6

V. THERMAL MODEL

Thermal model approach for permanent magnet machines is presented using simplified methods in

[2],[21].The thermal model is simplified by using symmetry to reduce the number of thermal resistances in the yoke, teeth, coil sides, end windings and end shields. The network is simplified as much as possible while keeping only the nodes that are necessary to model the temperature of the end windings and magnets accurately. The cross sectional view and the twelve node thermal model are shown in Figure 7 and Figure 8.

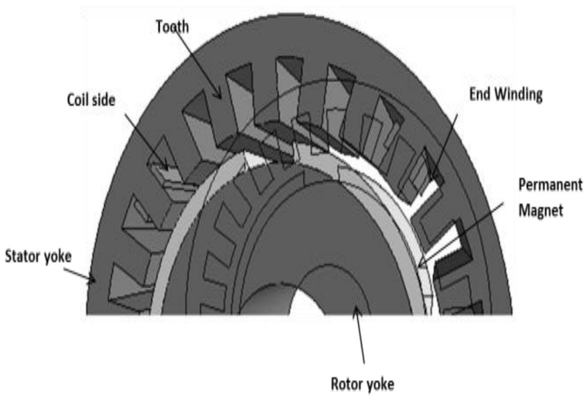

Figure 7 Cross sectional view.

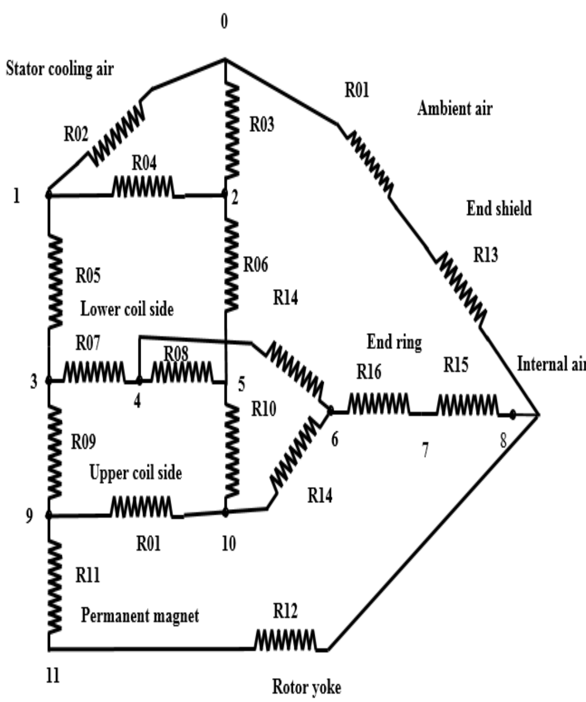

Figure 8.Twelve Node Thermal Model

The thermal resistances of the simplified model are given in Table 4. For example R02=(Ra+Rb)/S, where Ra and Rb are the detailed model parameters calculated as Ra= 1 / (3 l bts α1) and Rb=(0.5 hsy) / (lu bts λfe).[3]

Table 4

THERMAL RESISTANCE VALUES

Thermal Resistance	Value (ohms)	Thermal Resistance	Value (ohms)
R01	0.15	R09	0.01
R02	0.42	R10	1.35
R03	0.83	R11	37.71
R04	0.01	R12	9.38
R05	0.01	R13	25.98
R06	0.72	R14	0.19
R07	0.17	R15	1.05
R08	0.07	R16	0.05

The thermal model has twelve nodes and eighteen thermal resistances with ambient temperature as reference. The temperature rise problem is formulated as a matrix equation. The temperature drop ΔT across a given thermal resistance is calculated from the loss at power node P and the corresponding resistance, ΔT = P*R. Multiplying the loss vector with the inverse of the thermal conductance matrix gives the vector of temperature rises.

A further simplified lumped parameter model as in [21] is employed to model and simulate the thermal behavior of the machine. It is a simplified lumped model for PMSG with five nodes and five elements based on an eight node model with eleven elements. Similar to electrical circuit model, an equivalent thermal model including thermal resistances is adopted. The nodes are chosen at the interface between different materials or at loss generation points. The lumped parameter model chosen for the thermal analysis is shown in Figure 9. The thermal resistances are calculated based on equivalent conductive and convective thermal resistances which use the geometry and thermal characteristics of the machine.

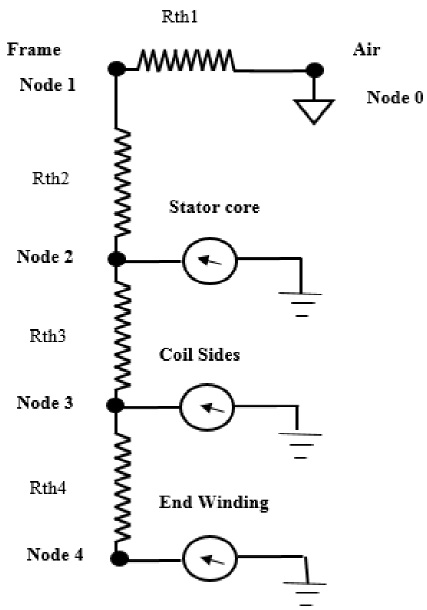

Figure 9 Simplified five node model

The resistances in the model represent the thermal resistivity as follows:

**Rth*1: Thermal resistance between the frame and the coolant =R51 =0.15 Ω

**Rth*2: Thermal resistance between the frame and the stator teeth=R54 = 0.01Ω

**Rth*3: Thermal resistance between the stator teeth and the coil sides =R58 = 0.01Ω

The temperature rise in different parts of the machine when compared to the twelve node model is given in Table 5.

The Simulink -Matlab diagram of the simplified thermal network model is shown in Figure 10. The thermal network model is constructed by using Simulink circuit simulator - SimPower Systems. In the model, losses are fed through the controlled current source blocks, and the temperatures are measured by using the voltage measurement block as the voltage equals temperature difference. The nodes correspond to the different sections of the motor. The comparison of temperatures calculated with the twelve node model and the simplified five node model in different parts of the motor is given in Table 5.The insulation material considered is Class E with maximum hot spot temperature of 120 degree. The design accommodates the requirement within the average range.

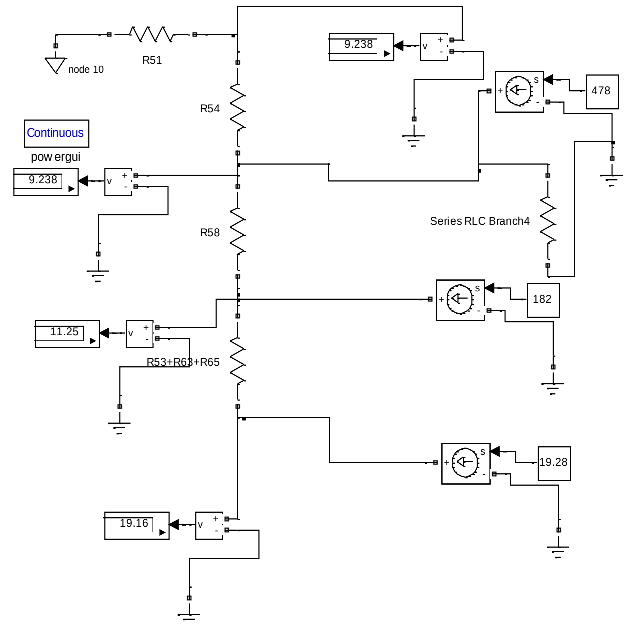

Figure 10 Simulink model of approximated thermal circuit.

Table 5.
TEMPERATURE IN MACHINE PARTS WITH AMBIENT TEMPERATURE =50^{O}

	Temperature rise (Degrees)	
	12 Node Model	5 Node Simulink Model
Frame	35	39
Stator Core	36	39
Coil sides	42	41
End winding	52	49

The steady-state temperature of the end winding is approximately the same in both the models. The hot spot occurs at the end winding and its temperature is 102 degrees. The design satisfies the temperature rise requirement for the given rating and selected class of insulation.

VI. CONCLUSION

A simplified analytical method is used for obtaining the electrical and magnetic parameters of the high speed PMSG. The geometric and performance parameters are calculated. This design satisfies the requirements of various parameters and it is suitable for high speed gas turbine power supply.

The flux density values obtained in the analytical method are compared with static 2D FEM using MagNet software and the values are nearly converging. The temperature rises in different parts of the machine using twelve and five node thermal models are nearly equal. The temperature evaluated at the hot spot is well below the margin limit. This validates the suitability of the designed PMSG for gas turbine run power supply units. The analysis shows that simple methodology can be utilized to design and analyze the machine.

REFERENCES

[1]. .A E Shahat , A KHamed and M. E.Shewy, “Sizing of high speed PM Generator for green energy applications”, Journal of Electrical Systems, 2010, p 510-516.

[2]. A Grauers, “Design of direct-driven permanent-magnet generators for wind turbines”, Ph.D thesis, Chalmers University of Technology, 1996.

[3]. Anita, S & Chellamuthu, Chinna. “Thermal Modeling of PMSG Generator for Gas Turbine Applications.” Indian Journal of Science and Technology. Vol 8(31). November 2015.

[4]. B,S.,Mekri,F.,Benbouzid, and J.FCharpentier, Performance comparison of three — and five-phase permanent magnet generators for marine current turbine applications under open-circuit faults, International Conference on Power Engineering, Energy and Electrical Drives (POWERENG), 2011,Date of Conference: 11-13 May 2011,Page(s):1 – 6

[5]. C Bailey, D M. Saban, , and P G-Pinto, “Design of High- Speed Direct-Connected Permanent-Magnet Motors and Generators for the Petrochemical Industry”, IEEE Transactions On Industry Applications, Vol. 45, No. 3, May/June 2009.pg 1159-1165.

[6]. D G Dorrell D A Staton and M I McGilp, Design of Brushless Permanent Magnet Motors – A Combined Electromagnetic and Thermal Approach to High Performance Specification,32nd Annual Conference on IEEE Industrial Electronics, IECON 2006,Pages 4853-4858.

[7] D-Min M,Jian and X Shen, Simulation and analysis of a variable speed permanent magnet synchronous generator with flux weakening control International Conference on Renewable Energy Research and Applications (ICRERA),Date of Conference: 11-14 Nov. 2012,pg1-6.

[8]. F W,MingZ,Wenpeng and Z,EGuan, Design features of high speed PM machines, Sixth International Conference on Electrical Machines and SystemsICEMS 2003.Nov9–11,2003–Vol1–P66–70

[9] G Y. Sizov D M. I Nabeel A. O. Demerdash, “Modeling and Design Optimization of PM AC Machines Using Computationally Efficient – Finite Element Analysis”, IEEE transactions on Industrial Electronics,2012.Vol 59 Issue 6,pg 2403-2413.

[10] Iurie RA, P Todos, I Nuc, “A review of the multiphase electric machines”, 6th International Conference on Electromechanical and Power Systems, October 4-6, 2007.pg 154-159.

[11]. I Boldea, “Variable speed drives”, CRC Press, 2006.

[12] J Huang, M Kang, J Yang, H Jiang, D Liu, “Multiphase machine theory and its applications”, ICEMS, 2008.pg 1-7

[13]. J E. Rucker, “Design and Analysis of a Permanent Magnet Generator For Naval Applications”, IEEE Electric Ship Technologies Symposium,2005.pg 451-458

[14]. K S Khan, “Comparative analysis of multiphase machines”, Master’s Thesis, Chalmer’s University of Technology, Sweden ,2008.

[15]. Lahne, H.C., Gerling, D., "Comparison of High-Speed High Power Machines based on the State of the Art", 41st Annual Conference of the IEEE Industrial Electronics Society (IECON2015), Yokohama, Japan, 09.-12.11.2015.

[16] Martin van der Geest, , Henk Polinder, Jan Abraham Ferreira, , and Markus Christmann, "Power Density Limits and Design Trends of High-Speed Permanent Magnet Synchronous Machines", IEEE Transactions On Transportation Electrification, Vol. 1, No. 3, October 2015, pg 266-276.

[17]. M Rilla," Design of a 60 kW, 9000 rpm non-salient pole PM machine", IEEE Proceedings of the International Conference on Electrical Machines,2008.pg 1-4

[18]. Mekri,F. Ben Elghali,S, Benbouzid, M.E.H.,Fault-Tolerant Control Performance Comparison of Three- and Five-Phase PMSG for Marine Current Turbine Applications, IEEE Transactions on Sustainable Energy, (Volume:4 , Issue: 2), April 2013, Page(s): 425 – 433.

[19]. 1. Nagomy A.S., Dravid N.V.Jansen R.H. Kenny B.H, (2005) "Design aspects of a high speed permanent magnet synchronous motor / generator for flywheel applications," IEEE International conference on Electric Machines and Drives 2005, P-635-641.

[20]. Nikita Uzhegov, , Emil Kurvinen, Janne Nerg, , Juha Pyrhönen, , Jussi T. Sopanen, , and Sergey Shirinskii, "Multidisciplinary Design Process of a 6-Slot 2-Pole High-Speed Permanent-Magnet Synchronous Machine" , IEEE Transactions On Industrial Electronics, Vol. 63, No. 2, February 2016.pg-784-795.

[21]. NMadani, "Design of permanent magnet synchronous generator for a vertical axis wind turbine", Master of Science Thesis, Royal Institute of Technology, Sweden, 2011.

[22]. S.Anita., C.Chellamuthu, "Design of Permanent Magnet Synchronous Generator for Gas Turbine applications." National Conference on Innovative Techniques in Power Engineering & Drives – ITPED'12, 22 March, 2012.

[23]. S Kato, Y Inui, M Michihira, and A Tsuyoshi, "A low-cost wind generator system with a permanent magnet synchronous generator and diode rectifiers" ,International Conference on Renewable Energies and Power Quality, Sevilla, 2007.http://www.icrepq.com/icrepq07/212-kato.pdf