DESIGN AND FINITE ELEMENT ANALYSIS OF AXIAL FLUX PERMANENT MAGNET GENERATOR FOR WIND TURBINE APPLICATIONS

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ABSTRACT: *This paper presents the design of 3kW axial flux permanent magnet generator considering wind turbine characteristics. The machine has ironless stator to produce sinusoidal voltage with less harmonic contents by completely eliminating the cogging torque of the machine. The machine performance is analyzed by finite element analysis since it reduces the time consumption and it used to validate the analytical design of the proposed axial flux permanent magnet generator. The airgap between stator and rotor are optimized, so as to determine the magnet dimensions and stator coil designs. The simulation results of proposed generator prove the reliability of the system for low speed direct drive wind turbine applications.*

Key words: *NdFeB 48, Dual Rotor, Axial Flux Permanent Magnet Generator, 3D Finite Element Analysis.*

1. Introduction

Wind is readily available in nature; hence the wind energy conversion systems are growing significantly worldwide. It is expected that by 2020, the electrical power generation from wind source in India would exceed 75 GW [1]. The electrical generators plays main role in conversion of wind energy to electrical energy. To utilize available wind at site for the production of electrical power, substantial developments have been made in the field of electrical generators. Small scale wind turbines are getting attention in these days because of its reliability over large scale conversion systems [2-5]. For small scale low speed systems, the variable speed generators have more advantages over fixed speed generation since it has very high power quality, smaller in size, low cost installation and absence of gearbox eliminates the noise and vibrations in the system [6]. Because of the absence of gearbox, the wind generation system would have very less amount of faults and expenses associated with maintenance [7].

The permanent magnet synchronous generators are well known for its high performance and efficiency would suits for low power variable speed turbines. Among various configurations of PMG, the Axial Flux Permanent Magnet Generator (AFPMG) has compact structure, capability of holding higher pole numbers for lower speeds, higher power density and torque density comparing to the radial flux machines [8-9]. There were many research

works have been carried out with simulations and experiments of wind energy conversion system based on PMGs, but only limited work has been done in the field of axial flux generators. Quasi- 3D method was employed in some studies to analyse AFPM generators [10-13]. Also some methods have been developed to optimize the back EMF and to reduce cogging torque of the generator using FEA in [14-16]. AFPM generators are classified as two types according to its design characteristics. They are iron cored structure and ironless structure. Ironless or coreless generators have numerous advantages like reduced weight, zero cogging torque, increased efficiency and design flexibility [17-18]. Also it provides reliability in designing large generator pole diameters. The cost of active material is slightly high in this case but that will be compensated in lower structural mass and higher generator diameter.

Variety of topologies and structures of AFPM generators are in use. In low speed wind turbine applications, a double sided rotor with single coreless stator sandwiched between rotors is considered. Fig. 1. shows the exploded view of the AFPM generator with surface mounted permanent magnets.

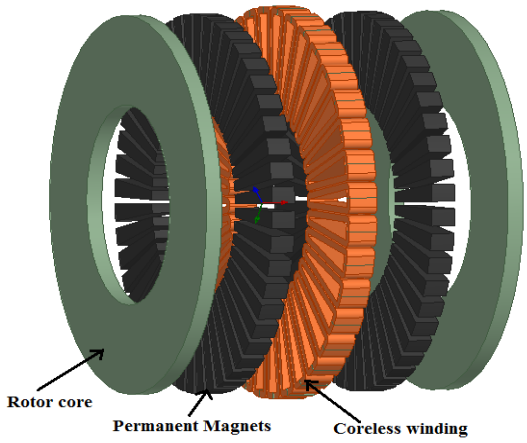


Fig. 1. Exploded view of the AFPM generator

In this paper an outer rotor AFPMG has been developed for gearless small scale wind energy conversion system. The machine parameters have been obtained from preliminary design and modified to the required output through finite element analysis. This paper is organized as follows: Section 2 presents wind turbine and wind speed characteristics, Section3 presents the analytical design of machine parameters and section 4 presents the validation of design parameters by 3-D FE analysis and results. Finally paper ends with the conclusion in section 5.

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2. Wind Turbine System

The wind turbine characteristics are to be considered in the designing of generator in order to predict the accurate performance. To facilitate the direct driven wind energy conversion system, the turbine blades are connected to the dual rotor single stator axial flux PMG. The rotor of both turbine and generator rotates about the same shaft, which is supported on the tower by means of a yaw mechanism. Fig. 2. shows a horizontal-axis wind turbine system that employs the proposed dual rotor single stator axial flux PMG. The turbine blades are connected on the flange surface of the rotor [19].

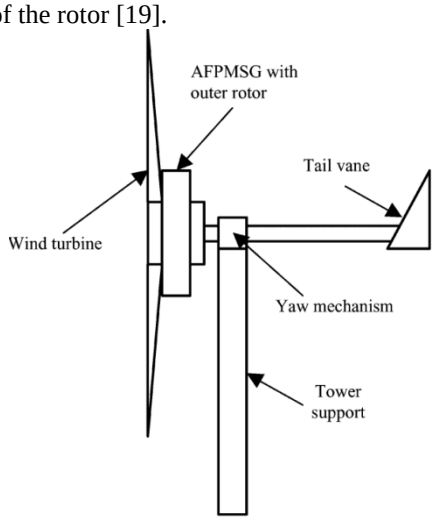


Fig. 2. Proposed arrangement of a horizontal-axis wind turbine system using internal stator AFPMG

The major aspect of wind turbine performance is power developed and it is determined by the aerodynamic forces generated by the wind. The efficiency of any wind turbine is described in terms of its power coefficient Cp which is the function of tip speed ratio and pitch angle of specific wind turbine blades [20]. This coefficient is given by the following mathematical expression.

$$C_p = 0.5176\,(\frac{116}{\lambda_i} - 0.4\beta - 5)\,e^{\frac{-21}{\lambda_i}} + 0.0068\lambda \quad (1)$$

Where,

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \quad (2)$$

where C_p is the power coefficient, β is the pitch angle of the blade and λ is the tip speed ratio. The swept area of the blade is,

$$A = \frac{\pi D^2}{4} \quad (3)$$

Where D is blade diameter in meters. The power produced by wind turbine can be obtained as follows,

$$P_t = \frac{1}{2}\rho\, v_\omega{}^3\; A\, C_p \quad (4)$$

Where, C_p is power coefficient, ρ is air density, A is rotor swept area, v_ω is free stream wind velocity.

The torque (T), on the blades is given by the ratio of the power extracted to the rotor speed (ω) and it is expressed as follows,

$$T = \frac{P_t}{\omega} \quad (5)$$

$$= \frac{1}{2\lambda}\,\rho\,\pi\, r_{turb}^3 v_\omega{}^2\, C_p \quad (6)$$

The blade pitch angle (□□□is□an important parameter affecting the characteristics of the power coefficient C_p and tip speed ratio (□□□ Hence it has been chosen carefully to optimize the power coefficient and tip speed ratio. The optimum results for the turbine are tabulated in Table 1. Fig. 3. shows the graph of turbine power coefficient versus tip speed ratio and pitch angle. The impact of blade pitch angle is a critical parameter for the aerodynamic optimization of untwisted blades. Positive pitch angle of (10^0) is suited for lowest wind speed regions. It enhances the capability of the wind turbines in terms of power coefficient and tip speed ratio. Fig. 4. shows the graph for pitch angle optimization with power extraction capability for the selected power coefficient and tip speed ratio.

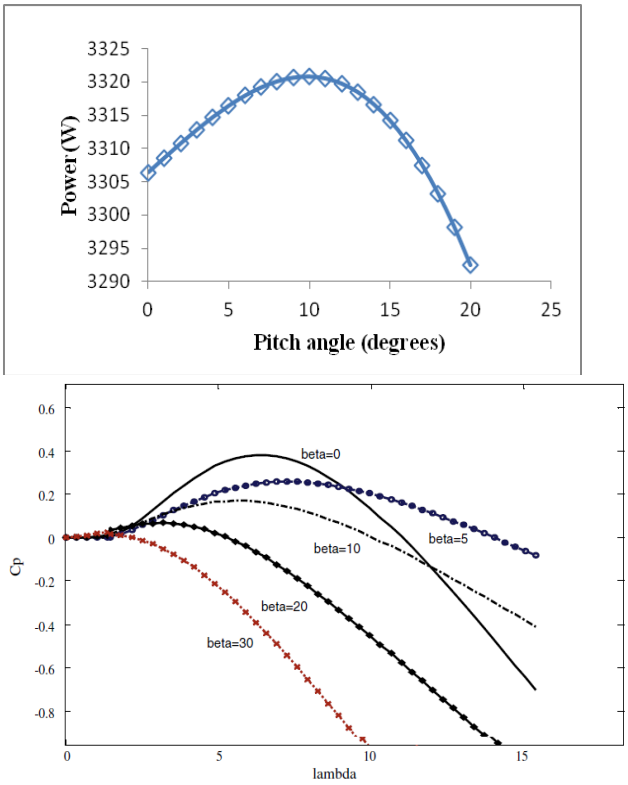


Fig. 3. C_p variations versus lambda and beta

Fig. 4. Pitch angle optimization with power extraction capability

Turbine specifications	Value
Blade diameter, D [m]	3

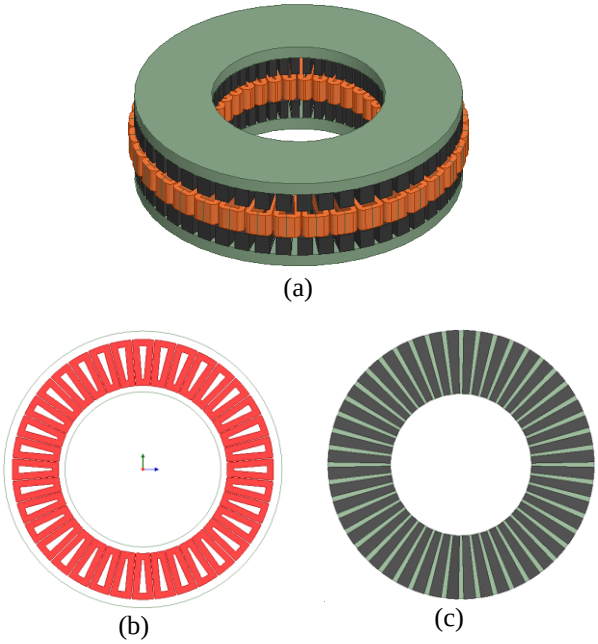
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Blade swept area, A [m^2]	28.26
Turbine output power, P_t [kW]	3.3
Rated wind velocity, V_{nom} [m/s]	10
Rated speed, N [rpm]	125
Turbine rated torque, T [Nm]	263.2

Table. 1. Optimized results for wind power generating system

3. Analytical Design

Analytical design of AFPM generator based on sizing equations is discussed in this section. The proposed coreless AFPMG consists of two parallel rotors and one stator sandwiched between rotors as given in Fig. 5. Trapezoidal permanent magnets are placed on the rotor back iron disc and the concentrated winding coils in the stator are held together by using composite material of epoxy resin.



(a) (b) (c)

Fig. 5. Structure of ironless AFPM generator. (a) 3-D Structure (b) Stator radial view (c) Rotor withpermanent magnet structure

A. *Main Design Equations*

Sizing equations of coreless AFPM generator have been presented in [21]. The magnetic flux density B_{mg} at the rotor disk can be calculated from the below equation,

$$B_{mg}=\frac{B_r}{1+\mu_{rrec}\frac{g+0.5T_s}{T_m}k_{sat}} \quad (7)$$

Where B_r is remanent flux density, μ_{rrec} is relative recoil permeability, g is mechanical clearance gap, T_s is thickness of stator, T_m is thickness of magnet pole. The thickness of magnet can be computed as in equation (8), Where B_m is the required maximum flux density in airgap and l_g is the length of airgap.

$$T_m = \frac{B_m B_r l_g}{2\mu_o H_c(B_r - B_m)} \quad (8)$$

The coil leg width w_c can be calculated from equation (9) for a value of fill factor taken is 0.7, the heat coefficient C_q = 0.3 W/ cm^2 and the electrical resistivity of the copper ρ = 1.68×10^{-8}.

$$w_c=\frac{I_{ac.max}\ N_c}{\sqrt{\frac{2\,C_q K_f T_s}{\rho}}} \quad (9)$$

End winding length can be calculated from inner and outer radius and it is expressed in equation (10),

$$l_e = 2\theta_m\,(r_o + r_i)\,\frac{1-0.6k}{p} \quad (10)$$

Where,

$$k = \frac{\theta_{re}}{\theta_m},\ \theta_m = \frac{\pi p}{Q}$$

θ_{re} and θ_m are electrical and mechanical degrees respectively.

From equation (11) and (12) the outer radius of the machine can be calculated and it is dependent on rated torque, airgap shear stress and inner to outer radius ratio [22].

$$R_{out} = \left(\frac{2T}{(1-\alpha^2)(1+\alpha)\pi\tau}\right)^{\frac{1}{3}} \quad (11)$$

$$\tau = \frac{T}{A_{rotor} r_e} \quad (12)$$

where T is the rated torque applied to the machine shaft, $A_{rotor}$is the active surface area where the stator current is interacting with the magnetic flux, r_e is the average radius of the rotor magnets, τ is average airgap shear stress and α is the ratio of inner to outer radius.

The induced emf (E_t) of the non- overlapping stator winding can be determined as follows,

$$E_t=\frac{q}{a}\frac{2\sqrt{2}}{p}\,\omega_e\,B_p\,N_c r_e\,l_a K_{pc} K_d \quad (13)$$

where q is the number of coils per phase, 'a' is number of parallel paths, p is number of pole pairs, ω_e is the electrical rotational speed, B_p is the peak value of air gap flux density, N_c is the number of turns per stator coil, r_e is the mean radius of the generator, K_{pc} is the pitch factor of the winding, K_d is the distribution factor of the machine and l_a is the active length of the machine.

If the chosen copper conductors are sufficiently thin, the skin effect is negligible and hence, I^2R loss id frequency independent, hence I^2R loss becomes (14),

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$$P_{cu}=2\,N_c I_{ph}^2 \rho \frac{l_{eff}}{S_c} \quad (14)$$

Where, N_c is number of turns per coil, I_{ph} is phase current, ρ is electrical resistivity of the copper, S_c is cross-sectional area of wire, l_{eff} is the effective length of the machine which is equal to l_a. Finlly efficiency of the generator can be calculated from equation (15),

$$\eta = \frac{P_{out}}{P_{out} + P_{cu} + P_{eddy}} \times 100\% \quad (15)$$

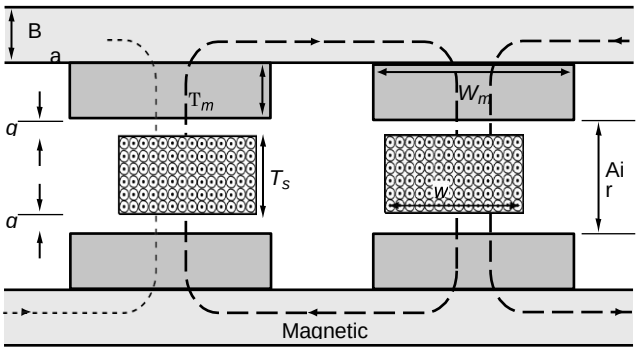


Fig. 6. Axial dimensions of the generator (rotor disks and magnets, stator coils and clearances)

Fig. 6. shows the axial dimensions of the generator includes the thickness of back iron rotor disks, the thickness of magnets T_m, the mechanical clearance gap g and the thickness of stator T_s. A reduction in total airgap could be achieved by minimizing the thickness of the resin layer over the magnets and the stator, resulting in higher induced voltages and higher power outputs.

4. Three Dimensional FE Analysis of AFPMG

The finite element technique is a numerical method for solving electromagnetic field problems, which are too complex to be solved using analytical techniques, especially those involving nonlinear material characteristics. In this section, a coreless AFPM generator is designed based on the sizing equations derived in section 3. The 3D Finite Element Analysis was used to analyze the magnetic circuit parameters and also to evaluate the validity of the analytical results. The machine dimensions obtained from sizing equations are illustrated in Table 2.

Parameter	Symbol	Value
Rated power, kW	P_{out}	3
Rated speed, rpm	N	125
Number of pole pairs	P	48
Number of stator coils	Q	36
Outer radius of the machine, mm	R_{out}	250
Inner radius of the machine, mm	R_{in}	132.5
Airgap length, mm	l_g	1
Number of coil turns	N_c	410
Current density, A/mm^2	J_{max}	4.15
Peak air gap flux density, T	B_p	1.415
Axial length of PM, mm	T_m	15.8
Efficiency, %	η	91
Ratio of inner to outer diameter	□□	0.53

Table. 2. Parameters and machine dimensions of AFPMG

The performance of the generator was analyzed and verified using Maxwell 17.2 3-D simulation. The magnetic flux density distribution for four pole pitch of the generator is shown in the Fig. 7. The NdFeB48 grade magnets are used here to deliver maximum flux at optimized airgap. It proves that the magnetic saturation in permanent magnet rotor disks is not of concern, since maximum value of flux density has been achieved. Flux plot directions of AFPM generator is given in Fig. 8. Asymmetry of the flux distribution in the rotor disk is due to the flux density of armature reaction.

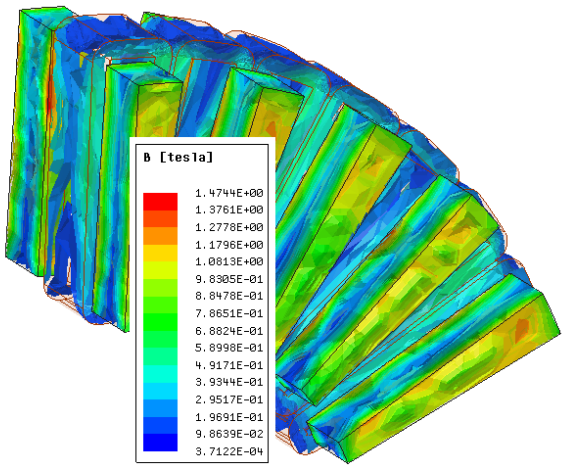


Fig. 7. Magnetic flux density distribution in AFPM generator

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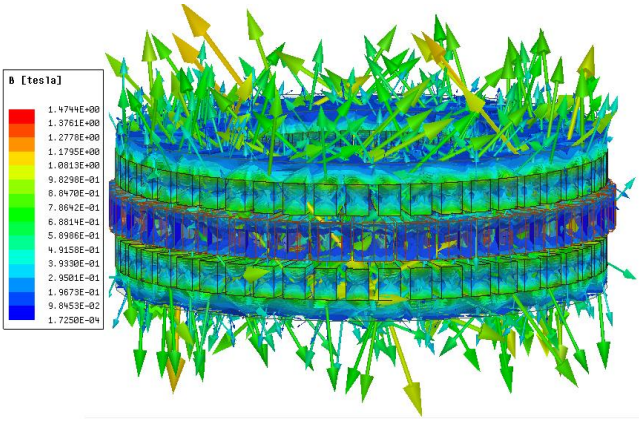


Fig. 8. Flux plot directions of the AFPM generator

Fig. 9. shows the flux linkage of stator coils. The maximum flux linking the coils is 0.85T. The induced three phase voltage and its harmonic spectrum achieved under rated load and power factor of 0.9 are presented in Fig. 10. From the figures it is observed that the generator has sinusoidal RMS output voltage of 265 V and the presence of harmonic contents is significant. The total harmonic distortion noticed from the picture is about 1.12%. Fig. 11. shows the phase current waveforms of the proposed AFPM generator. From the results obtained, there is a good agreement between analytical and FEM results.

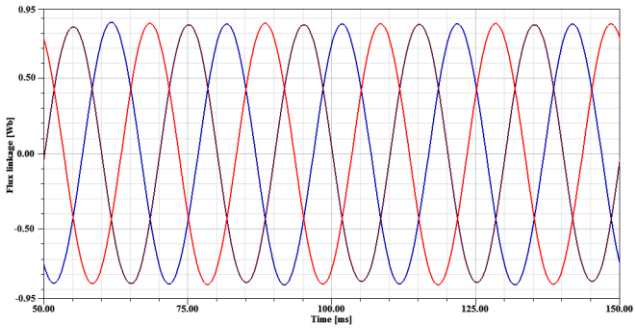


Fig. 9. Flux linkage in stator coils

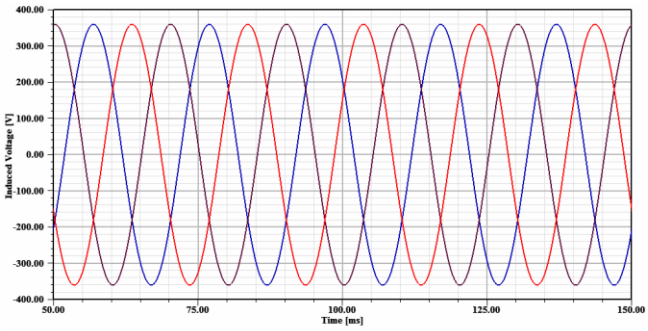


Fig. 10. (a) Three-phase induced voltage waveform

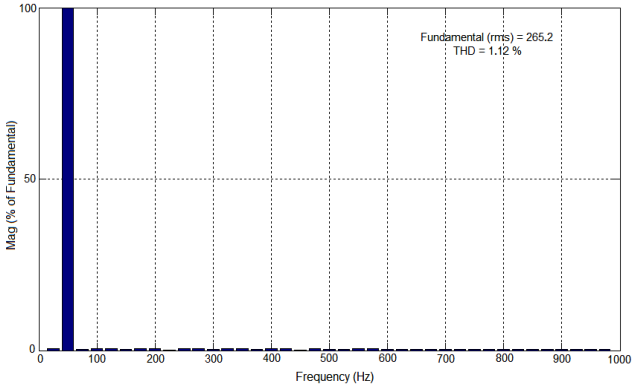


Fig. 10. (b) THD analysis of the AFPM generator under rated load and power factor of 0.9

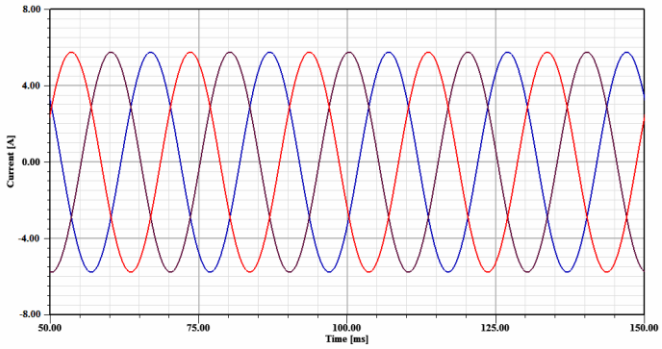


Fig. 11. Three-phase current waveform

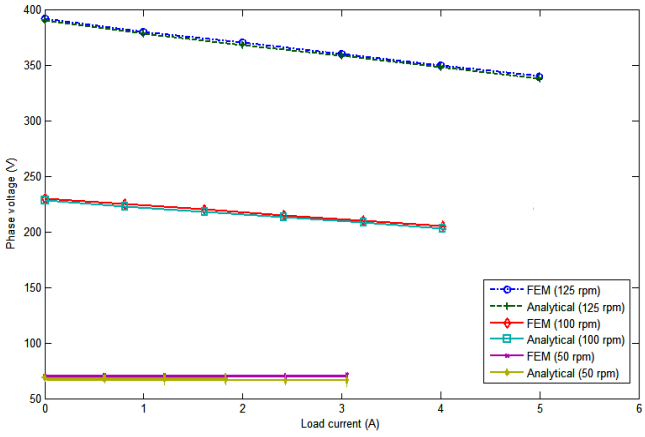


Fig. 12. Variation of phase voltage with respective to load current for various speeds of generator

The generator performance with load condition has been predicted for various values of load current and generator speeds. Obtained 3-D FEM results are evaluated and compared with the predicted analytical results. Fig. 12. shows the linear relationship of phase voltage with the load current under three different constant speeds.

5. Conclusion

The generator parameter optimization is the most important part in its design. In this paper, being compatible with wind turbine characteristics a 3kW axial flux

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permanent magnet generator has been designed. The parameters obtained from analytical design are used to develop the machine in Maxwell 3D. The coreless structure of stator part ensures the zero cogging torque and reduced weight. The rare earth magnets are used for their higher withstanding capability. From the analyses it is clear that the generator can be worked under low rpm and can be coupled directly to the turbine rotor and the results of proposed design structure shows the accuracy of the developed model.

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