DESIGN AND ANALYSIS OF DUAL-ROTOR RADIAL FLUX PERMANENT MAGNET GENERATOR FOR DIRECT COUPLED STAND-ALONE WIND ENERGY SYSTEMS

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Abstract
This paper presents the design of dual-rotor radial flux permanent magnet generator (DRFPMG) suitable for direct coupled stand-alone wind energy system (SAWES). Standard mathematical equations are used in the design of DRFPMG to get desired parameters such as speed, output power and output voltage. Finite-element analysis is performed in order to study the flux path, effect of magnetic field and induced emf. The magnetic field plotting, flux linkages and induced emf waveforms are visualized by FEA (Finite-Element Analysis) using MagNet Software. Thus it is found that the performance result of DRFPMG in the simulation exactly matches the theoretical design.

Index Terms: dual-rotor generator, Finite-Element Analysis (FEA), Stand-Alone Wind Energy System (SAWES).

I. INTRODUCTION

The computer-aided machine design play vital role in developing new design from old ones. It is valuable in two important ways. The first one is in the calculation and evaluation of large number of options, often characterized by small changes in a large number of parameters. The second one is in performing a very detailed electromagnetic and mechanical analysis without prototyping which is expensive and time-consuming [1]. The size and efficiency are the two main criteria to be considered in designing a permanent magnet machine. For constant electric and magnetic loadings the increase in diameter (D) increases both current and flux. But the increase in length (L) increases the flux alone. Hence the output power is proportional to D^2L. This reflects the influence of size on the output power of the machine [2].

Induction, synchronous and permanent magnet generators are generally used in SAWES and operated in direct coupled mode. The two main advantages of direct coupled generator are reduced noise and cost. The cost of the electricity produced by direct coupled generator is decreased due to elimination of gears, losses associated with gears and improvement in availability of such SAWES [3]. Noise reduction plays an important role when such systems are erected close to dwelling places. The rotational speed of a wind turbine varies between 30 to 200 rpm depending upon the size of the wind turbine and speed of the wind. But electricity has to be produced at the normal frequency range of 30 to 80 Hz. Because of the necessity to run the generator at unusually low rpm direct coupling results in a large diameter and huge number of poles. Permanent Magnet generators are highly efficient, robust and reliable. There is no need of external excitation. The field winding losses are eliminated from the rotor. The availability of high-energy density magnets such as Neodymium-Iron-Boron (NdFeB) allows the design of a generator required by direct coupled SAWES [4].

From the comparison of different generator topologies for wind energy system it is inferred that cost/torque of the radial flux permanent magnet generator is superior to other types of generator [5]. Radial flux generators use less magnetic material over other permanent magnet generators. The cooling condition of the magnets is high in outer rotor radial flux machines [6].

The unique features of dual-rotor radial flux machine include very short end windings, high overload capability, balanced radial forces, low cogging torque and low material costs [7]. Dual rotor radial flux machine is known for its high torque density and efficiency over induction and other permanent magnet machines. It has some meticulous features such as rotor-stator-rotor structure and double air-gaps due to unique mechanical configuration. As the output torque is proportional to the air-gap surface area for the constant electrical and mechanical loadings, torque density is improved. Since both the working surfaces of the stator core are used machine efficiency gets boosted up. It is used as motor in aerospace and automobile applications [8]. Hence it is proposed to design and analyze the dual rotor machine as a generator for SAWES.

This paper presents the design and analysis of DRFPMG suitable for direct coupled SAWES. Standard mathematical equations are used in the design of DRFPMG to achieve the desired parameters such as machine diameter, active length, speed, output power and output voltage. The economic aspect of the generator is taken care by optimizing the design between cost, power density and efficiency.

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The designed parameters are implemented in two-dimensional (2D) finite-element analysis using MagNet Software. The magnetic field plotting, flux linkages and induced emf waveforms are visualized in the software. The theoretical design is compared with the simulation results to evaluate the effectiveness of the design.

II. Construction and Operation of DRFPMG

The cross-sectional view of DRFPMG is shown in figure 1. The machine consists of an inner rotor and an outer rotor rotating at the same speed.

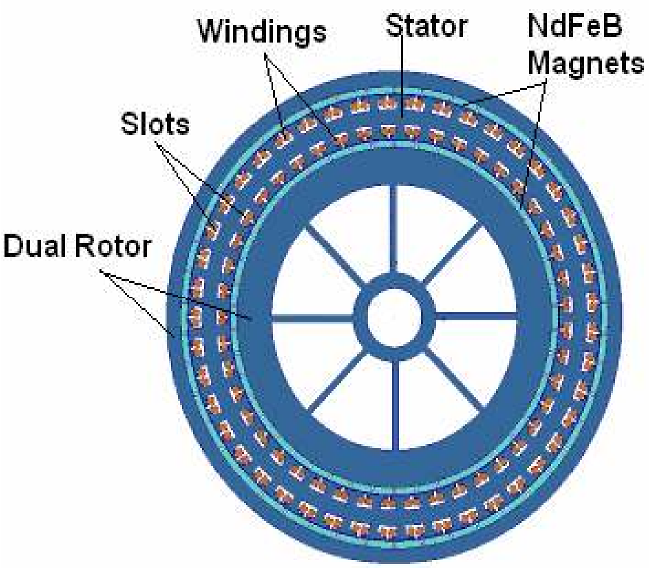


Fig. 1. Cross-Sectional View of DRFPMG

The high energy NdFeB magnets are surface mounted on the inner periphery of the outer rotor and on the outer periphery of the inner rotor. The permanent magnets are uniformly magnetized along inward/outward radial direction. The adjacent magnets of both outer rotor and inner rotor are magnetized in the opposite direction. The shaft of this dual rotor is directly coupled to the SAWES. The stator is nested between the two rotors. It consists of slots on both outer and inner periphery. The common back iron of the stator serves as return path for the flux lines. The single layer three phase windings are housed inside these slots. The three phase windings present in the inner slots are connected in series with that of the outer slots. An air-gap is formed between inner periphery of the outer rotor and outer periphery of the stator. Another air-gap is formed between outer periphery of the inner rotor and inner periphery of the stator. Thus dual air-gap is formed.

The assembly of the rotor-stator-rotor structure is as shown in figure 2. The stator is mounted at one end to a metal frame. Two rotors are attached together by an end disc that is designed as a cooling fan for the machine. One bearing set is provided at each end between the shaft and two frames. As the machine is run at low rpm the cantilevered mechanical structure of the outside rotor and the stator is preferred.

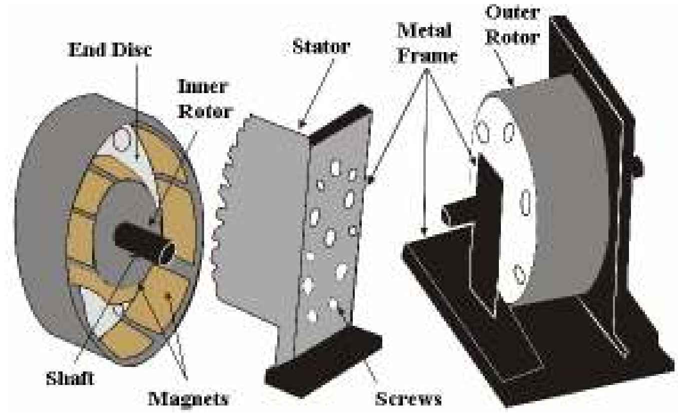


Fig. 2. Mechanical Assembly of DRFPMG

The flux path in DRFPMG is shown in figure 3. The inner and outer rotor magnets are magnetized in the opposite direction. The fluxes starts from one pole, travel along the circumference of the stator core, link the single layer three phase windings present in the slots and reaches the adjacent opposite pole. As the dual rotor rotates the flux produced by the inner rotor magnets are cut by three phase windings of the inner slots of the stator core. Simultaneously the flux produced by the outer rotor magnets is cut by the three phase windings of the outer slots of the stator core. The emf is induced in the windings present in the inner and outer slots of the stator simultaneously. Since both three phase windings are connected in series the emf produced gets added up and available at the terminals of the machine. Both the working surfaces of the stator core are used with common back iron, unlike the conventional machines. Thus DRFPMG work as two conventional radial flux permanent magnet machines connected in series.

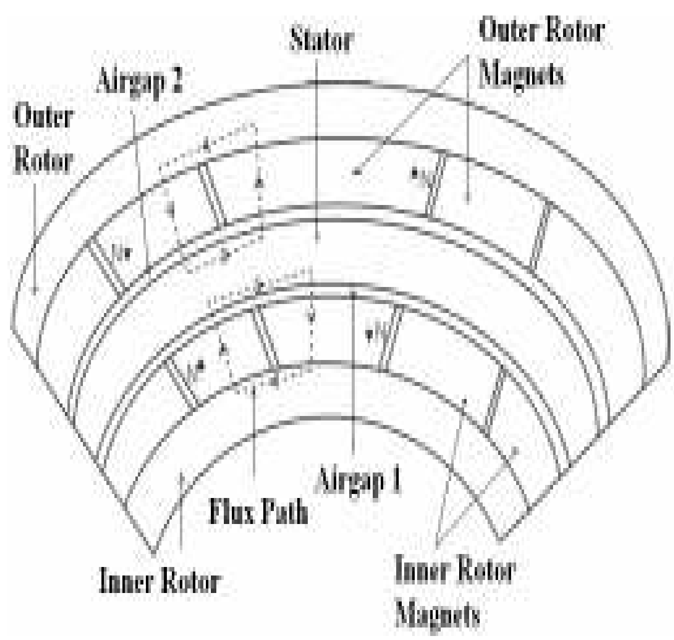


Fig. 3 Flux Path in DRFPMG

III. DESIGN OF DRFPMG

The following important technical features are taken into account while designing the DRFPMG.

- High efficiency and less cost.
- Large diameter and small length.
- Greater number of poles.
- Selection of suitable magnet grade.
- Less heating of the rotor magnets.
- Selection of suitable number of slots.
- Fractional pitch three phase single layer windings.
- Less losses in the stator windings.

Many unknown parameters are involved in the design of DRFPMG. Hence it is essential to assign some fixed values and after that determine the remaining as part of the design process. The parameters that are desired and kept fixed are given in Table I.

TABLE I
FIXED PARAMETERS

Parameters	Description	Unit
P_o	Output Power	Watts
S_r	Rated Speed of the Machine	rpm
η	Efficiency	%
B_g	Specific Magnetic Loading	T
J	Specific Electric Loading	A/m
g	Air-gap Thickness	M
N_{ph}	Number of Phases	-
d/w	Slot Depth/Width Ratio	-
K_s	Slot Fill Factor	-
B_r	Magnet Remanence	T
H_c	Magnet Co-ercevity	A/m
μ_o	Pemeability of Free Space	H/m
P_C	Gap Flux Factor	-
L/D	Machine Length/Diameter ratio	-
f	Frequency	Hz
V	Output voltage at No Load	V

Standard and simplified mathematical equations are used in the design of DRFPMG. The sizing of the machine is calculated by the following equation. The D^2L parameter and the diameters are calculated separately for the outer air-gap machine and the inner air-gap machine.

$$P_o = \frac{\pi^2 B_g J \eta S_r D^2 L}{60} \quad (1)$$

The number of poles directly depends on the rated speed and the frequency requirements. The number of slots is decided for three phases and 120^0 phase shift (electrical angle) is maintained between any two phases. The slot angle in mechanical (β_m) and electrical (β_e) degree is calculated from the equations (2) and (3).

$$\beta_m = \frac{360^0}{N_S} \quad (2)$$

$$\beta_e = \frac{360^0 * N_{PP}}{N_S} \quad (3)$$

where N_s and N_{PP} are the number of slots and number of pole pairs respectively.

The peripheral velocity (ω_p) of the rotors and pole transition time of the magnets (T_p) are given by equations (4) and (5).

$$\omega_p = \frac{\pi D S_r}{60} \quad (4)$$

$$T_p = \frac{\pi D}{N_m \omega_p} \quad (5)$$

The flux per pole is given by,

$$\Phi_p = \frac{B_g \pi D L}{N_m} \quad (6)$$

where N_m is the number of poles.

The volts per turn (V_t) and volts per coil (V_c) are calculated from equations (7) and (8).

$$V_t = \frac{2\Phi_p}{T_p} \quad (7)$$

$$V_c = \frac{V_{ph}}{N_{cph}} \quad (8)$$

where V_{ph} is the average dc voltage and N_{cph} is the number of coils per phase.

The slot width (W_s) and slot area (A_s) are determined from (9) and (10).

$$W_S = \frac{\pi D}{2 N_S} \quad (9)$$

$$A_S = W_S * d_S \quad (10)$$

where d_s is slot depth.

The conductor current density (J_a) is calculated from the following equation.

$$J_a = \frac{n_S I_C}{K_S A_S * 10^6} \quad (11)$$

where n_s is number of turns per coil, I_c is coil current.

The relative permeability of magnet and air-gap reluctance are determined from the equations (12) and (13).

$$\mu_r = \frac{B_r}{H_C \mu_o} \tag{12}$$

$$R_g = \frac{N_m g}{\pi D L \mu_o} \tag{13}$$

The magnet reluctance and magnet thickness are determined by the equations, (14) and (15).

$$R_m = \frac{H_C N_m}{B_r \pi D L} \tag{14}$$

$$T_m = \frac{P_C + R_g}{R_m} \tag{15}$$

The important design data obtained using the above mentioned equations are given in Table II.

TABLE II
MAIN DESIGN DATA

Parameter	Description	Value	Unit
P_o	Output Power	2	KW
S_r	Rated Speed of the Machine	120	rpm
f	Frequency	50	Hz
V	Output voltage at no load	82	V
D_{roo}	Outer Rotor Outer Diameter	0.3305	m
D_{roi}	Outer Rotor Inner Diameter	0.3005	m
D_{rii}	Inner Rotor Inner Diameter	0.1785	m
D_{rio}	Inner Rotor Outer Diameter	0.2385	m
D_{so}	Stator Outer Diameter	0.2995	m
D_{si}	Stator Inner Diameter	0.2395	m
L	Active Length	0.08	m
T_m	Magnet Thickness	0.005	m
R_m	Magnet reluctance	4.13×10^8	1/Hm
R_g	Airgap reluctance	2.2×10^6	1/H
J_a	Conductor current density	3.54	A/mm^2
N_{si}	Number of Inner stator slots	45	-
N_{so}	Number of Outer stator slots	45	-
N_{pri}	Number of Inner rotor Poles	46	-
N_{pro}	Number of Outer rotor Poles	46	-
Φ_p	Flu per Pole	0.0014	Wb
v_t	Volt per Coil	3	Volts
N_{cph}	Number of Coils per phase	8	-
ω_p	Peripheral Velocity	2.08	m/s
T_p	Pole Transition Time	0.011	s

The volume of active material and output power in the single rotor structure is 8.74×10^{-3} m^3, 1449 Watts respectively for the designed D^2L. The volume of active material and output power in the dual rotor structure is 4.8×10^{-3} m^3, 1896 Watts respectively (for same D^2L). The active material saved is 3.9×10^{-3} m^3 and the extra power generated is 447 Watts. Thus the advantages of the DRFPMG are found to be active material utilization, more output power and high efficiency than other permanent magnet machines.

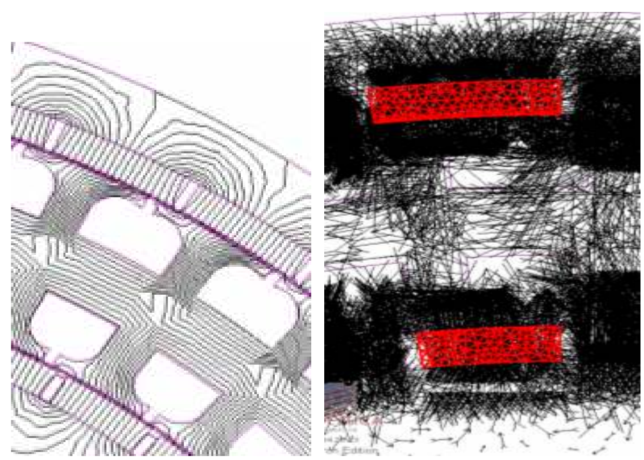
IV. FINITE ELEMENT ANALYSIS

The FEA of a machine is performed in order to verify the effectiveness of the theoretical equations used in the design process and validate the designed parameters. The FEA of the machine involves three stages, pre-processing, field solution and post-processing. In the pre-processing, mesh generation, material definition and problem definition are done. Iterations using Newton-Raphson and Conjugate-gradient procedures are widely used in field solution. Finally in the post processing stage, the quantities such as flux density, induced emf and torque are extracted from the potential solution [1].

In the FEA of DRFPMG, the problem definition is done by imposing all the designed parameters followed by material definition and mesh generation. The motor cross-section is divided into a set of triangular elements and two-dimensional simulation is preferred. In this section magnetic field plotting, flux linkage and induced emf are discussed.

A. Magnetic Field Plotting

The magnetic field plotting is generated by defining the geometry, imposing the choice of material and magnetizing the magnets in the required direction. A two-dimensional magneto static simulation is performed in order to get the different types of magnetic field plot such as contour plot, arrow plot and color plot. The contour plot shows the density of the magnetic flux lines. The arrow plot shows the direction of the flux lines. From the color plot, the flux density value at any point of the cross-section of the machine can be obtained. The contour plot and arrow plot are shown in figure 4(a) and 4(b) respectively.



(a) (b)

Fig. 4 Contour and Arrow Plots of DRFPMG

B. Flux Linkage and Induced EMF

In the calculation of flux and flux linkage the main flux paths are identified. The values of reluctances and permeances are assigned. The main flux crosses the air-gap and links the coils of the phase windings. Variations of flux linkage at no load against incremental rotor positions are shown in figure 5.

The figure 5(a) shows the maximum flux linkage that occurs between rotor magnets and stator teeth. The dark region between outer and inner slots shows that maximum amount of flux traveling along the circumference of the stator. In figure 5(b) the number of flux lines traveling around the slots is less and hence the darkness is less. In figure 5(c) the number of flux lines is only a few and the region around the stator slots is light.

(a) (b) (c)

Fig. 5 Flux Linkage at various rotor positions of DRFPMG

Generally the induced emf waveform is calculated to determine the torque and controller characteristics required for smooth operation of the direct-coupled SAWES. The ideal DRFPMG has a square-wave induced emf. When magnet leakage flux is taken into account the actual induced emf will take a trapezoidal shape.

V. Simulation Results

In this section the simulation results obtained using MagNet Software are discussed. The color plotting of the magnetic flux density, flux linkage waveforms and induced emf waveforms obtained as a result of simulation process are explained. The color plot of the magnetic flux density obtained as a result of 2D magneto static simulation is shown in figure 6.

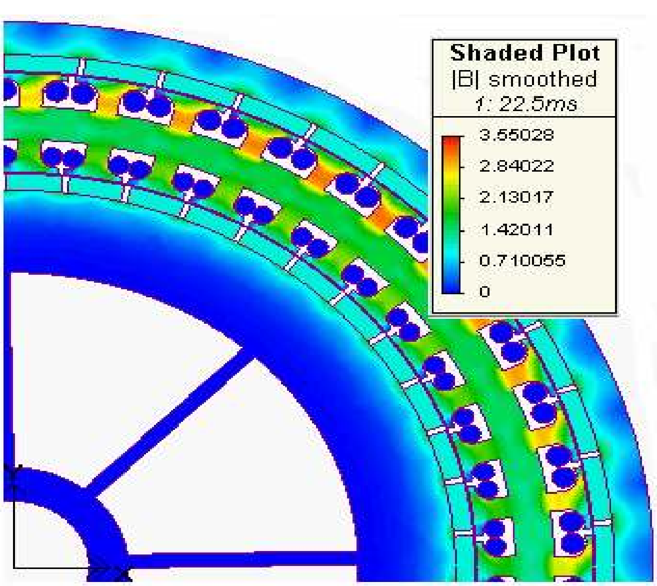


Fig. 6 Color Plotting of Magnetic Flux Density

The flux density at any point of the machine is found from this color plot. It is seen from the plot that magnetic flux density is maximum at places where the rotor magnets come in direct alignment with the stator teeth. The flux density gradually decreases as the slots are fractional pitched and stator teeth misalign progressively. The flux per pole and flux density are calculated using the theoretical investigation, and the design matches the 2D magneto static simulation results.

After the successful completion of magneto static simulation, the transient 2D with motion FEA simulation is performed for obtaining the flux linkage and induced emf waveforms. The DRFPMG is run at 120 rpm to produce an output voltage of 82V at no load. The flux linkage waveform of the inner rotor of DRFPMG is shown in figure 7. The flux linkage values calculated from theoretical design corresponds to the waveform obtained from the simulation.

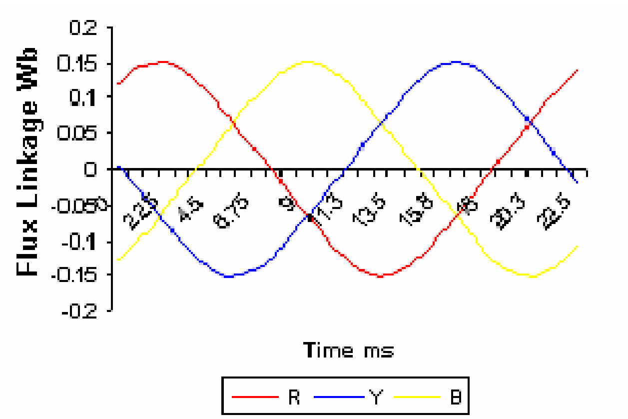


Fig. 7 Flux Linkage Waveforms of Inner Rotor of DRFPMG

The trapezoidal induced emf waveform at no load is shown in figure 8.

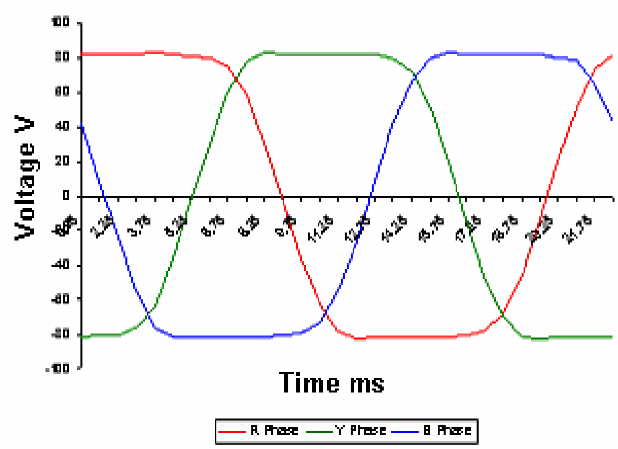


Fig. 8 No load Induced EMF waveform

The induced emf shown in the figure is the net output of both inner air-gap machine and outer air-gap machine of the DRFPMG. The peak voltage is 82 volts. The frequency is fixed at 50 Hz which may vary between 30 to 80 Hz during the operation in a SAWES. The power that can be generated using the output voltage matches the rated power assumed in the design process.

VI. Conclusion

Thus the design of dual-rotor radial flux permanent magnet generator suitable for direct coupled stand-alone wind energy system was performed. The analysis of the design was carried out using the finite-element analysis by MagNet Software. The main design data were given and the various magnetic field plots, flux linkages and induced emf waveforms were obtained as a result of simulation were discussed. It is concluded that the dual-rotor topology provides high efficiency and reduces the active material used. Moreover the dual-rotor machine helps to build a robust direct coupled stand alone wind energy system. This improves the successful operation and durability of the standalone wind energy system.

VII. Acknowledgement

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