Model and Design Analysis of Gearless PM Stator-less Contra-Rotation Wind Power Generator

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Abstract*—The objective of this paper is to propose an efficient, low cost and rugged design of medium sized gearless permanent magnet stator-less contra-rotation wind power generator (PMSLCRWPG. The earlier models of such medium sized generators, capable of generating less than one megawatt electric power, are facing huge mechanical losses due to wear and tear in the tightly coupled mechanical gear system. Due to this heavy arrangement in its mechanical assembly, the earlier design and its prototype could not function with high efficiency. The proposed design focuses on the performance of the model using the concept of stator-less dual rotor arrangement in the generator. The design was tested at various wind speeds and directions and the performance of the proposed permanent magnet machine has been experimented. The results of this sustainable and renewable model and design were compared with those of the existing models to promote green energy systems in the future.*

1. Introduction

Research interest in wind power generator has been developed significantly over the past few decades. The conventional energy sources are limited and have high pollution levels. Hence, more attention and interest have been paid to the utilization of renewable energy sources such as wind energy, fuel cell, solar energy, etc. Wind energy is the fastest growing and most promising renewable source among the economically viable ones. In the last two decades, the penetration of wind turbines in the power system has been closely related to the advancement of wind turbine technology and how to control it. With increasing penetration of wind-derived power in interconnected power systems, it has become necessary to model the complete wind energy systems in order to study their impact and also to study the wind power plant control. In spite of this development, advanced technologies are still needed to make the wind energy competitive with other energy supply techniques.

A new modeling and simulation of self-excited induction machine for the wind power generation system voltage and power output will be maintained at rated value with the variation of mutual inductance of stator and rotor windings of the machine with irrespective of the various wind velocities [1].

A novel contra-rotating tidal turbine includes two contra-rotating sets of rotor blades directly driving an open-to-sea permanent magnet generator (PMG). The balancing of the reactive forces by the use of contra-rotation, enables the use of a single-point compliant mooring system for station keeping [2]. A contra-rotating (CR) turbine comprises two sets of rotors one behind the other: one rotor rotates in a clockwise direction while the other rotor rotates in an anticlockwise direction [3]. The performance of the Field Oriented Control (FOC) and Direct Torque Control (DTC) schemes is evaluated in terms of torque and flux ripples, and their transient response to step variations of the torque command. Both schemes were compared and the FOC alone shows high flux and torque ripples [4]. The wind speed estimation can be made based on the sensor-less output maximum control for variable-speed WTG systems. A Gaussian radial basis function network (GRBFN) is used to provide a nonlinear input-output mapping for the wind turbine aerodynamic characteristics [5].

In a dual rotor wind turbine generator system, the machine consists of two rotors and a single stator. The general equations of motion for the constrained multi-body system were used to obtain the dynamic model for this new wind turbine generator system [6]. The design of the novel dual-stator hybrid excited synchronous wind power generator includes its structured features and its operating principles. No-load magnetic fields with different field currents are computed by a 3-D finite-element method [7].

A contra-rotating permanent magnet generator direct drive wind turbines that using a parametric finite element model, the magnetic design and pole-slot combination are optimized to meet the application requirements of high specific torque, low starting torque, and high efficiency [8], [9].Small-scale prototypes have been built to experimentally verify the performance of the small wind energy conversion system (SWECS). Wind tunnel tests of the power output, power coefficient, and turbine speed were carried out to ascertain the aerodynamic power conversion and the operation capability at lower wind speeds [10]. The problem of wind disturbance and aerodynamic parameter estimation of a Gun-Launched Micro Air Vehicle (GLMAV) which is a new Micro Air Vehicle (MAV) concept, intended for outdoor flights, and using two-bladed coaxial contra-rotating rotors [11].

This paper is presented in the following sections. In Section II, gives the model of the propsed system of the PMSLCRWPG. In Section III, Aerodynamic model of the wind turbine has been given. In Section IV, the design data for the PMSLCRWPG model. In Section V, modeling of the PMSLCR machine is given. Section VI, presents the principle of operation of PMSLDR machine. In Section VII, Experimental setup for the proposed system is given. In section VIII, results and discussion are presented, and section IX, gives the conclusion.

2. Model of the proposed system

It is to propose a low cost model and design of gear-less permanent magnet stator-less dual rotor wind power generator (PMSLCRWPG). It is possible to design it as stand-alone model for low power applications like domestic use in remote areas, such as highly isolated locations like hilly areas, where it is not possible to transmit the electricity through overhead lines or underground cables.

This type of wind power generation has low production cost. Therefore, this model is viable for implementing in large scale electricity generation for meeting high power requirements. This model has capable to generate economical and efficient power than a single rotor type wind electric generation system. Also, it can produce power approximately twice that of a single rotor power generation.

The per unit generation cost of five types (including now under consideration) of power generating plants like hydro, thermal, nuclear, wind power and PMSLCRWPG based system are shown in the table I. In case of PMSLCRWPG power generation cost is very low compared to other types and hence, it is more economical than other types of power plants.

TABLE I. UNIT COST C OMPARISON

Sl. No	Power Generation Cost Comparison Per kwh		
	Name of the power Plant	***Cost per Unit (kwh)***	***Cost of operation and maintenance***
1	Hydro power plant	0.855	Low
2	Thermal power plant	1.215	High
3	Nuclear power plant	3.645	High
4	Wind power plant	1.35	Low
5	PMSLDRWEG	0.67	Very Low

PMSLDRWEG = permanent magnet stator-less dual rotor wind electric generator.

As seen in Table I, there are three major power plants, namely hydro, thermal, nuclear and wind. The cost of power production through PMSLCRWPG is highly economical compared to other types of power plants.

3. Aerodynamic model of the wind turbine

The aerodynamic model of a wind turbine is characterized by the C_p-λ-β curves. Where C_p is the power coefficient, which is a function of both tip-speed- ratio λ and the blade pitch angle β. The tip-speed-ratio λ is defined by

$$\lambda = \frac{\omega_t R}{\nu_w} \tag{1}$$

Where,

R = blade length in m,

ω_t= the wind turbine rotor speed in rad/s

ν_w = the wind speed in m/s

The C_p-λ-β curves depend on the blade design and are given by the wind turbine manufacturer.

$$C_p = (\beta,\lambda)\sum_{i=0}^{4}\sum_{j=0}^{4}\alpha_{ij}\beta^i\lambda^j \tag{2}$$

Where, are coefficients. The curve fit is a good approximation for values of 2< λ <13. The values of λ outside this range are for very high and low wind speeds, respectively. The mechanical power that the wind turbine extracts from the wind is calculated. The aerodynamic torque $T_a$is calculated using the following relationship is given as

$$T_a = \rho\frac{C_p(\alpha,\beta)}{\lambda}\frac{1}{2}A_r R\nu_w^2 \tag{3}$$

Where, C_p = Coefficient of power; ρ = Air density, in kg/m^3; λ = Tip speed ratio; β = Blade pitch angle; R = Rotor blade radius in m, A_r= Swept area of the rotor blade in m^2.

$$P_m = \frac{1}{2}\rho A_r \nu_w^2 C_p(\alpha,\beta) = f(\nu_w, \omega_t, \beta) \qquad (4)$$

Where, $A_r = \pi R^2$ is the area swept by the rotor blades in m^2. At a specific wind speed, there is a unique wind turbine rotational speed to achieve the maximum power coefficient, $C_{pm,}$ which decides the maximum mechanical power.

4. Design data for PMSLCRWPG model

The main design parameters of permanent magnet stator-less contra-rotation wind power generator (PMSLCRWPG) such as speed, output voltage and output power is as shown in Table II.

TABLE II. RATINGS OF THE MACHINE

Parameters	Rating of the PMSLCR Generator		
	Descriptions	***Value***	***Unit***
Po	Output power	0.5	Kw
Sr	Rated speed	600.0	Rpm
f	Frequency	50.0	Hz
V	Output voltage at no load	68.0	Volts
J_s	Conductor current density	3.54	A/mm^2
Φ_p	Flux per pole	0.0014	Wb
V_t	Voltage per coil	2.5	Volts

The main mechanical and magnetic design data requirements of proposed model of the PMSLCRWPG as presented in Table III, are adopted in the design.

TABLE III. DESIGN DATA FOR THE MACHINE

Parameters	Design Data for PMSLDR Generator		
	Descriptions	***Value***	***Unit***
D_{so}	Stator outer diameter	0.2	M
D_{si}	Stator inner diameter	0.14	M
D_{ro}	Outer diameter of rotor	0.139	M
D_{ri}	Inner diameter rotor	0.079	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	Air gap reluctance	2.2*10^6	1/H
N_s	Number of stator slots	36	-

5. Modeling of PMSLCR machine

There are some standard and simplified mathematical equations are used for the design of PMSLCRG. The sizing of the machine is calculated by the following equations. The length and diameter are calculated.

$$P_o = \frac{\pi^2 B_g J \eta S_r D^2 L}{60} \qquad (5)$$

The number of poles directly depends on the rated speed and the frequency requirements. The number of slots are for three phases and 120^o phase shift (electrical angle) is maintained between any two phases. The peripheral velocity ω_p of the rotor is given as,

$$\omega_p = \frac{\pi D S_r}{60} \qquad (6)$$

The flux per pole is given by,

$$\phi_p = \frac{B_g \pi D L}{N_m} \qquad (7)$$

Where,
D =Overall diameter of the machine in m;
L =The overall length of the machine in m;
B_g =Gap flux density in wb/m^2;
N_m =The number of poles;
η = Proportional constant of the magnetic material.

The slot widths (Ws) in m and slot area (As) in m2 are determined from equations (8) and (9) respectively.

$$W_s = \frac{\pi D}{2N_s} \qquad (8)$$

$$A_s = W_s \times d_s \qquad (9)$$

Where N_s number of stator slots and d_s is slot depth in m. The conductor current density $J_a$in A/mm^{2}is calculated from the following equation as

$$J_a = \frac{n_s I_c}{K_s A_s \times 10^5} \tag{10}$$

Where n_s is number of turns per coil, I_c is coil current in Amperes.

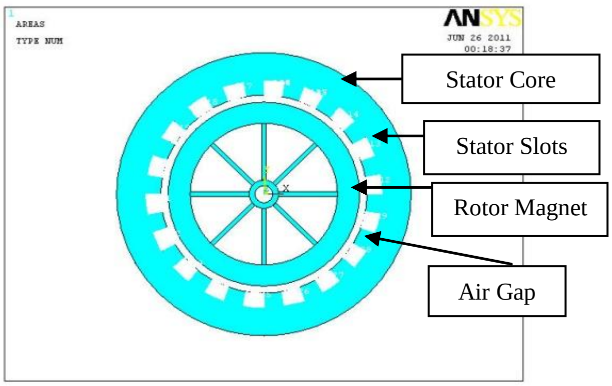

Figure 1. 2D CAD model of SLCRPMG

“Fig. 1”, shows the finite element method based CAD model of the PMSLCRG. The machine consists of a stator and rotor. The high energy Neodymium-Iron-Boron (NdFeB) magnet is surface mounted on the rotor. The permanent magnet is uniformly magnetized along radial direction. The shaft of this rotor is directly coupled to the wind turbine. The stator consists of slots on inner periphery, with the single layer three phase windings housed inside the slots. An air-gap is made between outer periphery of the rotor and inner periphery of the stator for providing suitable reluctance for the optimum flux distribution.

6. Principle of operation of PMSLCR machine

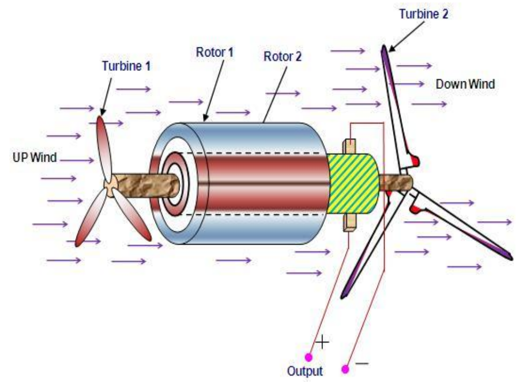

Figure 2. Schematic model of PMSLCRWPG

“Fig. 2”, shows the schematic diagram of PMSLCRWPG, in which it is drawn with the Microsoft Windows tools and, it consists of turbine 1 and rotor 1, turbine 2 and rotor 2. When the wind blows to the turbine 1 means up-wind, which can rotate the turbine 1 and rotor 1 (field) in the clockwise direction, then the same wind escapes and flows towards the turbine 2 is called down-wind, it also rotates the turbine 2 and rotor 2 (Armature) in the anti-clockwise direction.

“Fig. 3(a)”, shows the cross sectional view of PMSLCR machine. There are six poles in armature and the armature poles are made up of laminated coresfor to reduce the core losses. These poles are wound with the armature windings. The field core has four number of projecting poles or salient poles, which are made up of a permanent magnet material, hence it is known as permanent magnet field poles. The field portion is called as rotor 1 and armature portion is called as rotor 2. The rotor 1 and rotor 2 are coupled with wind turbines on both sides of the shaft of the machine. These two wind turbines are made up of domestic type fan blades.

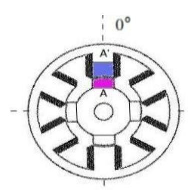

Figure 3(a). Position of Rotor1 Rotor2 at 0^o

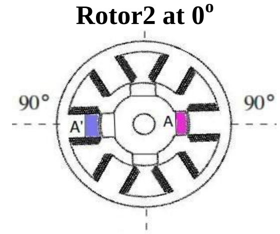

Figure 3(b). Rotor 1 and Rotor 2, when displaced at90^o

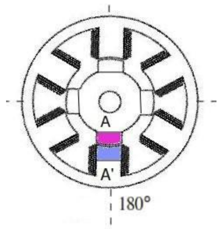

Figure3(c). Rotor1 and Rotor2 when displaced at 180^o

At an initial state, as per the Figure 3(a). the rotor 1 position and rotor 2 position are stayed at 0^o. The Figure 3(b). shows that, when both of the turbines are rotates, the rotor 1 pole (A) in clockwise direction by 90^o and the rotor 2 pole (A') rotates in anti-clockwise direction by 90^o. The Figure 3(c). shows that, in the similar manner both the rotors rotating in by another 90^o each. The rotor 1 pole (A) rotates 90^o in clockwise direction at 180^o (i.e., the generator takes only 180^o to complete one revolution) and the rotor 2 pole (A') rotates in an anti-clockwise direction at 180^o. Then the net flux cutting is for 360^o (i.e., the generator takes 360^o to complete two revolutions). Therefore, the flux cutting will be twice that of single rotor machine. Then the generator emf output is twice.

A. EMF Equation

Let,

Φ = Flux per pole in Wb, Z = Total number of armature Conductors, p = Number of poles, A = Number of parallel paths ,N_a= Armature rotation in rpm, N_f =Field rotation in rpm, $N=N_a+N_f$ - total rotation of SLDRPMG in rpm, E_g = Total Emf generated in Volts.

If
$N_a = N_f$
Total Emf generated,

$$E_g = 2\left[\frac{p\phi Z N_a}{60A}\right] \text{volts} \qquad (11)$$

7. Experimental setup for the proposed system

The PMSLCR machine is designed for the wind power applications to generate low cost electricity utilizing the wind energy. The energy conversion in wind electric generator is: as the wind blows, it rotates the turbine, and the wind turbine converts kinetic energy from the wind energy into mechanical energy. The mechanical energy is transferred to the generator through the rotor shaft and to generate electrical energy.

Figure 4. 0.373 kW (0.50 H.P) Prototype test model of PMSLCRWPG

"Fig.4", shows the photograph of proposed prototype test model of the low cost PMSLCRWPG. It is designed with special type of permanent magnet machine, which is coupled with a domestic pedestal fan blade in its one side shaft (i.e., turbine1) and armature is coupled with the another domestic pedestal fan blade (i.e., turbine 2), The turbine 2 has larger diameter than the turbine 1. The turbine 1 is coupled with rotor 1 and turbine 2 coupled with rotor 2. All these arrangements are supported with an iron stand with adequate foot support. When the pedestal fan is stager with blows the wind(upwind) rotates the turbine1and rotor 1. The escaping wind(downwind), flows over the turbine 2, which rotates the rotor 2 in opposite to the direction of the rotor 1. Therefore, the overall magnetic flux cutting will be twice that of single rotor machine and the electro motive force (emf) produced in terms of voltage is also twice as per "(11)".

8. Results and Discussions

For the analysis based test case results are given in the tables, as such the voltages given as single rotor generator voltage is V_1 and /;dual rotor generator voltage is V_2.As per the test readings the dual rotor generator voltage is higher than the single rotor voltage.

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TABLE IV. EXPERIMENTAL READINGS

Θ	**Wind flows between the Fan and the Generator 1Feet)**		
	N	V_1	V_2
00	00	0.00	0.00
10	36	6.00	10.50
20	44	8.00	18.00
30	165	10.00	27.00
40	182	12.00	30.00
50	184	22.00	33.00
60	357	24.00	37.50
70	370	27.00	40.50
80	425	30.00	45.00
90	475	38.00	58.50

Θ = Wind blow position Angle (Degrees), N=Speed (RPM), =Single Rotor Voltage (Volts), =Dual-Rotor Voltage (Volts) and L = Distance (metres).

TABLE V. EXPERIMENTAL READINGS

Θ	Wind flows between the Fan and the Generator 2Feet)		
	N	V_1	V_2
00	00	0.00	0.00
10	36	7.00	10.50
20	42	12.00	18.00
30	160	18.00	27.00
40	180	20.00	30.00
50	182	22.00	33.00
60	354	25.00	37.50
70	365	27.00	40.50
80	400	30.00	45.00
90	425	39.50	58.50

Θ = Wind blow position Angle (Degrees), N=Speed (RPM), =Single Rotor Voltage (Volts), =Dual-Rotor Voltage (Volts) and L = Distance (metres).

TABLE VI. EXPERIMENTAL READINGS

Θ	**Wind flows between the Fan and the Generator 3Feet)**		
	N	V_1	V_2
00	00	0.00	0.00
10	12	9.00	13.50
20	20	15.00	22.00
30	76	19.00	28.50
40	165	22.00	33.00
50	198	27.00	40.50
60	232	30.00	45.00
70	247	34.00	51.00
80	260	35.00	52.50
90	290	40.00	60.00

Θ = Wind blow position Angle (Degrees), N=Speed (RPM), =Single Rotor Voltage
(Volts), =Dual-Rotor Voltage (Volts) and L = Distance (metres).

As per the tabulated readings from Table IV to VI are voltage V_1 and voltage V_2 from different distances and different position angles of the wind blows, to the generator is given. There is obviously noted that the dual rotor generator voltage V_2 is more than the single rotor voltage V_1.

TABLE VII. EXPERIMENTAL READINGS

Lamp Loading of the Generator (Lamp Load 40W & 100W)		
V	***I For 40W***	***I For 100W***
0	0.00	0.00
10	0.10	0.16
20	0.12	0.24
30	0.13	0.26
40	0.14	0.27
50	0.15	0.30
60	0.17	0.33
70	0.18	0.37

I = Load Current in Amperes, V=Load Voltages, W=Power in watts

Table VII, shown that the voltage and current readings for 40 watts of lamp load and 100watts of lamp load are tabulated for various sets for the analysis.

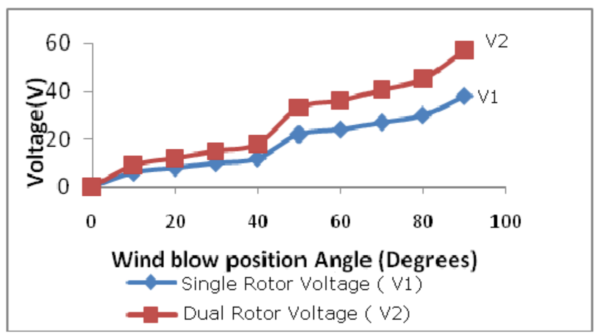

Figure 5(a). Graph for wind flow distance to the generator (1feet)

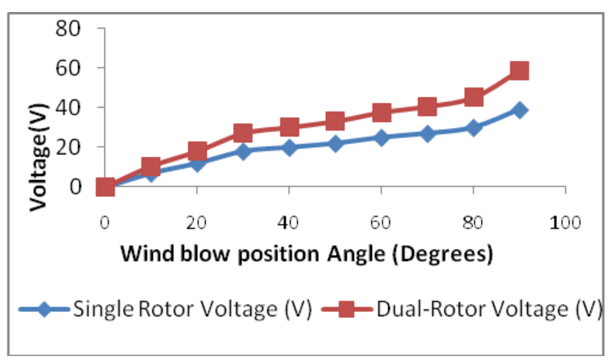

Figure 5(b). Graph for wind flow distance to the generator (2Feets)

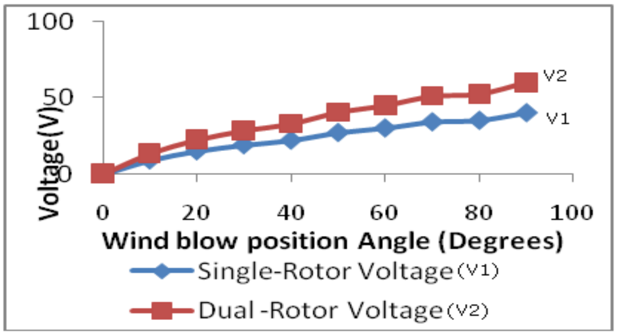

Figure 5(c). Graph for wind flow distance to the generator (3feets)

"Fig. 5(a) to 5(c)", shows the graphs for voltage versus wind blow position angle. There are two curves are shown that one is for single rotor generator voltage (blue curve) and other is dual rotor generator voltage (red curve).

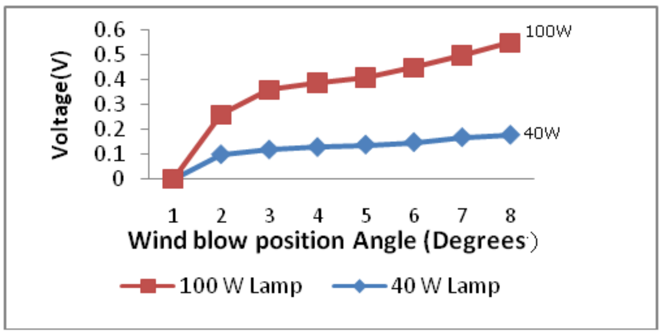

Figure 5(d). Load characteristics between load voltage and load current

"Fig. 5(d)", shows the graph for load voltage versus load current. There are two curves as show, In that one is for 40 watts lamp load (blue curve) and other is 100 watts lamp load (red curve).

9. Conclusion

This paper presented the stator-less contra-rotation PM wind power generator modeling, design and analysis. The test model is designed and tested for various wind speeds and voltages. This model will be enhancing as a large scale and better solution for future energy crises all over the world. This test model will best suit for the power generation from the renewable energy source as the wind energy. The output of single PMSLCRWPG will be equivalent to the output produced by two single-rotor generator. Thus it will be economical to construct one PMSLCRWPG than to construct two single rotor generators. This system is more useful to solve power problems – especially at remote and hilly areas. This design for large scale generation, will share power demands, considerably; also economically and reliably.

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BIOGRAPHIES

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