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A Modified Model of Axial Flux Permanent Magnet Generator for Wind Turbine Applications

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The Axial Flux Permanent Magnet Generators (AFPMGs) are gaining immense attention in the modern era. The single stage AFPMG topology consists of one stator disc which is held stationery between two revolving rotor discs attached with a common shaft. The number of poles of AFPMG depends on the winding pattern in which the coils are connected in series within stator disc. Connecting the coils in begin-to-end winding pattern, doubles the number of poles which also increases the active mass of AFPMG. The AFPMG considering begin-to-end winding pattern, can be operated at half shaft speed. This AFPMG is also having greater air gap flux density which, ultimately, improves the power density parameter of AFPMG. In this paper, a modified AFPMG has been proposed which is designed by considering begin-to-end winding pattern. A 380W single phase, single stage prototype model has been developed and tested. The test results show that power density of designed AFPMG with begin-to-end winding pattern has been improved by 32% as compared to AFPMG with begin-to-begin winding pattern. The proposed low speed and high power density AFPMG model can be actively deployed for wind turbine applications.

Keywords : Axial flux generator, Wind turbine, Permanent magnet generator, Neodymium permanent magnet, Power density

1. Introduction

The wind power generation is one of the extensively exploited renewable energy resources [1-3]. The wind turbine and electrical generator represent two major components of wind power generation system [1, 2, 4]. The AFPMGs are excessively used for wind turbine applications [5-7]. The improved power density, higher efficiency, low weight, compact size and low shaft speed are the highlighted characteristics of AFPMGs [2, 5, 6, 8, 9]. In general construction of AFPMG, the stator disc is placed between two rotor discs [2, 5-7, 10, 11]. Now a days, the rotor discs are attached with strong rare earth magnets called neodymium permanent magnets [4, 12-14]. The different topologies of AFPMGs are proposed and presented in literature.

The author [7]has reviewed different topologies for AFPMGs and discussed the various advantages. The rotor type of machine basically classifies the topology of machine as: axial flux induction machine, mounted permanent magnet machine and interior permanent magnet machine with squirrel cage, surface mounted permanent magnet and interior permanent magnet rotor structures respectively. The basic type of axial flux machine is single-single topology consisting of one stator disc and one rotor disc. The torus type axial flux machine consisting of one stator disc and two rotor discs which are sandwiched while internal stator disc topology. The rotor discs of this machine are adjusted either in repulsion mode: with identical poles of permanent magnets front to each other or in attraction mode: with different poles of permanent magnets front to each other. Besides, the stator disc may be iron cored, coreless, slotted and non-slotted. The torus type axial flux machine consisting of two stator discs and one rotor disc with internal rotor type structure is also present. The permanent magnets are fitted on both sides of the rotor disc. The rotor disc of this machine is made of non-ferromagnetic material because in this topology, the flux does not pass through rotor disc. However, the stator of these machines must be iron cored to facilitate the flux passage. The fourth topology of multi-stage axial flux machines is also getting enormous attention. The multi-stage axial flux machines are designed with multiple stator and rotor discs where rotor discs is always greater than stator discs by one. The windings of all stator discs can either be connected in parallel or series to enhance the current or voltage rating respectively. The permanent magnets are fitted on one side and both sides of sided rotors and internal rotors respectively. The rotor discs may be adjusted while considering permanent magnets either in attraction mode or repulsion mode. A hybrid machine is also addressed which was proposed by Dr. Hsu. This machine is having axial as well as radial fittings of permanent magnets on double sided rotor structure. The last and new machine addressed in this article consists of DC field windings as well as permanent magnets for controlled machine. The machine is single stator and double rotor topology.

In this paper, the AFPMG has been designed on

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single stage and single phase basis. The begin-to-end winding pattern has been followed for connecting coils of stator disc in series. The designed AFPMG has been fabricated and tested. The designed AFPMG has improved power density (167.55 W/kg) than 28 W AFPMG model addressed [2] (113.82 W/kg). The topology of designed AFPMG is shown (Figure 1) in which S1 is stator disc while R1 and R2 are two rotor discs attached with magnets, fitted with common shaft.

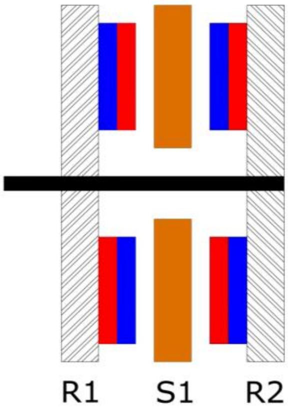


Figure 1. Generator topology.

2. Design of AFPMG Model

The procedure of electrical machine design follows many requirements while satisfying mechanical as well as electrical constraints [15]. The name plate ratings of AFPMG follow the design procedure of machine. The line voltage, phase voltage, current carrying capacity, poles, shaft speed and power rating contribute towards name plate of machine [16]. The name plate ratings of AFPMG are listed in Table 1.

Table 1. Name plate ratings of AFPMG model.

S. No.	Rating	Value
1	Power	380 Watt
2	Voltage	127 Volt
3	Frequency	50 Hz
4	Max. Current	3 Amp
5	Shaft Speed	500 rpm

The design considerations of AFPMG focus on the number of coils, number of magnets, winding type, coil pitch and winding connection type in accordance with required number of poles of machine. Begin-to-end is the type of end winding connection of interconnecting the coils within stator disc in such a way that begin and end limbs of one coil are connected with end and begin limbs of adjacent coil respectively. The configuration of begin-to-end connection is shown in Figure 2.

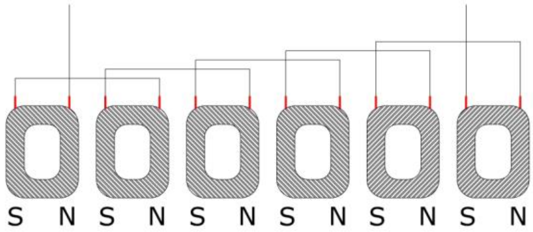


Figure 2. Begin-to-end winding pattern.

The begin-to-end connection requires stair winding with 1-3 coil pitch in which number of magnets is twice than number of coils on rotor and stator discs respectively and is also equal to number of poles of machine. The stator disc of AFPMG using begin-to-end connection is shown in Figure 3.

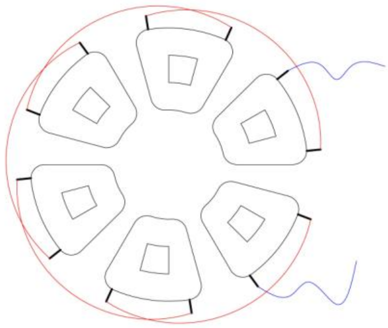


Figure 3. Begin-to-end connection in AFPMG.

Comparatively, for large number of poles, the machine wound with stair winding is heavier in mass than machine wound with begin-to-begin connection. But double number of magnets contribute to improve power density in two ways: first air gap flux density is increased and second shaft speed of AFPMG is halved. The stator and rotor discs of AFPMG showing begin-to-end connection and stair winding type is shown in Figure 4. The red and blue blocks represent the North and South poles of permanent magnets respectively.

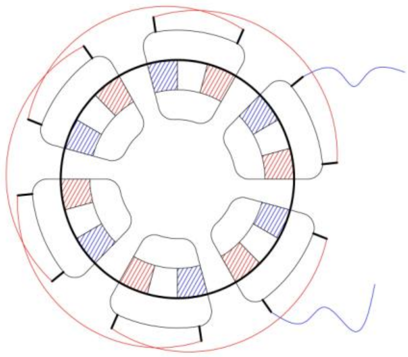


Figure 4. Coil-magnet overlapping for begin-to-end connection.

The main dimensions of axial flux generator may be determined with assumption of negligible leakage inductance and resistance [5]. Basically rated power of the machine is expressed as product of air-gap emf and air-gap current when these values are given for peak. [2, 5, 7, 17, 18]

$$P_r = \eta \frac{m}{T} \int_0^T e(t)\, i(t)\, dt \tag{1}$$

Where *e(t)* and *i(t)* are instantaneous voltage and current of AFPMG. Evaluating the expression, power of AFPMG is given by:

$$P_r = \eta m E_p I_p K_p \tag{2}$$

where

η Machine efficiency

m Number of phases of machine

E_p Peak voltage of rated per phase voltage

I_p Peak current of rated per phase current

K_p Electrical power waveform factor

The expression for peak value of rated per phase voltage is given by: [5]

$$E_p = K_e N_t B_g \frac{f}{p} (D_o^2 - D_i^2) \tag{3}$$

where

K_e emf factor which also incorporates the winding distribution factor K_w

N_t Number of turns of coil

B_g Air-gap flux density (T, Wb/m^2)

f Supply frequency (Hz)

p Number of pole pairs of machine

D_o Outer diameter of stator disc (m)

D_i Inner diameter of stator disc (m)

The expression for peak current of rated per phase current is given by: [5]

$$I_p = \frac{1}{1+K_\phi} K_i A \pi \frac{1+\lambda}{2} \frac{D_o}{2 m_1 N_t} \tag{4}$$

where

K_Φ Ratio of electrical loading on rotor and stator of generator

K_i Current waveform factor

A Electrical loading in ampere conductor per meter of stator disc (A/m)

λ Ratio of inner to outer diameter of stator disc

m_1 Number of phases per stator disc

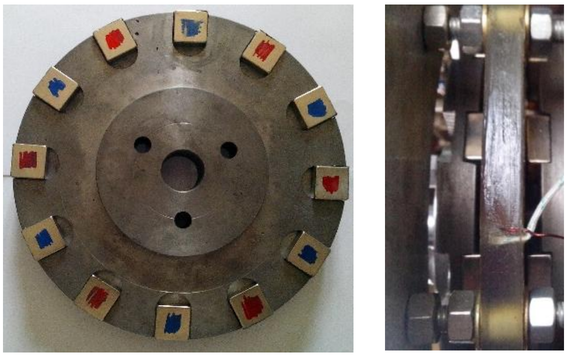
The initial design considerations are specified before computing the design parameter and dimensions of AFPMG. The usage of permanent magnets sets the value of $K_\phi=0$[5]. Similarly, the values of $m_1$and$m$ are selected on basis of stages and phases of AFPMG respectively. The emf, current and power waveform factors contribute their values from data of typical prototype waveforms against sinusoidal voltage waveform of AFPMG [18]. The design procedure has been followed and the design parameters have been computed which are given in Table 2.

Table 2. Computed specifications of AFPMG.

No.	Specification / Dimension	Aspect / Value
1	Number of poles	12
2	Number of coils of stator disc	6
3	Winding connection	Begin-to-End connection
4	Coil pitch	1-3 coils
5	Winding type	Stair winding
6	Number of magnets per rotor disc	12
7	Outer diameter of stator disc	304.8 mm
8	Inner diameter of stator disc	132.1 mm
9	Number of turns of coil	230
10	Length of Magnet	25.4 mm
11	Width of Magnet	25.4 mm
12	Thickness of Magnet	10 mm
13	Rotor disc diameter	254 mm
14	Axial length of stator disc	10 mm
15	Axial length of rotor disc	15 mm
16	Segment Arc	60°
17	Slot Arc	15°
18	Coil Arc	45°
19	Inter-magnet Displacement	30°
20	Machine Topology	1 Stator, 2 Rotor
21	Active Mass of AFPMG	2.268 kg

3. Fabrication of AFPMG Model

The AFPMG has been fabricated considering the design specifications and dimensions listed in Table 2. The assembly of AFPMG includes the fabrication of rotor discs and stator disc. Two rotor plates have been casted and slots for permanent magnets have been carved. There are 6 North and 6 South permanent magnets which have been attached on each rotor disc in alternate polarity. The rotor discs have been fitted on a common shaft within generator assembly. The rotor disc is shown in Figure 5(a). The stator disc template has been prepared in which 6 coils have been placed and filled with epoxy resin for coreless construction of stator disc. The winding coils have been connected in series while following begin-to-end winding pattern. The stator disc fitted with rotor discs and generator assembly is shown in Figure 5(b). Thus complete AFPMG model has been developed and shown in Figure 6.



(a) (b)

Figure 5. (a) Rotor disc, (b) Stator disc sandwiched between rotor discs.

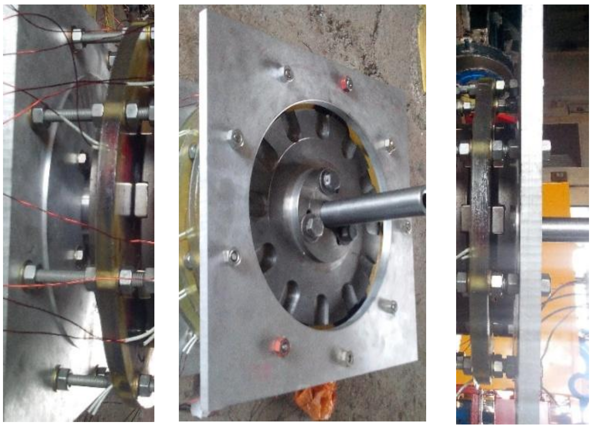


Figure 6. Complete AFPMG assembly and model.

4. AFPMG Testing and Results

After fabrication, the designed AFPMG has been coupled with variable speed DC motor fitted on machine testing bench. The shaft speed is measured by tachometer attached on testing bench. The AFPMG model is ready for testing and complete testing bench is shown in Figure 7.

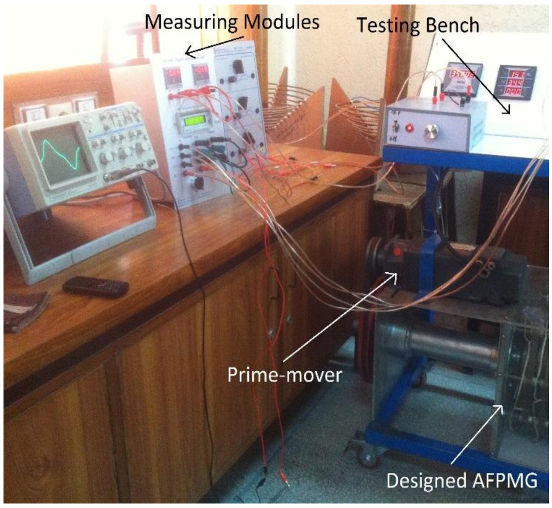


Figure 7. Generator testing bench.

The no-load test has been conducted on designed AFPMG model and observations have been recorded. The no-load voltage characteristics of machine against variable shaft speed are represented by Figure 8.

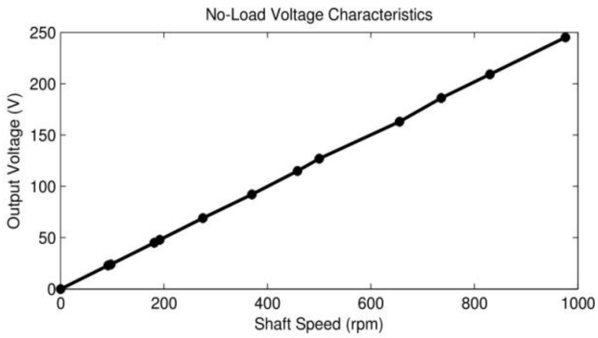


Figure 8. No-load test.

The load test has been performed on AFPMG model. The voltage regulation of AFPMG has been computed and comes out to be 17%. The voltage characteristics of AFPMG at load conditions are shown in Figure 9.

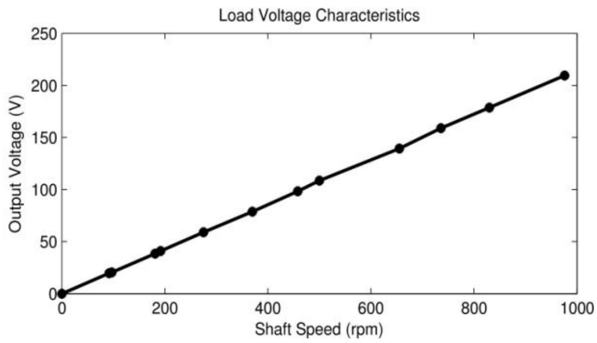


Figure 9. Load test.

The important parameter of AFPMG results is the power density which is the measure of power rating of machine against active mass of machine. The higher value of power density reflects the minimization of machine's active mass while maximizing the power rating [4]. The coils of fabricated and designed AFPMG have been connected in series while following begin-to-end winding pattern which increases the mass of machine and air gap flux density. Due to which, the power density parameter of AFPMG has been improved as compared to AFPMG with begin-to-begin winding pattern addressed in [2]. The comparison is presented in Table 3.

Table 3. Comparison of AFPMG results.

Parameter	Designed AFPMG with begin-to-end connection	AFPMG model with begin-to-begin connection[2]
Power Density (W/kg)	167.55	113.82

5. Conclusion

In this research paper, the winding pattern of connecting coils within stator disc has been modified from begin-to-begin pattern to begin-to-end. The modification doubles the poles of AFPMG and also increases the air gap flux density which in turn improves the power density parameter. This arrangement also incorporates the concept of low speed applications as shaft speed of AFPMG is halved. Designing three-phase and multi-stage machine is the future horizon of this work.

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