International Journal of
Scientific Engineering and Technology Research

ISSN 2319-8885
Vol.03,Issue.10
May-2014,
Pages:2047-2051

www.semargroup.org,
www.ijsetr.com

Design of the Coreless Axial-Flux Double-Sided Permanent Magnet Synchronous Generator for Wind Power System

SAINT SAINT SOE[1], YAN AUNG OO[2]

[1]Dept of Electrical Power Engineering, Mandalay Technological University, Mandalay, Myanmar, Email: seintssoe@gmail.com.
[2]Dept of Electrical Power Engineering, Mandalay Technological University, Mandalay, Myanmar, Email: yanaungoo@gmail.com.

Abstract: For the clean alternative renewable energy in rural area, electricity can be produced by wind power. Permanent magnet generators have been used for wind turbines for many years. Many small wind turbine manufacturers use direct-drive permanent magnet generators. In this paper, three-phase axial-flux permanent magnet synchronous generator (AFPMSG) is driven by wind turbine. Therefore, evaluation of the design and analysis of coreless stator (AFPMSG) is the goal of this paper. In this paper, study the coreless stator of (AFPMSG) for a 2 kW wind turbine application.

Keywords: Axial- Flux Permanent Magnet Synchronous Generator (AFPMSG), Wind Power, Direct-Drive Permanent Magnet Generator, Design.

I. INTRODUCTION

Wind power is the conversion of wind energy into more useful forms, such as electricity, using wind turbines. Most modern wind power is generated in the form of electricity by converting the rotation of turbine blades into electrical current by means of an electrical generator. Wind energy is considered to be a very clean, cheap and important renewable energy source particularly for rural areas, farms, remote on-shore and off-shore installation away from main electrical grid. It is easy to produce electricity because it is a natural resource which can be used freely and fuels become more expensive. Using permanent magnet generator, the electricity requirement can be fulfilled by generation from wind power in coastal regions, hilly regions and rural areas of Myanmar [1].

Axial-flux permanent magnet (AFPM) machines have become an important subject of study because of the development of neodymium magnets over the past 20 years. These machines offer many unique features. They are usually more efficient because of the fact that field excitation losses are eliminated resulting in significant rotor loss reduction. Thus, this machine efficiency is greatly improved and higher power density is achieved.PM machine advantages include lightweight, small size, simple mechanical construction, easy maintenance, good reliability, high efficiency, and absence of moving contacts. Various PM machine topologies have been proposed for direct-coupled wind generator applications, namely outer-rotor design, modular design, axial-field machine, TORUS generator and coreless generator. These machines have been developed mainly for used with horizontal-axis wind turbines. In this paper, study the double-rotor single-stator structure for AFPMSG.

II. WIND TURBINE GENERATOR SYSTEM

A. Wind Turbine (HAWT) System

Small-scale wind-turbine generator systems are proposed in this paper. Fig. 1 shows a horizontal-axis wind turbine system (HAWT) that employs the proposed direct-coupled AFPMSG. To facilitate direct coupling of the generator to the turbine blades, an outer-rotor machine configuration is used. The rotor rotates about a stationary shaft, which is supported on a tower by means of a yaw mechanism. The turbine blades are attached on the flange surface of the rotor.(HAWT) system using an outer-rotor AFPMSG[2].

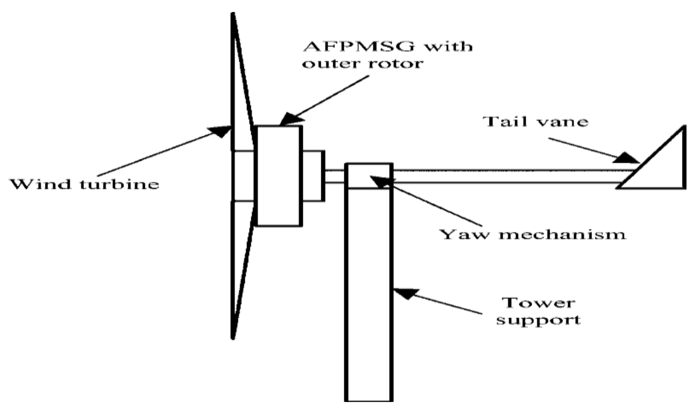


Fig.1. Proposed arrangement of a micro-horizontal-axis wind turbine.

B. Estimation of Wind Power

The purpose of a wind turbine is convert the kinetic energy available from the wind into rotating mechanical energy, while the purpose of the generator is to convert that mechanical energy to electrical energy (see fig 2).

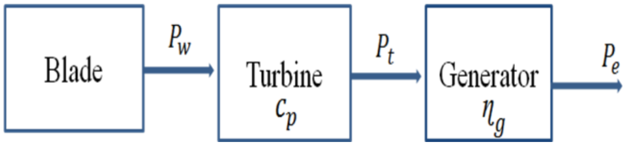


Fig. 2. Wind power generating system.

Blade swept area is,

$$A = \frac{\pi D^2}{4} \tag{1}$$

Where,

D = blade diameter, m

Power from the wind that can be extracted from the given volume of wind can be calculated by;

$$P_W = \frac{1}{2}\rho A v^3 \tag{2}$$

Where,

A = blade swept area, m^2

v = wind velocity, m^3

ρ = density of wind, kg/m^3

Turbine output power can be calculated by;

$$P_t = P_W \times C_p(\lambda) \tag{3}$$

Where,

$C_p(\lambda)$ = turbine power coefficient

Angular velocity from the wind can be calculated by the following equation,

$$\omega_r = \frac{\lambda \times v}{R} \tag{4}$$

Where,

R = blade radius, m

λ = tip speed ratio

Turbine torque is the following equation,

$$T = \frac{P_t}{\omega_r} \tag{5}$$

Where,

ω_r = angular velocity from the wind, rad/sec

P_t = turbine output power, kW

TABLE I: Result for Wind Power Generating System

Specification	value
Blade diameter, m	5.2
Blade swept area, m^2	21.24
Turbine output power , kW	2.2
Angular velocity, rad/sec	19.8
Turbine torque, Nm	118.18

III. DESIGN AND CONSTRUCTION OF AFPMSG

A. General Design Considerations

The AFPMSG's weight is reduced by using a large number of poles and high-energy neodymium-iron-boron (NdFeB) magnets for the rotor field. When driven by a low-speed wind turbine, the poles enable generation at a reasonable frequency range. This also reduces yoke thickness and the length of armature coil overhang. The low-speed generator design poses a less stringent demand on the mechanical strength of the rotor magnets. Since high-energy NdFeB magnets are used, an air gap disk winding design is feasible. The coreless armature design results in zero magnetic pull between the stator and rotor, eliminates iron loss, and improves generator efficiency (from fig 3). There is no cogging torque, so smooth running is assured. The double-sided AFPM machine with the double outer PM-rotor has the highest torque production capacity due to higher volume of permanent magnet material used[3] (from fig4).

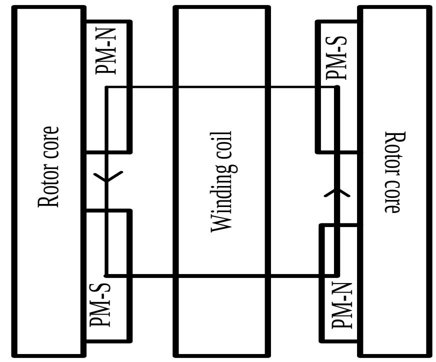


Fig. 3. Coreless axial-flux permanent magnet machine.

B. Theoretical Analysis for AFPMSG

An AFPM generator, like all conventional electrical machines, consists primarily of a rotor and a stator. The rotor comprises the two opposing steel disks which are interconnected. The stator is the coreless variety and is located between the two rotor disks.

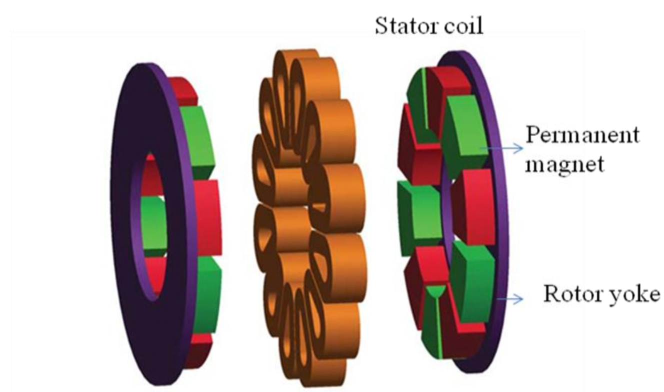


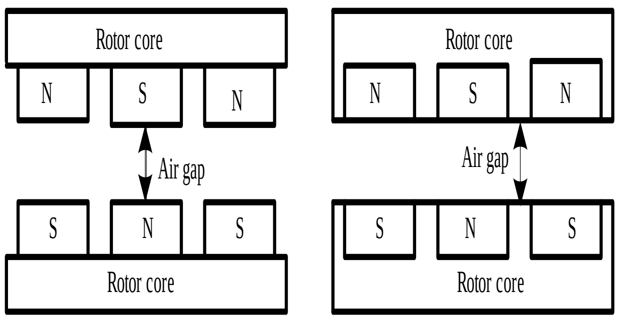
Fig.4. Double-sided AFPM machine with internal air cored stator.

1. Rotor

The rotor of the AFPM machine consist of interconnected steel disks with the permanent magnet attached on the outside circumference on the inner surfaces of the opposing rotor disks. The steel rotor disks are multifunctional, as the rigid steel construction maintains the necessary airgap length between the opposing magnet poles while providing the flux return path between the rotor poles. As the iron losses in the rotor are very small and can for all practical reasons be neglected, the rotor disk can be manufactured from solid iron, as opposed to laminated iron.

2. Magnet Placement

There are mainly two possible ways of mounting the permanent magnets in AFPM machines. The permanent magnet can either be mounted on the surface of the rotor disk or they are embedded in the rotor disk. The mounting possibilities are illustrated in Fig.5. The AFPM generator discussed in this study are of the surface-mounted topology.



Surface- mounted PM embedded PM

Fig.5. PM mounting type for AFPMSG

3. Stator

In a coreless AFPM machine the stator is located between the two opposing rotor disks. The coreless nature of the stator eliminated the lamination stamping during the manufacturing process of the stator winding. This leads to a much manufacturing process. The absence of the iron core for the coils of the stator winding creates a low flux density in the magnetic circuit of the coil, resulting in a low value of inductance for the coil in the coreless stator[4]. A popular coil shape for AFPM machine is toroidal-shape coil wound around an iron core. The stator windings of the AFPM machine in this paper are of the single-layer trapezoidal coil shape. The advantage of the trapezoidal coil shape is that it allows for the maximum coil flux linkage. The trapezoidal coil shape is illustrated in Fig.6.

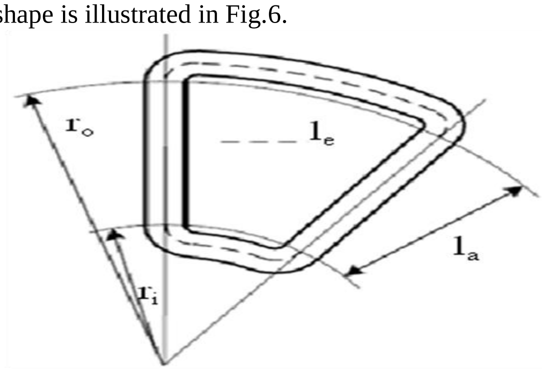


Fig. 6. Trapezoidal coil shape.

IV. DESIGN EQUATION FOR AFPMSG

This paper is designed for 2 kW axial-flux permanent magnet synchronous generators with coreless stator. The effective air gap for the machine can be calculated by the following equation;

$$l_{geff} = 2l_g + \frac{2l_m}{\mu_{mm}} + h_{sy} \quad \textbf{(6)}$$

Where,

l_g= air gap between magnet and stator disk

l_m = magnet length

μ_{rm}= relative recoil permeability of magnet

h_{sy}= stator thickness or axial thickness of winding plus core material

The airgap flux density due to magnet is the following equation;

$$B_g = \frac{2B_{rm}l_m}{\mu_{rm}l_{geff}} \quad \textbf{(7)}$$

The peak value of air-gap flux density;

$$B_p = \frac{2\sqrt{3} \times B_g}{\pi} \quad \textbf{(8)}$$

Where,

B_{rm}= remanent flux density

The stator outer diameter for AFPMSG can be calculated by the following equation;

$$D_{out} = 3\sqrt{\frac{\varepsilon P_{out}}{\pi^2 \lambda k_w n_s B_g A_m \eta \cos\varphi}} \quad \textbf{(9)}$$

Where,

k_w = stator winding factor

n_s = speed of the machine

P_{out}=output power rating

ε = the ratio of EMF to phase voltage

A_m = specific electromagnetic loading

The stator inner diameter for the AFPMSG,

$$D_{in} = D_{out} \times K_D \quad \textbf{(10)}$$

Where,

K_d = ratio of inner and outer diameter of machine

The average radius of the stator winding can be calculated by;

$$r_e = \frac{r_o + r_{in}}{2} \quad \textbf{(11)}$$

Active length of stator winding is the following equation;

$$l_a = r_o - r_{in} \quad \textbf{(12)}$$

Where,

r_o = outer radius of the stator

r_{in}= inner radius of the stator

Number of stator coils per phase can be calculated by;

$$q = \frac{Q}{3} = \frac{p}{2} \quad \textbf{(13)}$$

Where,

Q = the total number of stator coils

p = number of pole pairs

The RMS-value of the sinusoidal phase voltage of the non-overlapping winding can be calculated by the following equation;

$$E_{gen} = \frac{q2\sqrt{2}}{ap}\omega_e B_p N_t r_e l_a k_p k_d \quad \textbf{(14)}$$

Where,

a = number of parallel connected circuits

ω_e = electrical rotational speed

r_e = average radius of machine

B_p = peak air gap flux density

N_t = number of turn per coils

k_p = pitch factor of the winding

k_d = distribution factor of the winding

The phase resistance models the copper losses in the stator winding of the AFPM machine. The per-phase stator resistance can be calculated by,

$$R_i = \frac{N_t^2 q \rho_t (2l_a + l_e)}{a^2 k_f h_a \omega} \quad \textbf{(15)}$$

Where,

ρ_t = resistivity of copper

l_e = end-winding length of the winding

h_a = the axial height

ω = the width of a coil-side

The inductance of a phase winding consists mainly of mutual and leakage inductances. The AFPM generator utilizes a coreless stator winding topology, which results in a stator winding with a low inductance, L_i can be calculated by;

$$L_i = \frac{q(2l_a + l_e)^2 N_t^2}{h_a} \times 10^{-7} \times K_n \quad \textbf{(16)}$$

Where,

K_n = Nagaoka constant

The Stator copper losses are given by;

$$P_{cu} = 3I_{ac}{}^2 R_i \quad \textbf{(17)}$$

Where,

I_{ac} = the phase current

R_i = the per-phase stator resistance

The Stator eddy current losses are given by;

$$P_{eddy} = \frac{\pi l_a d^4 B_p^2 \omega_e^2 Q N_t N_p}{32\rho} \quad \textbf{(18)}$$

Where,

d = diameter of copper wire

ρ = resistivity of copper

B_p = peak air gap flux density

Output power of the generator can be calculated by;

$$P_{out} = 3E_{gen} I_{ac} \quad \textbf{(19)}$$

Where,

E_{gen} = the phase voltage of the winding

I_{ac} = the phase current

Input power of the generator is given by the following equation;

$$P_{in} = P_{out} + P_{cu} + P_{eddy} \quad \textbf{(20)}$$

Efficiency of the generator can be calculated by;

$$\eta = \frac{P_{out}}{P_{in}} \times 100\% \quad \textbf{(21)}$$

TABLE II: SPECIFICATIONS OF AFPMSG

Specifications	Value
Rated output power, kW	2
Rated voltage, V	58
Rated speed, rpm	188
Number of pole pairs	16
Number of phases	3
Frequency, Hz	50
Connection of stator winding	star

TABLE III: MECHANICAL DESIGN PARAMETERS FOR AFPMSG

Parameters	Value
Outer diameter of stator, m	0.579
Outer radius of stator, m	0.289
Inner radius of stator, m	0.174
Average radius of stator winding	0.232
Active length of stator winding	0.115
The number of turn per coil, turns	40
The total number of stator coil	24
Air gap, mm	2

TABLE III: ELECTRICAL DESIGN PARAMETERS FOR AFPMSG

Parameters	value
RMS value of sinusoidal phase voltage, V	58
The resistivity of copper, Ωm	1.8542×10^{-8}
The per phase stator resistance, Ω	0.2
The stator inductance, H	0.00168
The eddy current losses, W	77.21
The copper losses, W	79
The input power, kW	2.2
The output power, kW	2
The efficiency, %	90

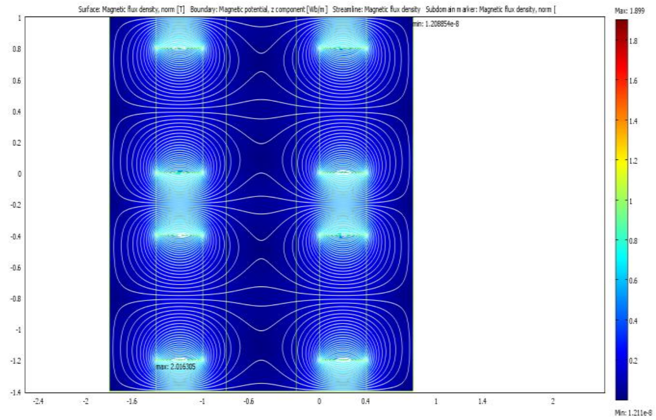


Fig. 7. Magnetic flux density for AFPMSG.

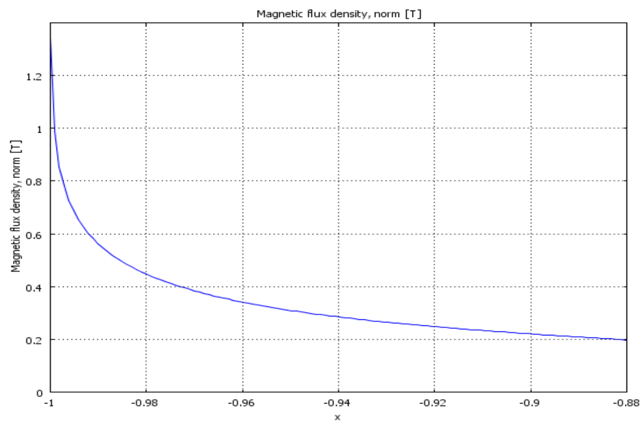


Fig.8. Air gap flux density under no load condition.

V. CONCLUSION

In this paper, the coreless stator (AFPMSG) was evaluated for use in small scale wind generator applications. The application of this machine to horizontal-axis wind turbine generator system is discussed. And then double-sided coreless stator of axial-flux permanent magnet synchronous generator is mainly emphasized in this study. Moreover, the finite-element method was used to compute the flux density in the generator components.

VI. ACKNOWLEDGMENT

First of all, the author would like to express grateful thank to Dr. Khin Thu Zar Soe, Associate Professor, and Head of Electrical Power Engineering Department, Mandalay Technological University, for her willingness to share ideas, experiences and guidance during presentation. The author would like to express deep gratitude to Dr. Yan Aung Oo, Associate Processor, Electrical Power Engineering Department, Mandalay Technological University, for his close guidance, accomplished supervision, help, support and sharing ideas and experience during the research of thesis.

VII. REFERENCES

[1] Renewable energy http://www.eia.doe.gov/kids/ infocar dnew.html#, May 2009.
[2] E. Muljadi, C. P. Butterfield, and U. H. Wan, "Axial-flux modular permanent-magnet generator with a toroidal winding for wind-turbine applications," IEEE Trans. Ind. Appl., vol. 35, no. 4, pp. 831–836, Jul./Aug.1999.
[3] B. J. Chalmers,W.Wu, and E. Spooner, "An axial-flux permanent-magnet generator for a gearless wind energy system," IEEE Trans. Energy Convers., vol. 14, no. 2, pp. 251–257, Jun. 1999.
[4] R. Wang, "Design aspects and optimization of an axial field permanent magnet with an ironless stator," Ph.D. University of Stellenbosch,2003.