A Five Phase Axial Flux Permanent Magnet Generator for Wind Turbine Application

R. Shanmugarajan[1], **P. Prabakaran**[2], **A. Ariventhan**[3]

[1 2 3]UG scholar, Department of EEE, AVS College of Technology, Salem, Tamil Nadu, India

Abstract: ***This project discusses the benefits of five-phase technology for Wind Turbine Application with Axial Flux Permanent Magnet BLDC Generator (AFPMG). The radial flux permanent magnet generator has a setback of very low speed applications because, of the presence of cogging torque. This can be overcome by using an axial flux permanent magnet generator which has no cogging torque and has more advantage than a radial flux generator. Investigations proved that the five-phase topology harnesses some specific and important benefits that are not provided by three-phase systems. The benefits include improved fault tolerance and reliability, and reduced voltage, torque ripple and size of DC link capacitor. These are general improvements that are sought after in many applications including renewable energy applications. The objective of the project is to design a five phase Axial Flux permanent magnet BLDC generator for 1000W at a wind speed of 9m/s. Performance analysis of Axial Flux permanent magnet is investigated. MATLAB/Simulink model for five phase rectifier and Generator model is discussed. Test results are also presented in this project.***

Keywords: Wind Turbine Generators, Multi-Phase Machines, Axial Flux Permanent Magnet DC Machines.

1. Introduction

a) Multiphase Technology

Multi-phase machine technology typically refers to machines with phase number greater than three. Traditionally, electrical energy has been generated by large-scale power stations using three-phase synchronous generators. Benefits includes low phase current, higher output power density and low torque. In addition, they can also be designed with partially pitched windings.

The driver for adopting the five-phase technology is that it harnesses some specific and important benefits that are not provided by traditional three-phase systems especially for renewable energy applications such as wind turbine generators. This includes improved torque density, efficiency and fault tolerance, reduced torque ripple and dc-link energy storage. In addition, they also can be designed with partially pitched windings, allowing a degree of shaping of the voltage waveforms. The combinations of multi-phase technology, permanent magnets and partially pitched windings provides improvements in performance, and optimized designs to make it suitable for use with diode rectifier circuits which predominate in small and medium scale generation. Such systems are particularly suited to small and medium scale wind turbines.

b) Permanent Magnet Generator

Brushless motors have a permanent-magnet rotor, single or multi-phase stator windings, a sensor to determine the rotor position and an inverter which feeds alternating current to the stator windings.

Electrical generators, used with wind turbines, are varied direct current generators, induction generators, synchronous generators, reluctance generators and permanent magnet generators have all been proposed. Direct current generators and synchronous generators require brush maintenance especially in applications at high altitude or where dusts and high wind can damage the brushes. Permanent magnet generators are the machine of choice in small wind turbines offering simple construction, low maintenance costs and self-exciting ability.

Axial flux permanent generator's unique disc-type profile of the rotor and stator of machines makes it possible to generate diverse and interchangeable designs. AFPM machines can be designed as single air gap or multiple air gaps machines, with slotted, slot less or even totally ironless armature. Since a large number of poles can be accommodated, these machines are ideal for low speed applications such as domestic wind turbine. Axial flux generator configuration favors the use of gearless system because it allows the use of higher pole number. Radial Flux machines will operate with medium and high speed applications. The combination of multiphase technology and permanent magnet provides improvement in performance.

2. Wind Turbine System

Wind turbine characteristics is analysed for the design of Generator, the maximum available power in the wind can be obtained if theoretically the wind speed after the rotor is reduced to zero.

$$P_{max,\ theo} = \tfrac{1}{2}\rho A V^3 \qquad (1)$$

Where, ρ is the air density, V is the wind speed and A is the area where the wind speed is reduced. In practice it is not possible to reduce the speed of the wind after the rotor to zero using a wind turbine, so a power coefficient Cp.

$$P_{max} = C_p \tfrac{1}{2}\rho A V^3 \qquad (2)$$

The performance coefficient, C_p is a function of tip-speed ratio (TSR).

$$TSR = \frac{\omega_s R}{V} \qquad (3)$$

Where R is the radius of the wind turbine rotor (m) and the TSR is used by wind turbine designers to properly match and optimize a blade set to a generator.

Three blades having a blade radius of 1.36 m and performance coefficient C_p is 0.5 were taken for our investigation. For the chosen turbine details with a wind speed of 9m/s, the estimated output power is 1000W with a speed of 440 rpm and shown in the figure 1. given below,

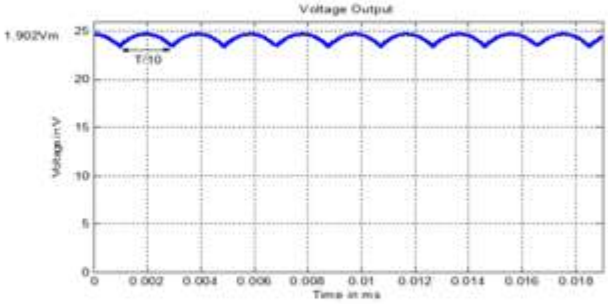

Figure 1: Fundamental five-phase output voltage

3. Design Configurations

a)Axial Flux Machine

Rotational motion can be obtained by swapping the orientation of the windings and magnetic field. In radial flux machines, the windings are oriented along the axial direction, and the flux flows in the radial direction. In axial flux machines, flux flows in the axial direction, and the windings are oriented along the radial direction as shown in Fig. 2. Because of their flat appearance, axial flux motors are informally called pancake motors. Figure 2-a shows a view of a rotor with magnets of alternating polarity. These magnets produce axial flux that interacts with windings in radial slots such as those shown in Fig. 2-b. In many applications, one rotor is mated to one stator as shown in Fig. 2-c.This configuration is simple but unbalanced. In addition to torque, this configuration exhibits very high axial force because the rotor magnets attempt to close the air gap. By converting the rotor yoke into a second stator as shown in Fig. 2-d, the rotor forces are balanced. This configuration sandwiches one rotor between two stators, and as a result, improves motor performance.

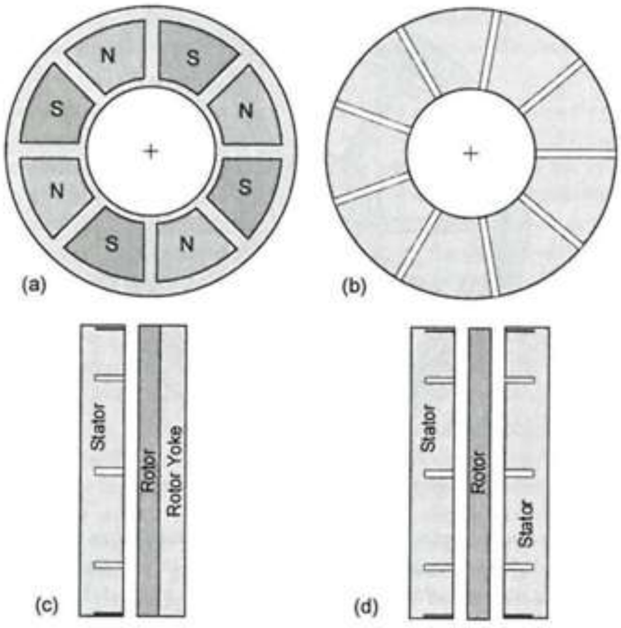

Figure 2: Axial Rotor Motor

Beyond special applications such as floppy disk spindle drives, the axial motor has not found widespread use. The primary reason is stator construction. Because flux flows axially, the stator must be laminated circumferentially. That is, the stator is often constructed by winding a ferromagnetic ribbon concentrically.

This construction orients slots at ever increasing distances from one another. As a result, this significantly increases stator manufacturing time and cost. This is much different than the laminations for the radial flux motor, where the slots are cut as part of the lamination stamping process. The axial flux motor has found use as the spindle motor for removable media computer drives because of the space constraints. In these applications, the stator windings are mounted directly on a printed circuit board, eliminating the troublesome laminated stator. Motors constructed in this way are often called printed circuit board motors.

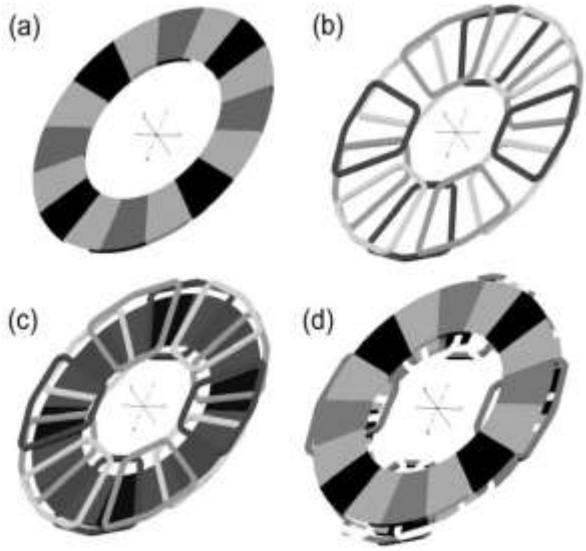

Figure 3: Construction of a five-phase, 8-pole AFPM brushless machines with PMs arranged in Halbach array: (a) PM ring; (b) stator winding; (c) one half of the twin rotor; (d)stator winding and complete twin rotor.

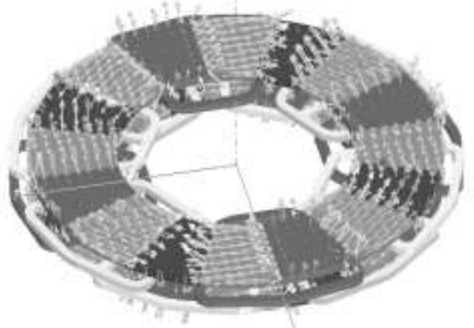

Figure 4: 3D magnetic flux density distribution excited by an 8-pole twin rotor with PMs arranged in Halbach array.

If a low speed, PM generator is required, it would be wise to consider an axial rotor design. This is particularly true if zero cogging torque is desired Also the axial permanent magnet machine has a large outside diameter which does not always suit wind turbines. If a high-torque, low speed machine is required, then an interior-rotor design would be appropriate. In addition, it has a smaller diameter, is more compact and can be easily connected directly to wind turbines or through a gear-box. In this research an interior rotor is selected as it is easier to manufacture using the traditional machine manufacturing processes that were available for this research.

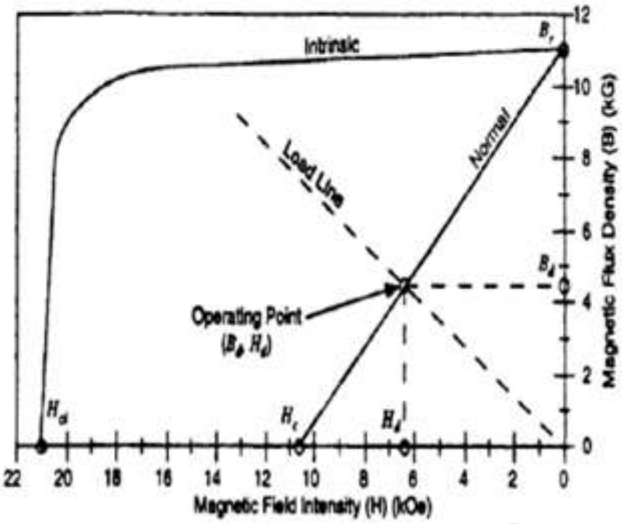

Figure 5: Demagnetizing B-H Curve

From the demagnetizing curve the flux density of the magnet is measured theoretically. Shown in the figure 5. above, in order to achieve output voltage from the five phase generator the Back EMF has to be calculated. The five-phase machine was to have an output phase voltage of 24V peak. The required no-load line back emf for the five-phase generator is then, shown in below Figure 6. Phasor diagram for five phase system,

$$V_L = 1.902 V_{ph} \quad (4)..$$

$$V_{ph} = 13.0 \ V \quad (5)..$$

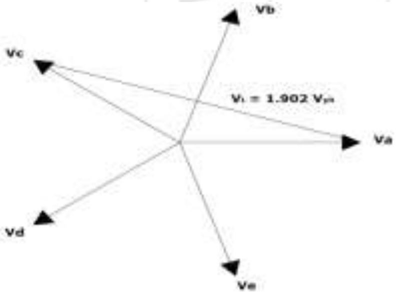

Figure 6: Phasor diagram for five phase system

The phase back emf constant k_e at a speed, of 440rpm, is calculated for five phase systems,

$$K_b = \frac{V_L}{\omega} \text{ (V/rad/s)} \quad (6)$$

For a given volume of the generator for radially oriented permanent magnet flux distribution, the output power is relation as given by the equation,

$$T\omega = K^2 Dl = EI \quad (7)$$

The electro motive force (emf) developed by the generator is given by,

$$EMF_{per-phase} = BlVN_{ph}\omega \quad (8)..$$

b) Cogging torque

Cogging torque describes the interaction of the rotor magnets acting on the stator teeth or poles independent of any current. Mathematically this torque was described as part of the general torque expression. While this torque is often considered beneficial in step machines, it is considered detrimental in brushless permanent magnet machines.

This dissatisfaction with cogging torque often lacks quantitative support. One of the first things engineers invariably do when they pick up a small machine is to spin the shaft with their fingers. The pulsations felt during this process are caused by cogging torque. In comparing several machines based on this qualitative examination, engineers will judge the one with the least cogging torque the best, even if it performs the worst in the actual machine application. In reality, cogging torque is often very small relative to the beneficial mutual torque produced by a machine. Furthermore, even a slight mismatch between the back EMF of the machine and the motor current often produces greater ripple torque than the cogging torque itself. In this situation, cogging torque is masked by the larger torque variation in the mutual torque. As a result, the qualitative shaft spin test is often misleading. Despite the insignificance of cogging torque in many applications and in the presence of mutual torque ripple due to back EMF-current mismatch, cogging torque is a motor characteristic worth understanding. Simply put, cogging torque is the torque created when the rotor permanent magnets attempt to align themselves with a maximum amount of ferromagnetic material. This is visually obvious for simple structures such as that shown in Figure 7.

But is more difficult to visualize for common machine structures despite the fact that the same fundamental phenomenon is occurring. To understand cogging torque, consider the cogging torque term from Cogging torque can be reduced by many methods skewing is one of the major method used in the reduction of cogging torque.

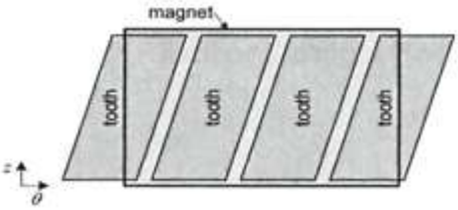

Figure 7: Skewed Stator slots

4. Five Phase Bridge Rectifier

The five-phase full-wave diode bridge rectifier is attracting research, it represents a middle ground between the three-phase and six-phase versions.

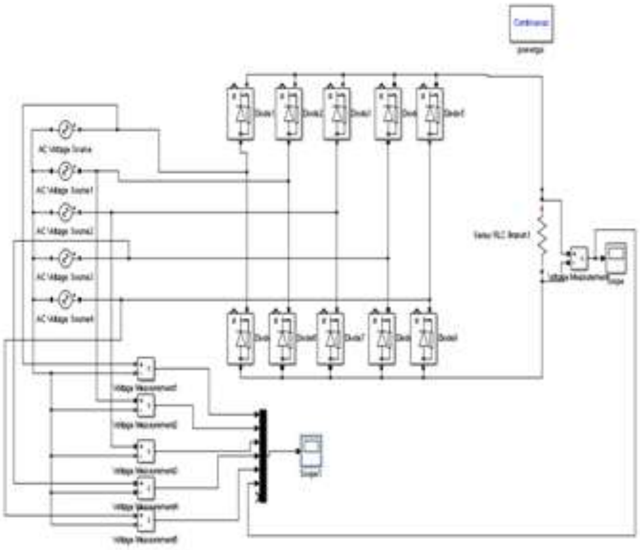

Figure 8.1: MATLAB/Simulink model offive-phase bridge rectifier

The advantages of the five-phase diode bridge rectifier when compared with three-phase are lower output ripple and rms phase current. The cost of diodes may be higher but the dc link capacitor requirement is lower leading to a potentially cheaper and more compact system. MATLAB/Simulink model is developed for the five phase permanent magnet generator their parameters of voltage, frequency and phase angle. Analysed generator is connected to the diode bridge rectifier and simulation is carried out for the given output voltage.

The output of the five phase bridge rectifier shows that the rectified output voltage has 1/10th of fundamental frequency and showin below figure 8.2.

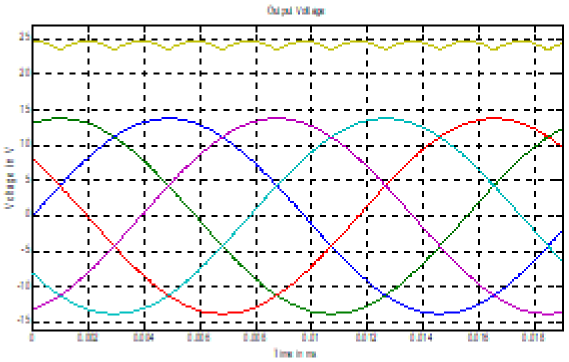

Figure 8.2: Output voltage of five- phase bridge rectifier

From the output voltage waveform, it shows the ripple voltage will be around 5.3%, but in three phase system the ripple will around 17%, which realizes a less ripple voltage than the three phase system and show figure 8.3.

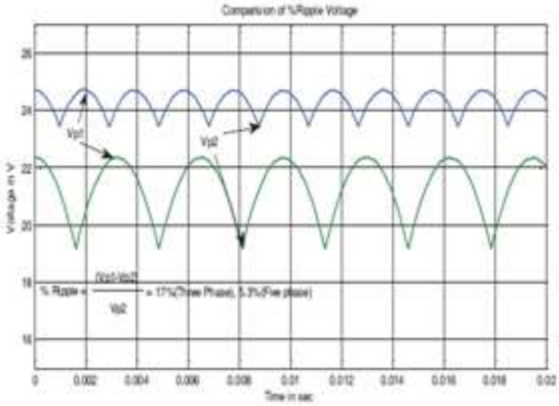

Figure 8.3: % Ripple Voltage

5. Conclusion & Future Enhancement

Analysis of five-phase axial flux permanent magnet BLDC machine for domestic wind turbine application has been investigated. The benefits of five-phase technology with bridge rectifier, is realized using MATLAB/Simulink. The output of five phase system shows reduction in ripple voltage than the conventional three phase system. The radial flux permanent magnet generator has a setback of very low speed applications because, the presence of cogging torque. This can be overcome by using an axial flux permanent magnet generator which has no cogging torque and have more advantage than a radial flux generator. For further development work the axial flux generator is chosen. Generator hardware model will be produced in the next phase of work.

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