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ANALYTICAL DESIGN OF AXIAL FLUX PMG FOR LOW SPEED DIRECT DRIVE WIND APPLICATIONS

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ABSTRACT

The dual rotor and single stator axial flux machine has been designed theoretically. The conventional radial flux machine is used before the invention of axial flux topology. The conventional topology is having lot of demerits such as large weight, core losses, length, and cooling system. The stator used here is a slot less stator. Because of the elimination of slots and iron part in the stator, Hysteresis loss and cogging torque of the machine is completely avoided. So the machine performance can be improved. The attractiveness of the permanent magnet generators is further enhanced by high energy permanent magnet materials like NdFeB.

Keywords – NdFeB 48, Dual Rotor, Axial Flux, Remanent flux,BH-Curve

I. INTRODUCTION

A wind turbine generator can convert kinetic energy from the wind to electrical power. It can also be called as an aero foil powered electricity generator.). Micro and small wind turbines are usually mounted on towers so they are exposed to more expected wind with a higher average speed. Small wind turbine systems, with a capacity ranging from 50W to 10kW and rotor diameter ranging from about 0.5m to 7 m, are primarily used in domestic and battery charging applications. Wind energy conversion system is has two types of generators. They are geared generators and direct driven generators. Now-a-days geared systems are replaced by direct driven systems because of its advantages like reduced cost of drive train and losses associated with energy conversion. The small wind turbines with permanent magnet generators can readily deliver power without undergoing the process of voltage buildup and no danger of loss of excitation.

II. PERMANENT MAGNET MACHINES

Permanent magnet machines are nothing but; it is having Rare earth magnets on either stator or rotor. The reduced weight of the magnet when compare to the coils; helps to place the magnets at rotor. By this cause we can be achieve higher speed than the speed obtained if coils are placed at the rotor. There are major three types of machines comes with permanent magnet configuration,

- Radial flux machines.
- Axial flux machines.
- Transversal flux machines.

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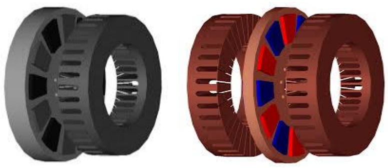
III. AXIAL FLUX MACHINES

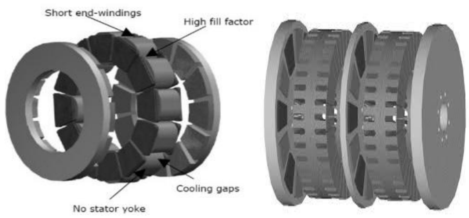
The axial Flux machine topology is offers greater performance in simple structure. Its operation is same as radial flux machines but its stator and rotor arrangement is axial direction. In Radial flux machine the air gap cannot be adjusted easily. Producing of vibrations and noises are quite high. This is high mass to torque ratio. But it has a large length, so place need for install the radial flux machine is large. There is a core Presents in a stator so eddy current loss, iron loss, saturation problem will rise.

IV. VARIOUS TOPOLOGIES OF AXIAL FLUX MACHINE

Axial flux machines are different from conventional machines in terms of the direction of the flux which runs parallel with the mechanical shaft of the machine. Axial flux machines are classified with their stator rotor arrangements. a slot less axial machine has the advantages like easy construction, no torque ripple and thus ensures the zero cogging torque. We can also achieve many possible topologies.



(a) (b)



(c) (d)

Fig 1: (a) single stator single rotor (b) dual stator single rotor (c) dual rotor single stator (d) multi stator multi rotor

V. DUAL ROTOR SINGLE STATOR

The slot less single stator double rotor is a typical structure of slot less AFPMG, which is often referred to as torus machine. Here the Slot less stator topology is used. By that arrangement we can reduce overall losses which is arises by core on stator, not only these advantages, the weight of the machine also can be reduced. The coreless coil wounded stator is placed between the rotor discs. These coils are hold by Epoxy resin. The machine stator is coreless and it consists of three phase winding in a trapezoidal coil shape by means of concentrated coils. The Leakage and mutual inductance in slot less air-gap windings are lower, and also effects due to slots, like flux ripple, cogging torque, high-frequency rotor losses and stator teeth, are eliminated.

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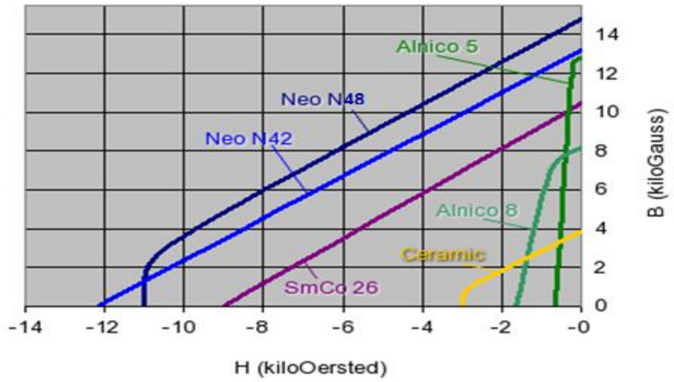
VI. SELECTION OF PERMANENT MAGNET

Many types of permanent Magnets are available in market such as ceramic, alnico, smco and NdFeB. Each type



made up of different materials, different strength and different remnant flux density.

Fig 2: various demagnetization curves for various types of magnets

The selection of permanent magnet is very important. The Magnets selected with its "BH" curve. The selection of Magnets should have large Demagnetizing value. Table (1) shows NdFeB magnets is having better remanent flux density and this type of magnets classified as three categories with respect to its withstanding capability at various temperature.

TABLE 1: Remanent Flux density (B_r) for various types of magnets

Magnet materials	Remanent flux density (B_r)	Temperature in Celsius
Ceramic	320	400
Alnico	560	540
Smco 1,5 (samarium cobalt)	770-860	260
Smco 2,17 (samarium cobalt)	830-980	350
NdFeB N (Neodymium Iron Boron)	1380	80

VII. DESIGN CONSIDERATION AND ASSUMPTIONS

In this section, an analytical design method is derived for the proposed three phase axial flux generator. It is important that the variables chosen for the design calculations are independent. The variables are summarized in

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table 2 and 3. Six variables are used as design variables. These variables can be used to calculate generator designs of different rated power and temperatures of the winding.

TABLE 2: Constants and Assumptions

Air gap	1 mm
Mechanical clearance	3 mm
Cut in Speed(m/s) (obtained from average wind velocity)	2.5 m/s
Frequency	50 Hz
Fill factor	0.7
Winding factor	0.955
Remanent magnetic flux density	1.37 T
Coercive field strength	1035 A/m
Machine efficiency	0.9

TABLE 3: Design Variables for Generator Design

Design variables	
T_m	Thickness of magnet
W_m	Width of magnet
L_m	Length of magnet
T_s	Thickness of stator
G	Mechanical clearance
L_g	Airgap length

VIII. DESIGN EQUATIONS

$$F = \frac{B_{mg}^2 A_m}{2\mu_0} \qquad (1)$$

Where F is force in Newton's, A_m is cross section of the area pole (m^2), B is magnetic induction exerted by the magnet, μ_0 is permeability of air.

μ_0 = Vacuum permeability = 1.257×10^{-6}.The magnet pole area A_m can be written in terms of the dimensions of the permanent magnet.

$$A_m=2\,(L_m W_m + L_m T_m + W_m T_m) \qquad (2)$$

Where L_m the length of the magnet is, W_m is the width of the magnet, T_m is the thickness of the magnet.

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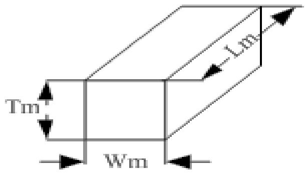

Fig 3: Magnet Parameters

Thickness of stator is calculated from thickness of magnets used and it is expressed in equation (3) ,
Where, Frequency = 50Hz.

IX. STATOR DESIGN:

The coils are connected in three phase system using star connection. The coil number Q can be calculated from (9) and thus the proper pole pair to coil combinations for creating a three phase system has

$$P_{out} = 3 \times E_t \times I_{ac} \times \cos\varphi \qquad (17)$$

been calculated. Number of Stator coils per phase is calculated using equation (10), Cutin speed and nominal speed are calculated By equation (11), The number of turns per coil Nc is calculated from (12), Where K_w is a winding coefficient equal to 0.95, q is the number of coils per phase, n is the RPM at cut-in and Number of turns per coil, E_f is the corresponding induced EMF voltage during cut-in

$$\frac{2Q}{3P} = 0.5 \qquad (9)$$

$$q = \frac{Q}{3} \qquad (10)$$

$$n_{cutin} = \frac{60}{2\pi}\frac{v_w \lambda_{opt}}{r_{turb}} \qquad (11)$$

$$N_c = \frac{\sqrt{2}\, E_f cutin}{q\, 2\pi\, K_w \Phi_{max}\, n_{cutin}\, {}^{p}/_{120}} \qquad (12)$$

$$I_{rms} = \frac{I_{ac.max}}{\sqrt{2}} \qquad (13)$$

The RMS Alternate Current of the generator is calculated from the equation (13),
The terminal voltage can be expressed in equation (14),

$$E_t = \frac{q}{a}\frac{2\sqrt{2}}{p} w_e B_p N_c r_e l_a K_{pc} K_d \qquad (14)$$

The phase current I_{ph} can be calculated from the equation (15)

$$I_{ph} = \frac{P_{nom}}{\sqrt{3}\, E_t} \qquad (15)$$

X. COPPER LOSS CALCULATION:

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Stator winding loss also known as I^2R, copper or joule loss is generated when the armature windings are excited by an external source. If the chosen copper conductors are sufficiently thin, the skin effect is negligible and hence, I^2R can reasonably assume to be frequency independent.

I^2R loss is described in the equation (16)

$$P_{cu} = 2\, N_c I_{ph}^2 \rho \frac{l_{eff}}{S_c} \qquad (16)$$

Where, N_c is Number of turns per coil, I_{ph} is phase current, ρ is electrical resistivity of the copper, S_c is cross-sectional area of wire, l_{eff} is the effective length of the machine which is equal to l_a.

XI. OUTPUT POWER AND EFFICIENCY CALCULATION:

Output power of the generator can be calculated from the equation (17)

Where, E_t is the terminal voltage of the machine, I_{ac} is ac current and power factor taken as unity.

Input power of the generator can be calculated from the equation (18),

$$P_{in} = P_{out} + P_{cu} + P_{eddy} \qquad (18)$$

Load resistance of the axial flux generator is calculated from the equation (19)

$$R_L = \frac{P_{out}}{I_{ac}^2} \qquad (19)$$

Efficiency of the generator can be calculated from equation (20)

$$\eta = \frac{P_{out}}{P_{in}} \times 100\% \qquad (20)$$

$$\text{Power density} = \frac{4P_{out}}{\pi\, D_{tot}^2\, L_{tot}} \qquad (21)$$

XII. ANALYSIS AND RESULTS

Peak air gap flux density has direct relation with airgap flux density. Increase in airgap length decreases the air gap flux density, this cause the decrease in eddy current of machine. In contrary with copper loss, eddy current loss in the conductor has inverse relation with the air gap

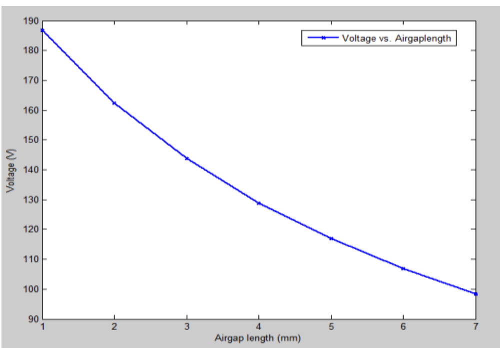

Fig.5 voltage

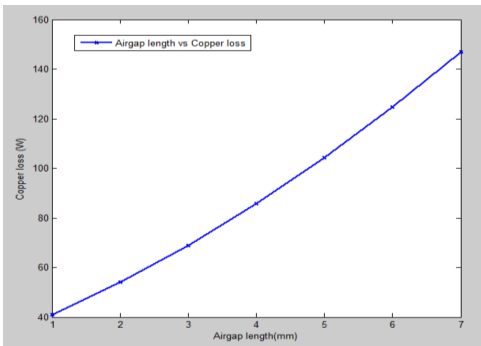

Fig.6 Current

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Efficiency of machine is determined from the power output and power input; The output power of the generator in equation (17) is changed, if there is change in the terminal voltage and maximum current which are depicted in equations (15) due to airgap length.

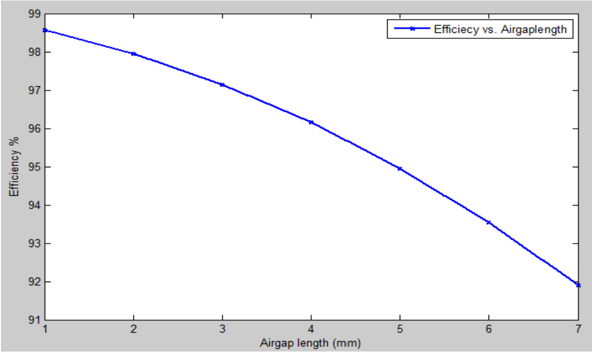

Fig 7: Efficiency as a function of the airgap length

Figure 7 shows that in the low speed AFPMG, the efficiency smoothly decreases by increasing the air gap between stator and rotor. This reduction in efficiency is much greater in conventional machines.

TABLE 4: Effect of change in Air gap Length

Airgap length	**Copper loss**	**Efficiency**
Airgap length increases	Increase	Decrease
Airgap length decreases	Decrease	Increase
Airgap (mm)	Copper loss(W)	Efficiency (%)
1	40.9	98.56
2	53.99	97.94
3	68.93	97.14
4	85.70	96.14
5	104.28	94.94
6	124.69	93.59
7	146.93	91.91

Power density is the amount of power per unit volume. Change in air gap length influences the output power of the machine as well as the power density.

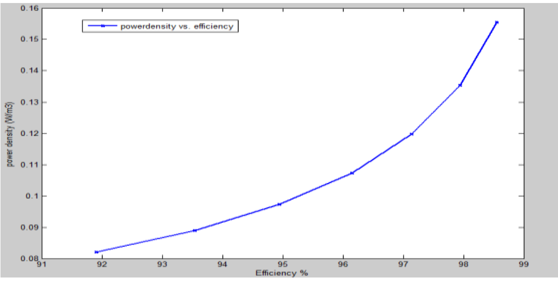

Fig 8: Relation between Power density and Efficiency at a nominal speed

TABLE 5: Power density optimization as a function of air gap length

S.No.	Airgap length (mm)	Power density (W/cm^3)	Efficiency %
1	**1**	**0.155**	**98.56**
2	2	0.135	97.94
3	3	0.119	97.14
4	4	0.107	96.14
5	5	0.097	94.94
6	6	0.089	93.59
7	7	0.082	91.91

The table 5 shows that the maximum power density and efficiency are achieved at an air gap length of 1mm.The various parameters of the developed 3kW axial flux permanent magnet machine were analyzed. The parameters are plotted in graph and their corresponding inferences given below. The developed EMF of the generator is directly related with speed of the turbine in direct coupled systems. The speed of the rotor and turbine are same. With the increasing speed, the rate of change of flux linkage with the stator coil gets increased, so the EMF developed in the concentrated stator coil is also increased. Figure 9 shows the relation between speed and induced voltage in stator winding.

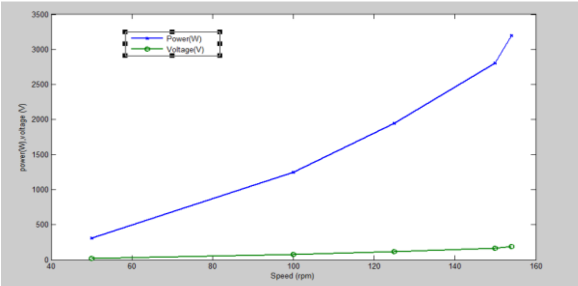

Fig 9: Voltage and power

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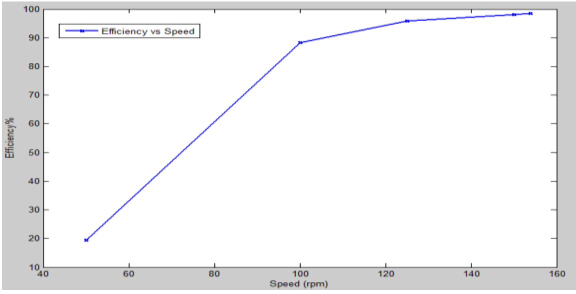

Fig 10: Efficiency

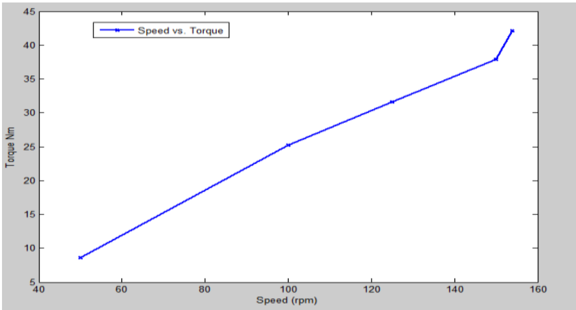

Fig 11: Torque of 3kW machine as a fucntion of generator speed.

In figure 10 the variation of efficiency versus speed is depicted. It shows the rise in efficiency with increase in speed. The efficiency reaches to 98 % at 154 rpm. Because of no core losses, the efficiency of coreless machines is higher than the one for the machines with iron cores. The use of concentrated winding decreases the need of large end windings and its associated joule losses.

TABLE 6: Specification of AFPMG

Specifications	Value
Rated Output Power,kW	3
Rated Voltage,V	184
Rated Speed, rpm	154
Number of Pole pairs	36
Number of phase	3
Frequency,Hz	50

TABLE 7: Electrical Design Parameters for AFPMG

Parameters	Values
RMS current value	5.7A
The Copper loss	40.8W
The output power	3000W
The Efficiency,%	98

XIII. CONCLUSION

This Axial Flux Machine is directly couple to wind turbine. This wind turbine is especially for urban areas. In Urban areas wind velocity is very less. So above machine design offers to get 3kW power from week wind. This wind is captured from long blade which is get from Blade optimization technique. The Higher grade NdFeB is used; so we can get greater flux from these magnets, not only this magnets also having less weight. Because of less weight, durability and vibration is very less. Place requiring for install it is very less. It can be mounting on roof tops. The absence of stator core is helps to eliminate hysteresis loss.

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