Optimal Generator Design For Gearless Wind Turbine

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1 INTRODUCTION:

Both induction and synchronous generators can be used for wind turbine systems [1]. Mainly, three types of induction generators are used in wind power conversion systems: cage rotor, wound rotor with slip control and doubly fed induction rotors. The last one is the most utilized in wind speed generation because it provides a wide range of speed variation. However, the variable-speed directly-driven multi-pole permanent magnet synchronous generator (PMSG) wind architecture is chosen for the prototype. Generator in this turbine offers better performance and overall higher efficiency [8]. It requires less maintenance because it does not have rotor current. What is more, PMSG can be used without a gearbox, which implies a reduction of the weight of the nacelle and reduction of costs.

1.1 Betz's Law:

It is the limitation in designing and extracting power from wind turbine. It is derived using laws of conversation of mass and momentum of a fluid. This constant number shows the maximum amount of mechanical work done by the wind in any turbine. According to the Betz' law, no wind turbine can extract more that 59.3 % of kinetic energy in wind. This law is very important, because no matter how devious or clever the turbine design is, under even ideal case only 16/27 (0.593) power coefficient factor can be achieved. Reason is kinetic energy of the of blowing wind is when transferred to hitting side of blade, wind is obviously slowed down after losing energy to blade and slowed wind moves behind the blade. If 100 % utilization was possible, it would mean 100 % extraction of kinetic energy from the wind and after extracting all the energy wind will stop blowing behind the blade.

1.2 Energy of wind and its absorption by blades

Wind speed is changing over time so the energy a turbine can yield from the wind also varies. For such variance we use instantaneous power to calculate the output power of turbine by adding small chunks over time. When wind hits the blade its kinetic energy is converted into mechanical energy. Power coefficient: It is the very important description and it shows the actual mechanical power produced with reference to the total available power of the wind. For this reason it is also known as the coefficient of performance. Mathematically it can be expressed:

C_p = Mechanical power generated / total available wind power

Where, total available power available is the wind power passing across the area of blades that is swept directly. And total available power available is the wind power passing across the area of blades that is swept directly. Amount of Power that can be absorbed by the Wind Turbine is:

$$P = 1/2 \times C_p \times \text{Air Density} \times A \times v^3$$

Where C_p = Power Coefficient
A = Swept Area of the turbine (Blades)
V = Wind Speed
Also the total power available in wind is given by:

$$P_w = c_P \frac{1}{2} \rho A v_w^3 \quad (1)$$

1.3 Tip Speed Ratio (TSR):

Tip speed ratio is the principle cumulative aerodynamic effect of the wind speed, rotor size and rotor's angular speed with taking into account the power coefficient of the turbine. It thus becomes the very important and convenient scaling parameter. There is tangential component of the drag which is responsible for the rotation of the blade and thus conversion of kinetic energy.

2 OPTIMAL DESIGN:

There are different configurations of both Induction generator and Synchronous generator. Since certain design configurations are tailored for specific purposes, comparing two different topologies can seem like comparison of apples and oranges. But there can be certain features of a system that make it efficient and more feasible. Thus optimal design can be defined around universally agreed qualities. Optimal design should consider every single factor into account. It can be chosen in absence of better alternative and it guarantees to work most of the time. This paper discusses and concludes an optimal design based on the following qualities of design: cost-efficiency(small construction cost), little to no requirement of maintenance, simplicity in design, scalability in size, ability to operate at low speeds (no requirement for geared mechanisms), low flux leakage, small copper losses, minimum temperature rise of the machine and power-efficiency. Certain generator designs exhibit few qualities more than others but discussion below attempts to fulfill all the requirements of an optimal design.

3 DESIGN OF SYNCHRONOUS GENERATOR:

In synchronous generator rotor rotates at same speed as the blade of turbine. Synchronous generator is better than Induction generator when it comes to design of wind turbine. Magnetizing current is not part of the stator current. Synchronous generators built under configuration shown by this paper will have better efficiency/power factor as compared to Induction generators. Another key advantage of synchronous generator is that it can have longer air gaps since there is no threat of magnetizing current unlike induction generator where air gaps must be kept small to limit magnetizing current. As a matter of fact, in synchronous generator, longer air-gaps reduce the armature reaction and the synchronous reactance. Variable speed wind system equipped with synchronous generator is capable of meeting the aerodynamic requirements in the great range of speed [3]. To keep TSR at optimum level, the rotor speed changes proportionally to the speed of wind. It makes rotor speed independent of the load conditions. Wide range of speed from zero to rated speeds is very significant for control purposes.

3.1 Permanent Magnet Synchronous Generator:
Unlike induction generator which requires another source for excitation, PMSG is self excited. It eliminates rotor copper losses. Also no external power is needed and maintenance is eliminated by avoiding brushes, slip rings and rotor windings. Lower maintenance and lower cost are the main reason for using PMSGs for direct-driven VAWT with variable speed system. PMSGs can be designed in different ways by manipulating shape, position and orientation of magnetization direction [1].

3.2 Making PMSG suitable for Wind Turbine:
First of all number of poles must be increased [1] since in direct-drive wind turbine, operating speed is very low. Usually in PMSG number of magnets is kept same as number of poles. But higher voltages can be achieved by increasing thickness of magnets. Generally NdFeB magnets are used [2] which assure fairly constant open-circuit voltage while being 11-12 mm thick. This factor must be considered in designing PMSG and may induce the need to search for better magnetic material. Since in Direct-Drive Wind turbine gears are eliminated and thus RPM of rotor cannot be very high, since it's directly synchronized with blade speed; one way to obtain desired output while maintaining low speed is increasing number of poles in the PMSG. Mathematically it can be shown that if number of poles is increased from 4 or 6 poles to about 60 poles, regular 60 Hz in output power can be achieved with even low speed.

$$\text{Frequency(Hz)}= \frac{\text{Number of poles} \times \text{rpm}}{120}$$

For prototype, we only needed to charge DC batteries and we were going to rectify the output anyway so we did not head for 60 Hz and used 12 poles instead of 60. As Permanent Magnets are used in the Generator, one usual risk is to possibly lose the polarization of the Magnets, which is affected by magnetizing inductance. Since Magnetizing Inductance is inversely proportional to the square of number of poles, increasing number of poles as stated above will avoid that problem as well.

3.3 Radial Flux vs. Axial Flux:
Air gap orientation basically determines whether generator is radial flux or axial flux. If the air gap (between rotor and stator) is in the direction of radius in cylindrical coordinates, generator is said to be radial flux. Otherwise if the air gap is in the direction of length of generator in cylindrical coordinates, generator is said to be axial flux as shown in the figure 2. Radial-flux generator is better than axial-flux because it is simpler and cost-efficient and in axial-flux generator, size can be easily scaled to meet the requirement.

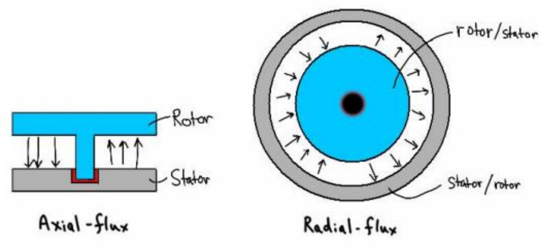

Fig. 2. *Direction of air-gap in axial-flux and radial flux*

3.4 Longitudinal vs. Transversal flux:
In transversal flux generator, plane of flux path and direction of rotor motion makes 90 degrees angle. One advantage of transversal flux is that magnetic loading and current loading can be adjusted independently. They are recommended for wind systems. Only disadvantage of PMSG with transversal flux is that it has high flux leakage and therefore poor power factor. To achieve lower flux leakage number of poles must be decreased since flux leakage and number of poles are inversely related which reduces the torque density. So Generator for the project has been designed with number of poles at the sweet spot between flux leakage and the torque density.

3.5 Outer rotor vs. Inner rotor in generator:
Rotor surrounds the stator in outer-rotor generators and in inner-rotor machine, rotor is closer to the shaft and stator winding surrounds it as shown in figure 2. In outer rotor generator rotor has higher radius than stator. Number of poles in outer rotor is generally higher for same pole pitch. One key advantage of outer rotor is that magnets are in full support against the centrifugal force and better cooling of magnets can be achieved. In inner rotor machine stator winding has higher copper losses and high temperature rise. In summary it is better for average generator (especially in wind turbines) to have stator winding closer to the shaft because it causes less temperature rise for same copper losses. Also magnets are in good support to centrifugal force and can cool easily.

3.6 Permanent Magnets Configuration :
There are also different topologies of PMSG depending on the arrangement of magnet on rotor. They are discussed as below: Surface mounted magnets [5] is the most basic and simple configuration where magnets are mounted on surface of rotor. They are also known as exterior magnets and they are glued or bandaged to the surface of rotor to sustain the centrifugal force. Magnets are usually magnetized in the radial direction. Construction of rotor in surface mounted magnet configuration is the easiest amongst all configurations so it is picked for the project wind turbine. Another configuration is inset magnets where the iron protrusions of rotor core are present where magnets are not present on the surface. These iron protrusion are called interpoles and cause saliency and inductance in all direction. Flux leakage is higher and is only used for its higher torque density. This configuration is not common in direct drive wind systems and should be avoided. Final configuration is

buried magnet or inner permanent magnet where magnets are magnetized in radial as well as circumferential direction. Burying magnets is a complicated process and prevention of flux from entering shaft is troublesome in itself. So it is also not the ideal configuration of magnets. So, simplest option is surface mounted magnets for PMSG which can prove to be efficient most of the time as compared to any other configuration. Surface mounted magnets are cost-efficient and feasible in the light of above discussion.

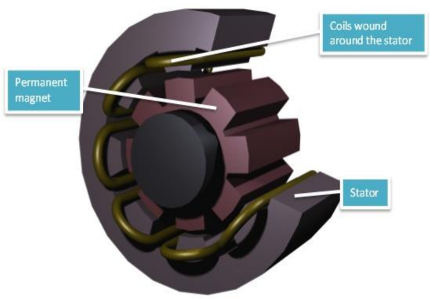

Fig. 3. *PMSG with inside rotor of Permanent Magnets*

4 WINDINGS:

Winding of generator can be divided into overlapping and non-overlapping winding. Over lapping winding can be further divided into distributed and concentrated. Non over-lapping winding is solely in concentrated way. Distributed winding is very popular in Brushless Alternative current machines. One key advantage is that it can give high winding factor when full pole pitch is chosen. Distributed winding is capable of giving smooth sinusoidal MMF. One disadvantage is long-end winding which are only to carry current from one coil to other. So long end windings are associated with copper losses and it is desirable to keep end windings as short as possible. Distributed winding also tends to have high production cost. Distributed winding should not be used if the size of machine is important parameter of design. For this purpose concentrated winding is chosen for building prototype and it is better choice for the construction of cost-efficient generator [4]. In concentrated winding coil is wound in concentrated manner around one tooth which has main advantage of having short end windings unlike distributed winding which has long end windings and cause copper-losses[7]. Concentrated windings show a very high fault tolerance in surface-mounted permanent magnets [6] which are already shown to better option in designing. Furthermore, concentrated winding limits high currents in short circuit conditions (by increasing leaking inductance and higher leakage inductance may be an advantage in this aspect). Voltage induced in stator has trapezoidal profile unlike distributed winding. One key advantage of concentrated winding is that coils are physically separated in a better way as compared to distributed winding, which is also desirable for better cooling of generator coils. Also synchronous generators with surface mounted magnets have little fluctuation in torque during each revolution (torque ripple).

5 READINGS:

Prototype was built in accordance with above research housing synchronous generator with following specifications: outer-rotor, radial flux, surface mounted magnets (NdFeB - 8 mm thick) and concentrated winding (12 coils with 40 turns per coil, wire gauge: 5.26mm^2). Results have been measured on different air speed using oscilloscope to measure voltage wave form and AC ammeter for deliverable current of generator. Blower type Air Gun has been used to mimic blowing wind against blades (1feet long and 5 inches wide). Tachometer available in the campus has been used for measuring rpm of the rotor at different wind speeds.

5.1 Voltage measurements:

Open-circuit voltage at different wind speed has been measured and corresponding rotor speed (rpm) has been noted down using tachometer.

Air speed(Blower)	***RPM***	***Voltage(V)***
9 m/s	300	28
4.7 m/s	150	13.8
2.1 m/s	70	8

Table 1. *Different Voltage levels at certain wind speed and rotor speed*

Fig. 4. *Voltage on oscilloscope with peak-peak value 8V*

5.2 Measurement of Short circuit currents:

Battery has been used for charging which draws current and ammeter is connected in series to measure maximum deliverable current of generator. Then Short Circuit Current has been measured at output terminal of generators using AC ammeter directly between the terminals. Figure 4 shows the maximum current draw from the generator output.

Fig. 5. *AC ammeter reading 0.4A*

Air Speed (Blower)	***RPM***	***Current I_L***
9 m/s	300	0.4
7.6 m/s	240	0.2
6.2 m/s	200	0.16
3.9 m/s	125	0.1

Table 2. *Current readings at different wind speeds*

6 MAXIMUM DELIVERABLE OUTPUT POWER:

Power output of the Generator (main generator for power generation) is calculated using the formula:

$$P_{out} = V_{rms} \times I_{rms}$$

We will consider the maximum rated values for calculating rated power of generator:

$$P_{out} = \frac{28}{\sqrt{2}} \times \frac{0.4}{\sqrt{2}}$$

P_{out} = ...att

6.1 Calculation of Power coefficient and its importance:

Power coefficient is very important in defining the capacity of turbine. It shows the power extraction of the turbine from wind and is important in defining the efficiency of turbine.

Mathematically:

$$\text{Power coefficient} = C_p = \frac{\textit{Output rated power}}{\textit{Wind power}}$$

Where wind power is equal to

$$P_w = (1/2)\, \rho\, A\, v^3$$

ρ = density of air (kg/m^3)
A_{swept} = area the wind is passing through the wind mill - perpendicular to the wind (m^2)
v = wind velocity (m/s)
ρ = density of air **1.225 kg/m** (At sea level and at 15 °C)
$A_{swept} = \pi \times$ rotor diameter $\times$ blade width
Rotor diameter = 0.6 meter
Blade width = 0.15 meter

A_{swept}=0.28m^2 (For this Prototype)

Velocity of wind = 9 m/s (for our rated measurements)

$$P_w = \frac{1}{2} \times 1.225 \times 0.6 \times 9^3$$
$$P_w = 267.9 \text{ watt (Joule / second)}$$

Thus $C_p = P_{out} / P_w$
C_p = 5.6/267.9
C_p =0.02

Importance of finding power coefficient of the turbine is that once power coefficient is known output power can be determined by simply knowing the wind speed.

$$P_{out} = ½\, C_p\, \rho\, A\, v^3$$
$$P_{out} = 0.007\, (v)^3$$

7 CONCLUSION:

This Research proposed a new generator design with low-cost configurations that is optimal for building small scale gearless turbines. Research focused on finding the optimal generator configuration that is cost-efficient and ideal for small scale wind turbines almost every single time. Paper concludes after thorough comparisons and investigations that Permanent Magnet Synchronous Generator with inner-rotor, radial-flux and concentrated winding is the optimal configuration for any slow speed operation (like direct-drive wind turbine). If low manufacturing/maintenance cost and scalability of generator size are the design factors, this configuration works on average more efficiently than any other model. On comparison with Induction Generator and different configurations of generator, it can be concluded that PMSG built in specific configuration proposed by this paper should be the first choice of any gearless turbine. Small Scale wind turbine (prototype built on this research) has 2% power coefficient while larger scale turbine with bigge…erator and better winding can efficiently extract powe… the wind and reach closet to Betz's limit under this p…ed design topology.

8 REFERENCES:

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