# DESIGN OF A SMALL SCALE WIND GENERATOR FOR LOW WIND SPEED AREAS

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**ABSTRACT:**
Most small scale level wind turbine generators are directly driven system, variable speed, and partially connected power electronic converter system. Choice of such system is to avoid costs associated with gearbox. However, due to low wind speed in most of the tropical countries, synchronous generators with smaller or medium speed Permanent Magnet (PM) generator design found to be important and given high performance efficiency. In order to be able to harvest wind energy in off-grid population efficiently, there was a need to design a synchronous generator that can be able to operate under low wind speed, directly connected to the end user. Hence, the study designed a six pole pair wind turbine generator using permanent magnet (PM) model, using Maxwell two dimensions (2D) and Rotational Machine Expert (RMxrpt) software. The designed PM AC wind turbine generator worked with efficiency of 93% at rotational speed (rpm) range from 50 to 350 with maximum power output of 980 watts.

**Keywords:** *Pole Pairs, Performance Characteristics, Permanent Magnet Wind Generator*

## INTRODUCTION
For wind power applications in particular, multi-pole permanent magnet generators have become very attractive especially in small ratings (Ocak 2012). Permanent magnet synchronous generators (PM AC) are one of the best solutions for small-scale wind power plants. Low-speed multi-pole PM generators are maintenance-free and may be used in different climate conditions. Potentially, permanent magnet generators offer a high efficiency in operational, simple and robust (Papathanassiou 1999). Basically, PM AC generators can be divided into internal and external machines, according to rotor direction in the air gap. The availability of modern high energy density magnet materials such as NdFeB, has made it possible to design special topologies (Rizk and Nagrial 2000). Most wind turbine generators currently installed in small scale levels are in directly driven system, variable speed, and partially rated power electronic converter. Choice of such system is to avoid the gearbox failures and leading to long downtimes, gearless full variable speed PM generators connected to the end user via a full rated power electronic converter are considered in several new installations. However, due to low wind speed in most of the tropical countries, synchronous generators with smaller or medium speed PM generator designs found to be important and given high consideration. In order to reduce the complexity of the drive train there are experimental proposals in literature where a synchronous generator that be able to operate under low wind speed can be directly connected to the end user

especially the off-grid population. Hence, the study designed a six pole pairs wind turbine generator using permanent magnet (PM) model and analysing it for small scale wind power harvesting at low wind speed area, using Maxwell two dimensions (2D) and

Rotational Machine Expert (RMxrpt) software.

## MATERIAL AND METHODS

### Permanent Magnet Generator Model

The Permanent Magnet Synchronous Generator (PMSG) is a machine whose excitation depends on the permanent magnet instead of the use of DC power. The excitation is normally associated with some losses, where for small machine excitation losses may reach up to 5 % (Ayehunie 2011). The PM synchronous machine is designed in such a way that the permanent magnets are in the rotor surface, where it is separated by the air gap with stator containing windings. The PMSG is very useful for wind turbine applications because it is smaller in physical size, has a higher efficiency and reliability and it also has high power output, though it lacks voltage control due to their constant excitation. This is one layout of PM generator, but there are several designs, like radial flux inner rotor, radial flux outer rotor, and axial flux. With reference to all these designs of PM generator, flux crosses the air gap from the rotor to the stator in the radial direction (Rucker 2005). This type of design is known as AC synchronous generator and this is as shown in Fig. 1.

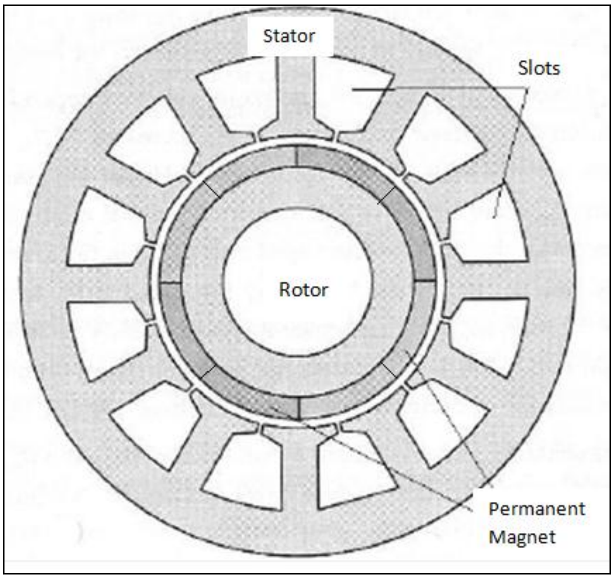



**Figure 1**: The configuration design of AC Synchronous wind turbine generator (*source:* Rucker 2005)

### Generator Performance Efficiency

Many authors have discussed several procedures and methods of finding the efficiency of the wind turbine generators and general performance of wind generator. The major consideration is the input mechanical power to the generator with the output electrical power and loss conditions of generator that can be determined from rotating speed of the machine (Tamura and Muyeen 2012). Both suggested that the efficiency of the generator can be determined using the ratio of total output power $P_o$ to the total input power $P_{in}$. The mechanical losses and stray load loss cannot be expressed in a generator equivalent circuit, but they can be deducted from the wind generator output. Wind speed was taken as mechanical input power to the system, where power produced were multiplied by the gearbox efficiency, but this should be for non-direct driven systems. The mechanical loss and stray loss were then deducted from the wind turbine output power. The external characteristic of the generator performance is considered as most important as it gives the relationship between the terminal voltage against output current and the resistive load (Guo et al. 2008). From the phase output equivalent electrical circuit of the generator shown in Fig. 2, the external characteristic can be derived as (Guo et al. 2008):

$$V = \sqrt{E^2 - I^2(\omega L_g \cos\theta - R_g \sin\theta)^2} - I_g(\omega L_g \sin\theta - R_g \cos\theta) \quad (1$$

where V is the terminal voltage and E is the back Emf. $I_g$ is the the load current, while ω is equivqlent to 2πf, which is angular frequency of the electricity. $L_g$ is inductance and $R_g$ is the phase resistance, while θ is the power factor of the load.

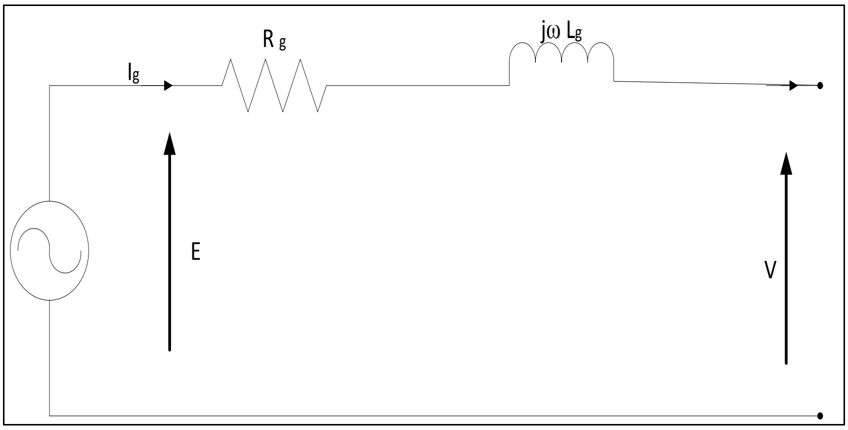



**Figure 2**: PM AC generator phase equivalent circuit

With reference to Equation (1), the external characteristics of the PM synchronous generator can be achieved when the load resistance is varied. During the variation of the load resistance the external behaviour of the current and voltage can be realised, which determine the generator characteristics. If the equivalent electrical circuit is considered, the electrical output power, the mechanical input power, input mechanical torque, and efficiency of the PM generator can be calculated per phase (Guo et al. 2008) as:

$$P_O = 3VI_g \cos\theta \quad (2)$$

Hence the total mechanical input power can then be computed as:

$$P_{in} = P_O + P_{cu} + P_{Fe} + P_{mec} \quad (3)$$

where $P_{cu}$ is copper loss, $P_{Fe}$ is iron loss and $P_{mec}$ is mechanical loss.
The efficiency therefore can be evaluted from equations (2) and (3) as:

$$\eta = \frac{P_{out}}{P_{in}}. \quad (4)$$

**Modeling and Simulation of Permanent Magnet Synchronous Generator**

Many softwares have been used to develop modeling the rotating electrical machines like generators. The most used softwares include Maple-software, HOMER software, Matlab, Gridlab-D Comsol and Maxwell. In this study Maxwell software was used in modeling the

PM AC synchrunus machine. This is premier electromagnetic field simulation software for scientists and engineers used in the designing and analysing 3-Dimension (3D) and 2-Dimension (2D) electromagnetic and electromechanical devices that includes generator, motors, actuators, transformers, sensors and coils (Liping 2012). The simulation model actually display the real situation in a simpler form, when the basic characteristics and the parameters of the machine are employed and analysed. In order to be able to use the Maxwell software, it is important to review the fundamental electromagnetic theories and application [9]. Some of these theorems includes the general theory of electromagnetic phenomena based on Maxwell's equations, which is a set of first-order vector partial-differential equations which relates the space and time changes of electric and magnetic fields to the scalar (divergence) and vector source densities. The Maxwell's equations in differential and integral forms that needed to be considered while dealing with Maxwell software includes Gauss' law of electric fields (Martin 2007):

$$\nabla.\vec{D}(\vec{r},t) = \rho(\vec{r},t) \qquad (5)$$

where ∇ is divergence, which is a vector operator, which measures the magnitude of a vector field's source or sink at a given point, in terms of scalar quantity.

Sometimes the divergence represents the volume density of the outward fluxof a vector field from an infinite volume around a given point and $\rho(\vec{r},t)$ is the macroscopic densities of free-charge or net magnetic charge density.

The designing was based in the Fnite Element Methodology (FEM) while the simulations was done to analyse the performance characteristics of the generator. The simulations involved the electromagnetic generator model and equations that represent electric circuit for the solution of finite element. The generator parameters were involved including the stator winding of the generator, which consists of circular cables and the rotor surface mounted, power, phase voltage, no load phase voltage, electrical current, electrical frequency, load resistance, load angle and overall efficiency.

The modeling that used the Maxwell Equation in 2D considered the assumption that the electromagnetic field inside the generator is axi-symmetrical. The effect of the 3D consideretion is such that it has effects like end region fields impedances in the circuit equations of the windings. The modeling developed involved the surface current source and the electromagnetic described by magnetic field and circuit equation from Maxwell's equation (Leijon et al. 2013):

$$\sigma \frac{\partial A_Z}{\partial t} - \nabla.\left( \frac{1}{\mu_o \mu_r} \nabla A_Z \right) = -\sigma \frac{\partial V}{\partial z} \quad (6)$$

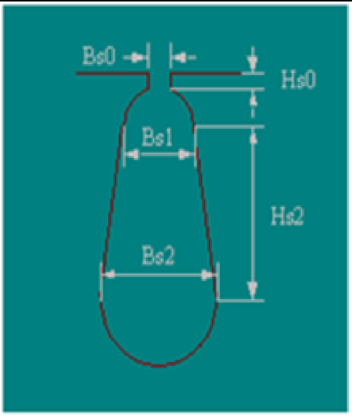
where, $\sigma$ is the conductivity, $\mu_o$ vacuum permeability and $\mu_r$ relative permeability, $A_z$ is the axial magnetic potential and $\frac{\partial V}{\partial z}$ is the applied potential.

**Permanent Magnet AC Synchronous Generator Design**

The general design of the PM AC Synchronous generator was based on the improvement of power output efficiency and to be able to operate efficiently in low wind speed area. The important generator parameters as an input to the maxwell software were as shown in Table1.

**Table 1: The locally PM AC generator parameter values**

| S/No | Parameters | Values (mm) |
|---|---|---|
| 1 | Rotor - Outer Diameter | 111mm |
| 2 | Rotor - Inner Diameter | 32 mm |
| 3 | PM magnet size | 10x30x47 mm |
| 4 | Rotor Length | 60 mm |
| 5 | Shaft Diameter | 32mm |
| 6 | Number of winding | 100 |
| 7 | Copper Wire Diameter | 1 mm |
| 8 | Number of Magnetic Poles | 6 |
| 9 | Air gap | 36 mm |
| 10 | Number of slots | 48 |
| 11 | Slots size | See Figure 3 |
| 12 | Stator - Outer Diameter | 198 mm |
| 13 | Stator - inner Diameter | 118mm |
| 14 | Core Pitch | 5 |




The slot size is as shown in Figure 3:

- BsO = 1.5 mm
- Bs1 = 5mm
- Bs2 = 8mm
- HsO = 1.5mm
- Hs2 = 25mm

**Figure 3** The Local Generator Slot Size

The designing considered fill factor, $\lambda_s$, wich is the extent that the conductor occupies the cross-sectional area on the slot determined the relation (Rucker 2005):

$$\lambda_S = \frac{Winding\ Area}{Total\ Slot\ Area} \qquad (7)$$

The impact of phase numbers can be realized in the power, current, and voltage ratings of the machine. For the fixed power, the phase number is proportional to the increase in voltage and the decrease in current or the increase in current and decrease voltage. In most cases higher phases are used more in generators than in motors due to connection to power electronics conversion form AC to DC and vice versa (Dogan et al. 2011).

Number of slots per pole and per phase is important parameter in generator design since it is used to determine the interactions relationship between the rotor poles and the stator windings. The fractional slot of the machine 'm' can be obtained through the relation (Rucker 2005):

$$m = \frac{N_s}{2pq} \quad (8)$$

where $N_s$ is number of slots, $p$ represents pole pairs and $q$ the number of phases.

The magnetic height and the air gap normally have the greater impact to the machine if not well designed, since they all affect the air-gap flux density ($B_g$) and hence induced voltage in the coils. The effect can easily be revealed in as (Rucker 2005):

$$B_g = \frac{h_m}{h_m + g_a} \times B_r \quad (9)$$

where $h_m$ is magnet height (mm), $g_a$ is air gap (mm) and $B_r$ is magnet remnant flux density *(T)*. **Figure 4 shows** Stator winding phase connections while **Figure 5** illustrates a 6 Pole Pairs Generator

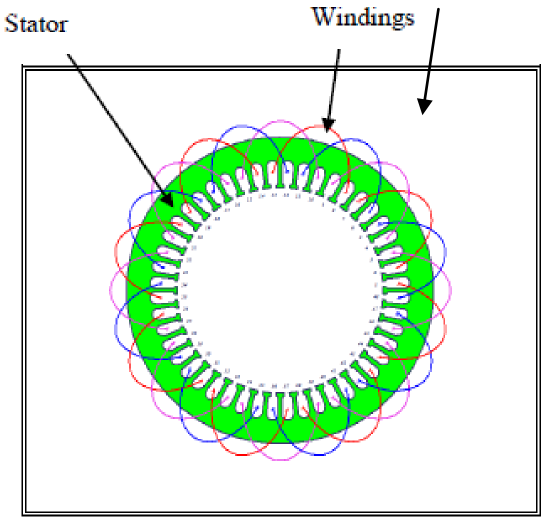



**Figure 4:** Stator winding phase connections

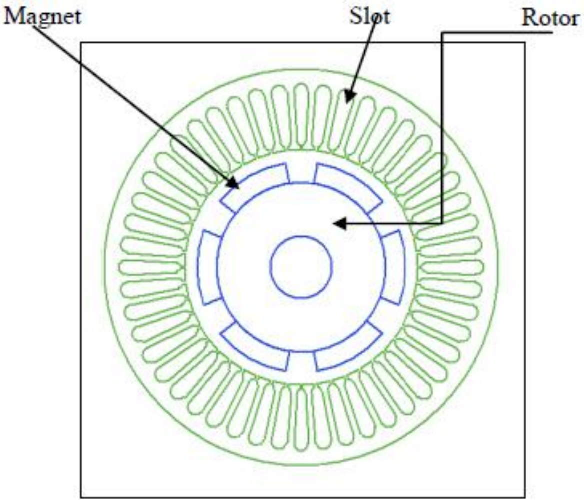



**Figure 5**: 6 Pole Pairs Generator

Therefore the air gap should be as small as possible to minimize the air gap flux density loss and also minimize the flux leakage which contributes to lower reluctance or permeance value. The magnet height is supposed to be larger than the air gap by a factor of 5 – 10 so as to have the uniform magnetic fields in the machine and when the number pole pairs increases, necessitate the decrease in magnet at the given constant value of power/torque. This can be expressed as (Rucker 2005):

$$\omega(2p) = 120 \times f \qquad (10)$$

where $\omega$ = angular speed (rpm), $p$ = number of pole pairs and $f$ = electrical frequency (Hz)

The operating temperature was selected 50 $^{o}$C and rated output power 1 kW was inserted to the model system. From the main menu 'Analyse All' was selected in the Maxwell RMxprt 2D Designed to run the simulation and give the results as proposed by the study, which was to have the improved efficiency generator in low wind speed areas. The designed PM AC Synchronous machine expected to work in high efficiency at rotational speed, starting from 50 rpm to 1300 rpm, which is equivalent to wind speed of 0.3 m/s to 7.8 m/s as converted through the relation (Kolar 2012):

$$Speed\ (Rpm) = \frac{60000 \times Speed\ (ms^{-1})}{\pi \times Rotor\ Diameter\ (mm)} \qquad (11)$$

The rotational speed was varied at the interval of 50 rpm (i.e. 50, 100, 150, 200…1300 rpm) where at each different rotational speed, the values of all parameters were recorded and the behaviour of the machine was examined. These parameters were recorded while running the new designed Generator at different angular speed at the state of Full Load Condition, whereas at the state of No Load, the parameters were computed by Maxwell software where the parameters were computed by the system. When all the required parameters were inserted correctly with some adjustment of some of them, the model simulation was run. The values from the state of No Load obtained as a result of the interaction between the magnetic field and the coil winding of the generator. These values were obtained before the simulation of the machine while the full load condition values were obtained during the simulation process. The design was repeated several times so as to minimize some errors.

## RESULTS AND DISCUSSION

The Maxwell 2D software and RMxprt output graph for the moving torque of generators is shown in Figure 6. The moving torque as observed the machine with 6 pole pairs decreased from zero to around -35 Nm and then increased to -32 Nm after which the moving torque tended to be sinusoidal.

Figure 7 shows winding current for the 6 poles generator as a function of time. The figure 8 shows that current in the winding of the machine changes from ± 22.8 A and then drops to ±18 A and continue in a smooth sinusoidal curve for all 3 phases. current loss in the windings seems to be very small that can be neglected.

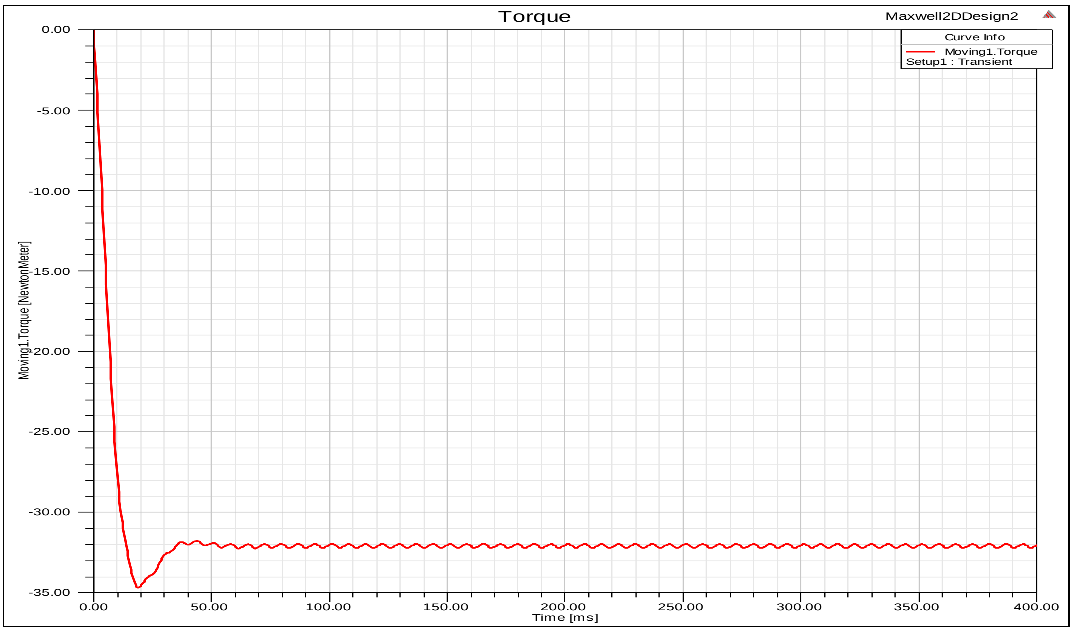



**Figure 6**: Moving Torque for 6 Pole PMG


**Figure 7**: Winding Current for 6 Poles PMG

Total loss of the optimum generator is shown in Figure 8 as given by the software. From the designing and simulation, it was noted that losses for few pole pairs machine are generally less than losses for many pole pairs machine.

At the beginning of motion, the losses of machine rose up to 1.38 kW and dropped to 0.76 kW within 30 ms of time and then fluctuated between averages of 0.8 kW and 0.85 kW.

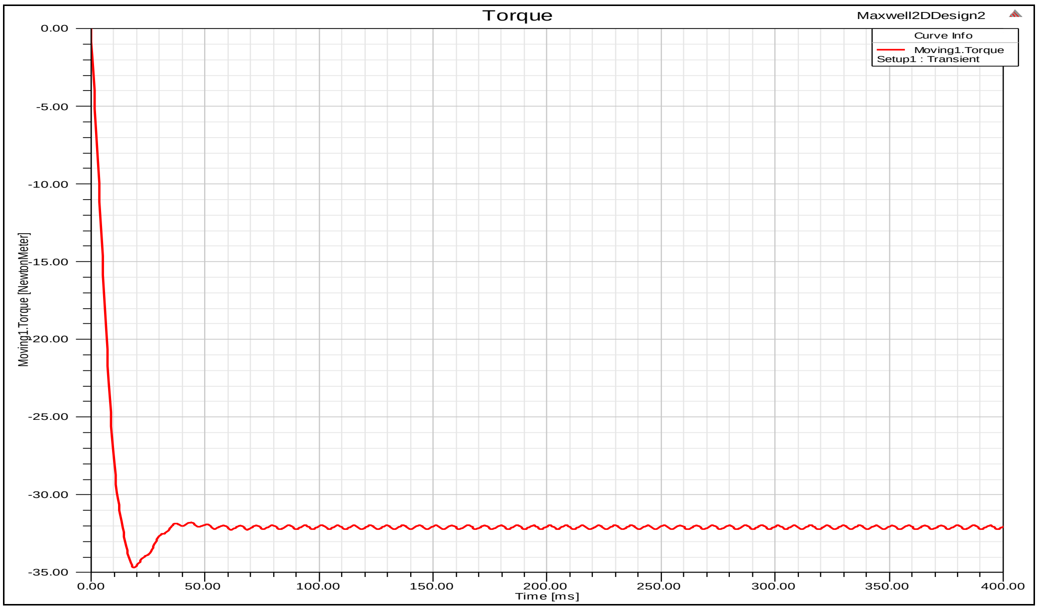



**Fig.ure 8**: Total Loss for 6 Pole Pairs PMG

Simulation results from RMxprt software showed the distribution of air gap flux density where the high total harmonic distortion (THD) of induced voltage as observed was 1.09 percent as shown in Figure 9. Such distortions might be due to some flux losses in the air gap as a result of size of space between the bar magnet embedded in the rotor surface.

Cogging torque for the optimised generator is shown in Figure 10. It can be noted that cogging torque is directly proportional to number of pole pairs of the machine. The generator with less pole pairs has small cogging torque, while the machine with high number of pole pairs has high cogging torque.

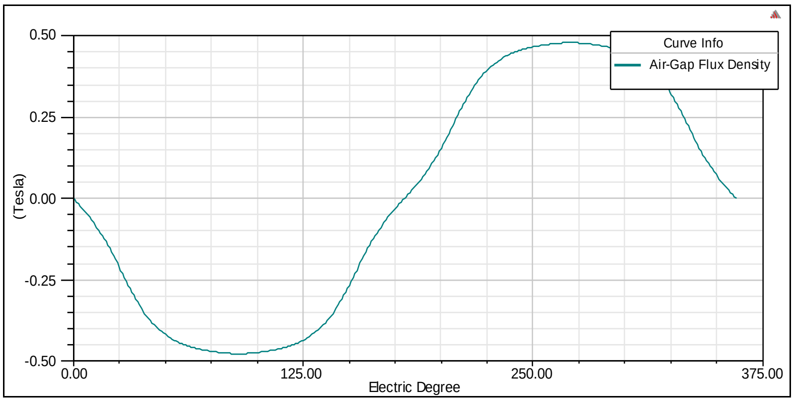



**Figure 9**: Air Gap Flux Density for 6 Poles PMG

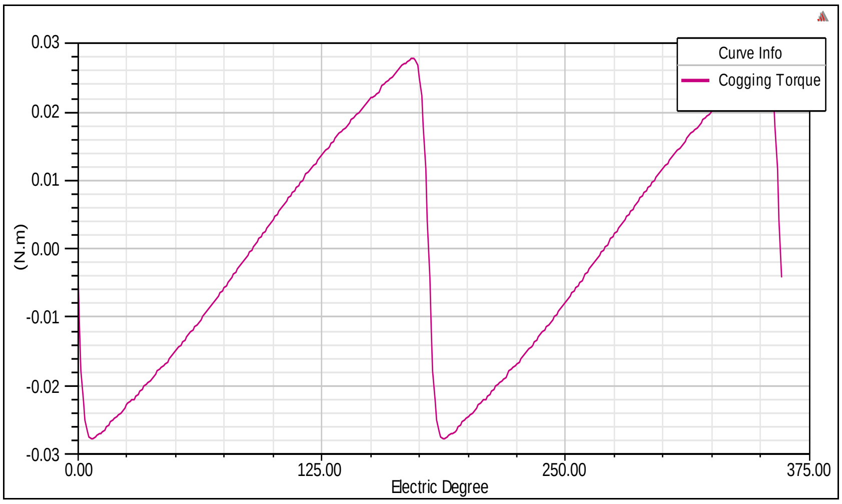



**Figure 10**: Cogging Torque for 6 Poles PMG

It is important to reduce cogging torque when designing the generator so as to reduce vibration of the generator during operations. Cogging torque interacts with magnetic flux at the air gap and the stator teeth, which create the periodic reluctance variations thereby causing the cogging torque to be periodic (Dosiek and Pillay 2007).

Figure 11 shows that there is no distortion observed in the phase voltage. The graph of phase voltage against electric degree shows that values of the induced voltage were ±70 Volts.

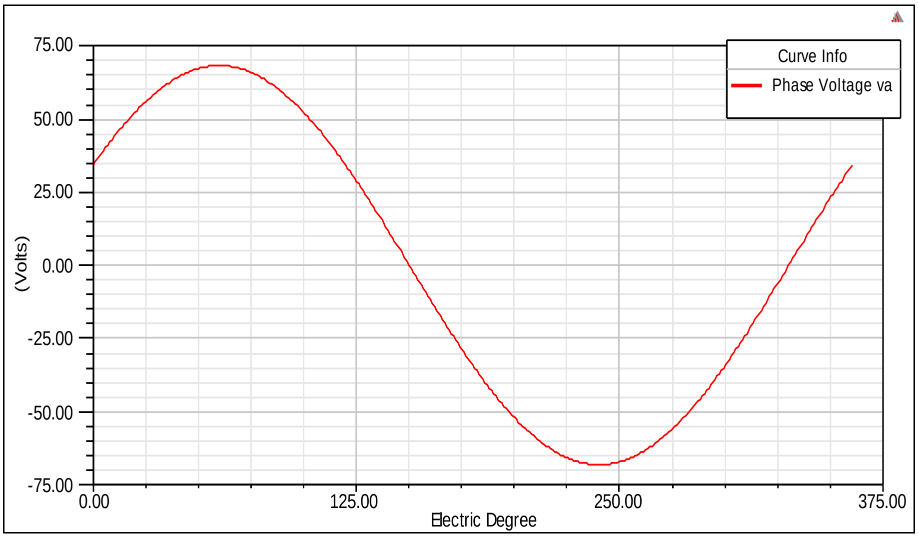



**Figure 11**: Phase Voltage for 6 Poles PMG

Distortion of line current was so small such that it could not be clearly observed as depicted in Figure 12, but the resultant current THD was easily noticed. The small distortion was seen in the 6 poles machine, but very little distortion was observed as pole pairs increases. Such distortion was due to wide space between magnetic bars, which cause cogging torque.

Generally, the fundamental standard of stator current waveforms can be expressed as (Sittisrijan and Ruangsinchaiwanich 2013):

$$I_{mh} = \sum_{n=1,2,\ldots}^{\alpha} I_n \sin(n\omega_e t + \theta_n) \quad (12)$$

where $I_n$ is a harmonic order of the peak current and $\theta_n$ is initial phase angle of the harmonic order phase current, ω is the angular speed and $t$ is time.

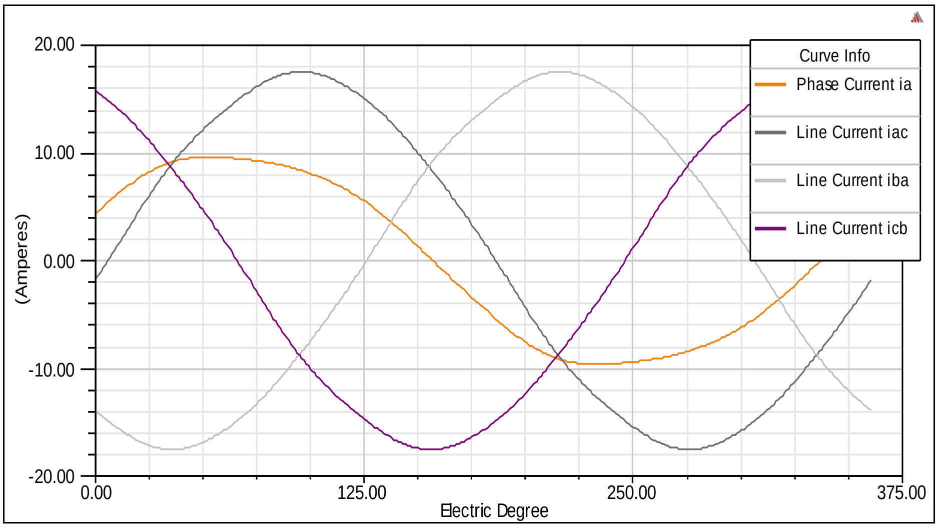



**Figure 12**: Phase and Line Current for 6 Poles PMG

When the stator current is unbalanced, stator current waveform becomes distorted, corresponding to the harmonic current spectrum where some percentage of the total harmonic distortion (THD) achieved at a certain level as shown in Figures 12.

Efficiency of the machines was computed by the software and eventually computed from the data generated by the software work sheet. It should be noted that efficiency of the machine is computed and presented in the graphs shown in Figure 13 by the Maxwell software. That was done under reference speed 350 rpm and rated speed of 1000 rpm. When there was change in reference speed, the graphs also changed till the highest value of efficiency where efficiency started to decrease slowly with an increase in rotational speed.

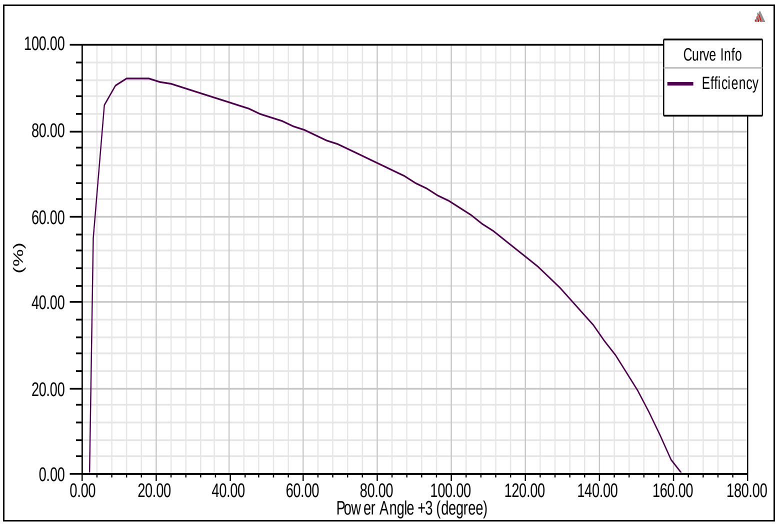



**Figure 13**: Efficiency for 6 Poles PMG

Efficiency of the designed generators was computed from data generated by the software during variation of rotational speed from 50 to 650 rpm for each machine. Output efficiency of the PM generator is presented in Figure 14.At 50 rpm, efficiency of the machine was 77.35 percent and at the 350 rpm efficiency of was 91.97 percent. With these values it can be concluded that the 6 poles machine works better at low wind speed as 8 and 4 pole pairs PMG (Rogers et a.l 2014).

Some of these parameters include power loss during the operation like friction loss, copper loss and iron core loss, torque and short circuit current. Figure 15 shows the loss of the 6 pole pairs machine, where by all the loss type are drown in the same graph. For detailed observation it can be seen that the big loss is contributed by the friction, while others contribute a small amount. At the low speed the friction loss is high and decreases with speed increase.

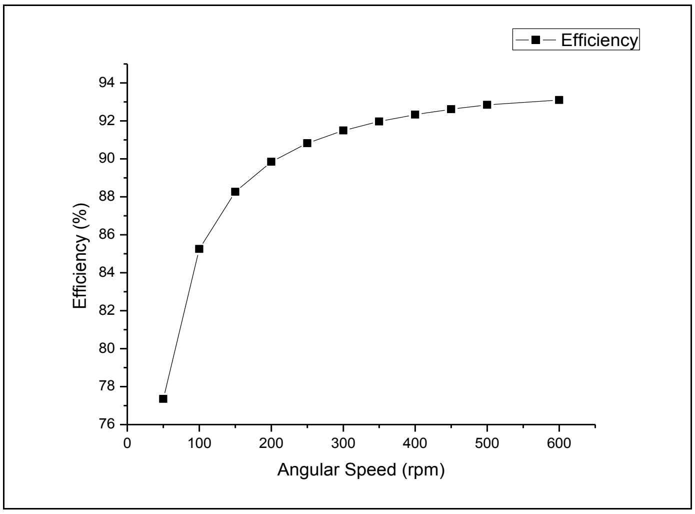



**Figure 14**: The output efficiency for 6 pole pairs PMG

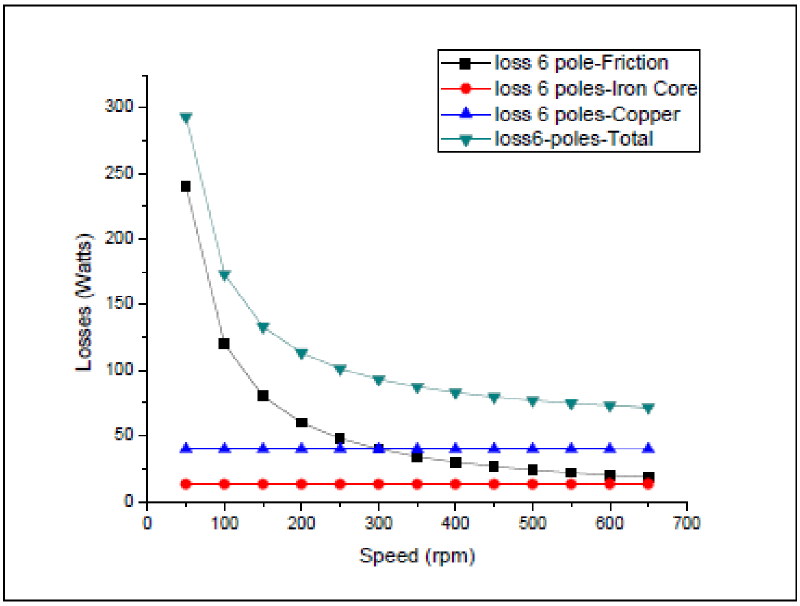



**Figure 15**: General loss information for 6-pole pairs generator

**CONCLUSIONS**

The expected output power of the designed generator was 1 kW, but it was observed that generator reached the maximum output power of 980 W at the rotational speed 350 rpm, which was the rated speed. From the rotational speed of 450 rpm, the generators produced the maximum power which is 1000 W, is at the equivalent to wind speed of 2.7 m/s. This concluded that the generators are good in terms of power output, though the machine can be improved further.

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