

## DESIGN AND FABRICATION OF RADIAL FLUX PERMANENT MAGNET GENERATOR FOR WIND TURBINE APPLICATIONS

\*M.M. ASHRAF, T.N. MALIK, S. ZAFAR and U.N. RAJA

Department of Electrical Engineering, University of Engineering and Technology, Taxila, Pakistan

(Received April 24, 2013 and accepted in revised form June 05, 2013)

Presently alternate energy resources are replacing conventional energy sources to produce electrical power to minimize the usage of fossil fuels. Wind power is one of the potential alternate energy resources and is being exploited and deployed actively. The wind energy system is basically composed of two core components: wind turbine and electrical generator. This paper presents the design and fabrication of permanent magnet generator for direct drive wind turbine applications. Radial flux permanent magnet generator (RFPMG) producing three phase alternating current voltage has been designed subject to satisfying the features of low operating shaft speed, higher power density, higher current density, cost effectiveness and compact structure. RFPMG design focuses on usage of neodymium permanent magnets for excitation instead of electromagnets to minimize the excitation arrangement challenges and losses. A 300 W prototype RFPMG has been fabricated. The performance of the generator has been evaluated on specially designed wind tunnel. The generator is directly coupled with wind turbine shaft to eliminate the gearbox losses. No load and load tests show that the performance of the machine is up to the mark. The improved design parameters of power density and current density are 73.2 W/kg and 5.9 A/mm<sup>2</sup> respectively. The same machine output has been rectified using bridge rectifier for battery charging application. The desired output voltages are obtained at minimum shaft speed of the generator. Thus the design of generator confirms its application with small scale domestic wind turbines producing direct current supply.

**Keywords:** Wind energy system, Radial flux generator, Permanent magnet generator, Direct drive wind turbine, Low speed generator, Variable speed generator

### 1. Introduction

This is the era of dispersed energy generation employing small distributed wind turbines independently [1]. The small wind turbines' ratings usually range up to 10 kW [2]. These small wind turbines can be installed on the roofs of houses situated near coastal areas and are good alternatives to cope with current energy crisis. Most often, small wind turbines uses permanent magnet generators [1, 3]. For high power density and current density, strong neodymium permanent magnets have taken the place of excitation system in the electrical generators [4-6]. Permanent magnet generators can be operated at low and variable shaft speed applications. These properties of low [7] and variable shaft speed [8] have made the electrical generator to be directly coupled with the shaft of wind turbine. Then the system is represented as Direct Driven Wind Turbine System [3, 6-10].

There are two types of permanent magnet machines for electrical generators; Radial Flux Machine (RFM) and Axial Flux Machine (AFM). Radial flux permanent magnet machines are

conventional machines which were used excessively for long time [5]. Radial flux permanent magnet machines have some advantages of compact structure, higher torque capability, higher efficiency due to absence of rotor windings and excitation losses, higher power density than conventional induction machines [5]. These machines also have good and quick arrangements for heat transfer from machine structure. That's why these machines can be loaded to larger extent than usual [5]. A brief literature is reviewed about RFPMGs in the subsequent paragraph.

There are different topologies of radial flux permanent magnet generators in literature. The direct driven permanent magnet radial flux generators have been discussed [3, 6] with stator and one rotor topology. These generators could be operated at low and variable shaft speed applications like wind turbines. The strong neodymium permanent magnets have been attached on the rotor for excitation purpose. The 20 kW and 400 W RFPMG models have been fabricated in [6] and [3] respectively. The RFPMG with double or dual rotors are also found in literature. The simulation of three RFPMG

\* Corresponding author : mansooruett@gmail.com

topologies with two contra rotating rotors has been presented [11]. The different design aspects of RFPMG with two rotors rotating in same direction have been addressed [12, 13]. These generator models have ironless stators with non-overlapping windings. The comparative design, comparison studies and different issues of RFPMGs have been demonstrated with transverse flux permanent magnet generators and torus machines [7, 8, 10].

In radial flux permanent magnet generator, the stator and rotor are made of iron core. The stator has windings on the core in form of coils while the rotor has permanent magnets arranged at equal degrees of angle on the circumference. The rotor is inserted in the stator, suitable air gap is maintained and end housings are fitted as shown in Figure 1. In this paper, same topology of generator produces three phase alternating current voltage and is rectified to get direct current voltage using bridge rectifier.

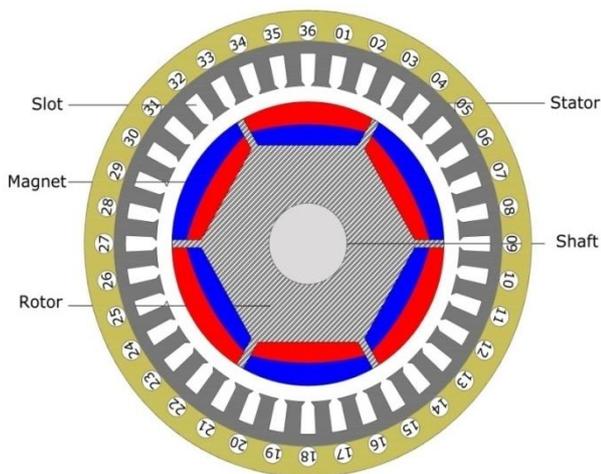


Figure 1. Radial flux design for generator model

In this paper, the design and construction of radial flux permanent magnet generator are discussed. The fabricated RFPMG model has higher power density (73.2 W/kg) than 20 kW RFPMG model discussed [6] (71.4 W/kg). The prototype RFPMG model has also higher current density (5.9 A/mm<sup>2</sup>) than 20 kW model (4.7 A/mm<sup>2</sup>) and 14.8 kW model (3.39 A/mm<sup>2</sup>) which are presented [6, 8].

The generator is directly coupled with wind turbine and wind turbine model is operated at wind speed of 7-8 m/s approximately. The features of low shaft speed, elimination of excitation losses and minimization of gear box losses demonstrate

the usage of RFPMG for low speed and direct driven wind turbine applications.

## 2. Generator Design

The general mathematical modeling for generator has been discussed in literature [14, 15]. The design process of generator includes the calculations of different dimensions and parameters of machine while considering name plate ratings, some design limitations, several fabrication challenges and satisfying the complex constraints. The name plate ratings of generator essentially consists of KVA, terminal voltage and full load current ratings. The RFPMG presented in this paper is of 300 W consisting of one stator and one rotor.

RFPMG has different parts like yoke, core, bearings, end housings, shaft, permanent magnets and windings etc. An important part of machine is stator core which is made of laminated iron strips packed together tightly to give the teeth-slots configuration.

The parameter of number of poles of generator is decisive depending upon the peripheral speed of rotor and availability and cost of dimension sized permanent magnets. The peripheral speed determines whether the rotor windings and mounted permanent magnets stay on the rotor surface during operation or not. Usually, small domestic wind turbines operate within the range of 250 rpm to 500 rpm maximum. So, the peripheral speed of the generator rotor has been calculated at 500 rpm. The proposed generator has been designed using the mathematical models given below.

Peripheral speed [14]:

$$v = \pi D n_s \quad (1)$$

where

D Armature diameter (m)

$n_s$  Synchronous speed (rps)

Pole pitch of stator windings [14]:

$$\tau = \frac{\pi D}{P} \quad (2)$$

where

D Armature diameter (m)

P Number of poles

KVA rating of generator [14, 15] :

$$KVA = 3 E_{ph} I_{ph} 10^{-3} \quad (3)$$

where

$E_{ph}$  Induced EMF per phase (V)

$I_{ph}$  Current per phase (A)

Voltage per phase [15]:

$$E_{ph} = 4.44 K_w f \phi T_{ph} \quad (4)$$

$$KVA = 3(4.44 K_w f \phi T_{ph}) I_{ph} 10^{-3} \quad (5)$$

where

$K_w$  Winding factor

$f$  Frequency (Hz)

$\phi$  Flux per pole in the air gap (wb)

$T_{ph}$  Number of turns per phase

Frequency of supply [15]:

$$f = \frac{n_s P}{2} \quad (6)$$

where

$n_s$  Synchronous speed (rps)

$P$  Number of poles

Specific electric loading [14]:

$$ac = \frac{6 I_{ph} T_{ph}}{\pi D} \quad (7)$$

where

$I_{ph}$  Current per phase (A)

$T_{ph}$  Number of turns per phase

Specific magnetic loading [14]:

$$B_{av} = \frac{\phi P}{\pi D L} \quad (8)$$

where

$\phi$  Flux per pole in the air gap (wb)

$D$  Armature diameter (m)

$L$  Stator core length (m)

KVA rating in terms of specific electrical and magnetic loading [14]:

$$KVA = (1.11 \pi^2 K_w B_{av} ac 10^{-3}) D^2 L n_s \quad (9)$$

where

$K_w$  Winding factor

$B_{av}$  Average flux density in the air-gap (T)

$ac$  Ampere conductor per meter of armature periphery (amp-cond/m)

Output Coefficient [14]:

$$C_o = (1.11 \pi^2 K_w B_{av} ac 10^{-3}) \quad (10)$$

Total Number of conductors of windings [14]:

$$T_T = 3 \times 2 \times T_{ph} \quad (11)$$

where

$T_{ph}$  Number of turns per phase

Stator impedance [14]:

$$Z_{ss} = \frac{T_T}{S_s} \quad (12)$$

where

$T_T$  Total number of winding conductors

$S_s$  Number of stator slots

Resistance of stator per phase [14]:

$$r_s = \rho \frac{L_{mts} T_{ph}}{a_s} \quad (13)$$

where

$\rho$  Resistivity of conductor material ( $\Omega/m$ )

$L_{mts}$  Length of mean turn of stator winding (m)

$T_{ph}$  Number of turns per phase

$a_s$  Cross section area of each conductor ( $mm^2$ )

The average value of DC voltage [16]:

$$V_d = \frac{2}{\pi} V_p \quad (14)$$

where

$V_p$  Peak alternating current voltage

Completion of design procedure has evaluated the different design specifications of the generator for fabrication. These design specifications include generator parameters and dimensions. The parameters and dimensions of designed generator are listed in Table 1.

### 3. Generator Fabrication

The generator model has been fabricated according to the dimensions and design parameters presented in Table 1. Fabrication of generator model includes the construction of stator and rotor as following.

Table 1. Design specifications of generator model.

| Parameter                                   | Value                              |
|---|------------------------------------|
| Shaft Speed (N)                             | 500 rpm                            |
| Shaft Speed ( $n_s$ )                       | 8.33 rps                           |
| Peripheral Speed ( $u$ )                    | 2.4086 m/s                         |
| Number of Poles (P)                         | 6                                  |
| Pole Pitch ( $\tau$ )                       | 0.0482 m                           |
| Cross Sectional Area of Conductor ( $a_s$ ) | 0.66 mm <sup>2</sup>               |
| Current per Phase ( $I_{ph}$ )              | 4 A                                |
| Number of Turns per Coil ( $T_{ph}$ )       | 240 turns                          |
| Total Number of Turns ( $T_T$ )             | 1440                               |
| Electrical Loading ( $ac$ )                 | 19929 amp-cond/m                   |
| Average Pull of Magnets ( $F_{pull}$ [17])  | 23 kg                              |
| Magnet grade                                | N42                                |
| Residual Flux Density ( $B_r$ [18])         | 1.3 T                              |
| Resistivity of Copper ( $\rho$ )            | 1.7241x10 <sup>-8</sup> $\Omega$ m |
| Number of phases                            | 3 phase                            |
| Number of coils in stator                   | 36                                 |
| Number of turns of each coil                | 20                                 |
| Size of copper conductor                    | SWG 20                             |
| Bridge rectifier                            | 35 A DC                            |
| Number of slots                             | 36                                 |
| Power Density (W/kg)                        | 73.2                               |
| Current Density (A/mm <sup>2</sup> )        | 5.9                                |
| Slot type                                   | Semi-enclosed                      |
| Stator length                               | 103 mm                             |
| Slot length                                 | 44 mm                              |
| Teeth width                                 | 5 mm                               |
| Maximum slot width                          | 5 mm                               |
| Air gap                                     | 2 mm approx.                       |
| Rotor diameter (Stator bore)                | 92 mm                              |
| Rotor length                                | 50 mm                              |

The name plate ratings of designed generator are listed in Table 2.

Table 2. Generator ratings.

| Rating  | Value   |
|---|---------|
| Maximum AC current per phase using star ( $\gamma$ ) configuration  | 4 A     |
| Maximum AC current per phase using delta ( $\Delta$ ) configuration | 7 A     |
| Output Power  | 300 W   |
| Terminal voltage in delta   | 32 V AC |

### 3.1 Stator Construction

The stator of generator has been fabricated according to the design parameters computed in previous section. The stator construction included some design considerations. All coils were placed in stator slots with computed coil pitch. The coils were connected in series while following begin-to-begin end winding connection. Three phase winding has been designed in same manner and are connected in star configuration. The differential portion of generator is shown in Figure 2.

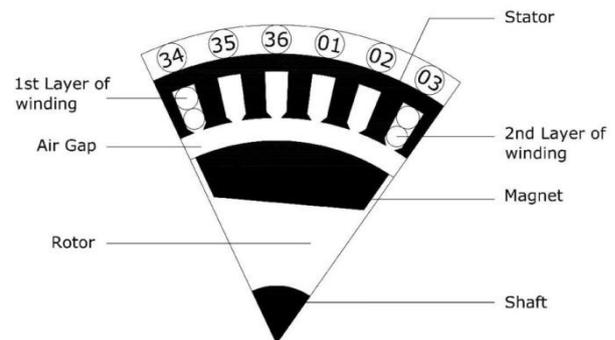


Figure 2. Design topology

The designed 3-phase winding scheme of stator is shown in following Figure 3.

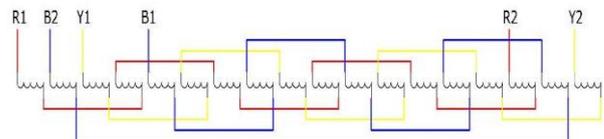


Figure 3. Designed winding scheme for stator.

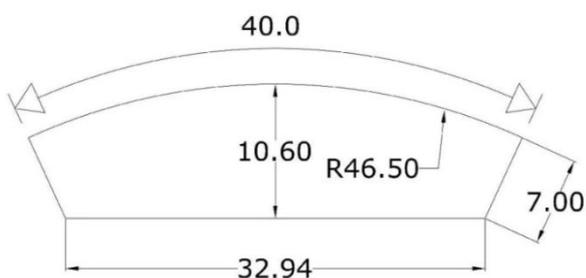
The fabricated stator of designed generator is shown in following Figure 4.



Figure 4. Stator of generator model.

### 3.2 Rotor Construction

The rotor of generator has been designed by placing permanent magnets on rotor. The radius of curvature of magnets has been designed in accordance with radius of curvature of rotor. This gives uniform magnetic field lines reaching stator through one complete journey of revolution. Figure 5 shows the drawing of magnet and actual diagram of neodymium permanent magnet is shown in Figure 6. Finally, the rotor of generator was fabricated and permanent magnets were mounted in the rotor slots as shown in Figure 7.



All Dimensions are in 'mm'

Figure 5. Auto CAD drawing for permanent magnets.



Figure 6. Neodymium permanent magnet.



Figure 7. Rotor of generator model with magnets.

### 3.3 Generator Assembly

Stator and rotor of generator were designed and fabricated as described in the previous sections. Thus final complete model has been prepared by inserting rotor within stator and final diagram is shown in Figure 8.



Figure 8. Complete generator model.

## 4. Wind Turbine

The designed generator has been tested by coupling with wind turbine. The brief mathematical modelling of wind turbine is discussed here. The mechanical output power that wind turbine extracts from wind is given by [1-3]:

$$P_m = \frac{1}{2} \rho_a A V_w^3 C_p(\lambda, \beta) \quad (15)$$

where

- $\rho_a$  Air density ( $\text{kg/m}^3$ )
- $A$  Swept area of turbine blades ( $\text{m}^2$ )
- $V_w$  Wind speed (m/s)
- $C_p$  Power coefficient

The tip speed ratio [19]:

$$\lambda = \frac{V_T}{V_w} \quad (16)$$

where

- $V_T$  Blade tip speed (m/s)

Blade tip speed:

$$V_T = \frac{2\pi R}{60} n \quad (17)$$

where

R Length of wind turbine blade (m)

n Shaft speed of wind turbine (rpm)

Tip speed ratio is function of shaft speed of wind turbine:

$$\lambda = \frac{2\pi R}{60} n \frac{1}{V_w} \quad (18)$$

The wind turbine designed with three blades is shown in Figure 9 and specifications are listed in Table 3.

Table 3: Specifications of wind turbine.

| Parameter            | Value   |
|----------------------|---------|
| Number of blades     | 3       |
| Length of each blade | 1.1 m   |
| Shaft speed          | 500 rpm |
| Cut in wind speed    | 5 m/s   |
| Operating wind speed | 8 m/s   |



Figure 9. Micro wind turbine model.

## 5. Generator Testing and Results Comparison

After fabrication of generator and wind turbine, the electrical generator has been directly coupled with the wind turbine to demonstrate towards direct drive wind energy system. The alternating current supply from electrical generator was then rectified to direct current supply by using bridge rectifier.

The complete wind power generation system was ready for testing as shown in Figure 9 and Figure 11.

This prototype model for wind power generation was placed in front of wind tunnel for wind tunnel testing. The speed of wind from wind tunnel is approximately 8 m/s. The No-Load and Load test results are summarized in the Table 4.

Table 4: Generator test results.

| Shaft Speed (rpm) | No-Load Test    | Load Test       |                 |        |
|-------------------|-----------------|-----------------|-----------------|--------|
|                   | V <sub>DC</sub> | V <sub>DC</sub> | I <sub>DC</sub> | P      |
| 0                 | 0               | 0               | 0               | 0      |
| 25                | 1.9             | 0.1             | 0.35            | 0.035  |
| 33                | 2.7             | 0.4             | 0.84            | 0.336  |
| 45                | 3.7             | 1.0             | 1.11            | 1.110  |
| 60                | 5.0             | 1.9             | 1.50            | 2.850  |
| 80                | 6.8             | 3.2             | 1.92            | 6.720  |
| 108               | 9.4             | 5.0             | 2.37            | 11.85  |
| 140               | 12.6            | 5.3             | 4.84            | 25.652 |
| 190               | 16.8            | 7.9             | 5.92            | 46.768 |
| 260               | 23.6            | 12.2            | 7.70            | 93.94  |
| 350               | 32.2            | 17.6            | 9.64            | 169.66 |
| 470               | 42.9            | 27.0            | 10.0            | 270.0  |

The test results show that the designed generator feeds the load at 12.2 V DC and 7.7 Amp current with shaft speed of 260 rpm. Thus designed generator operates at low shaft speed to produce the voltage sufficient for 12 V battery charging applications.

Voltage (No load & Full load) and power characteristics are shown in Figures 12, 13 and 14 respectively. The kink in Figure 13 shows that generator voltage remains approximately constant from 110 rpm to 135 rpm approximately at load conditions. The reason is that the voltage at load conditions may not be much stable at low operating shaft speed as compared to high shaft speed. The behavior can be seen in Figure 13.

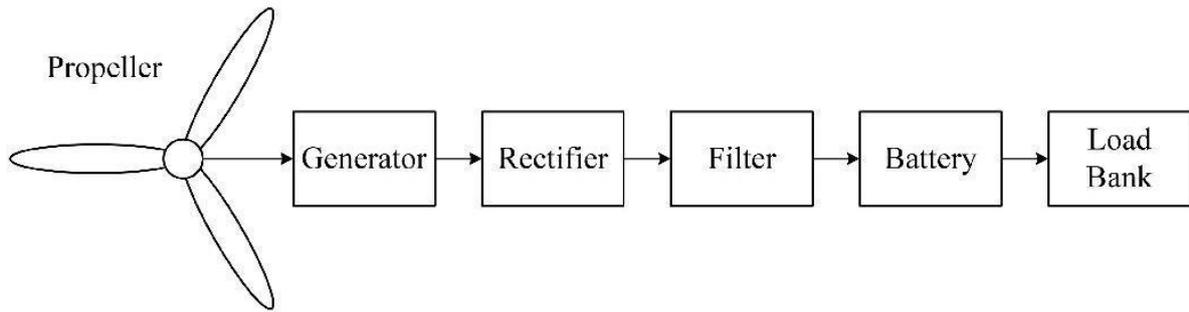


Figure 10. Wind power generation system.

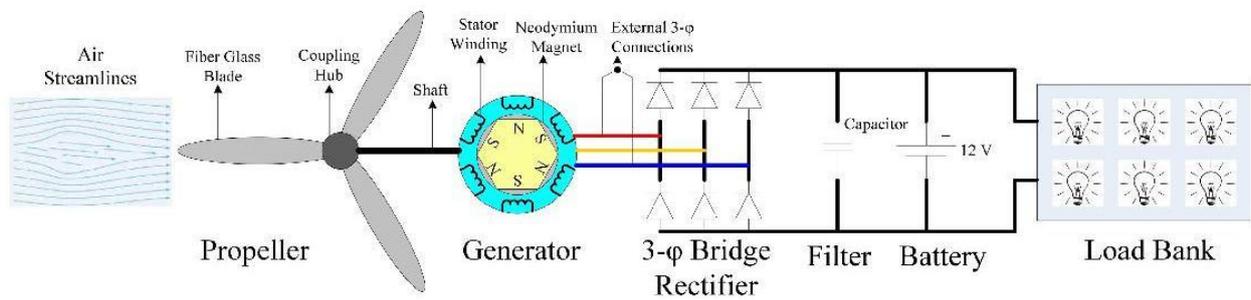


Figure 11. Testing of wind power generation system.

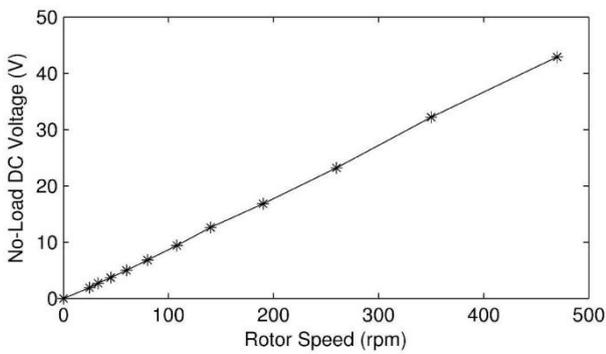


Figure 12. No-Load DC terminal voltage versus rotor speed.

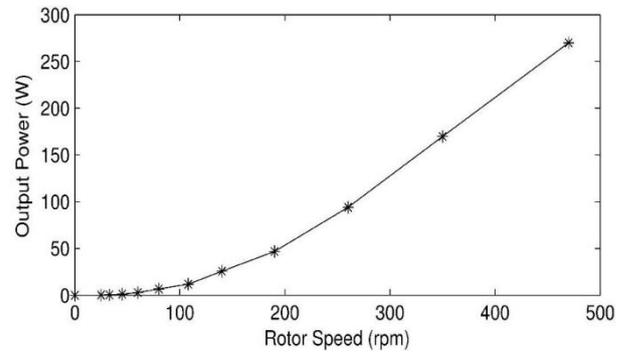


Figure 14. Output DC power versus rotor speed.

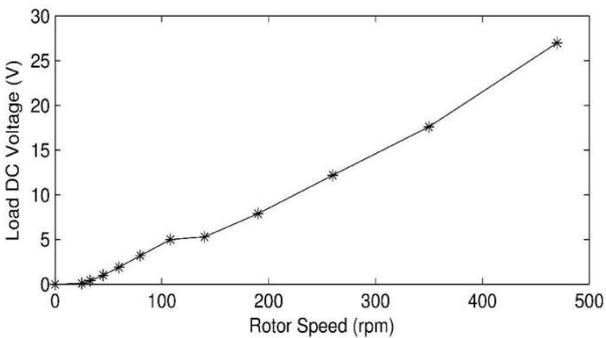


Figure 13. Load DC terminal voltage versus rotor speed.

The fabricated RFPMG has been compared in design parameters of power density and current density with existing ones addressed in [6, 8]. The comparison is listed in Table 5.

The high value of power density parameter reflects in reduction of generator mass in kilograms. The higher value of current density shows that RFPMG can provide high current at low operating shaft speed which is well suited for battery charging applications.

Table 5. Generator results comparison.

| Parameter                            | Fabricated RFPMG Model | 20 kW RFPMG [6] | 14.8 kW RFPMG [8] |
|--------------------------------------|------------------------|-----------------|-------------------|
| Power Density (W/kg)                 | 73.2                   | 71.4            | -                 |
| Current Density (A/mm <sup>2</sup> ) | 5.9                    | 4.7             | 3.39              |

## 6. Conclusion

The proposed RFPMG model in this paper is cost effective with compact structure size and free of excitation and gear-box losses. From the test results, it is shown that at 8 m/sec wind speed, the turbine has shaft speed of about 260 rpm at which generator produces significant direct current voltage sufficient for battery charging applications. This radial design of permanent magnet generator has demonstrated its use with domestic wind turbine for direct driven, low and variable speed generator applications. This type of wind turbine may be excessively deployed at roof tops in coastal areas and wind corridor areas. Moreover the radial flux machines have a problem of small aspect ratio (diameter over axial length) which results in high copper loss. In this generator model, the cogging torque losses may appear as a result of interlocking of permanent magnets with stator core slots. To avoid or to reduce the cogging torque losses, coreless stator can be constructed pointing to the axial flux machine design.

## Acknowledgements

The authors would like to appreciate the Electrical Machines Laboratory, Electrical Engineering Department, University of Engineering and Technology, Taxila, Pakistan for financial support and assistance in manufacturing the prototype model for the project.

## References

- [1] Design and Construction of Axial Flux Permanent Magnet Generator for Wind Turbine Generated Dc Voltage at Rated Power 1500 W, Electric Utility Deregulation and Restructuring and Power Technologies (DRPT), 4th International Conference (2011).
- [2] N.J. Olimpo Anaya-Lara, J. Ekanayake, P. Cartwright and M. Hughes, Wind Energy Generation Modelling and Control, John Wiley & Sons, Ltd. (2009).
- [3] Design of a Direct-Coupled Radial-Flux Permanent Magnet Generator for Wind

Turbines, Power and Energy Society General Meeting, IEEE (2010).

- [4] Electromechanical Design for an Optimized Axial Flux Permanent Magnet Torus Machine for 10kw Wind Turbine, Electrical Machines and Systems (ICEMS), International Conference (2011).
- [5] S.H. M. Aydin, T.A. Lipo, University of Wisconsin-Madison College of Engineering, Wisconsin Power Electronics Research Center 2559D Engineering Hall 1415 Engineering Drive Madison, WI 53706-1691, (2004) 11.
- [6] Design and Construction of an Optimum High Power Radial Flux Direct-Drive Pm Generator for Wind Applications, Industrial Electronics and Applications, ICIEA, 4th IEEE Conference (2009).
- [7] Issues with Low Speed Direct-Drive Permanentmagnet Generator Design &#X2014; Comparison of Radial-Flux Slotted and Torus Machines, IECON, 36th Annual Conference on IEEE Industrial Electronics Society (2010).
- [8] Comparison of Air-Cored and Iron-Cored Non-Overlap Winding Radial Flux Permanent Magnet Direct Drive Wind Generators, Energy Conversion Congress and Exposition (ECCE), IEEE (2011).
- [9] T.F. Chan and L.L. Lai, Energy Conversion, IEEE Transactions **22** (2007).
- [10] Comparative Design of Radial and Transverse Flux Pm Generators for Direct-Drive Wind Turbines, Electrical Machines, ICEM, 18th International Conference (2008).
- [11] Simulation of a Radial Flux Permanent Magnet Generator with Two Contra-Rotating Rotors, Electrical Machines, ICEM, 18th International Conference (2008).
- [12] Design Aspects of Medium Power Double Rotor Radial Flux Air-Cored Pm Wind Generators, Energy Conversion Congress and Exposition, ECCE, IEEE (2009).

- [13] J.A. Stegmann and M.J. Kamper, Industry Applications, IEEE Transactions **47** (2011)..
- [14] R.K. Agarwal, Principles of Electrical Machine Design, Dewan Sanjeev Kumar Kataria, 6 Guru Nanak Market, Nai Sarak, Delhi 110006, Delhi (2000).
- [15] S.J. Chapman, Electric Machinery Fundamentals, McGraw-Hill Higher Education (2005).
- [16] T.L. Floyd, Electronic Devices, Pearson Education, Inc., New Jersey, USA (2005).
- [17] <http://www.rare-earth-magnets.com/t-pull-force-calculator.aspx>. Pull Force Calculator.
- [18] <http://www.kjmagnetics.com/specs.asp>. Neodymium Magnet Physical Properties.
- [19] <http://www.windynation.com/articles/wind/tip-speed-ratio-how-calculate-and-apply-tsr-blade-selection>. Tip Speed Ratio: How to Calculate and Apply Tsr to Blade Selection.