An optimal design of coreless direct-drive axial flux permanent magnet generator for wind turbine

To cite this article: D Ahmed and A Ahmad 2013 *J. Phys.: Conf. Ser.* **439** 012039

View the article online for updates and enhancements.

An optimal design of coreless direct-drive axial flux permanent magnet generator for wind turbine

D Ahmed[1,3] and A Ahmad[2]

[1]Department of Electrical Engineering (DOEE), University of Engineering and Technology, Taxila, Pakistan

[2]University of Engineering and Technology, Taxila, Pakistan

E-mail: daniyal.ahmed@uettaxila.edu.pk

Abstract. Different types of generators are currently being used in wind power technology. The commonly used are induction generator (IG), doubly-fed induction generator (DFIG), electrically excited synchronous generator (EESG) and permanent magnet synchronous generator (PMSG). However, the use of PMSG is rapidly increasing because of advantages such as higher power density, better controllability and higher reliability. This paper presents an innovative design of a low-speed modular, direct-drive axial flux permanent magnet (AFPM) generator with coreless stator and rotor for a wind turbine power generation system that is developed using mathematical and analytical methods. This innovative design is implemented in MATLAB / Simulink environment using dynamic modelling techniques. The main focus of this research is to improve efficiency of the wind power generation system by investigating electromagnetic and structural features of AFPM generator during its operation in wind turbine. The design is validated by comparing its performance with standard models of existing wind power generators. The comparison results demonstrate that the proposed model for the wind power generator exhibits number of advantages such as improved efficiency with variable speed operation, higher energy yield, lighter weight and better wind power utilization.

1. Introduction

Renewable energy sources are those which are naturally replenished, for example, geothermal, solar, wind, and tidal. Wind power, being a readily and naturally available source, is growing significantly worldwide. Presently, the worldwide installed wind power capacity is around 200 GW. It is anticipated that by 2019, it would raise above 1000 GW indicating that wind power is really an important power source [1]. The key units in the conversion of wind energy to electrical energy are the wind power generators. The overall performance of the wind power generation system depends on the conversion efficiency of the power generators. These generators are run by wind turbines which are often made taller to utilize advantages of wind at higher altitudes such as uniformity, steadiness and high speed. For better stability and improved performance, these turbines require more complex and flexible towers along with lighter weight and smaller sized nacelles [2].

Significant advancements have been made in the field of wind power generators since the inception of utilization of wind for production of electrical energy. The commonly used generators are IG, DFIG, EESG and PMSG. IGs are simple, rugged and cost effective fixed speed generators that require no separate excitation source [3]. DFIGs with a partially rated rotor side converter are the mainstream technology in the market for wind turbines [4]. The DFIG operates at partial variable speed, which is

---

3 To whom any correspondence should be addressed.

about ±30 % above and below the rated speed. EESG and PMSG both are synchronous generators that can operate at full variable speed. These generators do not require reactive magnetizing current in comparison to IG and DFIG. EESG and PMSG are connected to the grid through a full scale power electronic converter and therefore are decoupled from the grid. The generators can operate at a wide variable frequency range for optimal operation and provide the option to implement gearless operation [5]. EESG requires DC excitation current for its operation which is provided from the grid through a rectifier. On the other hand, PMSGs use permanent magnets in place of field windings and hence are the most reliable wind power generators as they are independent from the grid and can operate even at the lowest wind speed of 3 m/s [6]. PMSG is further divided into Radial Flux Permanent Magnet (RFPM) and Axial Flux Permanent Magnet (AFPM) generators. The AFPM generator has higher power density and can operate more efficiently at low speeds as compared to its radial counterpart. Moreover, for same power ratings, AFPM has smaller volume and lower mass as compared to RFPM [7]. All the features of AFPM generator listed above make it the generator of choice for wind power generation system.

In the literature, many authors have worked on the full rated power converter system being used for PMSG-based wind conversion systems, for example, Xibo Yuan *et al.* [8] has worked on H-bridge converters and neutral point clamped converters [9] for PMSG wind power generation system. These are medium voltage, high power converters which have been cascaded in series resulting in the elimination of the grid side step-up transformer. These series cascaded converters have high reliability and fault-tolerant ability. At another place, a robust and reliable grid power interface system for wind turbines using a PMSG has been considered where an integration of a generator-side three-switch buck-type rectifier and a grid-side Z-source inverter is employed as a bridge between the generator and the grid [5]. At another place [10], a matrix converter has been used along with PMSG system which eliminates the bulky storage capacitors resulting in a direct ac-ac power conversion system. Some authors in [11], [12] and [13] have replaced the conventional transformer with a high frequency, all-solid-state power electronic transformer resulting in better power quality output and increased power density. Other authors have also worked on modeling and designing of PMSG, for example, Ming Yin *et al.* [14] has presented the complete model of a variable speed wind turbine system with radial flux PMSG for supplying power to the grid through HVDC link. The modeled generator is a high speed generator that requires a gear box for its integration with the wind turbine system. In [15] and [16], authors have also presented their models of PMSG for variable speed wind turbine generation systems. In [17], the author has designed an AFPM machine with flux switching capability resulting in the improvement of power density and reduction in cogging torque with better performance. In [18], the author has designed and optimized a nine-phase AFPM generator with concentrated winding for direct-drive wind turbine. The goal for optimization was to minimize the net mass of the generator along with maximizing its power factor. In [19], AFPM generator with concentrated windings has been used in wind energy conversion system. In [20], work has been done to improve the power quality of distributed winding AFPM generator for wind turbine systems. In [21], a high-speed AFPM generator has been optimally designed. The structure consists of single coreless stator in between twin rotors having steel core. However, the design and modeling of low-speed modular direct-drive AFPM generator with coreless stator and rotor for a wind turbine power generation system has not been reported. This paper, therefore, proposes such a system. Figure 1 shows the model of the proposed design of wind turbine generating system which has been prepared using the software Sketch Up [22]. The model is validated by making a nose to nose comparison with existing wind power generators (IG, DFIG & EESG). The comparison is made on the basis of wind power utilization and total energy yield over a fixed time span under similar wind conditions through simulations using the software Simulink/ MATLAB [23].
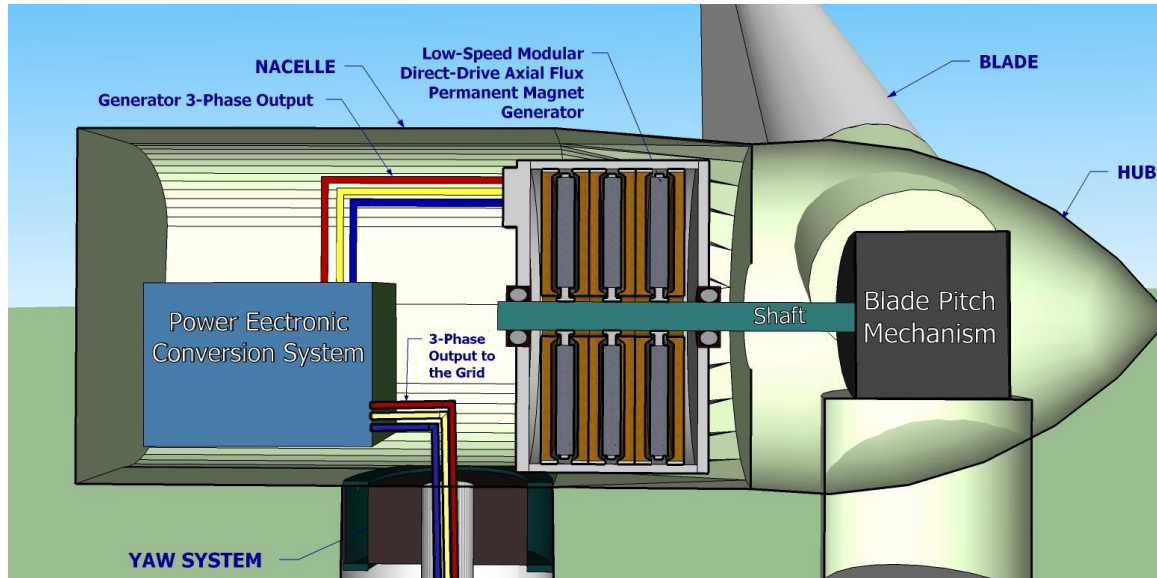
Figure 1. Wind Turbine Generating System Model using the Proposed AFPM Generator

2. Proposed generator design

Different topologies of AFPM generators exist in literature. Some designs have single stator and rotor while some have multiple stators and rotors. Depending on their configuration, AFPM generator can be classified as, single-sided, double-sided and multi-stage (modular) generator. These topologies are further classified on the basis of the type of stator and rotor being used, for example, coreless or cored generator, slotted or slotless generator etc.

The proposed generator consists of a multi-disc structure having three modules. Each module consists of two identical stator discs (armature) and single rotor disc (field). The stators are connected in series and the three modules are connected in parallel to increase the net output power. Both the rotor and the stator are coreless that is, they have non-ferromagnetic cores. A 2D model of this proposed design is shown in Figure 2. The coreless structure minimizes the attractive forces between stator and rotor and also reduces the cogging effect in torque, that is, torque pulsations are minimized at zero stator current. Such a complete coreless design results in reduction of overall mass of the generator and increase in the efficiency. With this design, direct drive low speed power generation with maximum wind power utilization is possible. Moreover, with a coreless structure the losses are also minimized.

In each module, the twin stator discs are fixed to the frame and are the stationary part of the machine. The stator coil is a three phase double layered toroidal type winding that is embedded in a resin or a plastic of high mechanical integrity which together make up a single stator disc. Similarly, in each module, the rotor disc, consisting of NdFeB rare-earth permanent magnets and its supporting non-magnetic material (aluminum or plastic) structure, is the rotating part which is directly connected to the shaft. Since this design does not include any ferromagnetic material in its core hence it is free from cogging effect and there are no core losses as well.
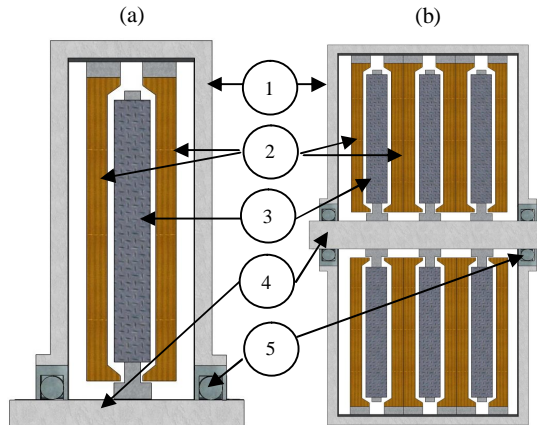
Figure 2. Proposed Coreless AFPM Generator (3 modules assembly): (a) single module (segment), (b) three module assembly; 1 – frame, 2 – twin coreless stator windings, 3 – permanent magnets (coreless rotor), 4 – shaft, 5 – bearing

The proposed design offers a high power or high torque density which has been achieved by arranging the permanent magnets in Halbach array [7]. In this arrangement, the angle between magnetic polarization vectors of two adjacent magnet pieces is 90°. By using this array, the magnetic field strength of the rotor disc is enhanced on the front side and diminished to zero (approximately) on the backside allowing the magnets to be attached to the non-ferromagnetic structure. The pattern of the magnetic flux lines for this arrangement, using the software FEMM (Finite Element Method Magnetics) [24], is depicted in Figure 3.
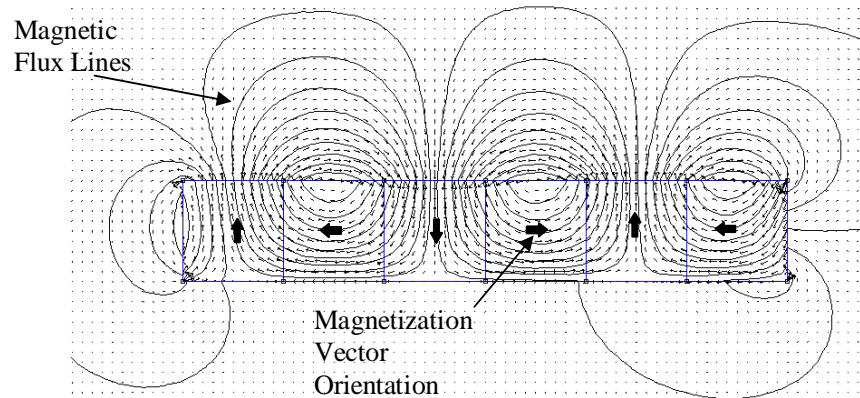
Figure 3. 90° Halbach array using NdFeB magnets

The magnetic field produced as a result of this pattern is a sinusoidal field. The peak value of magnetic flux density $B_{PM,peak}$ at front side of the rotor disc is:

$$B_{PM,peak} = 0.9 \times B_{remanent} \times \left(1 - e^{-62.83 * h_{PM}}\right) \tag{1}$$

In equation 1. $B_{remanent}$ is the remanent flux density and h_{PM} is the axial height of the permanent magnets. This value increases exponentially with increase in the height (depth) of a permanent magnet piece. In the proposed design, an optimized value has been evaluated by varying the height of the magnet keeping in consideration the efficiency, the desired power density and the cost of permanent magnets. The induced EMF E_{field} in a single stator is given as

$$E_{field} = 0.2441 \times p_{pp,mod1} \times \phi_{field,PM} \times N_{1s} \times \omega_{e,gen} \tag{2}$$

where $p_{pp,mod1}$ is the total number of pole pairs in a single module, $\phi_{field,PM}$ is the magnetic flux produced by the permanent magnets, N_{1s} is the number of turns per phase per stator disc for a single

module and $\omega_{e,gen}$ is the electrical angular speed of the generator. If I_{stator} is the phase stator winding current of single module, then the electromagnetic torque T_{em} developed is given by

$$T_{em} = 0.371 \times n_{ph} \times p_{pp,mod1} \times \phi_{field,PM} \times N_{1s} \times I_{stator} \tag{3}$$

In equation 3. n_{ph} is the phase number of the generator. The electromagnetic apparent power for a single module $S_{em,mod1}$ induced in the two stator windings is thus given as

$$S_{em,mod1} = n_{ph} \times (2 \times E_{field}) \times I_{stator} \tag{4}$$

The outer diameter $D_{out,gen}$ and the inner diameter $D_{in,gen}$ of the generator are calculated using the following sizing equations.

$$D_{out,gen} = \left(\frac{21.87 \times 10^3 \times P_{out,gen_{mod1max}}}{\omega_{gen,rpm_{max}} \times B_{PM,peak} \times A_{M,peak}} \right)^{\frac{1}{3}} \tag{5}$$

$$D_{in,gen} = D_{out,gen} \times 0.577 \tag{6}$$

where $A_{M,peak}$ is the peak value of the line current density of a single module. Since the relative recoil permeability of the NdFeB permanent magnets is unity [7], the d-axis and q-axis stator inductances (L_d and L_q) in the synchronous reference frame are equal and are calculated as:

$$L_{stator} = L_d = L_q = n_{ph} * \mu_0 * \frac{1}{\pi} * \left(\frac{1.0492 * N_{1s}}{p_{pp,mod1}} \right)^2 * \left(\frac{R_{out,gen}^2 - R_{in,gen}^2}{g_{air}} \right) \tag{7}$$

where μ_0 is the permeability of free space ($0.04\pi \times 10^{-6}$ H/m), g_{air} is the air gap (0.001 m) and $R_{in,gen}$ & $R_{out,gen}$ are the inner and outer radii of the generator. The design parameters of the proposed generator are shown in table 1.

3. Wind turbine and proposed generator dynamic model

The complete wind power generation system, as shown in figure 1, comprises the proposed low-speed modular AFPM generator coupled directly (without gearbox) to the wind turbine through a mechanical shaft. The output electrical power of the generator is fed to the grid through a power electronic conversion system. This section presents the mathematical models of the wind turbine, the drive train and the proposed AFPM generator. Since the scope of current research is designing and modeling of AFPM generator only, therefore, the models of power electronic conversion system and its control have not been discussed here. In this section, the mathematical models of the mechanical systems have been obtained using the Newton's law of rotational motion and those of electrical systems have been obtained using Kirchoff's Current and Voltage laws [25].

3.1. Wind Turbine

Before modeling the wind turbine, a suitable site needs to be selected since its meteorological data (wind speeds, air density, other land features etc) is required for modeling. Gharo, Pakistan has been selected as suitable site for the proposed system. The wind speeds selected for validation purposes are 12 m/s, 9 m/s, 6 m/s and 3 m/s. The variable wind speed input V_{wind} to the system has been modeled as follows using the step function:

$$V_{wind} = 12 * u_0(t) - 3 * u_{50}(t) - 3 * u_{60}(t) - 3 * u_{60}(t) - 3 * u_{70}(t) + 3 * u_{80}(t)$$
$$+ 3 * u_{90}(t) + 3 * u_{100}(t) - 12 * u_{150}(t) \tag{8}$$

The mechanical power extracted from the upstream wind V_{wind} by the turbine, that is, the turbine output power $P_{out,turbine}$ is:

$$P_{out,turbine} = \frac{1}{2} \frac{\pi}{4} D_{blade}^2 \rho_{gharo} C_p V_{wind}^3 \tag{9}$$

where D_{blade} is the blade diameter of the turbine, ρ_{gharo} is the air density at Gharo site and C_p is the power or performance coefficient of the turbine and its theoretical maximum value that can be achieved is 0.59 [26]. The air density at Gharo has been calculated using:

$$\rho_{gharo} = \rho_0 - 1.194 \times 10^{-4} E_{gharo} \tag{10}$$

where, ρ_o is the air density at sea level (1.225 kg.m^{-3}) and E_{gharo} is the Gharo site elevation from sea level (1750 m). The turbine output torque $T_{out,turbine}$ can be calculated from turbine output power using the following relation:

$$T_{out,turbine} = \frac{P_{out,turbine}}{\omega_{m,turbine}} \tag{11}$$

**Table 1.** Design parameters for one module of the proposed 90kW AFPM generator

Parameter	Symbol	Value
Nominal output power	$P_{out,gen_{mod1_{max}}}$	30 kW
Generator nominal angular speed in rpm	$\omega_{gen,rpm_{max}}$	25 rpm
Generator nominal angular speed in rad/s	$\omega_{m,gen_{max}}$	2.618 rad/s
Line voltage (Y connection)	$V_{ll-2s,mod1_{nom}}$	840 V
Number of phases	n_{ph}	3
Stator resistance	R_{stator}	0.425 Ω
Stator inductance	L_{stator}	0.0013 H
Number of pole pairs	$p_{pp,mod1}$	32
Pole pitch	p_{pitch}	0.05 m
Axial height of permanent magnet	h_{PM}	0.0138 m
Axial width of permanent magnet	w_{PM}	0.0191 m
Axial length of permanent magnet	l_{PM}	0.0191 m
Magnetic flux density peak value in the air gap	$B_{PM,peak}$	0.653 T
Outer diameter of generator	$D_{out,gen}$	1.596 m
Inner diameter of generator	$D_{in,gen}$	0.922 m
Average diameter of generator	$D_{ave,gen}$	1.259 m
Magnetic flux excited by permanent magnets	$\Phi_{field,PM}$	0.0086 Wb
EMF Constant	K_{emf}	3.235 V.s
Moment of inertia	J_{gen}	5.99 Kg.m^2

Where $\omega_{m,turbine}$ is the mechanical rotational speed of the turbine. The actual value of C_p depends on the tip speed ratio ζ and the pitch angle α_o. The equation for C_p, based on the variable speed turbine characteristics of [27], is

$$C_p = 0.73 * \left(\frac{151}{\zeta_i} - 0.58\,\alpha_0 - 0.002\,\alpha_0^{2.14} - 13.2 \right) * e^{\frac{-18.4}{\zeta_i}} \tag{12}$$

where, $\zeta_i = \dfrac{1.0}{\left(\dfrac{1}{\zeta + 0.02\alpha_0} - \dfrac{0.03}{\alpha_0^3 + 1}\right)}$ and $\zeta = \dfrac{\omega_{m,turbine} * R_{blade}}{V_{wind}}$

The Simulink model of the wind turbine is shown in figure 4. The parameters of the Turbine are shown in Table 2.
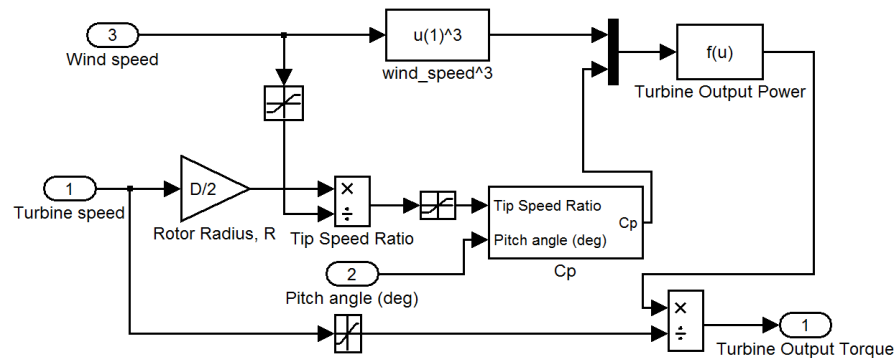
Figure 4. Wind turbine model

Table 2. Parameters for wind turbine

Parameter	Symbol	Value
Nominal Turbine Output Power	$P_{out,turbine_{max}}$	90 kW
Nominal Wind Speed	$V_{wind_{max}}$	12 m/s
Turbine Rotor Diameter	D_{blade}	15 m
Air Density at Site (Gharo)	ρ_{gharo}	1.01605 Kg/m3
Site(Gharo) Elevation	E_{gharo}	1750 m

3.2. Drive train

The wind turbine generation system uses a single mass drive train dynamic model. The inertia of the system (sum of inertias of blades, hub, shaft and generator) is J_{sys} and its angular velocity is $\omega_{m,gen}$. The losses due to friction in the proposed model are minimal since the gear box has been removed. The dynamic behavior of the drive train can be explained by the following differential equation:

$$J_{sys}\frac{d\omega_{m,gen}}{dt} = T_{e,gen} - T_{out,turbine} - F_{sys}\omega_{m,gen} \tag{13}$$

The Simulink model of the drive train is shown in figure 5 where as its parameters are shown in table 3. In this research, the combined damping effect of the turbine and the shaft has not been considered.

Table 3. Parameters for drive train.

| Parameter	Symbol	Value
Lumped Moment of inertia of complete system	J_{sys}	74.22 Kg.m^2
Lumped Friction factor of complete system	F_{sys}	0. 001189 N.m.s
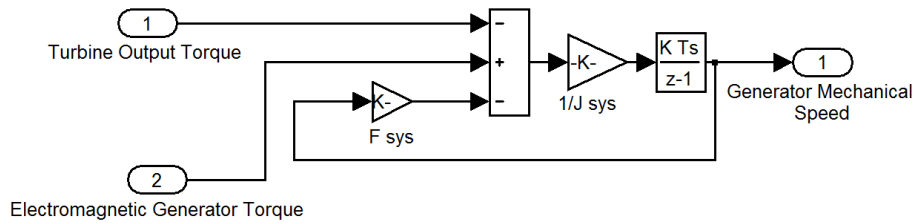
Figure 5. Drive train model

3.3.Proposed AFPM generator
The proposed direct-drive, modular AFPM generator has been designed in section 2 and its parameters, for a single module, are shown in table 1. Each module of the generator can be electrically described using the equivalent circuit shown in figure 6. The three phase voltage equation of the generator is as follows:

$$v_{abc} = e_{abc} - R_{abc} i_{abc} - L_{abc} \frac{di_{abc}}{dt} \tag{14}$$
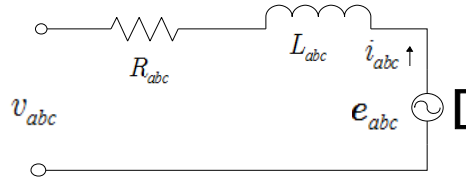
Figure 6. Equivalent Circuit of AFPM Generator

In equation 14. e_{abc} is the induced EMF and v_{abc} is the terminal voltage in the twin stators of a single generator module. In order to linearize the time varying inductances L_{abc}, the three phase dynamic equation at (14) can be converted into *dq0* or synchronous reference frame using the Park's transformation [28], as follows:

$$f_{dq0} = k_s f_{abc} \tag{15}$$

$$where, \ k_s = \frac{2}{3} \begin{bmatrix} Cos\theta_{e,gen} & Cos\left(\theta_{e,gen} - \frac{2\pi}{3}\right) & Cos\left(\theta_{e,gen} + \frac{2\pi}{3}\right) \\ Sin\theta_{e,gen} & Sin\left(\theta_{e,gen} - \frac{2\pi}{3}\right) & Sin\left(\theta_{e,gen} + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \ and \ \theta_{e,gen} = \int \omega_{e,gen} * dt$$

In above equation, $\theta_{e,gen}$ is the electrical angular displacement of the generator. After the transformation, the generator dynamic equations are:

$$v_q = e_q - R_{stator} i_q - \omega_{e,gen} L_d i_d - L_q \frac{di_q}{dt}$$

$$v_d = e_d - R_{stator} i_d - \omega_{e,gen} L_q i_q - L_d \frac{di_d}{dt} \tag{16}$$

$$v_0 = e_0 - R_{stator} i_0 - L_0 \frac{di_0}{dt}$$

The zero sequence quantities can be neglected since the proposed generator is electrically balanced [28]. Moreover, the d-axis reference frame is always aligned along the permanent magnet flux

position, making the EMF in d-axis of the stator to be zero. Therefore, the dynamic equations of the generator model become:

$$v_q = K_{emf}\omega_{e,gen} - R_s i_q - \omega_{e,gen}L_d i_d - L_q \frac{di_q}{dt}$$

$$v_d = -R_s i_d - \omega_{e,gen}L_q i_q - L_d \frac{di_d}{dt}$$

(17)

Since in (7), $L_d = L_q = L_{stator}$, the above equations in reduced form are:

$$\frac{di_q}{dt} = \frac{1}{L_{stator}}K_{emf}\omega_{e,gen} - \frac{R_s}{L_{stator}}i_q - \omega_{e,gen}i_d - \frac{1}{L_{stator}}v_q$$

$$\frac{di_d}{dt} = -\frac{R_s}{L_{stator}}i_d - \omega_{e,gen}i_q - \frac{1}{L_{stator}}v_d$$

(18)

Furthermore, the electromagnetic torque $T_{e,gen}$ of the proposed generator is:

$$T_{e,gen} = 4.85 * p_{pp,mod1} * i_q$$

(19)

The Simulink model for single module of the proposed generator is shown in figure 7.
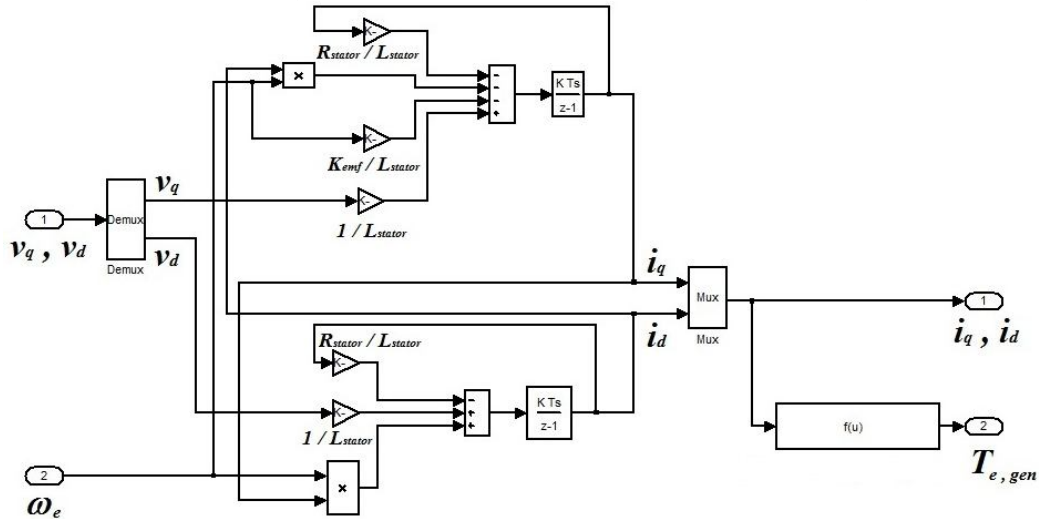
Figure 7. Electrical model of single module

4. Results and discussion

This section presents the comparative results of simulated active & reactive power outputs, energy yield outputs and rotor angular velocities of various wind power generators under variable wind speeds during their operation in wind turbines. The wind power generators under comparison comprise of the induction generator (IG), the doubly-fed induction generator (DFIG), the electrically excited synchronous generator (EESG) and the proposed direct-drive modular axial flux permanent magnet (AFPM) generator. The wind turbine power generation system model for the proposed AFPM generator has been constructed using MATLAB/Simulink. The standard MATLAB/Simulink models for the existing wind power generators, available at [23], have been used for the comparison studies.

In order to make a nose to nose comparison on the basis of wind power utilization and total energy yield, all the wind generators being used have same power ratings of 90 kW and are simulated using the same wind speed model. The variable wind speed model used as input for all wind turbine generators is shown in figure 8. Simulation results of the comparative studies carried out are depicted in following sub-sections. All the results, under each sub-section, are plotted on same magnitude scales. Moreover, their upper and lower limits have been mentioned explicitly.
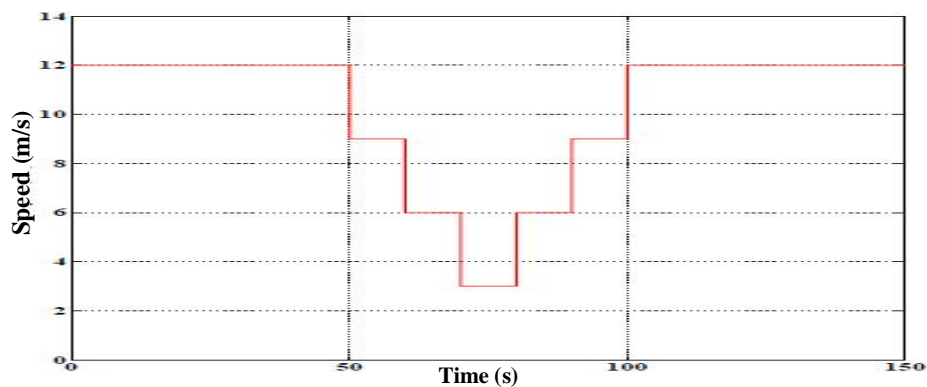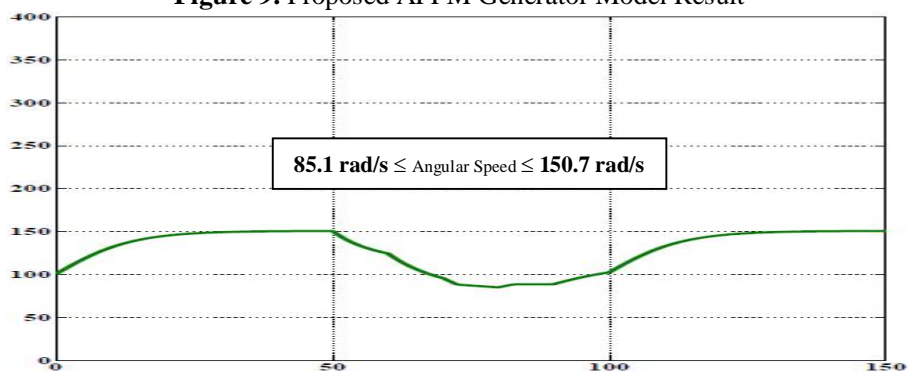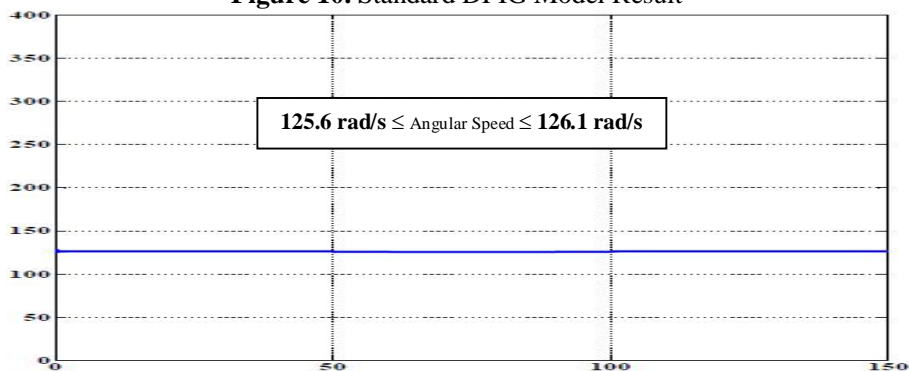
Figure 8. Wind Speed Input
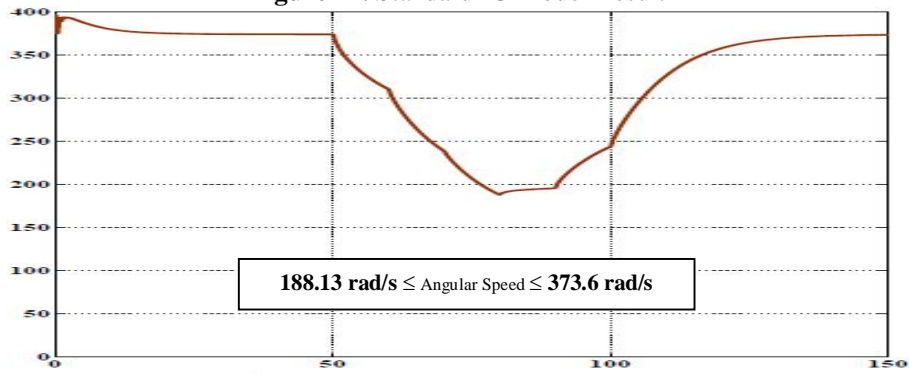
4.1. Mechanical rotational speeds (rad/s)

0.849 rad/s ≤ Angular Speed ≤ 2.618 rad/s
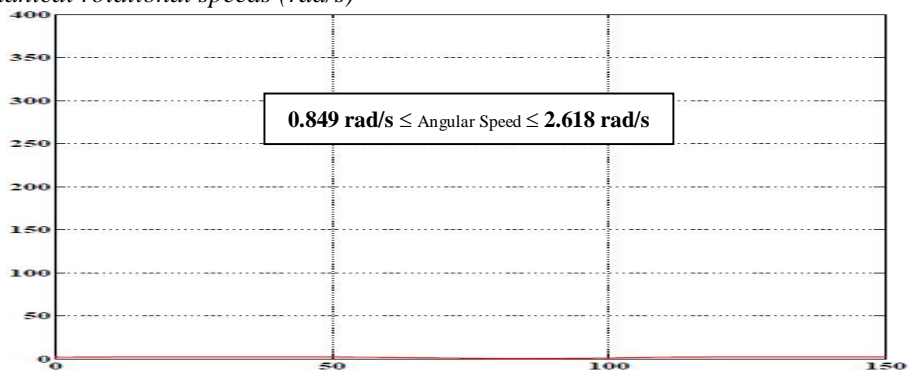
Figure 9. Proposed AFPM Generator Model Result

85.1 rad/s ≤ Angular Speed ≤ 150.7 rad/s

Figure 10. Standard DFIG Model Result

125.6 rad/s ≤ Angular Speed ≤ 126.1 rad/s

Figure 11. Standard IG Model Result

188.13 rad/s ≤ Angular Speed ≤ **373.6 rad/s**

Figure 12. Standard EESG model result

4.2. Active power delivered (Watts)

7.5 kW ≤ Active Power ≤ **86.94 kW**
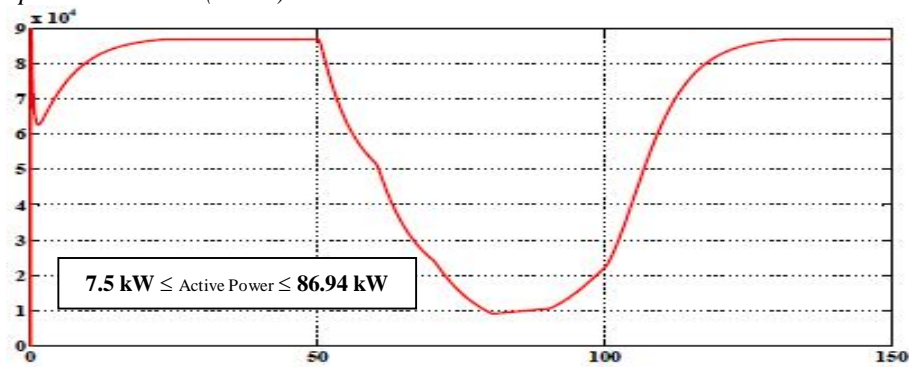
Figure 13. Proposed AFPM generator model result

0 kW ≤ Active Power ≤ **63.74 kW**
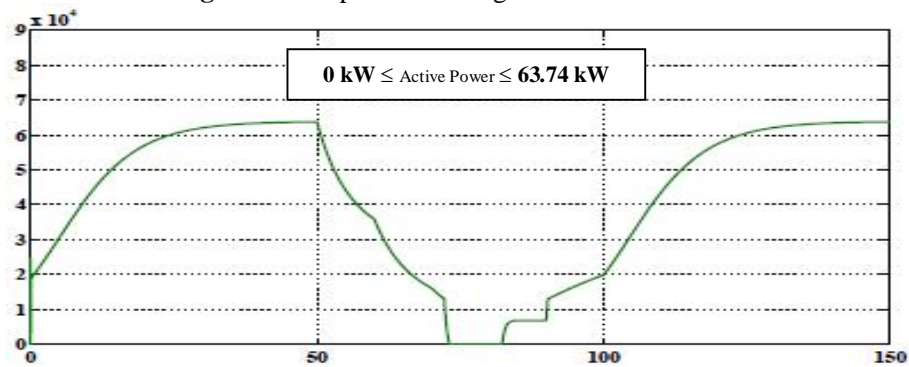
Figure 14. Standard DFIG model result

0 kW ≤ Active Power ≤ **55.33 kW**
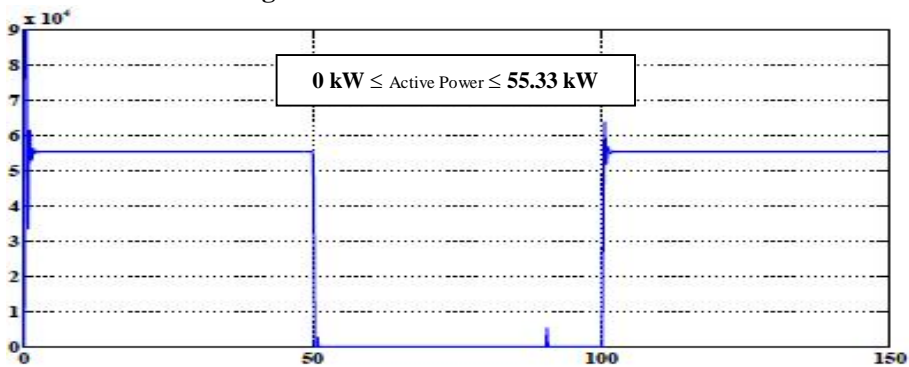
Figure 15. Standard IG model result

Figure 16. Standard EESG model result
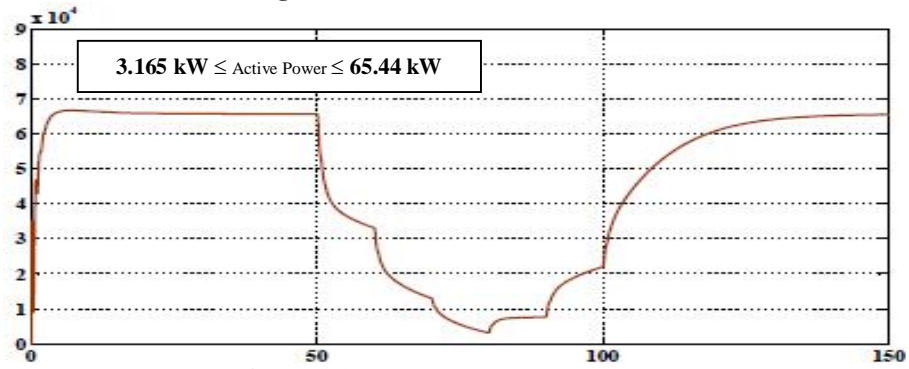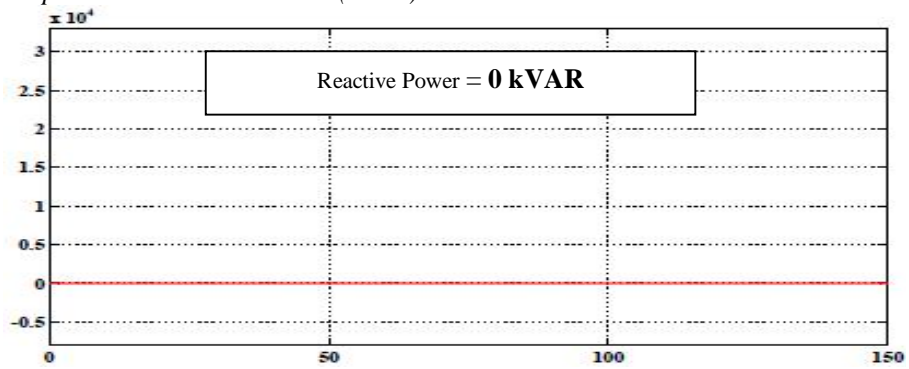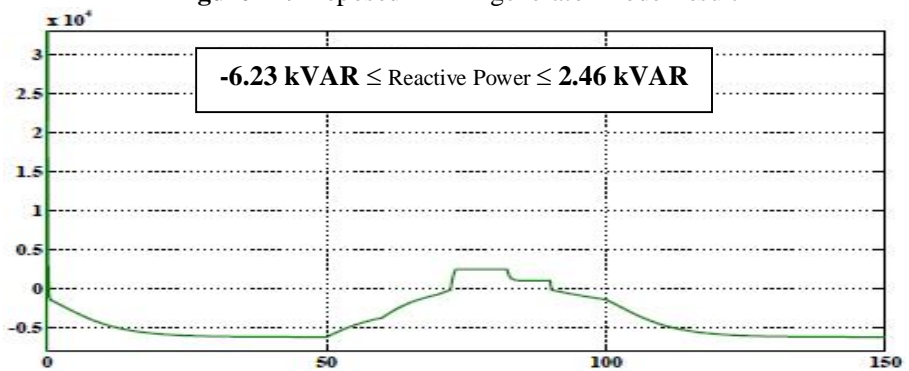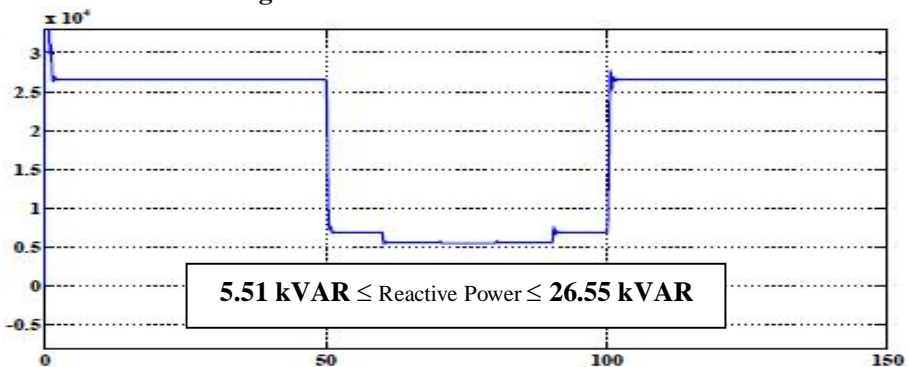
4.3. Reactive power delivered/absorbed (VARs)

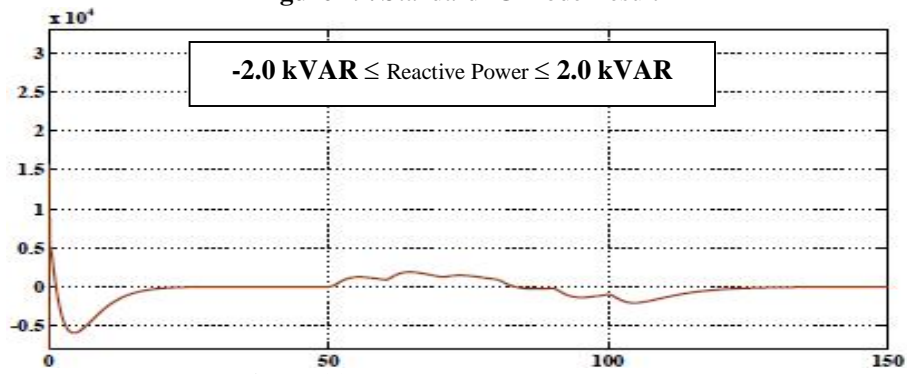
Figure 17. Proposed AFPM generator model result

Figure 18. Standard DFIG model result

Figure 19. Standard IG model result

-2.0 kVAR ≤ Reactive Power ≤ 2.0 kVAR

Figure 20. Standard EESG model result

4.4. Energy yield (Watt-hours)

0 ≤ Energy Yield ≤ **2598 Wh**
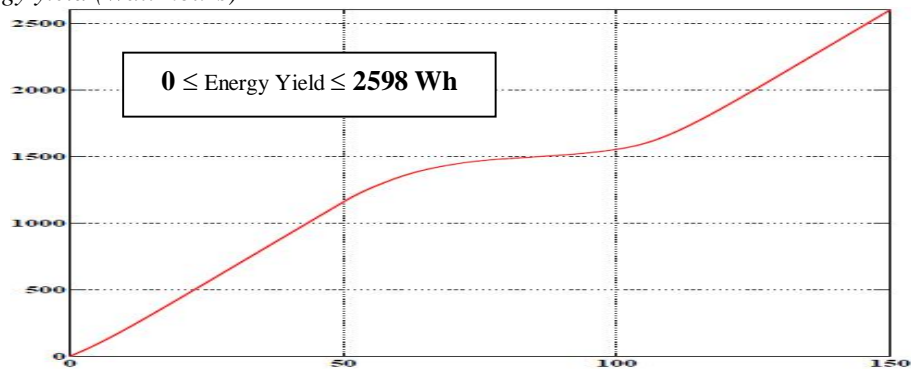
Figure 21. Proposed AFPM generator model result

0 ≤ Energy Yield ≤ **1756 Wh**
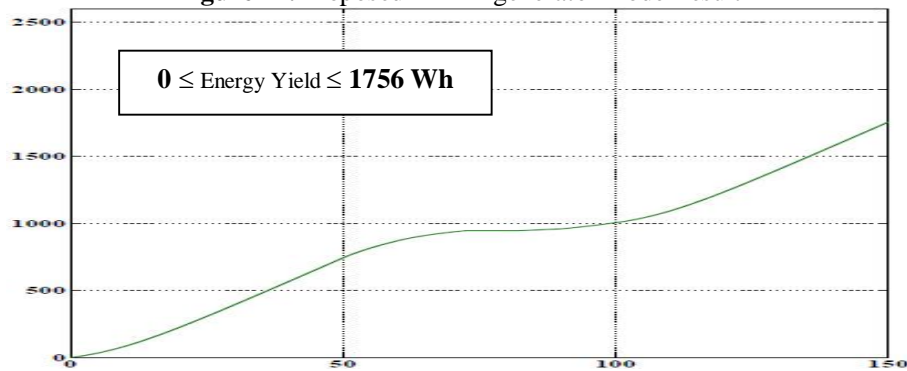
Figure 22. Standard DFIG model result

0 ≤ Energy Yield ≤ **1538 Wh**

Figure 23. Standard IG model result

$0 \leq$ Energy Yield $\leq$ **1955 Wh**

Figure 24. Standard EESG model result
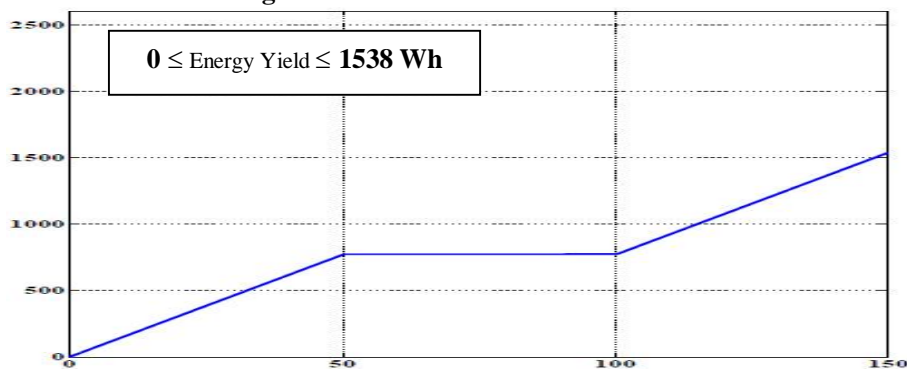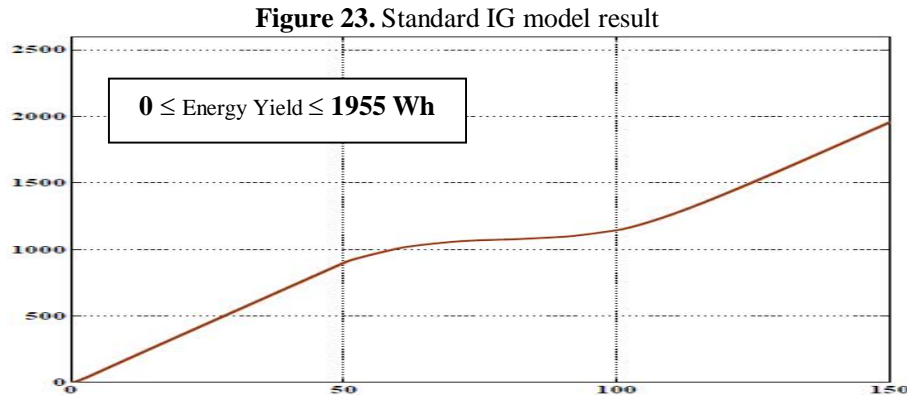
4.5. Performance comparison

The innovative design of a low-speed modular, direct-drive AFPM generator with coreless stator and rotor for a wind turbine power generation system has been developed and implemented using dynamic modeling techniques in MATLAB/Simulink. This proposed design has been compared with standard existing wind turbine generator models. The efficiency comparison with variable speed operation and the total energy yield comparison for depicting better wind power utilization have been shown in table 4 and table 5 given below.

Table 4. Efficiency Results.

Wind Speed (m/s)	Percentage improvement in efficiency of the Proposed AFPM Generator compared to:		
	DFIG	IG	EESG
12	26.69%	36.36%	24.73%
9	31.06%	IG stalled	34.62%
6	46.68%	IG stalled	42.62%
3	DFIG stalled	IG stalled	66.33%

Table 5. Energy Yield Results.

Percentage improvement in Energy Yield of the Proposed Generator compared to:		
DFIG	IG	EESG
32.41%	50.80%	24.75%

The comparison results demonstrate that the proposed model for the wind power generator exhibits improved efficiency with variable speed operation, higher energy yield and better wind power utilization. Moreover, the proposed generator's maximum efficiency at the rated operating conditions is 96.6% as compared to the value of 95.7% of the model of AFPM generator proposed in [21]. The proposed design has also reduced the weight of the nacelle since it uses non-ferromagnetic cores that are lighter in weight compared to the ferromagnetic material and provides a gearless turbine system.

5. Conclusion

In this paper, an innovative design of a low-speed, direct-drive AFPM generator is proposed. The proposed model has a modular structure with coreless stator and rotor. It was proved through simulation results that the proposed model has improved efficiency for variable speed operation,

compared to the standard models of existing wind power generators. Moreover, it was also proved that the proposed model exhibits number of other advantages such as higher energy yield, lighter weight and better wind power utilization.

References
[1]   Blaabjerg F, Iov F, Terekes T, Teodorescu R and Ma K 2011 Power Electronics - Key Technology for Renewable Energy Systems *2nd Conf. on Power Electronics, Drive Systems and Technologies* (Tehran, Iran: 16-17 February 2011) pp 445-66
[2]   Wang Y A and Xiao D M July 2011 Prototype design for a high-voltage high-frequency rectifier transformer for high power use *IET Power Electronics* **4** 615-23
[3]   Li H and Chen Z 2008 Overview of different wind generator systems and their comparisons *IET Renewable Power Generation* **2** 123-38
[4]   Blaabjerg F and Chen Z 2006 *Power Electronics for Modern Wind Turbines* (USA: Morgan & Claypool)
[5]   Zhang S, Tseng K J, Vilathgamuwa D M, Nguyen T D and Wang X Yu January 2011 Design of a robust grid interface system for PMSG-based wind turbine generators *IEEE Transactions on Industrial Electronics* **58** 316-28
[6]   Cheng K W E, Lin J K, Bao Y J and Xue X D 2009 Review of the Wind Energy Generating System *8th Int. Conf. on Advances in Power System Control, Operation and Management* (Hong Kong, China: 8-11 November 2009) pp 1-7
[7]   Jacek F. Gieras, Rong-Jie Wang and Maarten J. Kamper 2008 *Axial Flux Permanent Magnet Brushless Machines* vol 2 (Springer)
[8]   Yuan X, Li Y, Chai J and Ma M 2009 A Modular Direct-Drive Permanent Magnet Wind Generator System Eliminating the Grid-Side Transformer *13th European Conf. on Power Electronics and Applications (*Barcelona, Spain: 8-10 September 2009) pp 1- 7
[9]   Yuan X, Li Y and Chai J 2010 A Transformer-less Modular Permanent Magnet Wind Generator System with Minimum Generator Coils *25th Annual IEEE Applied Power Electronics Conf. and Exposition* (Palm Springs, California, USA: 21-25 February 2010) pp 2104-10
[10]   Gupta R K, Castelino G F, Mohapatra K K and Mohan N 2009 A Novel Integrated Three-Phase, Switched Multi-Winding Power Electronic Transformer Converter for Wind Power Generation System *35th Annual Conf. of IEEE* (Porto, Portugal: 3-5 November 2009) pp 4481-6
[11]   Basu K, Somani A, Mohapatra K K and Mohan N 2010 A Three-Phase AC/AC Power Electronic Transformer-Based PWM AC Drive with Lossless Commutation of Leakage Energy *Int. Symp. on Power Electronics Electrical Drives Automation and Motion* (Pisa, Italy: 14-16 June 2010) pp 1194-200
[12]   Basu K and Mohan N 2010 A Power Electronic Transformer for Three Phase PWM AC/AC Drive with Loss Less Commutation and Common-mode Voltage Suppression in 36th Annual Conf. on IEEE Industrial Electronics Society (Glendale, Arizona, USA: 7-10 November 2010) pp 315-20
[13]   Banaei M R and Salary E 2011 Power Quality Improvement Based on Novel Power Electronic Transformer *2nd Power Electronics, Drive Systems and Technologies Conf.* (Tehran, Iran: 16-17 February 2011) pp 286-91
[14]   Yin M, Li G, Zhou M and Zhao C 2007 Modeling of the Wind Turbine with a Permanent Magnet Synchronous Generator for Integration *IEEE Conf. on Power Engineering Society General Meeting* (Tampa, Florida, USA: 24-28 June 2007) pp 1-6
[15]   Venkatraj S and Mohan G September 2011 Modeling of wind farms with variable speed direct

driven permanent magnet synchronous generator wind turbines *International Journal of Research and Reviews in Electrical and Computer Engineering* **1** 982-90

[16] Rolan A, Luna A, Vazquez G, Aguilar D and Azevedo G 2009 Modeling of a Variable Speed Wind Turbine with a Permanent Magnet Synchronous Generator *IEEE Int. Symp. on Industrial Electronics* (Seoul, Korea: 5-8 July 2009) pp 734-9

[17] Lin M, Hao L, Li X, Zhao X and Zhu Z Q October 2011 A novel axial field flux-switching permanent magnet wind power generator *IEEE Transactions on Magnetics* **47** 4457-60

[18] Brisset S, Vizireanu D and Brochet P May/June 2008 Design and optimization of a nine-phase axial-flux PM synchronous generator with concentrated winding for direct-drive wind turbine *IEEE Transactions on Industry Applications* **44** 707-15

[19] Gerlando A D, Foglia G, Iacchetti M F and Perini R September 2011 Axial flux PM machines with concentrated armature windings: design analysis and test validation of wind energy generators *IEEE Transactions on Industrial Electronics* **58** 3795-805

[20] You Y M, Hwang K and Kwon B 2010 Optimal Design of Distributed Winding Axial Flux Permanent Magnet Synchronous Generator for Wind Turbine Systems *14th Biennial IEEE Conf. on Electromagnetic Field Computation* (Chicago, Illinois, USA: 9-12 May 2010) p 1

[21] Wang R J, Kamper M J, Westhuizen V D and Gieras J F January 2005 Optimal design of coreless stator axial flux permanent-magnet generator *IEEE Transactions on Magnetics* **41** 55-64

[22] Trimble SketchUp Software for 2D/3D Modeling: http://www.sketchup.com/

[23] MATLAB and Simulink Software for Technical Computing: http://www.mathworks.com/

[24] Finite Element Method Magnetics Software for Two-Dimensional Planar Electromagnetic Modeling: http://www.femm.info/wiki/HomePage/

[25] Franklin G F, Powell J D and Naeini A E 2002 *Feedback Control of Dynamic Systems* (New Jersey, USA: Prentice Hall)

[26] Patel M R 1999 *Wind and Solar Power Systems* (USA: CRC Press)

[27] Muyeen S M, Tamura J and Murata T 2009 *Stability Augmentation of a Grid-connected Wind Farm* (Springer)

[28] Krause P C, Wasynczuk O and Sudhoff S D 2002 *Analysis of Electric Machinery and Drive Systems* IEEE Press Series on Power Engineering (USA: John Wiley & Sons)