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Commonly used Wind Generator Systems: A Comparison Note

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Abstract

Amongst all renewable energy generation sources, wind power exhibits fastest growth rate. The increasing number of wind farm installations worldwide demand low maintenance, cost and failure rates with high efficiency. Determining the optimal drive train configuration amongst various configurations available for wind turbines is a challenge. In this paper commonly used, doubly fed induction generator with single stage gear box (GDFIG), doubly fed induction generator with multi stage gear box (DFIG) and the direct-drive permanent-magnet generator (DDPMG) are compared. Modelling of wind turbine with efficiency computations is presented. Considering common wind turbine parameters, performance of GDFIG, DFIG and DDPMG is compared through an experimental study. Considering a reference 5 MW variable speed wind turbine, efficiency of DDPMG is 96% when compared to 93.58%, 93.12% for DFIG and GDFIG. The experimental results presented prove that the DDPMG is a preferable solution considering low cost and high efficiency.

Keywords: *Wind turbine, Grid, renewable energy, gearbox, multi-gear, Permanent magnet generator*

1. Introduction

The Worldwide in the past decade primary emphasis is laid on adopting environmental friendly renewable energy generation mechanisms. Ever-increasing energy demand and depleting fuel resources have helped the adoption of renewable energy generation mechanisms. Low costs, abundant availability and eco-friendly nature of wind energy make it a popular energy generation source. To harness wind energy for power generation, wind turbines are used. Wind turbine generators convert kinetic energy of the wind into mechanical and electrical power. The growth of wind energy based power generation is evident from a recent report published by Global Wind Energy Council (GWEC) [1]. Estimated wind energy generation capacity considering various scenarios till 2050 is shown in Figure 1. In order to attain such growth it is essential to minimize cost and improve efficiency of currently available wind generation mechanisms.

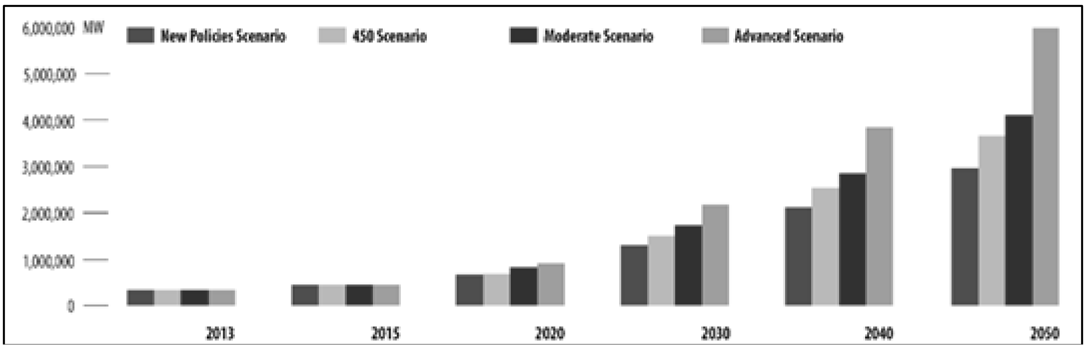

Figure 1. Global cumulative wind power capacity projected by GWEC till 2050 [1]

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Wind energy is harnessed through wind farms connected to a grid for distribution. Wind farms are basically classified into offshore and onshore types [2]. Offshore wind farms are commonly adopted [3]. In this paper offshore wind systems are considered. Wind turbines are essential components of offshore wind generation farms [4]. A wind turbine consist of various mechanical/electrical components and control subsystems. Blades, rotor hub, bearings, transmission shafts, gearbox, generator systems, control and feedback systems are a few components/subsystems of a wind turbine. To improve efficiency and minimize costs of wind turbines researchers have proposed efficient techniques to improve performance of blades [5] [6], rotors [7], gearbox [8-10], shafts [11], generators [10, 12]. Fault diagnosis and fault minimization techniques for wind turbines are presented in [13, 14]. A detailed survey of the control strategies adopted by researchers for wind turbines and challenges currently existing is presented in [15].

A major issue that currently exists is to ascertain the wind turbine configuration (i.e. type of gearbox, generator, control mechanism etc.) that is low in cost, maintenance, has low failure rates and efficient. To address this issue researchers in [16-20] have compared various wind turbine configurations. Based on these comparisons [16-20] studied it is evident that induction generators (IG) and permanent magnet generators (PMG) are the most commonly used. No conclusions with respect to the gearbox configuration (i.e. single gear systems or multi-gear systems) or direct drive configuration can be drawn. Observations and experimental study presented in [16-20] consider different turbine configuration that arise ambiguity.

In this paper three turbine configurations namely GDFIG, DFIG and DDPMG are compared. A variable speed wind turbine model is considered. Rotor dynamics, drive trains/ gearbox and generator modelling is considered as key components of the wind turbine model. Cost and scaling model of the wind turbines is adopted from [21]. To compare performance of GDFIG, DFIG and DDPMG uniform wind turbine parameters from [22] is considered. Experimental results presented prove better performance of DDPMG when compared to GDFIG and DFIG. Similar observations is reported in [19] and [20]. In this paper [23] the dynamic reaction of the wind turbine gearbox system is taken under different excitation circumstance. The main reliability problems which comes in the current wind energy business is due to gearbox failure. The gearbox excitation circumstances is represented by the both internal and external excitation. By the help of numerical integration method with frequency spectrum and time history, the dynamic reaction of wind turbine gearbox subcomponents are examined. The essential mechanism is study by the suggested dynamic model with include of gearbox component, bearing and gears.

The significance of DDPMG for offshore wind turbines is discussed in [24]. Significance of direct drive systems in wind power generation is described. To improve performance and reduce costs of permanent magnet generators hybrid genetic algorithm [25] with pattern search [26] operation is used. Establishing the appropriate objective function is discussed. Including material properties and structural modelling is essential. Results presented prove that by using appropriate objective functions and genetic optimization improved generator designs are possible.

A low-speed hydraulic pump and single stage gearbox transmission are utilized by a hydraulic power transmission technology discussed in this paper [27]. The transmission technology holds the stable-torque feature of a hydrostatic transmission and reduces the hydraulic pump displacement. Simple structure of a hybrid power transmission system and model of system are design and constructed in this paper by using Matlab software. When the wind speed is greater than rated value then pitch control algorithm and when wind speed is less than the rated value then constant-frequency variable speed control algorithm are analyzed and simulated. The experimental and simulation results shows that a hybrid power transmission stabilized the torque of wind turbine generation system and meets the demands in several working situations.

The modern wind turbines [28] are improved up in relations of output power into multi megawatt. Though, the energy profit of turbine is balance by the enlarged mass and cost. The problem is that, in realistically how much larger can wind turbine? In this paper, at a single support configuration make use of multi-rotor system. Advantage of standardization can be offered by multi-rotor wind turbine systems and it also offer easiness of maintenance and installation. In the paper comparison is done between the NREL 5 MW multi rotors wind system and 5 MW single-rotor baseline system. Multiple rotors are rationalized by the use of scaling curves possession the 5MW standard mechanism as reference[29].In this paper, the wind generator proposed system design has extended for the grid connection through DC/AC converter control. The DFIG has used in wind turbine with the AC/DC converter [30]. Complete DFIG mathematical model is present which has driven by the DC machine.

Four types of drive train configurations are considered in this paper [31] over sites range, which is differentiated by their distance. Failure data rate from offshore and onshore wind turbine are used where systematically data was not available. It taken as an input with the requirements of repair resource for operation and maintenance and offshore accessibility model to evaluate operation and maintenance and availability costs for wind farms that consists 100 turbines. The results shows that turbines with direct drive permanent magnet generator have lower operation and maintenance costs and higher availability in comparison of doubly fed induction generators. And this is also followed by turbines with single stage.

The remaining manuscript is organized as follows. Proposed wind turbine modelling is discussed in section 2. Experimental study and comparisons is in section 3. Concluding remarks and future work is discussed in the last section.

2. Research Method

Key components of the wind turbine model considered in this paper are shown in Figure 2.

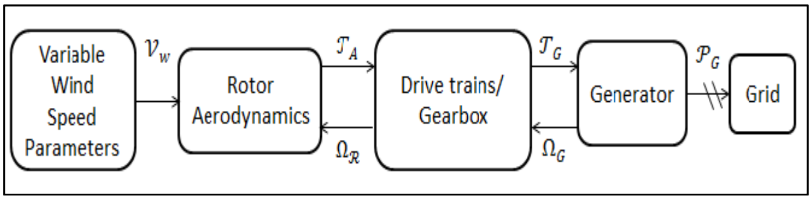

Figure 1. Variable speed wind turbine model

2.1. Wind Turbine Drive Train Dynamics

Nomenclature used in modeling:

Prameter	Abbreviation	Parameter	Abbreaviation
E	Turbine efficiency	$\mathcal{T}_G$	Generator electromagnetic torque (Nm).
E_g	Gear box efficiency	$\mathcal{T}_L$	Low-speed torque (Nm).
E_G	Generator efficiency	$\mathcal{T}_H$	High-speed torque (Nm).
E_C	Conversion efficiency	$\mathcal{K}_G$	Generator external damping $(Nm/radsec)$.
$\mathcal{P}_t$	Rated turbine power (W)	$\mathcal{K}_\mathcal{R}$	Rotor external damping $(Nm/radsec)$.
$\mathcal{V}_w$	Wind speed(m/s).	$I_\mathcal{R}$	Rotor inertia(kg^2/m).
D_a	Air density(kg/m^3).	I_G	Generator inertia(kg^2/m).
$\mathcal{R}_r$	Rotor radius (m).	I_t	Turbine total inertia(kg^2/m).
$\mathcal{P}_A$	Aerodynamic power(W).	$\mathcal{K}_t$	Turbine total external damping $(Nm/radsec)$.
$\mathcal{T}_A$	Aerodynamic torque (Nm).	$S_\mathcal{R}$	Rotor external stiffness $(Nm/radsec)$.
Λ	Tip speed ratio.	S_G	Generator external stiffness $(Nm/radsec)$.
$\mathcal{C}_\mathcal{P}(\Lambda)$	Power coefficient.	S_t	Turbine total external stiffness $(Nm/radsec)$.
$\mathcal{C}_\mathcal{T}(\Lambda)$	Torque coefficient.	m_g	Gearbox ratio
Ω_t	Rated turbine speed.	m_w	Wheel ratio
$\Omega_\mathcal{R}$	Rotor speed (rad/sec).	Ω_G	Generator speed(rad/sec).

This paper deals with the efficiency enlargement and cost control of Variable Speed Wind Turbine. Figure 2 shows the VSWT Global Scheme. The modeling of Variable Speed Wind Turbine proposed in this model can be explained by Figure 3 and that study of [32] and [33] inspired to propose the above mentioned model. The Variable Speed Wind Turbine (VSWT) model catches the aerodynamic power $(\mathcal{P}_A)$which is given by:

$$\mathcal{P}_A = \frac{1}{2}\pi D_a \mathcal{R}_r^2 \mathcal{C}_\mathcal{P}(\Lambda)\mathcal{V}_w^3, \quad (1)$$

In the above equation $\mathcal{C}_\mathcal{P}(\Lambda)$ represents the power coefficient in which $\mathcal{C}_\mathcal{P}$ shows the conversion efficiency which is a function of Λ as well as the pitch angle (γ) of a VSWT. Λ which is known as tip speed ratio that can be represented as follows:

$$\Lambda = \frac{\mathcal{R}_r \Omega_\mathcal{R}}{\mathcal{V}_w} \quad (2)$$

The characteristics of $\mathcal{C}_\mathcal{P}$ and its function Λ for the different-different values of pitch angle γ. For the one unique value of pitch angle γ the wind turbine is the most efficient. To keep the system at optimum tip speed Λ_{opt} , the speed of rotor is varied in accordance with the rated value of speed which termed as $\mathcal{C}_{\mathcal{P}max}$.Then, to control the blade pitch angle it rotates at max. Speed which is based on aerodynamics [34].
The aerodynamics power $\mathcal{P}_A$ which is also known as rotor power is defined as follows:

$$\mathcal{P}_A = \Omega_\mathcal{R} \mathcal{T}_A \quad (3)$$

The relation between torque coefficient and power coefficient considering for tip ratio Λ is

$$\mathcal{C}_\mathcal{T}(\Lambda) = \frac{\mathcal{C}_\mathcal{P}(\Lambda)}{\Lambda} \quad (4)$$

The aerodynamics torque is given by,

$$\mathcal{T}_A = \frac{1}{2}\pi D_a \mathcal{R}_r^3 \mathcal{C}_\mathcal{T}(\Lambda)\mathcal{V}_w^2 \quad (5)$$

Then, optimum torque is computed using,

$$\mathcal{T}_{opt} = h_{opt}\Omega^2 \quad (6)$$

Where:

$$h_{opt} = \left(\frac{1}{2\Lambda_{opt}^2}\right) D_a \pi \mathcal{R}_r^5 \mathcal{C}_{\mathcal{T}max} \quad (7)$$

In Equation (7) optimal tip speed ratio is represented by Λ_{opt}.

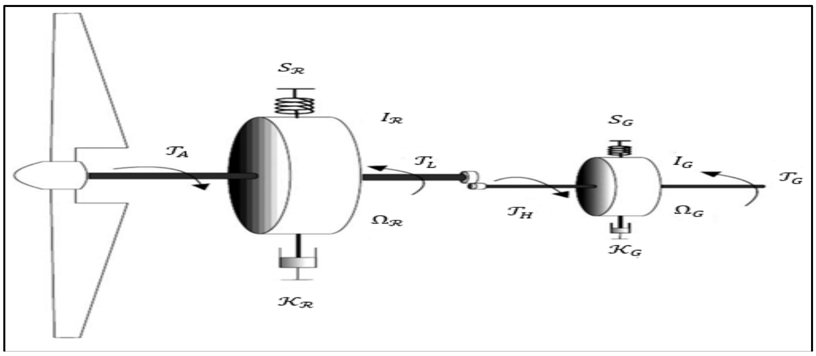

Figure 2. Wind turbine drive train dynamics

The wind turbine is rotated with speed of $\Omega_{\mathcal{R}}$ by $\mathcal{T}_A$ which is represented in the Figure 3 There two type of torque are generated ,one which is known as low speed torque and another one is high speed torque. The high speed torque ($\mathcal{T}_H$) is generated to drive the generator. $\mathcal{T}_G$ is used to brake the high speed torque.

To brake the speed of rotor low speed torque ($\mathcal{T}_L$) is used. To get the generator speed (Ω_G) the speed of rotor is incremented through the gearbox by using gearbox ratio (m_g).

The below differential equations shows the rotor dynamics,

$$\begin{aligned} I_{\mathcal{R}}\dot{\Omega_{\mathcal{R}}} &= \mathcal{T}_A - (\mathcal{K}_{\mathcal{R}}\Omega_{\mathcal{R}}) - (s_{\mathcal{R}}\Phi_{\mathcal{R}}) - \mathcal{T}_L \\ I_G\dot{\Omega_G} &= \mathcal{T}_H - (\mathcal{K}_G\Omega_G) - (s_G\Phi_G) - \mathcal{T}_G \end{aligned} \quad (8)$$

The gearbox ratio m_g is computed using:

$$m_g = \left(\frac{\Omega_G}{\Omega_{\mathcal{R}}}\right) = \left(\frac{\mathcal{T}_L}{\mathcal{T}_H}\right) \quad (9)$$

Using (8) and (9),

$$I_t\dot{\Omega_{\mathcal{R}}} = \mathcal{T}_A - (\mathcal{K}_t\Omega_{\mathcal{R}}) - (s_t\Phi_{\mathcal{R}}) - \mathcal{T}_G \quad (10)$$

Where,

$$\begin{aligned} I_t &= I_{\mathcal{R}} + (m_g^2 I_G) \\ \mathcal{K}_t &= \mathcal{K}_{\mathcal{R}} + (m_g^2\mathcal{K}_G) \\ S_t &= S_{\mathcal{R}} + (m_g^2 S_G) \\ \mathcal{T}_G &= m_g\mathcal{T}_{em.} \end{aligned} \quad (11)$$

Since the S_t turbine external stiffness << 1, which shows that inertia of rotor and generator are dominating together which shows only the drive train is used for controlling the wind turbine.

$$I_t\dot{\Omega_{\mathcal{R}}} = \mathcal{T}_A - (\mathcal{K}_t\Omega_{\mathcal{R}}) - \mathcal{T}_G \quad (12)$$

The final generated power $\mathcal{P}_G$ is,

$$\mathcal{P}_G = \mathcal{T}_G\Omega_{\mathcal{R}} \quad (13)$$

2.2. Gear Box Modeling

2.2.1. Single Stage and Multi Stage Gearbox Modelling

To minimize cost and size increasing gear ratio m_g is considered. Increasing m_g also increases speed. Cost and weight of the gearbox model have to be considered. Increment in the ratio of gearbox will increase the mass of gearbox. Weight of the single stage gearbox G_{g1} mainly concentrated on shaft torque level and stage ratios chosen, which is shown Equation 14:

$$G_{g1} = \frac{(3.2 \times \mathcal{T}_H \times X_s \times X_w)}{1000} \quad (14)$$

where $\mathcal{T}_H$ the gearbox output is torque (Nm); X_s is the service factor which consider failure by metal fatigue and surface damage. If m_w is the wheel ratio then weight factor X_w which is given as [35]

$$X_w = \frac{1}{\mathcal{W}} + \frac{1}{\mathcal{W}.m_w} + m_w + m_w^2 + 0.4\frac{(1+m_w)}{\mathcal{W}}(m_g - 1)^2 \quad (15)$$

where $\mathcal{W}$ is the single stage planet wheel number and $m_w = \frac{m_g}{2} - 1$.

The wind generator system with the three-stage gearbox G_{g3} is consider to be $\Omega_{\mathcal{R}} = 1500\ rpm$ rated generator speed, the mass weight for three-stage gearbox scaled roughly based upon the low-speed shaft torque [36].

$$G_{g3} = 10.35\,\mathcal{T}_L + 1950 \tag{16}$$

where for the low speed shaft (kNm) $\mathcal{T}_L$ is the input mechanical torque.

The gearbox losses are of two types, first bearing losses and another one teeth losses, which are dependent on the input power, other than this lubricant losses & seal losses also exists which can be dependent on the speed of rotor. These losses are considered as, so that it is reasonable to neglect [37]. Power of gearbox is shown below,

$$\mathcal{P}_{gear} = k_g \mathcal{P}_t \frac{\Omega_{\mathcal{R}}}{\Omega_t} \qquad 17)$$

where k_g represents loss constant (here, $G_{g1} = 1.5\%$ and $G_{g3} = 3\%$ [38]).

2.2.2. Direct Drive

At present days, some of the wind turbine system have adopted the concept of gearless turbine, a direct driven multipole generator system is used as a substitute of gearbox at the generator. A direct drive machinery has acclaimed for its design, it is less composite than the gear box technology, less maintenance and ease at operation. For the use in offshore wind improvements the application direct drive particularly preferred. Efficiency 1 is assumes for the proposed model of direct drive scheme.

2.3. Wind Generator Modeling

Induction generator for GDFIG and DFIG is considered. Permeant magnet generator is considered for DDPMG.

2.3.1. Induction Generator

Squirrel cage induction generator (SCIG) and doubly fed induction generators (DFIG) are predominantly used for wind generation. Usually in small wind turbines SCIG are used where as in large wind turbines DFIG are used.

In Figure 4 a Grid connected wind turbine model for GDFIG and DFIG is shown. It consists of two types of windings, one specified as stator windings and another one is rotor windings. A capacitor which is specified as dc-link is kept in between the rotor side convertor and grid convertor. The control of torque is possible, reactive and active power at the stator terminals as well as the speed of DFIG can control with the control of generator-side converter. DFIG speed can be varied in two modes either Super Synchronous or Sub Synchronous in bidirectional way. Active power to grid is always feed by DFIG stator side.

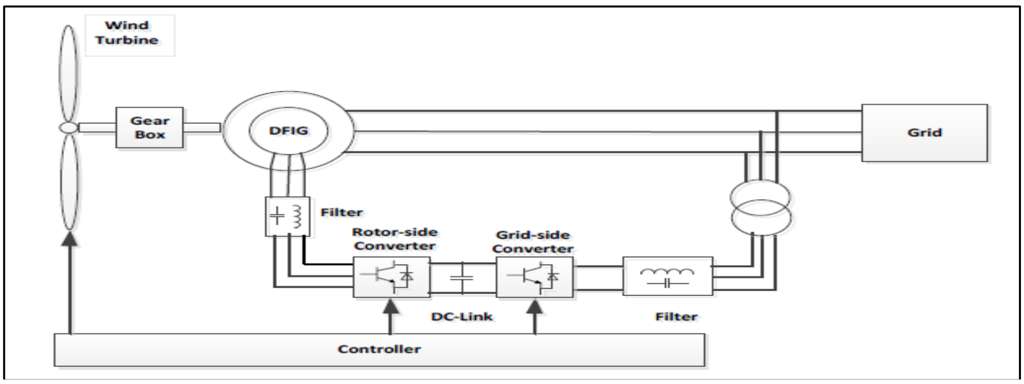

Figure 3. Grid connected wind turbine model for GDFIG and DFIG

2.3.2. Permanent Magnet Generator

A permanent magnet generator is type of linear generator in which electric energy is obtained by the mechanical energy. It has high efficiency, high force density at low speeds and electrical contact between the translator (moving part) and stator is not occur.

Variable speed wind turbine uses a PMSG with full-scale converter arrangement. Through a full-scale power converter, the phase winding of stator are connected to grid A gearless concept is implemented by some type of wind turbines that means no gearbox is used with generator, wind turbine directly driven only with generator.

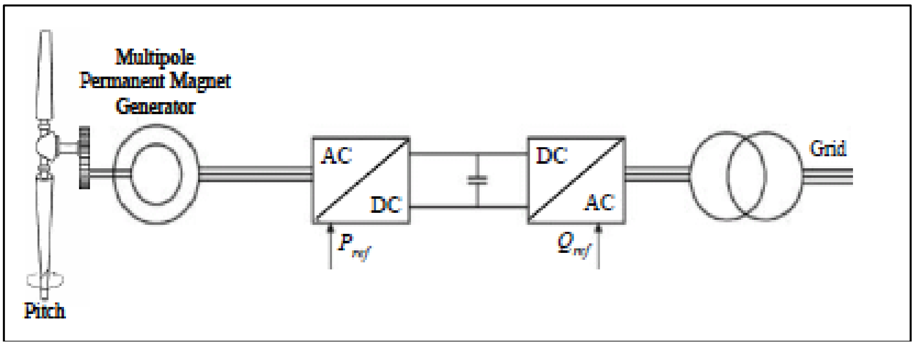

Figure 4. Grid connected wind turbine model of DDPMG

In the permanent magnet generator the rotor shaft is driven by the unit of blades and the rotor are made of permanently magnetic material. When the magnetic rotor is drive by the rotating blades, a magnetic field interacts with the multiple winding of the stator. The rotating line of magnetic force cause of an alternating voltage in the windings. Figure 5 depicts an example of a wind turbine with a permanent-magnet direct-drive generator [39].

The amount of torque densities present in Direct-drive permanent magnet generator is higher comparison to electrically excited synchronous machines. Some direct-drive permanent magnet design is presented in [40]. We have some alternative method to reduce the mass of permanent magnet generator, which is presented in [41]. The most common method is radial flux permanent magnet machine.

2.4. Efficiency of Wind Turbine

The overall efficiency E of a wind turbine is computed using

$$E = E_g \times E_G \times E_C \qquad (18)$$

Efficiency E is a quantitate measure depicting working of a turbine and also enables in determining actions to be considered to increase the efficiency and cost reduction. Generator efficiency E_G for GDFIG, DFIG and PMSG is derived from curve fitting equations defined in [42].

3. Experimental Study and Performance Comparisons

In this section performance of the GDFIG, DFIG and GDFIG wind turbines is compared. Performance comparison under variable speed conditions and efficiency is presented. The proposed wind turbine models for GDFIG, DFIG and DDPMG are realized using MATLAB/SIMULINK. All simulations are carried out using MATLAB 2012b on a Windows 10 operating system (64 bit) PC with 8GB of RAM and Intel core i7 3.4GHz processor. Uniform wind turbine parameters are obtained using reference $5-MW$ model proposed by NREL. A three bladed variable speed wind turbine is considered to compare performance of GDFIG, DFIG and DDPMG. Wind turbine parameters considered is summarized in Table 1.

Table 1. Wind turbine parameters for GDFIG, DFIG and DDPMG

Parameters	GDFIG	DFIG	DDPMG
Rated power (MW)	5.29661	5.29661	5.29661
Rated rotor speed (rpm)	12.1	12.1	12.1
Rotor diameter (m)	126	126	126
Swept area ($\times 1000\, m^2$)	1.24453	1.24453	1.24453
Mean wind speed (m/s)	11.4	11.4	11.4
Hub height (m)	2.4	2.4	2.4
Cut in wind speed (m/s)	3	3	3
Cut out wind speed (m/s)	25	25	25
Optimum tip speed ratio	7.55	7.55	7.55
Maximum power coefficient	0.482	0.482	0.482
Air density (kg/m^3)	1.225	1.225	1.225
No of Blades	3	3	3
Rotor orientation	Upwind	Upwind	Upwind
Control	Variable Speed	Variable Speed	Variable Speed
Drivetrain/Gearbox	Single-Stage	Multi-Stage	Direct-Drive
Hub-height (m)	90	90	90
Rated tip speed (m/s)	80	80	80
Cut-in rotor speed (rpm)	6.9	6.9	6.9

3.1. Performance Considering Variable Wind Speeds

In this section the wind speed is varied using a Gaussian function. A simulation time of $300\ s$ is considered. The wind speed variation is shown in Figure 6. The corresponding aerodynamic power P and torque τ is shown in Figure 7 and Figure 8.

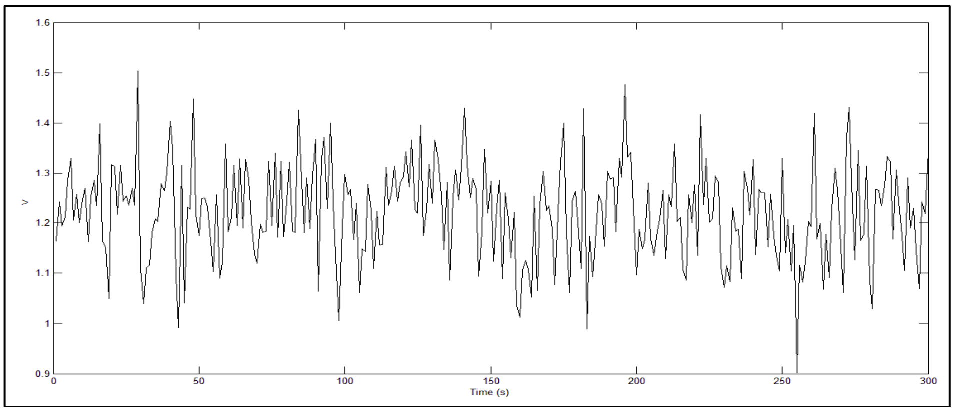

Figure 5. Wind speed variation v with respect to time

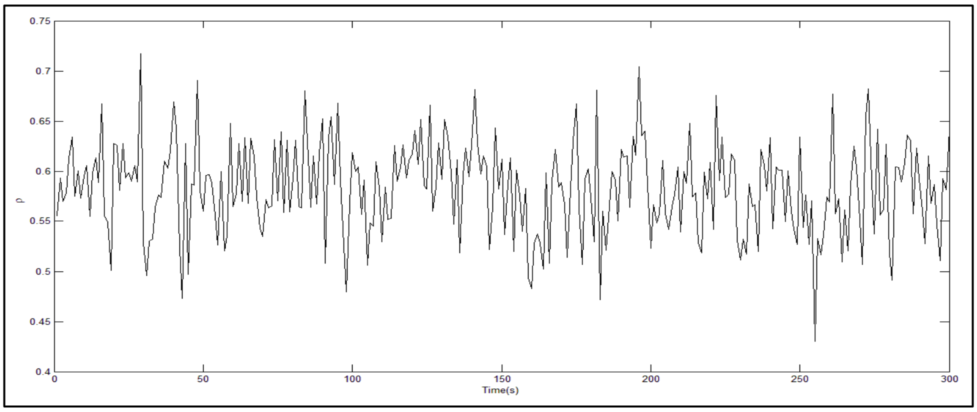

Figure 6. Aerodynamic power P delivered to main shaft considering variable wind speed

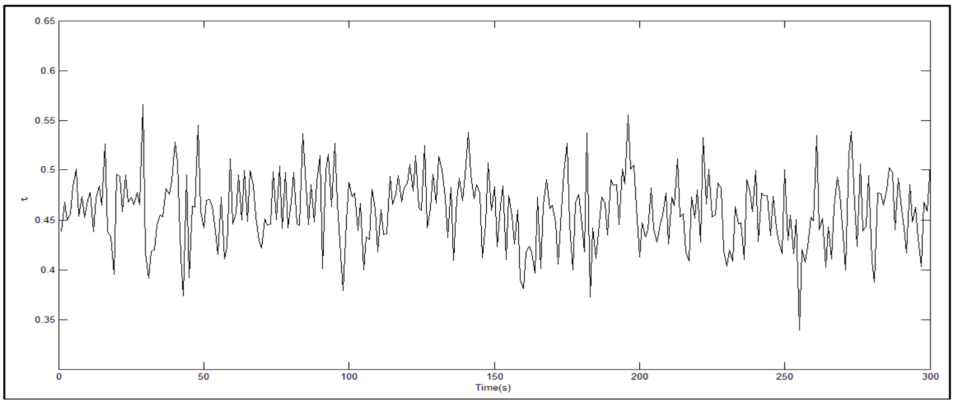

Figure 7. Aerodynamic torque variations observed due to wind speed variations

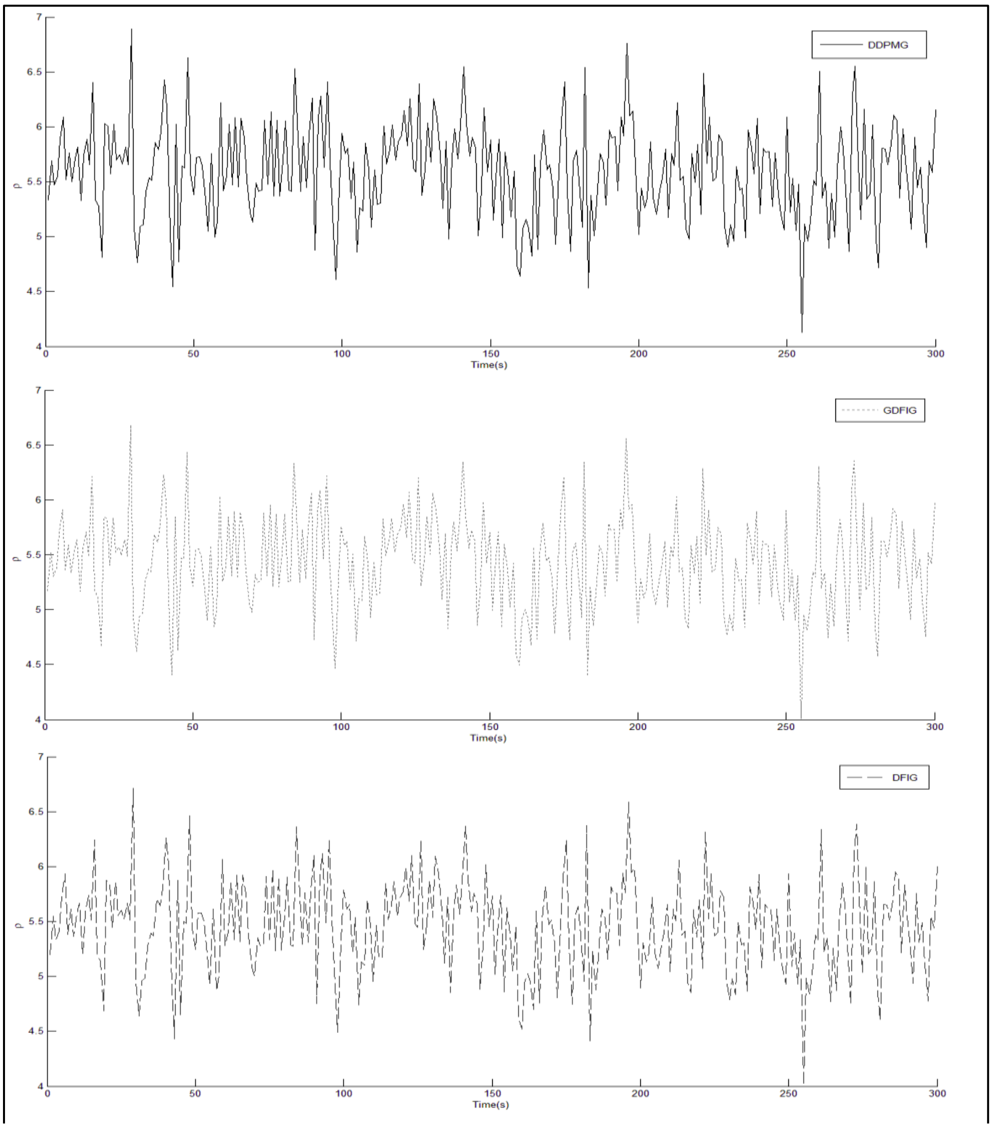

Figure 8. Performance comparison of power generated by DDPMG, GDFIG and DFIG under varying wind speed conditions

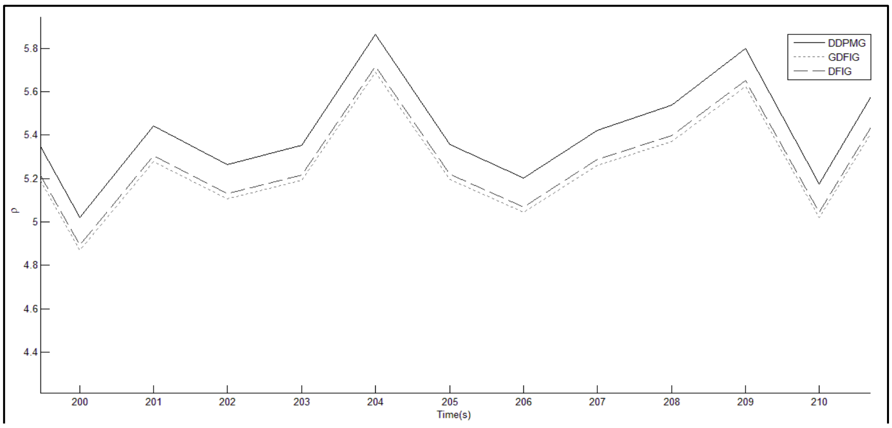

Figure 9. Performance comparison of power generated by DDPMG, GDFIG and DFIG under varying wind speed conditions at time interval of 200s to 210s

The performance of GDFIC, DFIG and DDPMG is studied considering wind speed variations and the output power from the generator is noted. The output power observed is shown in Figure 9 of the paper. Best performance of the DDPMG is observed. Similar variations in power and torque are reported in [43], thereby validating the results obtained. The DFIG exhibits better wind energy conversion when compared to GDFIG. The power generated by GDFIC, DFIG and DDPMG in time span between of $200s$ to $210s$ is shown in Figure 10. From figure 10 superior performance of DDPMG is evident when compared to its induction generator counterparts i.e. GDFIG and DFIG.

3.2. Efficiency Comparisons

To compare efficiency of the GDFIC, DFIG and DDPMG wind turbines, parameters from Table 1 are considered with constant wind speed. The conversion efficiency observed at rotor is noted. Conversion efficiency of 51.5% is reported across GDFIC, DFIG and DDPMG. The efficiency at the gearbox for GDFIG, DFIG is 96% and 98.5%. The efficiency observed at the generators is 95%, 97%, 96% for GDFIC, DFIG and DDPMG. Generator efficiency is derived by curve fitting presented in [42]. Higher generator efficiency is reported in DFIG when compared to GDFIG and DDPMG. The conversion, gearbox and generator efficiency observed for GDFIC, DFIG and DDPMG is graphically shown in Figure 11. The efficiency error bars for conversion, gearbox and generator is also shown. The cumulative efficiency in wind energy conversion for GDFIG, DFIG and DDPMG is shown in Figure 12. Wind energy conversion efficiency of DDPMG is 96% when compared to 93.58%, 93.12% for DFIG and GDFIG.

The results obtained prove that the DDPMG is a preferred choice for wind farm constructions. Similar results are reported in [19] and [20].

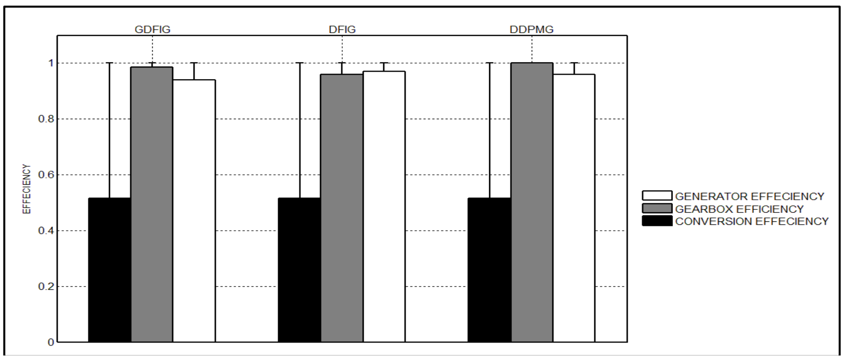

Figure 10. Conversion, gearbox and generator efficiency comparisons for GDFIG, DFIG and DDPMG

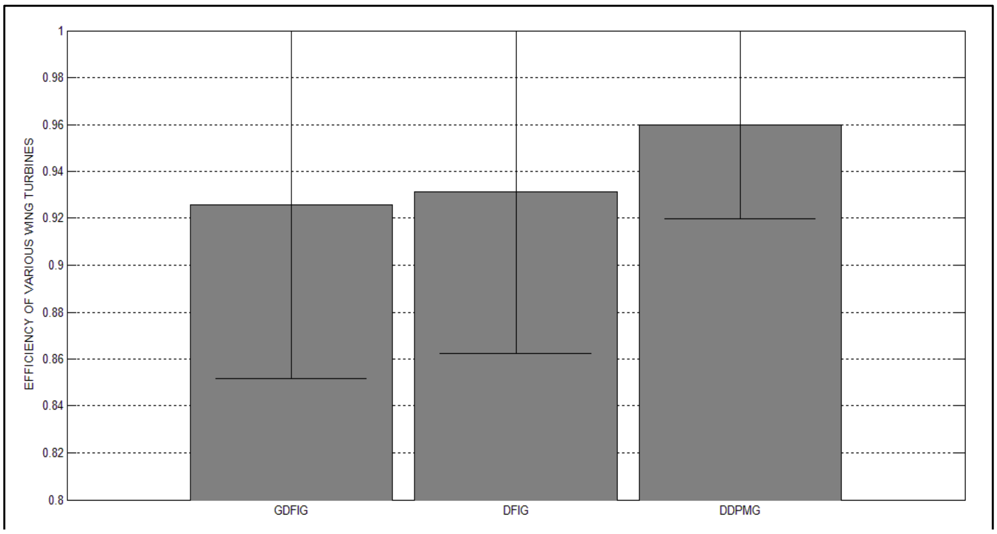

Figure 11. Wind energy conversion efficiency comparison for GDFIG, DFIG and DDPMG

4. Conclusion

The significance of wind energy and its growth prospects is discussed in this paper. The current wind energy generation systems and their corresponding drawbacks is discussed. Asserting wind turbine configuration from a set of varied options currently in place is a problem that exists. In this paper three wind turbines GDFIG, DFIG and DDPMG is compared. Modeling of the wind turbine components is presented. Results obtained from experimental study prove that DDPMG is a preferred choice.

Wind energy conversion efficiency of 96% is reported in case of DDPMG. Higher wind conversion efficiencies have been reported in the literature studied. Higher wind conversion efficiency is possible by accurately designing permanent magnet generators. The future of the work presented here is to optimize design parameters of permanent magnet generators to improve overall efficiency and reduce cost.

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