Mathematical Modeling and Simulation Analysis of A DC Motor Based Wind Turbine Emulation System

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Abstract

The cost of implementing an actual wind turbine is quite high, therefore a wind turbine is emulated to obtain the characteristics of a real wind turbine. The concept of emulation involves the torque control of a DC motor according to the reference torque generated from the turbine. In this paper, a separately excited DC motor is controlled using a first quadrant DC Chopper to obtain the wind turbine characteristics. First, a MATLAB program is written to obtain the theoretical power and torque characteristics of the turbine. Then, the turbine is simulated using mathematical modeling of DC motor and chopper to obtain the desired theoretical torques. The model is tested for two different wind turbines and is validated using the simulation results obtained. Also, both the turbines are simulated with a three-phase rectifier and results are presented which can be used for laboratory purpose. Hence, this paper is intended to propose an accurate model which saves the cost of actual implementation of turbine and provides a study platform for researchers in this domain.

Keywords: Wind Energy Systems, DC Chopper, PI controller, Wind Turbine Emulator

INTRODUCTION

In recent scenario, where there is a limited availability of conventional sources, the renewable energy sources are significant members of a power system. Wind power is one of the commonly used renewable energy resource which has various advantages like availability, cost, clean and green energy, etc. [1]. A lot of research activities are being carried out in this area, but it is difficult to implement an actual wind turbine for research in laboratories. Therefore, a wind turbine emulator is required which can emulate the actual behavior of a turbine. Several authors have published their work in this field. Researchers have used squirrel cage induction motors, permanent magnet synchronous motors and separately excited DC motors etc. to emulate the wind turbine. To emulate the wind characteristics, the input wind speed profile is an important aspect. Studies consider the input wind as a stochastic or a deterministic profile. Authors have modelled the wind by decomposing it in an average speed component and high frequency fluctuations. Some studies have considered it as a sum of several harmonics or variable scalar function versus time.

Authors have preferred inverter controlled induction machine as a wind simulator over DC machine [2-3]. The paper [4] has presented an induction motor driving a dc generator for emulation. The effect due to wind shear and tower shadow are studied in the paper [5]. In paper [6], flux and torque control of induction motor is incorporated. Some of the papers have used permanent magnet synchronous motor [7-8] in preference to DC motor. Authors have used boost converters [8], rectifiers [9-11] or other converters for the control of motor. Papers [12-13] use forth quadrant chopper to obtain the wind simulator and paper [14] implements the same using FPGA.

In paper [15], dc motor is used to drive self-excited induction generator. Authors in Refs. [16], discuss the harmonics in the torque generated due to torsional oscillation. A. Mahdy and others [17] describes the implementation using analog electronic circuits to generate a specific reference wind speed. In [18], a three-mass system including a turbine, a gear box and a generator connected with two elastic shafts is constructed. An armature and field controlled motor is used in paper [19]. The experimental verification for DC motor coupled to a double fed induction generator for a 300W prototype is performed in [20]. A small wind conversion system is studied using a dc motor-generator set which can be connected to a micro-grid [21]. Authors in [22] present the simulation, considering, the pitch control and additional wind effects and shaft dynamics.
In this paper, a separately exited DC motor is opted to emulate a wind turbine. The obvious reasons for using a DC motor are easy to understand concepts and less complicated speed and torque control. As discussed above, the previous works done use converters like a rectifier or a four-quadrant chopper. Some of the authors have used mathematical modeling of turbine, but the converter is generally not modelled using equations. In this study, a mathematical model of a first quadrant DC chopper is developed and applied to mathematical model of wind turbine. PI based control is implemented to control the IGBT switches of chopper. PI controller is also simulated using mathematical equations. As the complete model uses mathematical modelling for all the subcomponents, i.e. turbine, chopper, PI controller and dc motor, the accuracy of the model can be considered high compared to the ones available in literature. Also, the model is simulated with a rectifier instead of a chopper and results are presented for both the ac-dc and dc-dc converters.

Fig.1 shows the block diagram for basic concept of wind emulation system. To implement this work, the wind turbine is first modelled using mathematical equations. Then, the theoretical power and torque characteristics are obtained using these equations in a MATLAB program. This theoretical torque acts as the reference torque for closed loop control of DC motor using mathematical model of first quadrant DC chopper. Thus, an easy to implement wind emulator is mathematically simulated using MATLAB and results are obtained for deterministic wind speed profiles. Two different wind turbines are simulated so that the results obtained can be considered closer to the actual turbine. The torque obtained from dc motor can be fed to the generator and the electricity can be supplied to the load.

**Figure 1. Basic concept of wind turbine emulation**

### WIND TURBINE MODEL

The mechanical output power obtained from the wind generators is given by [10]:

\[
P_m = \frac{1}{2} \rho A v^3 C_p(\lambda, \beta)
\]

where, \( \rho \) is the air density (kg / m\(^3\)), \( v \) is the wind speed (m/s), \( A \) is the area swept by the rotor blades (m\(^2\)) and \( C_p(\lambda, \beta) \) is the performance coefficient.

The parameter \( C_p \) defines efficiency of power extraction. It is a nonlinear function of Tip Speed Ratio (\( \lambda \)) and pitch angle of the blade (\( \beta \)). \( \lambda \) is the ratio of rotational speed of turbine (\( \omega_t \)) to linear speed of blade tips and is given by:

\[
\lambda = \frac{\omega_t \times R}{v}
\]

where, \( R \) is the radius of the blade. In this paper, a fixed pitch turbine with varying speed is taken into consideration, hence \( \beta \) is kept fixed at 0°. Various versions of equation for obtaining \( C_p \) have been defined by authors in previously published papers. In this paper, the following two equations (3), (4) are used for \( C_p \) [23], [10]:

**Turbine 1:**

\[
C_p = 0.00234 + 0.03227\lambda - 0.076354\lambda^2 + 0.061857\lambda^3 - 0.015155\lambda^4 + 0.001514\lambda^5 - 0.000055\lambda^6 \tag{3}
\]

**Turbine 2:**

\[
C_p = 0.5176(116(1/\lambda i - 0.4\beta - 5)e(-21 * 1/\lambda i) + 0.0068 \lambda \tag{4}
\]

Where, \( 1/\lambda i = (1/(\lambda + 0.08\beta)) - (0.035/(\beta^3 + 1)) \) \tag{5}

Fig. 2a and Fig. 2b show the simulated plot of power coefficient \( C_p \) with Tip Speed Ratio for turbine 1 and turbine2 respectively. It can be observed that the maximum \( C_p \) (0.3921) for turbine1 occurs at \( \lambda = 5.321 \) and for the turbine2, the maximum \( C_p \) (0.48) occurs at \( \lambda = 8.148 \).
Fig.3a and Fig.3b show the power characteristics for both the turbines for different wind speeds from 1 m/s to 14 m/s and rated speed is considered as 12 m/s. These are the theoretical values of power and torque which are obtained from a MATLAB program using equations mentioned in this paper.
The torque of the turbine is stated as:

\[ T_t = \frac{P_m}{\omega_t} \]  

(6)

Fig. 4a and Fig. 4b show the torque characteristics for both the turbines.
The other parameters of both the turbines which are used in this paper are given in Table 1.

Here, G is the gear ratio and S is the scaling factor and can be defined as:

\[ G = \frac{\omega}{\omega_t} \]  
(7)

\[ S = \frac{\text{rated machine power}}{\text{rated turbine power}} \]  
(8)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Turbine 1</th>
<th>Turbine 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of blades</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>( \beta )</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( \rho )</td>
<td>1.08</td>
<td>1</td>
</tr>
<tr>
<td>R</td>
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<td>1.5</td>
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<tr>
<td>G</td>
<td>7.4</td>
<td>0.5</td>
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<tr>
<td>S</td>
<td>1</td>
<td>1/3</td>
</tr>
</tbody>
</table>

Figure 4b. Torque Characteristics for turbine2

Emulation of Wind Turbine Characteristics using DC motor

A separately excited DC motor, whose parameters are given in appendix, is controlled to follow the reference torque generated by wind turbine at a given wind speed and rotor speed. The emulation of the actual turbine means the machine torque must be followed according to the generated torque and speed. To obtain the closed loop torque of DC motor, the PI control is used. The first quadrant DC chopper in continuous current mode is used to control the motor. Also, the model is simulated with a three-phase rectifier instead of DC chopper and results are shown for both the turbines. The control strategy is shown in Fig.5. In Fig.6, the simulation model with DC Chopper is presented. Fig. 7 shows a subsystem which includes the mathematical modelling of a first quadrant DC chopper. Fig.8 shows the input wind speed profile applied to the system.
**SIMULATION RESULTS**

The proposed model is simulated using MATLAB/SIMULINK to obtain the desired torque and rotor speed. Fig 9,10, 11 show the results obtained for turbine1. The torque is obtained by simulating the turbines with rectifier and chopper. Fig. 9 shows the generated torque of DC machine with chopper. Fig. 10 shows the torque obtained for same turbine with rectifier controlled motor. It can be observed that the torque characteristics obtained with simulation vary according to the input wind speed and closely follows the theoretical torque characteristics of the turbine 1 (Fig. 4). Fig. 11 shows the rotor speed for turbine1 which also follows the speed obtained in Fig. 4.
Fig. 12, Fig. 13 and Fig. 14 present the simulated results for turbine 2. The generated torque of DC motor is shown with chopper and rectifier respectively. Also, the rotor speed is shown. It can be observed that the torque of the dc motor at 12 m/s is 8 Nm and it follows the theoretical turbine torque (shown in Fig. 5). In Fig. 14, rotor speed at 12m/s is 50 radians per second and it matches with the rotor speed shown in Fig. 5. This can be verified for all the speeds. As the torque and speed are following the reference turbine values, the results obtained are closer to actual system. The simulated values are little lesser than the theoretical values due to the frictional losses in DC motor. The results are also verified for other input speed profiles.
CONCLUSIONS

The proposed model illustrated in this paper accurately emulates the turbine characteristics for all the wind speeds. The theoretical reference torque obtained from turbine is accurately followed by the generated torque from the DC machine. The mathematical model is tested for two turbines and results are presented. Also, the model is tested for other input wind profiles. The accuracy of the model is high as the complete mathematical model is used for all the components including turbine, first quadrant chopper, PI controller and motor. Also, the results are shown for rectifier controlled DC motor. The results presented in this paper can be used to study wind energy systems and can save a huge cost of implementing actual wind turbine.

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Appendix

DC Motor Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Rated power</td>
<td>1 KW</td>
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<tr>
<td>Rated speed</td>
<td>1450 rpm</td>
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<tr>
<td>Rated armature voltage</td>
<td>120 V</td>
</tr>
<tr>
<td>Armature resistance</td>
<td>0.2Ω</td>
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<tr>
<td>Armature inductance</td>
<td>73mH</td>
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<tr>
<td>Rated field voltage</td>
<td>240 V</td>
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<tr>
<td>Rated field current</td>
<td>0.88A</td>
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<tr>
<td>Mutual inductance</td>
<td>1.068H</td>
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<tr>
<td>Inertia</td>
<td>0.014kgm²</td>
</tr>
<tr>
<td>Friction coefficient</td>
<td>0.01Nms</td>
</tr>
</tbody>
</table>

REFERENCES


Conversion Systems Operating over a Wide Range of Wind Velocity”, http://dx.doi.org/10.1007/978-3-642-03454-1_13.


