Design and Control of One kilowatt DC Motor-based wind Turbine Emulator

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Abstract: Due to high cost of wind turbines and the need of research and development in lab scale systems, this paper introduces the design and control steps of one kilowatt wind emulator using a variable speed DC-motor system controlled by a full wave controlled Rectifier Bridge. The dynamics of wind turbine system is considered in the proposed emulation system. The dynamics of the designed system is presented under deterministic and stochastic wind speed profiles. The paper also illustrates the design steps of current control loops PI-controllers to control the DC motor torque.

Keywords—Wind Energy, Wind Turbine Emulation System, DC Motor Drive.

I. Introduction

A wind turbine emulator (WTE) is equipment which is used for producing the real wind turbine characteristics in the laboratory. This emulator emulates the dynamic and static behaviour of the real wind turbine without the need of natural wind resource and actual wind turbine.

For the purpose of research tests, a system is designed to emulate the wind turbine characteristics. The emulator can be used to drive the DFIG in a similar way like an actual wind turbine; by generating torque similar to the aerodynamic torque at a given wind speed. The purpose of wind turbine characteristic emulation is to study and develop the WECS in the laboratory without the need for high cost real wind turbine. Squirrel cage induction motor (SCIM), permanent magnet synchronous motor (PMSM) and DC motor are usually used for emulating mechanical power characteristics of wind turbines in the laboratory I-VII. These motors are controlled to have power curves similar to the wind turbine characteristics.

The objectives of this paper are:
1) Modeling and emulating 1KW wind turbine which can be used in the laboratories,
2) Obtaining Power-speed and torque-speed characteristics from the modeled turbine and
3) Controlling separately excited DC motor model to obtain the wind turbine characteristics (DC motor-based emulation).

II. Wind turbine model

Wind turbine is the prime mover of the WECS. So, the modeling and emulation of wind power is important in studying and improving different wind systems. The mechanical output power of the wind turbine is given by equation (1).

\[ P_m = \frac{1}{2} \rho \pi R^2 C_p(\lambda, \beta) v_w^3 \]  \hspace{1cm} (1)

Where \( \rho \) is the air density in (Kg/m\(^3\)), \( R \) is the radius of the swept area in (m), \( C_p \) is the power coefficient and \( v_w \) is the wind speed in (m/sec). The power coefficient is defined as the ratio of the turbine mechanical power to the power available by the wind.

This coefficient is a function of TSR (\( \lambda \)) and the blades pitch angle (\( \beta \)) in (deg). TSR is the ratio of the blade tip speed to the wind speed as illustrated in equation (2).

\[ \lambda = \frac{\omega_i R}{v_w} \]  \hspace{1cm} (2)

Where \( \omega_i \) is the rotor angular speed in (rad/sec).

The aerodynamic mechanical torque of the wind turbine is given by (3).

\[ T_m = \frac{1}{2} \rho \pi R^3 C_p(\lambda, \beta) v_w^2 \]  \hspace{1cm} (3)

As pointed in IX, the power coefficient, \( C_p(\lambda, \beta) \), is a non-linear function of the tip speed ratio, \( \lambda \), and the blade pitch angle, \( \beta \). The \( C_p(\lambda, \beta) \) curve can be derived from field test on the wind turbine. An empirical equation is used to model the \( C_p, \lambda \) and \( \beta \) surface, based on the turbine characteristics, is given by equation (4), I-III, X.

\[ C_p(\lambda, \beta) = C_1 \left( C_2 - \frac{1}{\lambda_i} - C_3 \beta - C_4 e^{C_5 \lambda} + C_6 \lambda \right) \]  \hspace{1cm} (4)

Where the parameters \( C_1 \) to \( C_6 \) are constants and \( \lambda_i \) is given by equation (5).

\[ \frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - 0.035 \beta^3 + 1 \]  \hspace{1cm} (5)

Table 1 gives a typical value of the parameters \( C_1 \) to \( C_6 \). These parameters change from one turbine to another based on the aerodynamic characteristics of the turbine. Figure 1 shows the power coefficient characteristic for different values of \( \lambda \) and \( \beta \) of the turbine with the parameters shown in Table 1. The maximum value of the power coefficient (\( C_p = 0.48 \)) is achieved at \( \beta = 0 \) deg and \( \lambda = 8.108 \). Also, Figure 2 shows the power coefficient curve at \( \beta = 0 \).

| Table 1: parameters of the power coefficient equation |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| \( C_1 \)       | \( C_2 \)       | \( C_3 \)       | \( C_4 \)       | \( C_5 \)       | \( C_6 \)       |
| 0.5176          | 116             | 0.4             | 5               | 21              | 0.0068          |

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By looking at the wind turbine power and torque equations, (1) and (3), it can be noticed that the inputs are the wind speed, the blades pitch angle and the rotor speed and the output is the aerodynamic torque. As a result, the wind turbine model must have the same inputs, outputs and characteristics. The role of the used motor (DC, PMSM or SCIM) is to generate the reference torque requested by the wind turbine model. The complete strategy is illustrated in Figure 3. The torque scaling factor, S_t, is given by equation (6). This allows the reproduction of the actual turbine aerodynamic characteristics but on the used machine scale to avoid the machine damage.

\[
S_t = \frac{P_{\text{machine}}}{P_{\text{turbine}}} \quad (6)
\]

Where \( P_{\text{machine}} \) is the nominal machine power and \( P_{\text{turbine}} \) is the nominal turbine power.

The Simulink model of the 3 KW wind turbine is shown in Figure 4. This model is developed by equations (1)-(5), with \( R = 1.5m \) and \( \rho = 1\text{Kg/m}^3 \). The next two sections are explaining wind turbine emulation in detail using DC motor and PMSM respectively.

**III. Emulation of wind turbine dynamics using DC motor**

A separately excited 1 KW DC motor is used to emulate the turbine characteristics mentioned in section II. The DC motor is controlled to follow the reference torque given by the wind turbine at certain wind speed, certain blade pitch angle and certain rotor speed. The basic idea to emulate real wind turbine is that the generated torque and speed of the DC motor should comply accord with the aerodynamic characteristics of the wind turbine, which means machine torque has to be controlled according to the model output torque. The controller used for this is a proportional integral controller as it is easy in design and implementation.

**A. Control scheme**

In the wind turbine emulation system, the DC motor must operate with closed loop torque. In this system, the DC motor imposes torque in the electrical generator shaft according to a reference signal torque produced by turbine model.

The parameters of the used machine are shown in Table 2. The field circuit of the motor is supplied by the rated voltage to give the rated flux without any control. The way of controlling the DC machine and emulating the wind turbine is illustrated in Figure 5.
Table 2: 1KW DC motor parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated armature voltage, (v_a)</td>
<td>120 V</td>
</tr>
<tr>
<td>Rated power</td>
<td>1 Kw</td>
</tr>
<tr>
<td>Rated speed, (\omega_r)</td>
<td>1450 r.p.m</td>
</tr>
<tr>
<td>Rated armature current, (i_a)</td>
<td>8.3 A</td>
</tr>
<tr>
<td>Armature resistance, (R_a)</td>
<td>5 (\Omega)</td>
</tr>
<tr>
<td>Armature inductance, (L_a)</td>
<td>73 mH</td>
</tr>
<tr>
<td>Rated filed current, (i_f)</td>
<td>0.88 A</td>
</tr>
<tr>
<td>Field resistance, (R_f)</td>
<td>280 (\Omega)</td>
</tr>
<tr>
<td>Field inductance, (L_f)</td>
<td>15.29 H</td>
</tr>
<tr>
<td>Mutual inductance, (L_m)</td>
<td>1.068 H</td>
</tr>
<tr>
<td>System inertia, (J)</td>
<td>0.014 Kg.m²</td>
</tr>
<tr>
<td>System friction coefficient, (B)</td>
<td>0.01 N.m.s</td>
</tr>
</tbody>
</table>

B. Current control loop PI controller design

The equivalent circuit of the separately excited DC motor is shown in Figure 6. So, to control the armature current, \(i_a\), the voltage across the inductor, \(V'_a\), must be controlled. The transfer function of the armature current loop in S-domain is

\[
G_p(s) = \frac{l_a(s)}{V'_a(s)} = \frac{1}{L_a S + R_a}
\]  

(7)

Where \(V'_a\) is the voltage drop across the inductor as illustrated in equation (8).

\[
v_a = v_a - K_e\omega_r
\]  

(8)

Where \(\omega_r\) is the rotor speed in (rad/sec) and \(K_e\) is the voltage constant which equals the torque constant, \(K_t\), and can be calculated as presented in equation (9).

\[
K_e = K_t = L_m i_f
\]  

(9)

The transfer function of the armature current loop can be written as shown in equation (10) where \(\tau\) the circuit time is constant and \(K\) is value corresponding to the inverse of the armature resistance.

\[
G_p(s) = \frac{1}{L_a S + R_a} = \frac{1}{1 + \frac{L_a}{R_a} S} = \frac{K}{1 + \tau S}
\]  

(10)

Implementing a filter transfer function as follows:

\[
C(s) = \frac{1}{G_p(s)} f(s) = \frac{1}{1 + \lambda S}
\]  

(11)

And selecting a first order system filter as follows:

\[
f(s) = \frac{1}{1 + \lambda S}
\]  

(12)

So,

\[
C(s) = \frac{1}{(1 +\lambda S)^2} \frac{\tau S + 1}{K(\lambda S + 1)}
\]  

(13)

With \(G_p(s)\) and \(C(s)\), the equivalent PI controller is obtained using the following equation:

\[
G_{pi}(s) = \frac{C(s)}{1 - C(s)G_p(S)} = \frac{\tau S + 1}{K(\lambda S + 1)}
\]  

(14)

From equation (14) the PI controller parameters, \(K_i\) and \(K_p\) can be determined based on the value of \(\lambda\). This means that \(\lambda\) drives the current response of the system because it directly affects the controller gains. As a result, using small values of \(\lambda\) gives a faster closed-loop response but it also increase the current overshoot and vice versa, XI. By trying different values of \(\lambda\) to meet the response requirements which is 20% maximum overshoot and settling time = 0.1 sec, \(\lambda\) equals \(10^{-3}\).

After \(\lambda\) is selected the values of the PI controller are obtained by using equation (14) as following:

\[
K_i = \frac{1}{K \lambda} = \frac{1}{\frac{73}{5} \times 10^{-3}} = 5000
\]  

(15)

\[
K_p = \frac{\tau}{K \lambda} = \frac{73 \times 10^{-3}}{\frac{5}{5} \times 10^{-3}} = 73
\]  

(16)

Figure 6: the equivalent circuit of the separately excited DC motor

IV. Simulation results

The WTE presented in Figure 3 is implemented and simulated in Matlab/Simulink, as shown in Figure 7 and the result is shown considering deterministic variable wind speed and stochastic wind speed profiles. Figure 8 shows the wind turbine characteristics at different wind speeds and also the figure shows the load torque characteristic, the electrical generator characteristic with the rotor speed, used to test the model.

Simply, the DC motor emulates the wind speed characteristics if and only if at given wind speed the rotor speed is one of the points of intersection, between the load characteristic and the turbine characteristic, shown in Figure 8 according to the wind speed. Actually, the rotor speed will be a little bit smaller than the points indicated in Figure 8 due to the presence of mechanical losses in the shaft and electrical losses in the DC motor.
Figure 7: Matlab simulation of WTE system

Figure 8: The load torque characteristic and the wind turbine characteristics at different wind speeds

For deterministic wind speed profile as shown in Figure 9 the corresponding turbine rotor speed is shown in Figure 10. As presented in these two figures the rotor speed is little a bite smaller than the values shown in Figure 8. As a result, the system accurately emulates the wind turbine characteristics. Also, Figure 11 shows the electromechanical torque produced by the motor and how it increases with increasing the wind speed.

Figure 9: Wind speed profile

Figure 10: Dynamic behavior of emulated wind turbine speed

Figure 11: Generated torque of the DC machine

For stochastic wind speed profile, as shown in Figure 12, the emulated torque exactly follows the reference torque produced by the wind turbine model, as presented in Figure 13. Figure 14 presents the rotor speed for this stochastic wind speed profile. Figure 15 presents the load power and the input electrical power supplied to the DC motor. The difference between the two powers, as illustrated above, is due to the losses in the armature circuit and the losses due to rotor friction.

Figure 12: Stochastic wind speed profile
V. conclusion
The designed system illustrated in this paper can emulate the dynamic behavior of a typical wind turbine under both stochastic and deterministic wind speed profiles. The one kilowatt motor used in this simulation work tracks perfectly the static and dynamic behavior of a given wind speed profile by controlling the electro mechanical torque of the motor. The matching factor used in the simulation gives the ability to emulate the characteristic of large wind turbine using a low power DC motor which is essential in studying and improving the wind energy conversion systems.

The designed steps illustrated in this paper can be used to design any DC motor to make this task.

- REFERENCES


