Modeling & Simulation of Variable Speed Wind Turbine with Resonant DC-DC Converters

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Abstract—This paper deals with modeling and simulation of variable speed wind turbine (VSWT) with DC-to-DC converter for stand-alone wind energy system. The wind turbine system consists of synchronous generator (SG), diode rectifier, buck DC- DC converter and inverter is present. Based on this electrical model, a Simulink model of the system are simulated by using MATLAB Simulink power system blocks. This converter has advantages like reduced transformer size, reduced filter size and current source characteristics. The Simulink circuit model for closed loop system of VSWT is developed and the same is used for simulation studies.

Keywords—Converter, DC to DC Converter, MATLAB, Resonant Inverter, Synchronous Generator.

I. INTRODUCTION

SMALL-SCALE stand-alone wind energy is increasingly viewed as a viable and sometimes preferred source of electrical energy. Consider, for example, remote villages in developing countries or ranches located far away from main power lines. Wind energy is a quiet alternative to remote diesel generation—generation that sometimes depends on excessive transportation and fuel storage costs—and an economically justifiable alternative to a grid connection. It has been shown that a remote load has only to be a matter of a few miles away from a main power line for a stand-alone wind generator to be cost-effective. Wind turbines, however, are not always very efficient in the wind speeds that are most common to a region. Typically, wind energy systems are designed to be highly efficient in high wind speed and have a cut-off wind speed—below which no energy is captured. In remote locations where wind energy is used for battery charging, the energy lost below the cut-off wind speed could be used for trickle charging or maintaining a battery’s fully charged state. Wind turbines are most efficient when they are operated at one specific tip-speed to wind-speed ratio (TSR). Therefore, for the efficient capture of wind power, turbine speed should be controlled to follow the ideal TSR, with an optimal operating point which is different for every wind speed.

A typical, small- scale, stand-alone, wind electric system is composed of a wind turbine, a permanent-magnet generator, a diode bridge rectifier, and a dc power system. In many small-scale systems, the dc system is at a constant dc voltage and is usually comprised of a battery bank, allowing energy storage; a controller to keep the batteries from overcharging; and a load. The load may be dc or may include an inverter to an ac system.

Unfortunately, there can be significant problems connecting a wind generator to a constant dc voltage. At low wind speeds, the induced voltage in the generator will not be high enough to overcome the reverse bias in the diode bridge. At high wind speeds, the electrical frequency increases and the reactive impedance of the generator will be high, while the impedance of the battery load will be low. In this case, the poor impedance matching will limit power transfer to the dc system. In response to these problems, researchers have investigated incorporating a dc–dc converter in the dc link. While allowing a constant dc voltage to the load, a dc–dc converter will allow the voltage at the output of a diode bridge rectifier to be controlled. In low wind speed conditions, the voltage may be lowered to prevent the dc link from reverse biasing the diode rectifier. Under high wind speed conditions, the voltage may be increased, reducing I2R losses. In addition, adjusting the voltage on the dc rectifier will change the generator terminal voltage and thereby provide control over the current flowing out of the generator. Since the current is proportional to torque, the dc–dc converter will provide control over the speed of the turbine.

Control of the dc–dc converter may be achieved by means of maximum power point tracking or by means of a predetermined relationship between wind speed and rectifier dc voltage. Maximum power point tracking requires continuous variation of the dc voltage to determine whether the output power may be increased.

This system is relatively complex and may have limited use in tracking rapid changes to the system. The relatively high turbine inertia can cause a significant time lag between the change to the dc-link voltage and any observed change in power. Use of a predetermined relationship between wind speed and voltage may also have difficulties. Accurate wind speed measurement is difficult and requires the use of a relatively expensive anemometer if it is to be used for system control. The system proposed in this work makes use of a predetermined relationship between generator electrical frequency and dc-link voltage.

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This paper deals with a buck dc–dc converter that achieves high wind turbine efficiency across a wide range of wind speeds. The system is designed for use in remote locations and, therefore, includes a simple control strategy and a fault-tolerant topology. The control circuit included fault detection and has been tested with a parallel redundant dc link. The literature [1] to [9] does not deal with the simulation of closed loop controlled DC to DC converter with wind system modeling. This paper deals with simulation of closed loop controlled DC to DC converter with wind system modeling.

![Schematic representation of modeled VSWT coupled Synchronous Generator for stand-alone systems.](image)

**Fig. 1** Schematic representation of modeled VSWT coupled Synchronous Generator for stand-alone systems.

<table>
<thead>
<tr>
<th>Effective Turbine Radius</th>
<th>1.0m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase to Phase Inductance</td>
<td>3.3mH</td>
</tr>
<tr>
<td>Phase to Phase Resistance</td>
<td>0.51ohms</td>
</tr>
<tr>
<td>Peak per Phase Torque Constant</td>
<td>0.71Nm/A</td>
</tr>
<tr>
<td>Poles</td>
<td>8</td>
</tr>
<tr>
<td>System Inertia</td>
<td>1.2kg-m²</td>
</tr>
<tr>
<td>System Damping</td>
<td>0.16Nm/k RPM</td>
</tr>
</tbody>
</table>

**TABLE I**

**WIND ENERGY SYSTEM DATA**

The fundamental equation governing the power capture of a wind turbine is

\[ P_t = \frac{1}{2} \rho A C_p v^3 \]  

Where, \( P_t \) is turbine power, \( \rho \) is air density, \( A \) is the swept turbine area, \( C_p \) is the turbine coefficient of performance and \( v \) is wind speed.

The coefficient of performance is a function of TSR, described by

\[ TSR = \frac{\lambda}{v} \]  

Where, \( \lambda \) is the tip speed ratio, \( \lambda = \frac{\omega M R}{v} \) \( \omega \) is rotational speed, \( \omega = \frac{1}{2} \rho A C_p v^3 \) \( v \) is wind speed. A typical curve is shown in Fig. 2. The maximum power captured by the wind turbine will occur when the TSR is approximately 7.5, corresponding to a \( C_p \) of 0.35.

**B. Wind Turbine**

The wind turbine is described by the following equation

\[ \lambda = \frac{\omega M R}{v} \]  

\[ P_{\omega} = \frac{1}{2} \rho A R^2 C_p v^3 \]  

\[ T_{\omega} = \frac{P_{\omega}}{\omega} \]  

Where, \( \lambda = \frac{\omega M R}{v} \) \( M = \) blade angular speed [mechanical rad/s] \( R = \) blade radius [m] \( v = \) wind speed [m/s] \( P_{\omega} = \) mechanical power from wind blades [kW] \( \ell = \) air density [kg/m³] \( C_p = \) power coefficient \( T_{\omega} = \) mechanical torque from wind blades [N-m]
The mechanical torque obtained from equation (6) enters into the input torque to the synchronous generator, and is driving the generator. CP may be expressed as a function of the tip speed ratio (TSR) \( \lambda \) given by equation (4) [7].

\[
C_P = (0.44 - 0.0167 \beta) \sin \frac{\pi(\lambda - 2)}{13 - 0.3\beta} - 0.00184 (\lambda - 2) / \beta
\]  

(7)

Where, \( \beta \) is the blade pitch angle. For a fixed pitch type the value of \( \beta \) is set to a constant value.

C. Synchronous Generator

The Mat lab/Simulink provides a fully developed synchronous generator model, which is based on generalized machine theory [2] and with this model both sub-transient and transient behavior can be examined. It is considered that the synchronous generator is equipped with an exciter identical to IEEE type 1 model [6]. The exciter plays a role of meeting the dc link voltage requirement. Since the synchronous generator is a direct drive type with low speed and a high number of poles, the wind turbine and the generator are rotating at the same mechanical speed via the same shaft. Therefore, shaft dynamics can be characterized by a swing equation on a single mass rotating shown in equation (6). The shaft dynamics and the rotating mass can be represented by multi-mass torsional shaft model of Mat lab/Simulink, which can be easily interfaced with the synchronous machine model.

\[
J_M \frac{d\omega_M}{dt} = T_M - T_E - D\omega_M
\]  

(8)

Where,

- \( J_M \) = a single rotating inertia [kg-m²]
- \( T_M \) = electric torque produced by generator [N-m]
- \( D \) = damping [J-s/rad]

In variable speed operation, the rotating speed of the wind generator is not consistent with the electrical synchronous speed of the electric network and generally much slower than the speed. The electrical base frequency of the machine in the built-in models must be set to a value corresponding to the rated mechanical speed of the wind turbine specified by a manufacturer or a designer. Equation (9) and (10) give the value for the electrical base speed of the synchronous machine \( \omega_B \).

\[
f_B = \frac{P \cdot RPM_{TUR}}{60}
\]  

(9)

\[
\omega_B = 2\pi f_B = \pi \cdot \frac{P \cdot RPM_{TUR}}{60}
\]  

(10)

Where,

- \( f_B \) = electrical base frequency of the generator [Hz]
- \( P \) = number of poles
- \( RPM_{TUR} \) = mechanical rated speed of the turbine [rpm]

III SIMULATION RESULTS

Simulation is done using MATLAB and the results are presented here. Closed loop system of DC-DC converter is shown in figure 3. Scopes are connected to measure the driving pulses, DC output and current. Wind turbine model is connected to closed loop DC – DC converter. The wind turbine model is shown in figure 4. The input voltage with disturbance is given to the wind turbine model at the input side of DC – DC converter. The input side of wind turbine model is shown in figure 5. The output waveform of wind turbine model is 48V is given as input to the DC – DC converter. The input waveform of DC – DC converter is shown in figure 6. 48 V is stepped down and it is rectified using an uncontrolled rectifier. DC output voltage waveforms are shown in figure 7. It can be seen that the output is free from ripple. The output voltage is sensed and it is compared with a reference voltage of 12V. The error is given to a PI controller. The output of PI generates pulses with reduced width. When these pulses are applied to the MOSFET’s in the output rectifier, the output reduces to the set value .Thus the closed loop system is capable of reducing the steady state error. The parameters of \( K_P = 4 \) and \( K_I = 0.1 \) are used for simulation studies.
The modeling and simulation of closed loop controlled DC-DC converter systems are simulated using MATLAB version 7.1 and the results are presented. This converter is popular due to reduced EMI, reduced stresses and high power density. The simulation studies indicate that LCL type DC-DC converter can be used with stand-alone wind generator. Constant voltage can be maintained at the output of DC-to-DC converter by using a PWM rectifier at the output. Simulation results indicate the validity of closed loop model. Embedded controlled DC to DC converter is fabricated and it is tested. The closed loop system is implemented using PI controller. The closed loop system may be attempted with a better intelligent controller.

**REFERENCES**


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