Modeling and Control of Direct Drive Variable Speed Stand-Alone Wind Energy Conversion Systems

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Abstract -This paper proposes a small wind energy conversion system comprises permanent magnet synchronous generator (PMSG), uncontrolled rectifier, conventional H-Bridge inverter and dc-dc bi-directional converter. The dc-link capacitor is connected to a storage system through bi-directional power flow link. A hybrid pulse width modulation (HPWM) controller is used to regulate the ac load voltage and frequency while the power flow control is achieved by bi-directional dc/dc converter. A maximum power point tracking (MPPT) control is employed where the storage system is used to feed the required power balance between the wind power and the load power. The complete system is studied, analysed and simulated using PSIM to validate the system performance. Finally, simulation and experimental results have been provided.

Index Terms - PMSG, HPWM, Bi-directional Converter, and Power flow controller.

I. INTRODUCTION

Wind energy is clean silent and emission-free source of energy. Using small wind energy conversion system increases rapidly nowadays all over the world due to its availability, small size, high performances, low cost installation, and it has low weight compared to induction generators. PMSG is used more frequently in small wind turbine application due to its robustness, reliability and high efficiency when connected to variable speed wind turbine [1]. Optimum operation of wind energy conversion system is achieved by running the wind turbine at variable speed while using gear box increases the mechanical losses and thus decreases generator efficiency so the proposed system is direct drive. Most papers [2], [3], [4] are considering using PMSG and normally include controlled three phase ac to dc conversion which can be used to track maximum power to capture the maximum available wind power from the wind turbine besides achieving unity power factor at the generator side. The dc/ac inverter is used to regulate the load voltage and frequency and for stand-alone systems. Additionally, a battery power flow controller is used to balance the load power as the wind power changes [3], [4]. According to grid connected systems, the MPPT control is achieved using the dc/ac inverter and the controller achieve unity power factor at the grid side.

This paper is targeting small wind turbine applications which is required to work offline and with a cost effective. The proposed system is composed of a wind energy conversion system using PMSG with cheap conventional uncontrolled rectifier and dc/dc bi-directional converter that connected to the dc-bus voltage to manage and control the power delivered to the load [5]. The storage system can be charged / discharging based on the power delivered from the wind. Additionally, a MPPT control algorithm is employed to achieve maximum power from the wind by employing an incremental conductance method [6] which changes the generator loading to reach the desired optimum condition using the bi-directional converter. A HPWM controller is applied to maintain load voltage constant also to reduce inverter switching losses and thus improving the efficiency of the overall system.

II. THE PROPOSED WIND ENERGY CONVERSION SYSTEM CONFIGURATION

The complete system configuration is shown in Fig 1. The system comprises small wind turbine, PMSG, conventional single phase inverter (H-Bridge) and bi-directional dc/dc converter. 1.25 kW wind turbine power is used, the maximum available wind speed is assumed to be 12m/s and the output voltage is 400Vdc. Direct drive PMSG is connected to the wind turbine. Due to its robustness, reliability and efficiency can be improved by reducing the generator losses by operating at unity power factor. Figure 1 indicates the complete control technique of the proposed system; three arms LC filters are applied across the generator terminals to reduce the generator voltage and current harmonics. Uncontrolled rectifier is connected through the three phase LC filter. The bidirectional converter used to control charging and discharging battery pack beside MPPT of the wind energy conversion system. A conventional single phase dc/ac inverter is connected through the dc link capacitor. The load is connected to the inverter through a second order filter (LC filter) to eliminate the output voltage and current harmonics. The well known HPWM is applied to the inverter to regulate the load voltage and frequency [7].

A. Wind turbine model

The wind turbine model has been designed from the characteristics equations which describe the whole small wind system [8].
The wind turbine output power is proportional to cubic wind speed, rotor swept area, rotor power coefficient and air density as given by (1). The relation between rotor power coefficients as a function of tip-speed ratio at different pitch angles is given in (2) and (3) which is empirical equation. Equations (2) and (4) are used to achieve optimum design of wind turbine. Input torque to the PMSG is governed by (5).

\[ P = 0.5 \rho A v_w^3 C_p(\lambda, \beta) \]  
(1)

\[ C_p(\lambda, \beta) = C_1 \left( \frac{C_2}{\lambda_1} - C_3 - C_4 \beta \right) e^{-\frac{C_5}{\lambda_1}} + C_6 \lambda \]  
(2)

\[ \frac{1}{\lambda_1} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{1 + \beta^2} \]  
(3)

\[ \lambda = \frac{\omega}{v_w} \]  
(4)

\[ P_R = \omega T \]  
(5)

Where: \( v_w \) is the wind speed (m/s), \( A \) is the rotor swept area (m\(^2\)), \( C_p \) is the rotor power coefficient, \( \rho \) is the air density (kg/m\(^3\)), \( P_R \) the wind power (W), \( T \) is the shaft torque (N.m), \( \lambda \) tip-speed ratio, and \( \beta \) is the pitch angle in degrees. The values of the constants are: \( C_1 = 0.5176, C_2 = 116, C_3 = 0.4, C_4 = 5, C_5 = 21 \) and \( C_6 = 0.0068 \). The aforementioned equations are characterizing the wind turbine system. From these equations the relationship between wind turbine power and generator speed at various wind speed can be drawn as shown in Fig. 2. The relationship between rotor power coefficient \( C_p \) and tip-speed ratio at various pitch angles (\( \beta \)) can be drawn as shown in Fig. 3.

The designed wind turbine model is simulated using PSIM to validate the actual wind turbine performance and it is connected to the PMSG to change the mechanical input torque according to the aforementioned equations. Also the PMSG model should take the mechanical losses into account. Since the input torque is variable thus the generator output voltage frequency are variable too. A controller will be employed to fix both the magnitude and frequency and thus the load will be fed by a constant voltage / frequency supply.
B. Maximum Power Point Tracking (MPPT) Algorithm

To get fast tracking for maximum power, it is preferable to use incremental conductance method [6] which is based on the fact that maximum power occurs when the variation of \( \frac{dP}{dV} = 0 \). Since the dc power across uncontrolled rectifier is governed by equation \( P = VI \), from which the following equation:

\[
\frac{dP}{dV} = I + \frac{\Delta I}{\Delta V}
\]  

(6)

The following constraints are used to calculate the MPPT using the incremental conductance method:

\[
I + \frac{\Delta I}{\Delta V} = 0 \quad \text{At MPP} 
\]  

(7)

\[
I + \frac{\Delta I}{\Delta V} > 0 \quad \text{Left to MPP} 
\]  

(8)

\[
I + \frac{\Delta I}{\Delta V} < 0 \quad \text{Right to MPP} 
\]  

(9)

Fig. 4: Flow chart of the incremental conductance MPPT method.

Equations (7), (8) and (9) are used to determine the location of the operating point. Based on these equations the controller can easily take the decision of increasing or decreasing the operating voltage to reach maximum power point. Figure 4 shows the flow chart for the employed MPPT.

C. Bi-directional dc/dc Converter

The bi-directional converter connected across the dc-link to adjust power flow to/from the battery storage system [9]. When the wind power is larger than the load power, the buck switch \( S_6 \) is activated to charge the battery pack. On contrary, when the wind power is smaller than the load power the boost switch \( S_5 \) is activated to discharge the battery pack. The MPPT calculation technique is used to feed the reference signal to the voltage controller of the bi-directional converter to adjust the dc-link voltage to operate the small wind energy conversion system at maximum power. The power flow controller determines which switch buck switch \( S_6 \) or boost switch \( S_5 \) should be activated to make the power balance between the wind power and the load power [5]. In achieving both power flow control and maximum power point control, the dc bus voltage will be variable. In this case, the buck switch \( S_6 \) is activated only when the input wind power is larger than the specified load power. A certain time delay is considered between the buck and boost switches to guarantee that the two switches don’t operate at the same time.

D. H- Bridge Inverter

H-bridge inverter is being used as a dc/ac converter which can regulate the load voltage and frequency. A hybrid pulse width modulation controller (HPWM) method is applied to reduce the switching losses in a full-bridge inverter in which two switches of the four switches of the H-bridge inverter operate at high frequency and the other two switches operate at low frequency (load frequency) [7]. Also, it is applied to regulate the load voltage at 220V.

E. Complete system efficiency

To study the system efficiency, the whole WECS has been simulated for different values of output powers. Fig. 5 shows the efficiency of the overall system versus the output power. It has been found that the efficiency will be low at low output powers. Fig. 5 indicates that the efficiency will be greater than 90% for output power greater than 500 W and it will decreases rapidly at more lighter loads. Obviously the best operation of that system can be attained near the rated values.

III. SIMULATION RESULTS

The complete system is built inside PSIM software package and the power stage parameters are listed in Table 1. The whole system has been simulated under two step change in the wind speed from 10 m/s to 12 m/s at t=0.4s. Then step
change from 12m/s to 8m/s at t=0.7s. Simulation results show the performance of the whole system. Fig. 6 and Fig. 7 show the three phase generator voltages and currents respectively due to the above mentioned step change in wind speed. It can be noted that both voltages and currents are almost sinusoidal waveforms. Fig. 8 depicts the dc-link voltage and the battery charging current according to MPPT algorithm. The figure shows the merit of the controller that can maintain the dc bus voltage at constant values based on the power captured from the wind. In addition, it shows that the battery current can change its direction to balance and keep the load power constant. For the chosen system, the battery is almost charging except for very short time it discharges. Figure 9 shows the turbine power (the input torque to the PMSG), the input power, the load power, and the battery power. It is clear that the load power equals the input power plus the battery power, thus the power balance is satisfied at the dc bus terminal. Figure 10 shows the rotor power coefficient which is almost constant near 0.42 which is confirms the MPPT operation even if under wind speed step change. The HPWM switches control signals are shown in Fig. 11. As mentioned before, two switched will be operated at high switching frequency while the other two switches will be operated at power frequency which is 50 Hz.

The ac output load voltage and current are shown in Fig. 12. Obviously, the load voltage magnitude is almost constant during the step change because of the HPWM controller is employed to adjust it. Also, the current is lagging the voltage with certain phase angle due to the inductance of the load.

### TABLE I

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
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</thead>
<tbody>
<tr>
<td>Wind turbine power rating</td>
<td>1.25kW</td>
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<tr>
<td>Load RMS Voltage</td>
<td>220V</td>
</tr>
<tr>
<td>Output ac load voltage frequency</td>
<td>50Hz</td>
</tr>
<tr>
<td>Bi-directional converter switching frequency</td>
<td>100kHz</td>
</tr>
<tr>
<td>Inverter switching frequency</td>
<td>10kHz</td>
</tr>
<tr>
<td>Input three phase LC filter</td>
<td>0.5mH and 120µF</td>
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<tr>
<td>dc-link capacitor value</td>
<td>1.5 mF</td>
</tr>
<tr>
<td>Bi-directional converter inductance</td>
<td>0.5mH</td>
</tr>
</tbody>
</table>

Fig. 5: Complete system efficiency versus output power

Fig. 6: The three phase generator voltages due to step change in wind speed from 10m/s to 12m/s at 0.4s.

Fig. 7: The three phase generator currents due to step change in wind speed from 10m/s to 12m/s at 0.4s.

Fig. 8: Dc link and battery current variations at various wind speed.
IV. EXPERIMENTAL RESULTS

To validate the proposed system, an experimental prototype of the uncontrolled rectifier and for the conventional inverter has been built, experimentally tested, and compared with the simulation results. Figure 13 shows the experimental set up. A single phase load with 440Ω was used. The inverter circuit was built using power MOSFET of type 16N60 as switches, and the three-phase bridge rectifier was built of diode type 8ET106. The three-phase voltages are supplied from three-phase ac source. The inverter switching frequencies are 50 Hz for two switches and 10 kHz for the other two switches. The switching signals are generated using an FPGA of type XC3S400 as a controller. Figure 14 shows the input three-phase ac source voltages with 120 peak-to-peak voltage and 50 Hz frequency. Thus the dc-link voltage obtained is shown in Fig. 15 with amplitude of approximately 60 V. The four switches control signals are indicated in Fig. 16 with two switches operate at low frequency and two switches with high frequency. Open loop control applied to the H-bridge inverter to convert it to single phase voltage across the load terminals as shown in Fig 17. The load voltage and load current are not pure sinusoidal due to the small value of the ac capacitor used for the inverter prototype.
IV. CONCLUSION

This paper proposes a small wind turbine energy conversion system for isolated load applications. The system includes a PMSG, uncontrolled rectifier, battery storage system. A MPPT control algorithm based on the incremental conductance method is employed to harvest the maximum power from the wind. This maximum power is used as a reference signal to operate the power flow controller required by the storage battery system. This storage battery system is use to balance the power comes from the wind and the power required by the load. A bi-directional dc/dc converter is used to change the dc bus voltage to achieve MPPT and control the power flow in the same time. A HPWM controller also is used across the inverter side to regulate the load terminal voltage and reduce switching losses. Simulation and experimental results have been provided to validate the system.

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REFERENCES


