Grid integration of PMSG based wind energy conversion with battery storage system

Venkatachalam K M, V. Saravanan
Department of Electrical and Electronics Engineering, Arunai Engineering College, Anna University, Tamil Nadu, India

ABSTRACT

In this paper, the design and implementation of a permanent magnet synchronous generator (PMSG) based wind energy conversion system and battery bank storages are connected to utility grid. It has phase locked loop (PLL) control strategy as it provides for control single-phase grid connected inverter with constant dc-link voltage. The dc-link is interfaced to a permanent magnet synchronous generator through diode bridge rectifier (DBR) with dc-dc boost converter, battery bank and single phase voltage source inverter (VSI). The dc-link voltage is maintained constant value of 48 V by controlling dc-dc converter with help of perturb and observe (P&O) algorithm based maximum power point tracker (MPPT). The VSI output voltage and frequency values are controlled based on grid parameters using PI controller and sinusoidal pulse width modulation (SPWM) technique. In this grid connected system is simulated and performances are analyzed through MATLAB software. The prototype experimental results are verified through 1 kW PMSG, 48 V battery bank with single phase grid connected system.

1. INTRODUCTION

The power demands are increasing due to demand of the conventional fuel sources. Renewable energy source based power generations are needed to distribute and compensate the requirement with uninterrupted continuous power supply. Wind energy electrical conversion system is a most popular in overall renewable energy sources. In this wind energy conversion system is operating the non-linear characteristics due to continuous variation of wind velocity [1-5]. Various techniques are implemented for extracting maximum power from wind energy conversion system and fed to the utility grid. In last few years permanent magnet synchronous generators (PMSG) are used in wind energy conversion system because it is a direct driven fully controlled machine [6-11]. The maximum power extracted from PMSG wind system with help of perturb and observe (P&O) method based maximum power point tracker (MPPT) [12-18].

The variable ac three phase electrical output of the PMSG is converted to dc electric power by using three phase diode bridge rectifier (DBR) and it’s consisting of six diodes. In this DBR dc output is boost and regulated output power is fed to the inverter with help of dc-dc boost converter [19-21]. The dc-link voltage is a reference value for MPPT and compare with actual value of the PMSG output power, this error value is given to the PI controller. In this PI controller can vary dc-dc converter pulse signal based on error values for maintain constant dc-link voltage. The inverter is convert dc power into ac power and connected to the grid and it’s maintaining constant grid voltage with required constant grid frequency. The VSI output voltage is
measured by phase locked loop (PLL) and converted to direct axis and quadrature axis (dq0) [22]. The dq axis conversion voltage and reference voltage is compared and error value is given to the VSI driver circuits. The single phase voltage source inverter (VSI) is controlled by many driver control technique like sinusoidal pulse width modulation (SPWM), space vector modulation technique. The most suitable an easy control technique is a SPWM method to drive the voltage source inverter [23-24]. In this proposed grid connected system consist of (i) PMSG based WECs, (ii) diode bridge rectifier (DBR), (iii) dc-dc boost converter, (iv) single phase voltage source inverter (VSI), maximum power point tracker (MPPT), battery bank storage system.

2. GRID CONNECTED SYSTEM DESCRIPTION

The proposed grid connected system as shown in Figure 1. It is comprised of permanent magnet synchronous generator based (PMSG) WECs operating with maximum power point tracker (MPPT), battery is using for energy storage, voltage source inverter (VSI), LC filter and single phase utility grid. The WECs is designed at maximum power rating of 1 kW. The MPPT is extract maximum power from PMSG and to control dc-dc converter for constant voltage. The battery bank designed the combination of series and parallel connection of battery with respect to required voltage and current. The battery bank is designed with 8 battery of 12 V, 100 Ah. A constant DC bus voltage is maintained by bidirectional converter and it power transfer to the VSI. The VSI is fed the power from PMSG wind conversion system with battery bank. The VSI single phase output is fed to the utility grid through LC filter. It is used for pure AC power feed to the grid without any harmonic disturbances. The constant voltage, current and frequency are fed to the utility grid. In this system configuration helps extract the maximum power from WECs at varying wind velocity, load and power fed to the utility grid. The system ensure constant power feed to the grid that excess WECs energy is stored to the battery bank which is useful for peak load demand and to maintain constant output power during fluctuation of wind velocity and load.

![Figure 1. Block schematic of the proposed system](image)

3. PROPOSED SYSTEM DESIGN AND MODELING

The proposed system design of single phase two stage grid connected WECs system is described in this section. The design of grid connected system is based on utility grid standard voltage and frequency. The switching frequency of the inverter is higher than the line frequency.

3.1. Wind turbine model

The mechanical power output captured from the wind turbine is given by [10, 25].

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

(1)

where \( \rho \) is the density of the air (kg/m\(^3\)), \( A \) is the area of the rotor blade, \( C_p \) is a power co-efficient of the wind turbine, \( \beta \) is the rotor blades pitch angle, \( V_w \) is a wind velocity (m/s), \( \lambda \) is a tip speed ratio and it can be written as:

\[
\lambda = \frac{R \omega_m}{V_w}
\]

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where R is the radius of blade in meter, $\omega_m$ is the angular speed of the rotor (rad/sec). The power co-efficient of the wind turbine $C_p$ is derived based on the characteristics of wind turbine.

$$C_p(\beta, \lambda) = \sum_{i=0}^{4} \sum_{j=0}^{4} a_i \beta^i \lambda^j$$  \hspace{1cm} (2)$$

Figure 2 represents the $C_p$ vs $\lambda$ curve, the maximum output power captured from the wind turbine at constant wind speed irrespective of wind velocity. Hence the same wind turbine maximum output power delivered at different wind velocity corresponding to maximum power point tracker. In a wind turbine direct drive-train system are classified as a single-mass and two-mass depends on the application. In variable speed wind application, the limited wind speed variation, single-mass drive system is sufficient because the shaft oscillation is very less and easy control the grid connected system in order to active power control. The single-mass drive mathematical relation is given in (1) \hspace{1cm} [10].

$$T_m = J_eq \frac{d\omega_m}{dt} + B\omega_m + T_e$$  \hspace{1cm} (3)$$

where $T_m$ is the mechanical torque, $J_eq$ is the total equivalent inertia of the rotor of wind turbine and generator, $B$ is the damping co-efficient, $\omega_m$ is the angular speed of the rotor (rad/sec).

![Turbine Power Characteristics (Pitch angle beta = 0 deg)](image)

Figure 2. Wind turbine output power vs speed

while the wind speed variation is more, the shaft oscillation and grid connected systems are heavily disturbed. In order reduce the shaft oscillation two-mass drive systems are used as represented in Figure 3. The two-mass drive mathematical relation given in (2).

$$\frac{d\omega_t}{dt} = \frac{1}{J_t}(T_t - T_{db} - T_{sa} - T_{s})$$  \hspace{1cm} (4)$$

where $\omega_t$ is the angular speed of the wind turbine, $J_t$ is the moment inertia of the wind turbine, $T_t$ is the mechanical torque WT bearing, $T_{db}$ is the turbine resistant torque in turbine, $T_{sa}$ is the turbine resistant torque in blades, $T_s$ is the torsional stiffness torque.

$$\frac{d\omega_g}{dt} = \frac{1}{J_g}(T_g - T_{dg} - T_{ag} - T_{g})$$  \hspace{1cm} (5)$$

where $\omega_g$ is the angular speed of the generator, $J_g$ is the moment inertia of the generator, $T_{dg}$ is the turbine resistant torque in generator bearings, $T_{ag}$ is the turbine resistant torque in generator, $T_g$ is the turbine resistant torque in generator, $T_g$ is the generator electrical torque.
3.2. PMSG model

The PMSG model is represented in the synchronous reference (Vd, Vq) frame [6].

\[
V_d = R_i + \lambda_{ds} - \omega \psi \tag{6}
\]

\[
V_q = R_i + \lambda_{qs} + \omega \psi \tag{7}
\]

where \(V_d, V_q\) and \(i_d, i_q\) are the dq stator voltage and current components, respectively. \(\psi_d, \psi_q\) are the stator flux linkage, \(R_s\) is the stator resistance, \(\omega_e\) is the angular speed of the rotor. The PMSG developed electromagnetic torque is:

\[
T_e = 1.5P \left( \lambda_{ds} i_q - \psi_{d} i_q \right) \tag{8}
\]

\[
T_e = 1.5P \left( \psi_{pd} i_q + (L_{dq} - L_{d} - L_{q}) i_d i_q \right)
\]

where \(P\) is a number of pole pairs, \(L_d, L_q\) are the inductance of the stator reference frame, \(\psi_{pm}\) is a rotor magnetic flux linkage.

3.3. Design of diode bridge rectifier (DBR) and boost converter

The three phase diode bridge rectifier (DBR) is consist of three set of diode. It is covert three phase variable ac electrical supply into variable dc electrical supply. The output voltage of the DBR is based on speed of the wind turbine. The diode bridge rectifier (DBR) output is fed to dc-dc boost converter, which are boosting the DBR voltage and maintain constant output dc voltage. In excremental setup, the required input voltage to store energy in the battery is 48 V constant dc supply. In the DBR output voltage is lower and variable than the battery input voltage depends on solar radiation. The relation between the DBR output voltages \(V_{wind}\), boost converter output voltage \(V_{dc}\) is defined as duty cycle \((D)\) of boost converter.

\[
D = 1 - \frac{V_{wind}}{V_{dc}} \tag{9}
\]

The required input inductor \((L_{in})\) value to maintain the continuous conduction mode (CCM) operation is:

\[
L_{in} = \frac{V_{wind}}{\Delta I_{wind}} = \frac{V_{wind}^2}{0.1P_{wind}} \left( 1 - \frac{V_{wind}}{V_{dc}} \right) \tag{10}
\]

where \(I_{wind}\) is the minimum rippled input current, \(T\) is the time of switching cycle, \(P_{wind}\) is the maximum output power from Solar PV array.

3.4. Design of DC-link capacitor and inductor

The DC-link capacitor is transfer power from input to output with control manner. The DC-link capacitor value is depends on the DC bus voltage as:

\[
C_d = \frac{P_d}{2 \times \Delta V_{dc} \times V_{dc}} \tag{11}
\]
where $V_{dc}$ is a minimum allowable ripple in the DC-link voltage, $P_{dc}$ is a dc power, $I_{dc}$ is a DC current, $\omega$ is a line frequency.

The inductor is coupling element between the boost converter and voltage source inverter (VSI). It is used for elimination of high frequency switching harmonics. The inductor design calculation as:

$$L_f = \frac{m \cdot V_{dc}}{6 \cdot f_s \cdot h \cdot \Delta I_c}$$  \hspace{1cm} (12)

where $f_s$ is a switching frequency, $\Delta I_c$ is a ripple current, $m$ and $h$ are the constant parameters.

### 3.5. Design of bidirectional converter

The bidirectional converter is to control the DC output voltage ($V_{dc}$) and battery current ($I_b$). It is designed for the power rating of $3kW$ and operating frequency is $20 kHz$. The bidirectional converter is connected between the battery and DC bus, is operated on two modes. While battery is charging the converter can operate buck operation and while battery is discharging the converter can operate boost operation. The bidirectional converter operating mode is desired by the inductor and duty cycle of the converter is as:

Duty cycle \hspace{0.5cm} \left(D\right) = \frac{V_b}{V_{dc}}

$$L_{dc} = \frac{D \left(V_{dc} - V_b\right)}{f_s \Delta I_L}$$ \hspace{1cm} (Buck mode)

$$L_{dc} = \frac{D V_b}{f_s \Delta I_L}$$ \hspace{1cm} (Boost mode)

where $V_b$ is a battery voltage, $V_{dc}$ is DC bus voltage, $I_L$ is a ripple current in the battery, $f_s$ is switching frequency.

### 4. PROPOSED SYSTEM CONTROL TECHNIQUE

The control of the dc-dc boost converter output impedance is matches to the varying DBR impedance for get maximum power. The bidirectional converter is control the DC-link voltage ($V_{dc}$), battery current ($I_b$) as a reference value of the converter. The voltage source inverter (VSI) is controlled by the PI controller based on availability of wind power or battery power. The MPPT controller, boost converter controller, and voltage source inverter controller are explained in the following sections.

### 4.1. Maximum power point tracker (MPPT) controller

The MPPT is tracks the maximum power from PMSG wind energy conversion system using simple perturb and observe method by sensing the dc-link current. To measured and comparing the previous dc-link current $I_{dc}$ (k-1) and present dc-link current $I_{dc}$ (k). If the present dc link current $I_{dc}$ (k) is more than the previous dc-link current $I_{dc}$ (k-1), the perturbation is increases up to maximum power point. If the present dc link current $I_{dc}$ (k) is less than the previous dc-link current $I_{dc}$ (k-1), the perturbation has to be decrease. The DC bus current is positive when the PMSG power available in excess to battery and fed to grid. When the wind power is not sufficient feet to grid, the deficit power is fed from battery by DC bus current is negative.

### 4.2. Voltage control of boost converter

The dc-link voltage ($V_{dc}$) is compared with reference dc voltage of $200 V$ and fed to PI controller. The error signal of the PI controller is compared with carrier waveform of $20 kHz$ to produce the pulse width modulation (PWM) gate signal is control the boost converter switches as shown in Figure 2. The PI controller parameters ($K_p$, $K_i$) values are set by manual tuning method. The $K_p$ and $K_i$ values are depends on the system behavior and response. The $K_p$ and $K_i$ values are set as 0.015 and 0.4 in PI controller by using this method.
4.3. Grid synchronization

The single phase grid has voltage is 415 V (rms) and frequency is 50 Hz. The voltage source inverter voltage magnitude and frequency should match with the grid voltage magnitude and frequency. The grid voltage and frequency are measured using phase-locked loop (PLL) and it’s compared with the VSI voltage and frequency and the error is reduced by using PI controller. The PI controller is forced to matches the VSI and grid using Sinusoidal pulse width modulation (SPWM) with reference signal. The voltage source inverter equivalent circuit and control circuit as shown in Figures 4(a) and (b).

![Figure 4](image)

(a) Figure 4. The voltage source inverter, (a) Equivalent circuit of the VSI, (b) Control circuit of the VSI

The grid voltage is fed to phase-locked loop (PLL) and its output current is to be maintaining constant magnitude and it is reference for this control circuit. PI controller parameters $K_p$ is 0.25 and $K_i$ is 80.836 are obtained. The PI controller voltage control loop transfers function as:

$$
\frac{i_L(s)}{V_i(s)} = \frac{1}{L_s + r}
$$

where $i_L$ is a current through inductor, $V_i$ is a VSI output voltage, $r$ is a resistance.

5. RESULTS AND DISCUSSION

The proposed single phase grid connected system is validated on a simulation at steady state condition of wind speed is 12 m/s. The implemented perturb and observe (P&O) algorithm based maximum power point tracker (MPPT) for wind generator is track the maximum power and output voltage is compared with the dc-link voltage. The dc-dc converter and grid side inverter is effectively transferred the renewable energy power generation to utility grid, which is validated from the simulation results as shown in Figures 5 (a) and (b). It shows the simulation results of single phase inverter output voltage and current under constant wind speed of 12 m/s with corresponding value of total harmonic distraction (THD) waveforms. The experimental hardware prototype implemented for single phase grid connected system. The maximum power tracked from the 1 kW PMSG wind generator using MPPT, its convert and regulated to dc constant 48V dc supply with help of wind charge controller. The charge controller is interfaced to 48V, 800 Ah battery bank and 1.5 kW single phase grid tie inverter.
When the availability of wind speed is more the generated electrical power is fed to grid or to battery for charging, wind speed is not reached to above cut-in speed the PMSG cannot generate the electrical power. In this situation the power flows from grid to battery bank using bidirectional converter. The experimental result of PMSG wind generator three phase output voltage and single phase inverter voltage, current, and total harmonic distraction (THD) at various load condition are measured by power quality analyzer as shown in Figures 6-9. The proposed system specifications are provided in Table 1.

Figure 5. Simulation results of, (a) Output voltage and current of VSI, (b) Voltage and current THD of VSI

Figure 6. PMSG wind generator output voltage
Figure 7. Inverter voltage, (a) Current at 260 W lamp load, (b) THD at 260 W lamp load

Figure 8. Inverter voltage, (a) Current at 820 W lamp load, (b) THD at 820 W lamp load

Figure 9. Inverter voltage, (a) Current at 1680 W lamp load, (b) THD at 1680 W lamp load

Table 1. Designed specification of the WECs

| S.no | Specifications of WECs          |
|------|---------------------------------|
| 1    | PMSG rating                     | 1 kW                             |
| 2    | Number of blades                | 3                                |
| 3    | Rotor diameter                  | 2.72 M                           |
| 4    | Available wind speed            | 4 to 6 m/s                       |
| 5    | Wind charge controller          | 48 V                             |
| 6    | Battery bank                    | 48 V, 800 Ah                     |
| 7    | Grid-tie inverter               | 1.5 kW                           |

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6. CONCLUSION

This paper presented a PMSG based wind energy conversion system and battery bank interfaced through a common dc-link. The dc voltage is regulated and maintained constant to an MPPT of PMSG through dc-dc converter. The wind charge controller duty cycle variation is depends on the wind generator output power, the system extract maximum power from PMSG and transfer to the utility grid through grid side inverter at variable wind velocity. The grid side inverter is controlled using phase locked loop technical with PI controller. The proposed grid connected wind energy conversion system performances are validated through MATLAB SIMULINK and prototype hardware experimental setup.

ACKNOWLEDGEMENTS

This work was supported by Wind Energy Division, Ministry of New & Renewable Energy, Government of India under grant (IFD Dy. No. 1429 dated 04/11/2016, Demand No. 61/69, Budget Head: 2810.00.104.04.05.31/35).

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**BIOGRAPHIES OF AUTHORS**

Mr. Venkatachalam K M received bachelor degree in Electrical and Electronics Engineering from Anna University, Chennai in 2014. He has received master degree in Electrical Drives and Control from Pondicherry University, Puducherry in 2016. Currently he is pursuing Ph.D. degree in Electrical Engineering, Anna University, Chennai. His area of research includes renewable energy, inverters and micro-grid. He published 10 papers in conferences and journals.

Dr. V. Saravanan working as professor in Department of Electrical & Electronics Engineering, Arunai Engineering College, Tiruvannamalai, Tamil Nadu, India and has been carrying out R & D activities sponsored by various agencies of Government of India in the area of renewable energy systems. He has teaching/industrial experience of about 15 years. His research interests include solar photovoltaic power systems, distributed renewable energy systems, smart/microgrid. He published more than 70 research papers in journals, conferences and exhibitions.