Power Flow Control of Permanent Magnet Synchronous Generator Based Wind Energy Conversion System with DC-DC Converter and Voltage Source Inverter

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Abstract

The aim of this paper is to discuss about mega-watt wind energy conversion system (WECS) using permanent magnet synchronous generator (PMSG). The configuration consists of a diode rectifier, a buck converter and a voltage source inverter (VSI). The advantage of using diode rectifier is that it provides a low cost solution to convert ac power into dc. Using the grid synchronous voltage orientation method, the active power is controlled by d-axis current whereas the reactive power is controlled by q-axis current. The phase angle of utility voltage is detected using software PLL (Phased Locked Loop) in d-q synchronous reference frame. Proposed scheme gives a low cost and high quality power conversion solution for variable speed WECS.

Keywords— WECS, PMSG, Voltage Source inverter, DC-DC Converter, Diode rectifier

Introduction

Wind power is one of the cheap and endless alternative energy sources, and is now increasingly utilized in electric power system for the sustainable development. The worldwide installed wind turbine capacity reaches 282,755 Megawatts (MW) by the end of 2012, whose energy production equals to 3% of the global electricity consumption. It is predicted that the global installed capacity will be more than 1000,000 MW by the year 2020 [1]. There are three basic configurations of the current source Converters for WECS. The first one uses PWM current source rectifier (CSR) and PWM current source inverter (CSI) [2], established and the reliability is proven [3], but, the poor grid waveforms, lack of reactive power control, and extra investment on the compensation system will counteract more or less its low cost advantage in modern WECS; the third one is diode rectifier and PWM CSI inverter, where both active and reactive powers transferred to the grid can be controlled but with limited
range [4]. For maximum wind power extraction methods [6-8] can be summarized as turbine-generator speed control, direct power control and wind speed sensorless control. In this paper, the method of tracking turbine-generator speed for maximum power is implemented at the rectifier side. The rectifier controller is also optimized for the generator operation, either to help adjust generator terminal voltage or to minimize generator winding loss. The converter configuration for the direct drive PMSG based WECS is shown in Fig. 4. buck converter between the rectifier and the inverter. The PWM current of the VSI, grid side line current and the capacitor bank current are represented by $i_{wi}$, $i_s$ and $i_c$, respectively.

I. Wind Energy Conversion System
The development of a WECS involves technologies in various aspects. Up-to-date technologies have been consistently applied to WECS and results in miscellaneous designs available on the market or in the literature. However, the modern grid connected high power WECS utilizes power converters without exception and shares a common configuration, as shown in Fig. 1. A variable-speed WECS typically consists of a wind turbine, an optional drive train (gear or gearless), a generator (synchronous or induction), a power converter and a step-up transformer.

![Fig. 1. Basic configuration of the contemporary WECS](image)

The power converter for WECS can be categorized into two main groups: voltage source converter (VSC) and current source converter (CSC). Both types of converters include two-stage power conversions, AC to DC and DC to AC.

II. Wind Turbine Characteristics
The mechanical power extracted by the wind turbine depends on a few factors. (1) indicates the power contained in the flowing air passing the defined area of the wind turbine blades, where $\rho$ is the mass density of air, $A$ is the swept area of turbine blade and $u_W$ is the wind speed. Furthermore, with consideration of the power coefficient $C_p$ the mechanical power obtained in the wind turbine can be expressed in (2) [10]:
Power Flow Control of Permanent Magnet Synchronous Generator

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

The power coefficient \( C_p \) is determined by the aerodynamic design of the turbine and varies with the turbine blade pitch angle \( \beta \) and tip speed ratio \( \lambda \). \( \lambda \) is the ratio of turbine blade tip linear velocity to the wind speed defined by (3) [9], where \( \omega_r \) and \( R \) are turbine rotational speed and radius respectively.

\[ \lambda = \frac{\omega_r R}{v_w} \]  

The power coefficient \( C_p \) can be modeled by following equation [10],

\[ C_p(\lambda, \beta) = c_1 \left( \frac{c_2}{\lambda_1} - c_3 \beta - c_4 \right) e^{-\frac{c_5}{\lambda}} + c_6 \lambda \]  

in which

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

Table 1. lists the values for the coefficients of \( c_1 \) to \( c_6 \), from which the sample curves of \( C_p \) can be plotted and are shown in Fig. 2. It can be viewed that there is a maximum power coefficient for a defined pitch angle \( \beta \). For example, the correspondent maximum \( C_p \) is about 0.48 when the optimal tip speed ratio \( \lambda_{opt} \) equals 8.1 in the case of zero degree pitch angle.

<table>
<thead>
<tr>
<th>( c_1 )</th>
<th>( c_2 )</th>
<th>( c_3 )</th>
<th>( c_4 )</th>
<th>( c_5 )</th>
<th>( c_6 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5176</td>
<td>116</td>
<td>0.4</td>
<td>5</td>
<td>21</td>
<td>0.0068</td>
</tr>
</tbody>
</table>

It is a natural expectation that the WECS should be controlled to operate at the optimal rotational speed to maximize the generated power at different wind speeds, that is the so-called maximum power point tracking (MPPT).
Fig. 2. Power coefficients over tip speed ratio at various pitch angles

III. Permanent Magnet Synchronous Generator (PMSG) Model

PMSG based WECSs eliminate or reduce the mechanical stages of the gearbox and saves cost and maintenance. Most designs of PMSG for WECS use a surface-mounted permanent magnet rotor since it leads to a simple rotor design with a low weight [11]. Because the magnet is surface-mounted and the permeability of a permanent magnet is very close to that of air, the armature reactance can be much smaller in a PMSG with surface-mounted magnets than that in an EESG. The surface-mounted PMSG is also referred to as non-salient pole PMSG, in which the \(d\)-and \(q\)-axis synchronous inductances are considered the same. From the literature, the synchronous inductance of a PMSG for high-power low speed wind applications is usually above 0.4pu [12, 13].

Fig. 3. Equivalent circuit of PMSG in synchronous frame
The generator terminal voltage $v_g$ in this case is the same as the capacitor voltage $v_{cr}$ of the generator-side converter. The dynamic equations are provided in (5)

$$
\begin{bmatrix}
    v_{c_{rd}} \\
    v_{c_{rq}}
\end{bmatrix}
= \begin{bmatrix}
    \frac{d\psi_{gd}}{dt} - \omega \psi_{sq} - R_s i_{gd} \\
    \frac{d\psi_{gq}}{dt} - \omega \psi_{gd} - R_s i_{gq}
\end{bmatrix}
$$

(5)

where

$$
\begin{cases}
    \psi_{gd} = -L_d i_{gd} + \psi_f \\
    \psi_{gq} = -L_q i_{gq}
\end{cases}
$$

Here, $\psi_f$ is the magnetic flux linkage of the rotor. $R_s$ is the generator resistance. $L_d$ and $L_q$ are d-and q-axis synchronous inductances, which are the sum of the leakage inductance and the magnetizing inductance. Since the rotor is assumed to have surface-mounted magnet, $L_d = L_q$ is hence valid for the following discussions

$$
T_g = 1.5 \rho L_{p} \left( \psi_f - (L_q - L_d) i_{gd} \right)
$$

$$
T_m - T_g = \frac{1}{P} \frac{d}{dt} \omega
$$

(6)  

(7)

IV. Proposed System Configuration

The proposed converter configuration for the direct drive PMSG based WECS is shown in Fig. 4. The converter consists of a six-pulse diode rectifier for interfacing the generator, a PWM VSI for integration into the grid, and a buck converter between the rectifier and the inverter. The PWM current of the VSI, grid side line current and the capacitor Fig 4. proposed converter configuration for a PMSG-WECS

A buck converter is added in the DC link to interconnect the diode rectifier and PWM CSI. It can be seen from Fig. 4, that the buck converter shares the same DC link inductor $L_{dc}$ with the PWM VSI, while its filter capacitor $C_{dc}$ assists to smooth out the diode rectifier output.
V. Overview Of The Control System
The block diagram of the control scheme for the system is shown in Fig. 5. The system control objectives are achieved through proper control of the active switching devices in the buck converter and the PWM VSI. The buck converter provides one control freedom through duty cycle adjustment of the device $S_D$ from which the maximum power point tracking can be realized, while the PWM VSI offers both modulation index ($m_i$) and delay angle ($\alpha$) adjustment by employing the space vector modulation (SVM) scheme, from which the reactive power and the DC current control can be achieved.

VI. MAXIMUM POWER POINT TRACKING
The buck converter is controlled to satisfy full range operation of maximum power point tracking. The MPPT is obtained through the generator speed regulation to the optimum values

\[ \omega_g^* \]

\[ \omega_g \]

Fig. 6. Control of Buck Converter
VII. DC-Link Current Minimization
The currents flowing through the DC link inductance and the switching devices are all defined by the DC link current.

\[ V_{cd} \quad V_{ds} \quad V_{cq} \quad V_{qs} \]

\[ \theta_s \]

PLL

d/dt

\[ \Omega_s \]

\[ V_c \quad V_s \]

Fig. 7. Grid voltage PLL and coordinate transformation

The grid voltage \( v_{qs} \) is then equal to zero. The active and the reactive powers to the grid can be calculated by,

\[ P = \frac{1}{2} (v_{ds}^2 + v_{ds} v_{qs}) = \frac{1}{2} v_{ds}^2 \]
\[ Q = \frac{1}{2} (v_{ds} v_{qs} - v_{ds} v_{qs}) = \frac{1}{2} v_{ds} v_{qs} \]

The related d-, q-axis grid currents, \( i_{ds} \) and \( i_{qs} \), are then derived by,

\[ i_{ds} = \frac{P}{1.5 v_{ds}} \]
\[ i_{qs} = \frac{Q}{1.5 v_{ds}} \]

The proposed control scheme for DC current minimization based on above consideration is detailed in Fig below.
Fig. 8. DC current minimization

The objective active power $P^0$, which is correspondent to the value under MPPT, and the reactive power reference $Q^*$, which is based on the requirement from the grid, are applied to calculate the objective $d$-axis ($i^0_d$) and $q$-axis ($i^0_q$) components of the grid current; with the capacitor bank compensation taken into account, the $d$-axis ($i^0_{dwi}$) and $q$-axis ($i^0_{qwi}$) components of the PWM current can be derived.

VII. Grid Reactive Power Control

The reactive power and the DC current for the VSI are tightly controlled based on the adjustment of the modulation index ($m_i$) and delay angle ($\alpha$). The DC current reference for inverter $i^*_{dci}$ is compared with the actual $i_{dci}$, the error is applied as the input of the PI regulator, from which the active ($d$-axis) grid current reference $i^*_{ds}$ is derived, the reactive ($q$-axis) grid current reference $i^*_{qs}$ is calculated according to (4. 5-4). The active and the reactive PWM current, $i^*_{dwi}$ and $i^*_{qwi}$, can be calculate with capacitor bank current compensation being taken into account, as described in (12) and (13)

$$i^*_{dwi} = i^*_{di} + i^*_{cdi} \tag{12}$$
$$i^*_{qwi} = i^*_{qi} + i^*_{cqi} \tag{13}$$

The magnitude of the PWM current reference $i^*_{wi}$ and the inverter firing angle $\alpha_i$ are calculated by (14) which can be applied for SVM scheme.
\[
\begin{align*}
\omega_i &= \tan^{-1} \left( \frac{i_{qi}^*}{i_{di}^*} \right) \\
\mathbf{i}_{wi} &= \sqrt{(i_{di}^*)^2 + (i_{qi}^*)^2}
\end{align*}
\]

(14)

VIII. SIMULATION AND EXPERIMENT RESULTS

Table 2. Parameter for generator and grid

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMSG rating</td>
<td>2MW</td>
</tr>
<tr>
<td>Stator resistance</td>
<td>0.168</td>
</tr>
<tr>
<td>Ld=Lq</td>
<td>0.194H</td>
</tr>
<tr>
<td>Rated grid phase voltage</td>
<td>1732V(rms)</td>
</tr>
<tr>
<td>Grid frequency</td>
<td>50Hz</td>
</tr>
<tr>
<td>Pole pairs</td>
<td>30</td>
</tr>
</tbody>
</table>

The study of the results proves that the control strategy developed in this paper is well performed. In this simulation it has been applied a step variation in the input wind speed. This step is increased at 1s with 2m/s. It can be analyzed how the control parameter are varying in function of the input power variation which will be vary with the input wind speed variation.

![Fig. 6. 1 Rotor Speed of Generator](image-url)
Fig. 6.3 Active power

Fig. 6.3 Reactive Power

Fig. 6.4 DC Link voltage
In this paper, a novel control scheme for PWM VSC indirect-drive wind energy system was proposed. Control scheme was developed for independent active and reactive power control while maintaining the maximum converter efficiency and extracting the maximum power. The proposed scheme decouples the active power and reactive power control of grid side. The dc link current is minimized in steady state to reduce the devices switching loss and conduction loss for achieving maximum efficiency. Simulation and experimental results obtained verified the proposed control strategy.
References