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Power Flow in PMSG Connected Wind Energy Conversion System through Current Source Converter Using Space Vector Modulation Technique

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Abstract

This paper proposes to work on power flow system for a wind turbine comprising a grid connected through Permanent Magnet Synchronous Generator and a power converter where it is employed as the bridge between the generator and the grid for megawatt power generation. At this power level, current source converter (CSC) topology possess favourable features such as simple structure grid friendly waveforms, controllable power factor, and reliable grid short-circuit protection and those are better than voltage source converter topology. Current-source converter not only controls real and reactive power flow in the network, but also regulates the dc link current. In this paper, back-to-back space vector pulse width modulation (SV-PWM) technique is used in current-source converter (CSC) topology is proposed for high-power wind energy applications. The system's dynamic performance is further improved by adopting generator-side power feed forward controller. Simulation results are provided to verify the proposed control scheme.

Keywords

Permanent Magnet Synchronous Generator, Current Source Converter, Space Vector – Pulse width Modulation, Power Feedforward controller

1. Introduction

Wind energy is a promising technology and becomes more and more interesting player on the market of energy production. The wind energy produces electricity by converting kinetic energy of the wind to electrical power.

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As shown in Figure 1, the fundamental components of wind energy conversion system include wind turbine, drive train, electrical generator, possible power electronic converter, and transformer for connection with the grid. The generator transforms mechanical energy to electrical energy with variable frequency and variable magnitude. The electrical frequency of the generator may vary as the wind speed changes, while the grid frequency remains unchanged, thus allowing variable-speed operation of the wind turbine. In this paper permanent magnet synchronous generator [2] considered to convert mechanical energy to electrical energy because it's have no slip ring maintenance, no rotor windings and dc excitation becomes attractive due to higher efficiency.

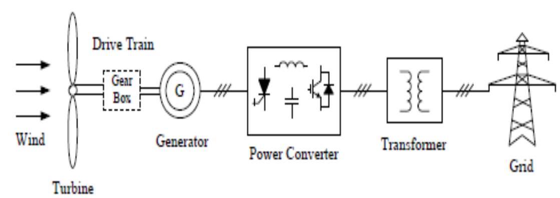

Figure 1: Basic components of wind energy conversion system

The proposed power system consists of a wind turbine is directly coupled to the permanent magnet synchronous generator (PMSG), which is connected to the grid-connected isolated transformer through a full-power back-to-back CSC and where filter capacitors are parallel connected at both sides to assist current commutation as well as filter out switching harmonics as shown in figure 2. In modern PMSG the active and reactive power flows WTGs designs, the power condition systems (PCS)[1]is typically built using a full-scale power converter made up of a two-stage power conversion hardware topology [6] that meets all the constraints of high quality electric power, flexibility and reliability imposed for applications of modern distributed energy resources. In this paper, a minimum dc-link current control strategy [8] for variable speed operation is proposed to reduce the overall system loss and the thermal stress on switching devices.

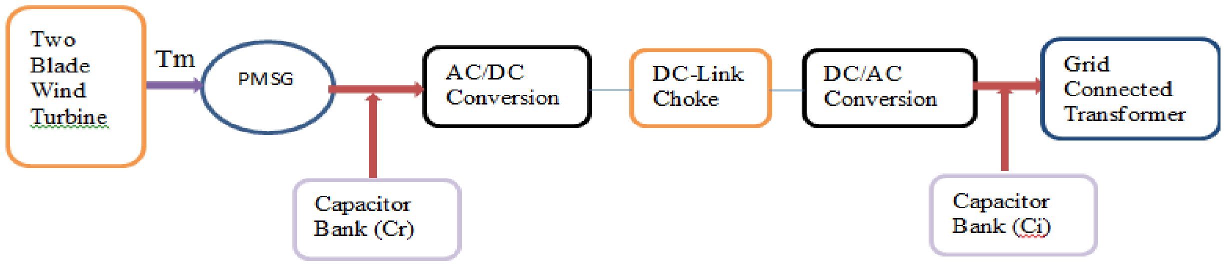

Figure 2: A wind energy conversion system using PWM CSR and PWM CSI.

The CSC requires a dc-link inductor to provide a smooth dc current for operation. When a CSC is connected to the grid, filter capacitors at the grid side result in constant leading reactive power. A phase-locked loop (PLL) is commonly used in grid-connected converters mainly for grid-synchronization [10]. In this paper using two phase locked loops at both sides of the converters.

The major modulation schemes for the PWM CSC are selective harmonic elimination (SHE), trapezoidal pulse-width modulation (TPWM) and space vector modulation (SVM) [9]. In a traditional CSC-based drive system, an offline PWM method—selected harmonic elimination (SHE)—is normally used at the grid side due to the capability of eliminating a number of unwanted low-order harmonics. In this paper space vector modulation technique is adopted at both sides of converter controllers [13]. Several methods [17]–[19] were developed for power factor control. Unity power factor is achieved by phase-shifting the modulating signals according to the converter operating point, which is not straightforward for line-side active and reactive power control. Two proportional-integral (PI) regulators were proposed in to adjust modulation index and phase angle directly.

The following parts will give a detailed explanation about the power system and operation of proposed system control strategy.

A. Aerodynamic Turbine Model

The modeling of the wind turbine for electrical system design mainly focuses on the amount of captured power from the wind and thus the mechanical torque applied to the shaft of the generator. The mechanical power extracted from the wind depends on many factors. A simple equation of the power characteristics of wind turbines:

$$P_m = \frac{1}{2}\rho\pi R^2 \upsilon^3 C_p(\lambda,\beta) \qquad (1)$$

Where ρis the air density, ν is the wind speed, R is the blade radius and Cp is the power coefficient. The value of Cp as 0.39 at 2 degrees pitch angle and 8.17 is tip speed ratio of the aerodynamic turbine. The Cp value is usually given as a function of two parameters Cp = F (λ,β) where βis the blade pitch angle and λ is the tip speed ratio which are defined in [19]. The relation between torque and mechanical power is given by the following equation:

$$T_m = \frac{P_m}{\omega_{\omega t}} \qquad (2)$$

With a multi-pole synchronous generator it is possible to operate at low speeds and without gearbox. Therefore the losses and maintenance of the gearbox are avoided.

B. PMSG Model

The dynamic model of PMSG has been built in the d-q rotating reference frame, where the q-axis goes ahead 90 from the d-axis with respect to the direction of rotation. The electrical model of the PMSG in the d-q synchronous reference frame as shown in figure 3, with the voltage and torque equations are given by (3) –(5).

$$V_d = i_d R_s + L_d \frac{\partial i_d}{dt} - w_r L_q i_q \qquad (3)$$

$$V_q = i_q R_s + Lq\frac{\partial i_q}{dt} + w_r(L_d i_d + K_e) \qquad (4)$$

$$T_e = \frac{3}{2} p i_q((L_d - L_q) i_d + K_e \qquad (5)$$

The PMSG is assumed to have equal d-axis and q-axis synchronous inductances, hence $L_d = L_q$. Where V_d and Vq are voltages in the d-q axis, id and iq are the current in the d-q axis, Rs is the stator resistance, L_d and Lq are the d-q axis inductance, !r is electrical rotational speed, Ke is permanent magnetic flux given by the magnets and finally **p** is the number of pole pairs. The Figure4 shows the equivalent electric circuit of PMSG in d-q-rotating reference frame.

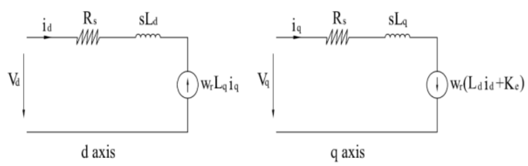

Figure 3: Equivalent circuit of PMSG in d-q reference frame

C. Converter Model

The concept of back–to–back converter topologies is to maintain constant frequency in grid. The three-level neutral point clamped (NPC) converter [4] and multilevel modular converter [5], were proposed for wind energy conversion based on voltage-source inverter technology. Load-commutated inverter (LCI) based power system was proposed in [6]. In this paper, back-to-back pulse width modulation (PWM) current-source converter (CSC) topology is proposed for high-power wind energy applications. Compared with VSC and LCI-based configurations, PWM CSCs provide a simple topology solution and excellent grid integration performance, such as sinusoidal current and fully controlled power factor. The dc link reactor provides natural protection against short-circuit fault, and therefore, the fault ride through strategy required by the grid code [7] can be integrated easily into the system. In this paper the power converter consists as generator side IGBT bridge circuit and grid side Gate Turn-off Thyristors(GTO's) bridge circuit was proposed as shown in figure 4 (a) and 4 (b). The IGBT diode circuit is considered as preferable to the GTO diode circuit for conversion of AC to DC while using space vector modulation technique.

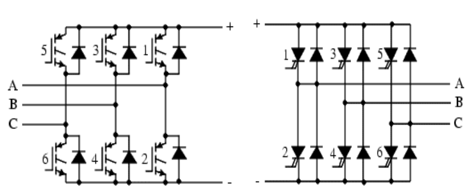

Figure 4(a) Figure 4(b)
Figure 4(a): IGBT Diode Bridge circuit;
Figure 4(b): GTO Diode Bridge Circuit.

2. System Control Scheme

In a variable-speed WECS, the generator speed or torque should be regulated to achieve maximum power point tracking [11]-[13] of the wind turbine. In this paper, generator-side equations are derived with respect to the generator rotor flux oriented synchronous reference frame, whereas grid-side equations are obtained based on the grid voltage oriented synchronous frame.This paper mainly focuses on the generator and converter control, and therefore the wind turbine pitch control is not discussed. The generator and grid-side CSCs both employ the SVM scheme proposed in [14]-[15] for gate signal generation, such that flexibility in control and excellent harmonic performance can be achieved. As an effort to reflect industrial practice in high-power medium-voltage CSCs, the switching frequency of the power devices is limited to be within 600Hz.

3. Generator-Side Controller

In normal operation, the generator controller receives the speed reference from MPPT and regulates the rotor speed. The control scheme is developed based on generator-rotor-flux-oriented synchronous frame.The reactive power requirements for generator-side and grid-side are different. On the generator side, the reactive power control helps obtain desired generator terminal voltage and current; while on the grid side, reactive power control is to regulate the bus voltage or meet other grid operating requirements.Its output gives reference to the torque producing current i^*_{gq}. *d*-axis generator current, i^*_{gd}, is set according to the generator operation requirements. Capacitor currents are subtracted from the generator currents to obtain the converter current references they are

$$
\begin{aligned}
i^*_{d\omega r} &= \omega_g^{*2} L_d C_r i^*_{gd} + \omega_g^{*} R_g C_r^{*}{}_{gq} - \omega_g^{*2} C_r \psi_f \\
i^*_{q\omega r} &= \omega_g^{*2} L_q C_r i^*_{gq} - \omega_g^{*} R_g C_r i^*_{gd}
\end{aligned}
\quad (6)
$$

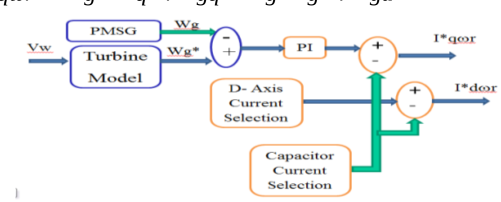

Figure 5: Generator side currents

4. Grid-Side Controller

In this paper the grid assumed stiff, the controller is developed based on grid voltage oriented control, such that the *d*-axis of the synchronous reference frame is aligned with the grid voltage vector. The control structure is shown in Fig.6. The PLL generates noise free synchronous angle θ*v*and the angular frequency ω*s* it helps to generate the pulses for the grid side converter. The controller is composed of two independent control loops for real power and reactive power regulation, respectively.The grid voltage Vs has only d -axis component V_{ds} while q-axis component V_{qs} equals to zero. The active and reactive power outputs as follows

$$\left.\begin{aligned} P_0 &= 1.5 V_{ds} i_{ds} \\ Q_0 &= 1.5 V_{ds} i_{qs} \end{aligned}\right\} \quad (7)$$

The steady-state capacitor voltages at the grid side as follows

$$\left.\begin{aligned} V_{dci} &= R_0 i_{ds} - \omega_s L_0 i_{qs} + v_{ds} \\ V_{qci} &= R_0 i_{qs} + \omega_s L_0 i_{ds} \end{aligned}\right\} \quad (8)$$

where R_0 and L_0source impedance. The capacitor currents are obtained by using capacitor voltages as $i_{dci} = -\omega_s C_i V_{qci}$ and $i_{qci} = \omega_s C_i V_{dci}$. The reference current of the grid-side converter i_{dwi} is the sum of the grid output current and capacitor current, which is derived as

$$\left.\begin{aligned} i_{dwi} &= i_{dci} + i_{ds} \\ i_{qwi} &= i_{qci} + i_{qs} \end{aligned}\right\} \quad (9)$$

Assuming that the grid-side converter is operating at unity power factor with $i_{qs} = 0$, then $i_{q\omega i} = i_{qci}$. Considering the converter PWM modulation technique and steady-state operation, the relationship between dc link current and m_{ai} can be obtained in (10). Here, m_{ai} is the modulation index of the grid-side converter.

$$m_{ai} I_{dc} = \sqrt{i^2_{dwi} + i^2_{qwi}} \quad (10)$$

The dc current references calculated based on the generator output power with the assumption of loss less system and m_{ai}=1

$$I^*_{dc} = \sqrt{\left(1-\omega_s^2 L_0 C_i\right)^2 \left(\frac{P_g}{1.5V_{ds}}\right)^2 + \omega_s^2 C_i^2 \left(V_{ds} + \frac{P_g R_0}{1.5V_{ds}}\right)^2} \quad (11)$$

The d-axis current of the grid-side converter is

$$I^*_{d\omega i} = \left(1-\omega_s^2 L_0 C_i\right)\left(\frac{P_0^*}{1.5V_{ds}}\right) \quad (12)$$

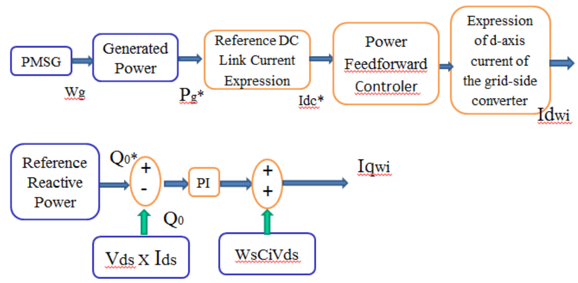

Figure 6: Grid side currents

5. Power Feedforward Controller

To improve the performance of dc current control, power feedforward controller is adopted in this paper as shown in figure 7. The instantaneous generator output power is sensed and fed forward to grid-side dc-link current controller. The power disturbance from the generator side will directly adjust the controller output of the grid-side converter, which will greatly improve the system dynamic performance and ensure stable dc current operation. Assuming that the converters are loss less and all the passive components are ideal. The voltage across the dc link choke is $V_{Ldc} = L_{dc} p i_{dc}$ and the instantaneous power P_{dc} in the dc link is therefore obtained as

$$P_{dc} = V_{Ldc} i_{dc} = P_g - P_0 \quad (13)$$

$$Pg = \frac{T_e \omega_g}{P} = 1.5 \psi_f i_{qg} \omega_g \quad (14)$$

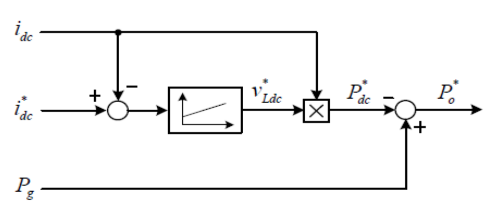

Figure 7: dc-link current regulator with generator power Feedforward [3].

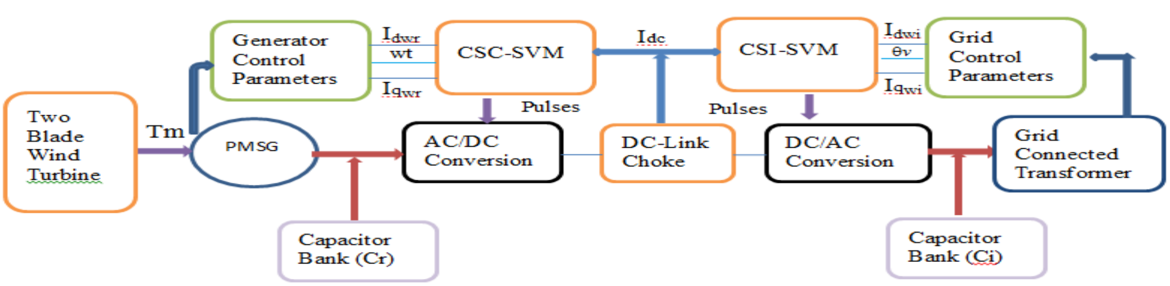

Figure 8: A wind energy conversion system using SVM-Technique

6. Simulation Results

The control strategies for the CSC-PMSG-WECS are simulated in Matlab/Simulink for a 2MW WECS. System parameters are listed in Appendix A.The torque from wind turbine drives the generator to slowly speed up until it reaches 50% of the reference speed. Once the speed is over the threshold, both generator-side and grid-side converters start operating. The start-up process takes a long simulation time. The simulation results are provided in Fig.9. In order to simulate the transient response of the proposed control system, a step-down from 12m/s to 10m/s at 3s and a step-up from 10m/s to 12m/s at 7s are applied to the wind speed. Specially, a speed reference ramp function is applied to avoid large transient. The rotor speed follows the reference speed very well in steady state.

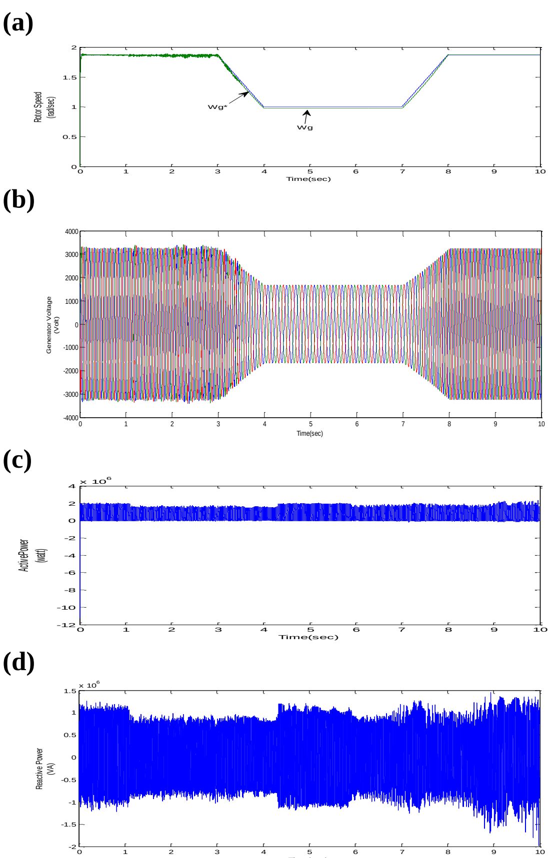

Figure 9: Power flow response in wind speed step changes (from 12to10 m/s at 3 s and from 10 to 12 m/s at 7s). (a) Generator speed. (b)Generator output voltage (c) Grid output real power. (d) Grid output reactive power.

7. Conclusion and Future Work

In this paper, the current source control scheme in PWM power converter based direct driven wind energy conversion systems was proposed. The proposed control strategy was developed for independent active and reactive power flow while extracting the maximum power from wind. In this proposed control system space vector pulse width modulation technique is employed at both sides of the converters based on their control algorithm (FOC at the generator side converter and the grid side is VOC) separately. In this paper the proposed control switching algorithm reduced the devices' switching loss and conduction loss for achieving maximum overall efficiency. Generator power feedforward method is employed to ensure stable dc link current operation. By using this generator and grid control techniques the output active and reactive power flow can able to track the speed variations smoothly.

Appendix A
System Parameters

Paramerters	**Simulation**
System Ratings	
Power	2MW
Voltage	3200V
Current	300A
Frequency	60Hz
Generator Parameters	
Synchronous Inductance	0.4pu
Stator Resistance	0.01pu
No. of pole pairs	32
Converter Parameters	
Generator-side Capacitor	0.3pu
Grid-side Capacitor	0.5pu
Grid-side Line Inductance	0.1pu
DC-Link Choke	1pu
Device Switching Frequency	540Hz

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