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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, 275Megawatts (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 byi_{wi}, $i_s$andi_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

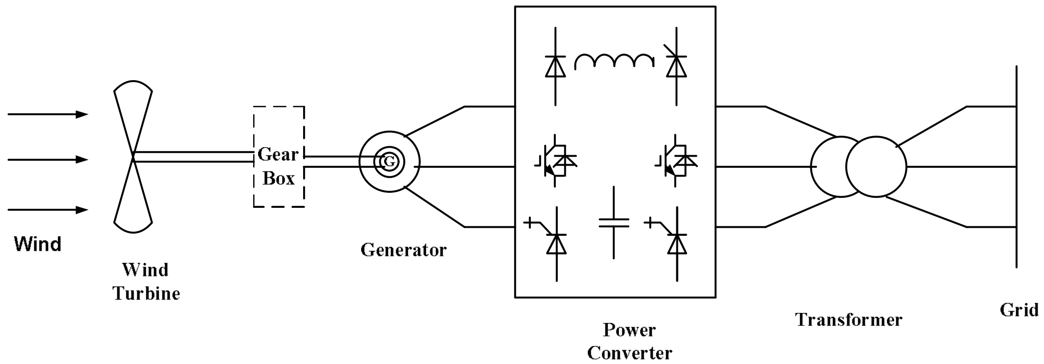

Fig. 1. Basic configuration of the contemporary WECS

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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 ρ is the mass density of air, A is the swept area of turbine blade andv_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]:

$$P_w = \frac{1}{2}\rho A v_w^3 \tag{1}$$

$$P_T = \frac{1}{2} C_P(\lambda, \beta) A v_w^3 \tag{2}$$

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

$$\lambda = \frac{\omega_T R}{v_w} \quad (3)$$

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

$$C_p(\lambda, \beta) = c_1\left(\frac{c_2}{\lambda_1} - c_3\beta - c_4\right)e^{\frac{-c_5}{\lambda_1}} + c_6\lambda \tag{4}$$

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 β. For example, the correspondent maximum C_P is about 0. 48 when the optimal tip speed ratio λ_{opt} equals 8. 1 in the case of zero degree pitch angle.

Table 1. Values of c_1 to c_6 for MPPT

c_1	c_2	c_3	c_4	c_5	c_6
0. 5176	116	0. 4	5	21	0. 0068

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).

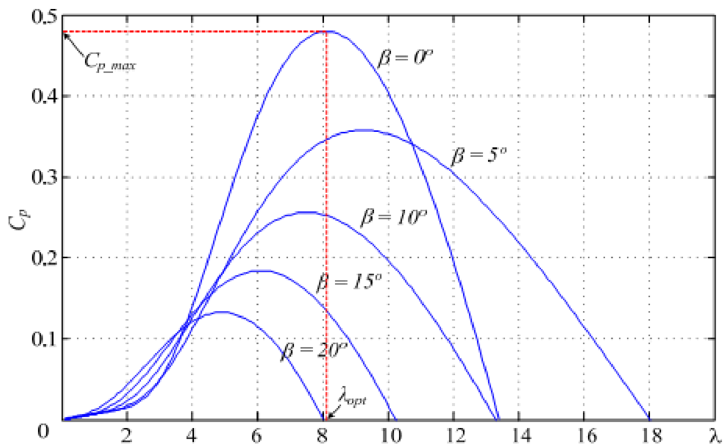

Fig. 2. Power coefficients over tip speed ratio at various pitch angles

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].

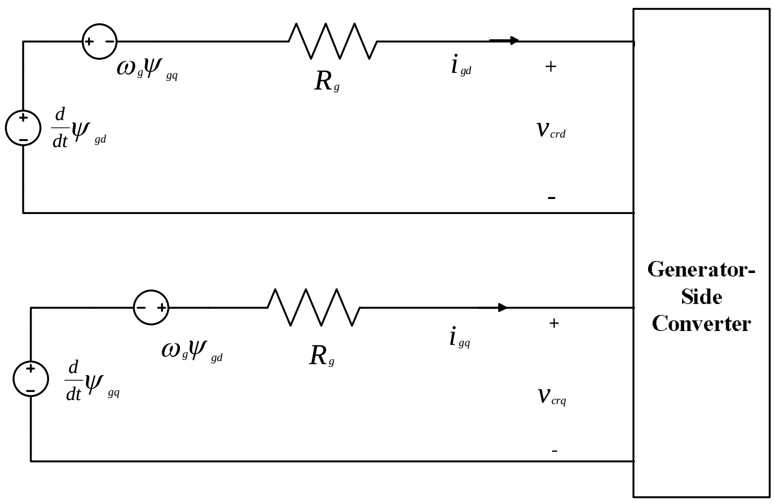

Fig. 3. Equivalent circuit of PMSG in synchronous frame

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)

$$\begin{bmatrix} v_{crd} \\ v_{crq} \end{bmatrix} = \begin{bmatrix} \frac{d\psi_{gd}}{dt} - \omega_g \psi_{gq} - R_g i_{gd} \\ \frac{d\psi_{gq}}{dt} - \omega_g \psi_{gd} - R_g i_{gq} \end{bmatrix} \tag{5}$$

where

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

Here, ψ_f is the magnetic flux linkage of the rotor. R_g 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

$$T_{eg} = 1.5 P i_{gq} \left(\psi_f - \left(L_q - L_d \right) i_{gd} \right) \tag{6}$$

$$T_m - T_{eg} = \frac{J}{P} \frac{d}{dt} \omega_g \tag{7}$$

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

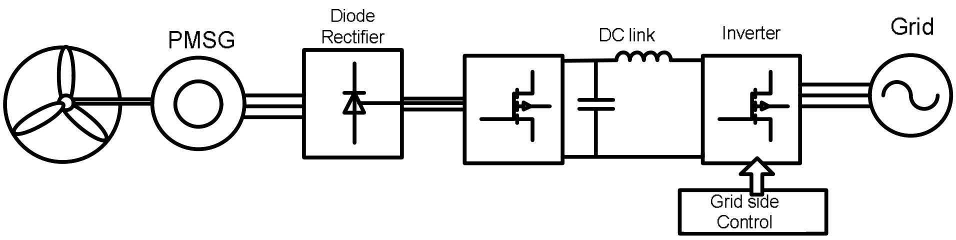

Fig. 4. proposed converter configuration for a PMSG-WECS

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.

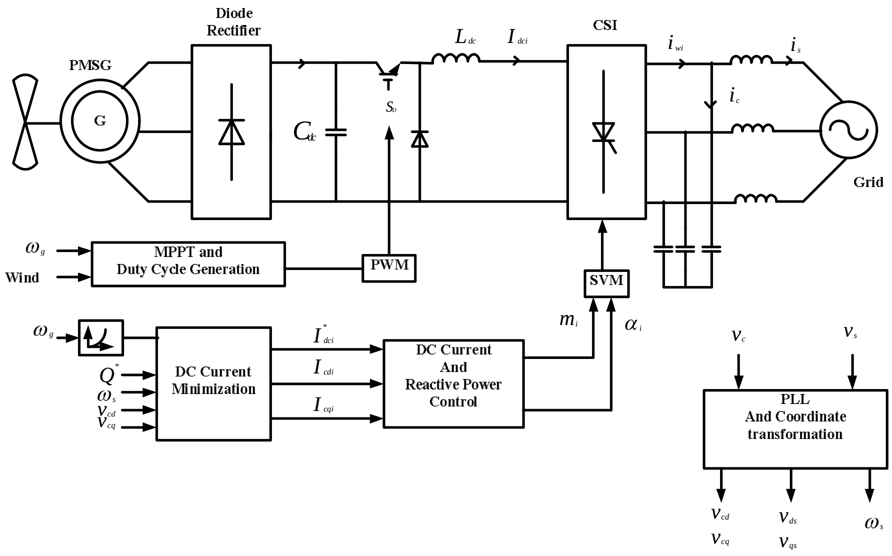

Fig. 5. Block diagram of the control scheme for the proposed system

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 VSIoffers both modulation index (m_i) and delay angle (α) 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

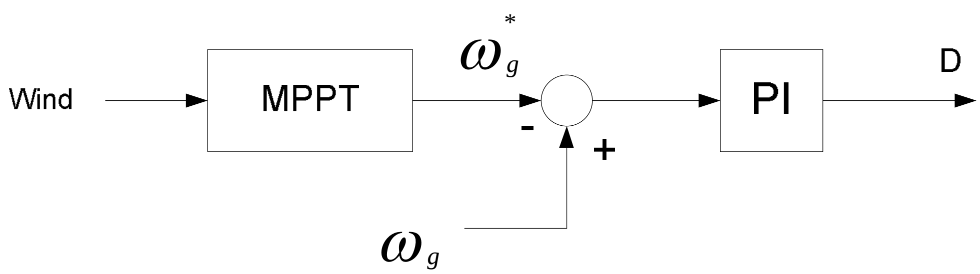

Fig. 6. Control of Buck Converter

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

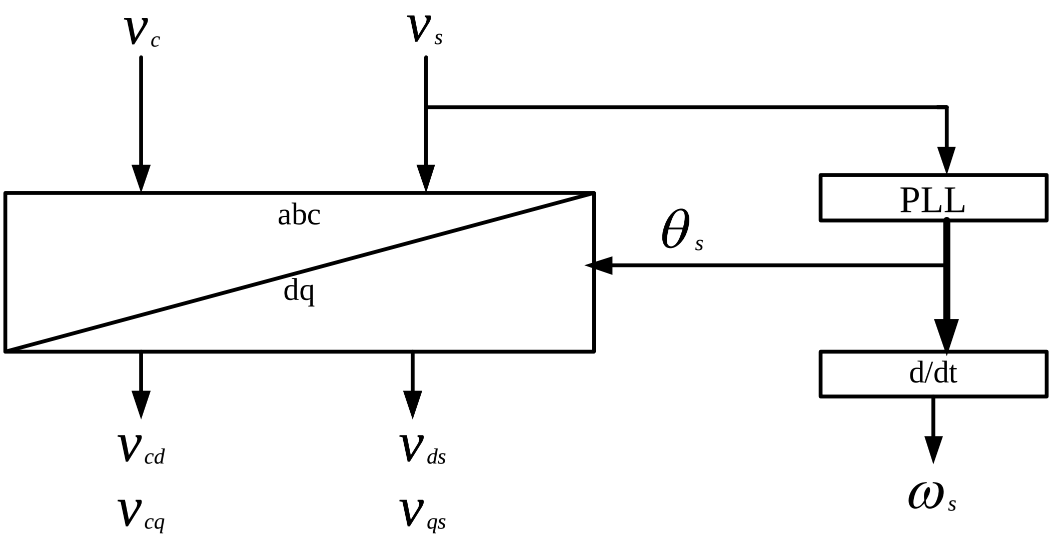

Fig.. 7. Grid voltage PLL and coordinate transformation

The ***q***-axis grid voltage v_{qs} is then equal to zero. The active and the reactive powers to the grid can be calculated by,

$$P = 1.5\left(v_{ds} i_{ds} + v_{qs} i_{qs}\right) = 1.5 v_{ds} i_{ds} \tag{8}$$

$$Q = 1.5\left(v_{qs} i_{ds} - v_{ds} i_{qs}\right) = -1.5 v_{ds} i_{qs} \tag{9}$$

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

$$i_{ds} = P / 1.5 v_{ds} \tag{10}$$

$$i_{qs} = -Q / 1.5 v_{ds} \tag{11}$$

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

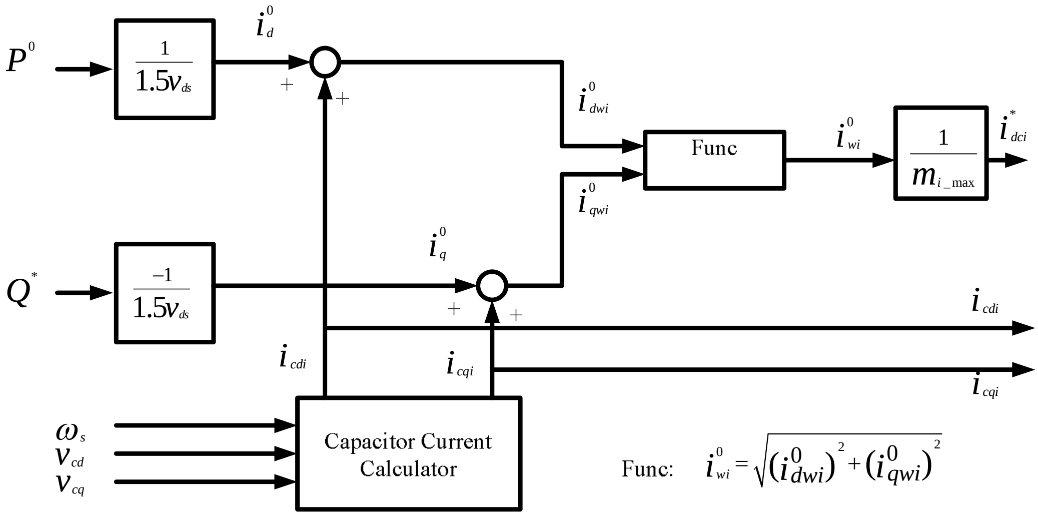

Fig. 8. DC current minimization

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 $(i_d^0)$and q-axis (i_q^0)components of the grid current; with the capacitor bank compensation taken into account, the d-axis (i_{dwi}^0) and q-axis (i_{qwi}^0) components of the PWM current can be derived.

VII. Grid Reactive Power Contol

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 (α). The DC current reference for inverter i_{dci}^* is compared with the actual i_{dci}, the error isapplied 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 referencei_{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)

$$i_{dwi}^* = i_{ds}^* + i_{cdi} \tag{12}$$

$$i_{qwi}^* = i_{qs}^* + i_{cqi} \tag{13}$$

The magnitude of the PWM current referencei_{wi}^* and the inverter firing angleα_i are calculated by (14) which can be applied for SVM scheme.

$$\begin{cases} i_{wi}^{*} = \sqrt{\left(i_{dwi}^{*}\right)^{2} + \left(i_{qwi}^{*}\right)^{2}} \\ \alpha_{i} = \tan^{-1}\left(i_{qwi}^{*} / i_{dwi}^{*} \right) \end{cases} \quad (14)$$

VIII. SIMULATION AND EXPERIMENT RESULTS

Table 2. Parameter for generator and grid

PMSG rating	2MW
Stator resistance	0. 168
Ld=Lq	0. 194H
Rated grid phase voltage	1732V(rms)
Grid frequency	50Hz
Pole pairs	30

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

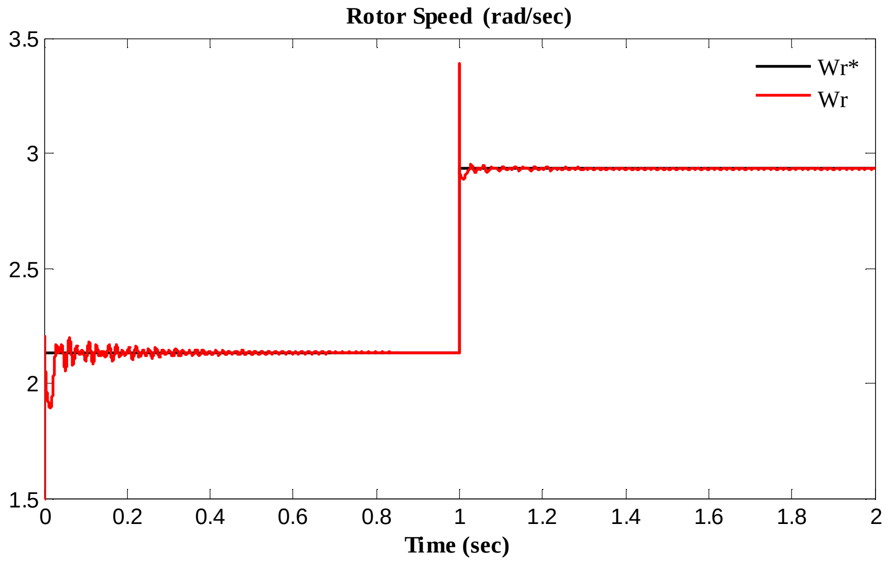

Fig. 6. 1 Rotor Speed of Generator

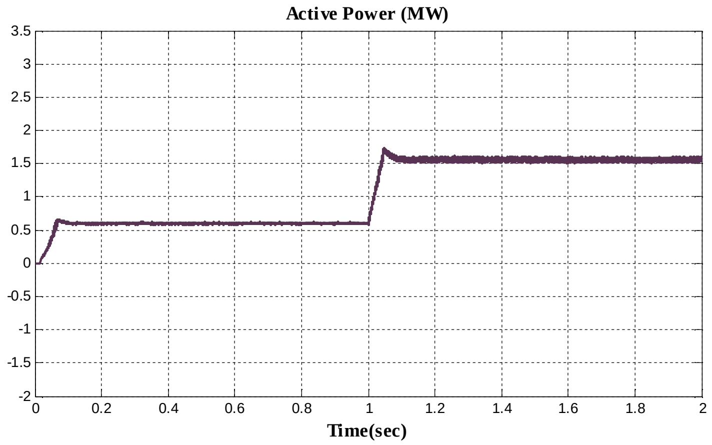

Fig. 6. 3 Active power

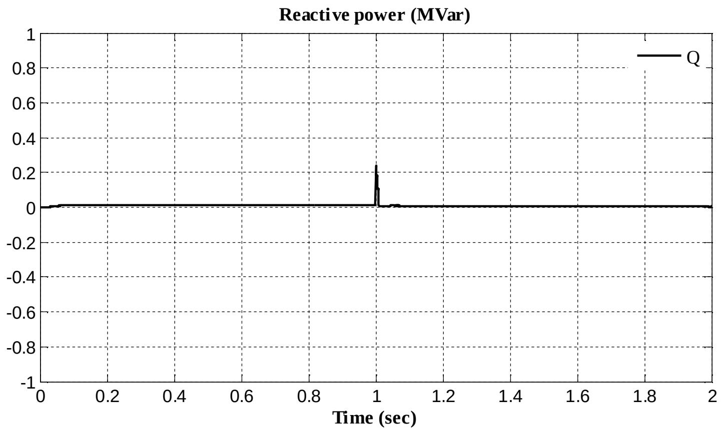

Fig. 6. 3 Reactive Power

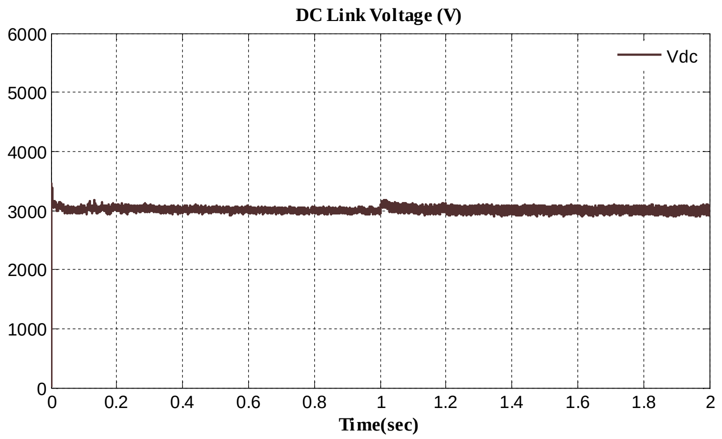

Fig. 6. 4 DC Link voltage

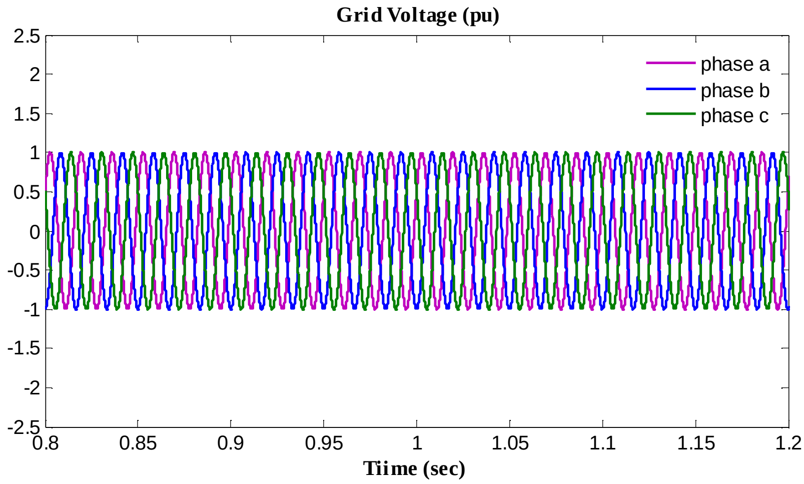

Fig. 6. 5 Grid Voltage

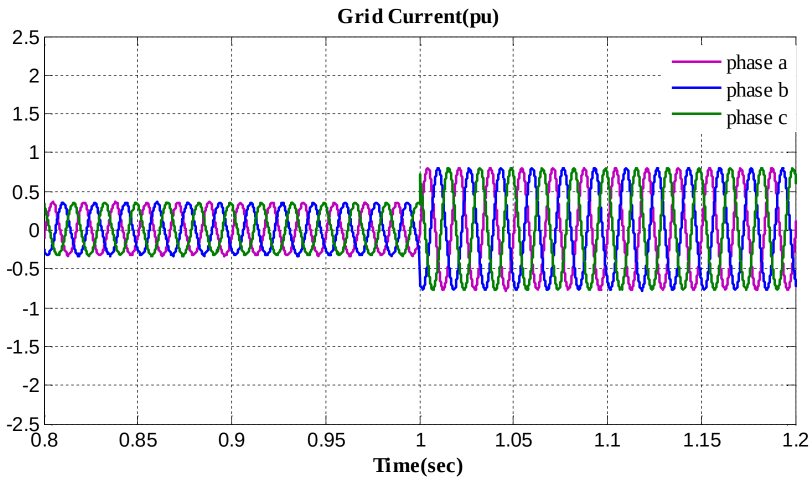

Fig. 6. 6 Grid Current

IX. Conclusion

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.

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