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Power Flow Control in Variable speed Wind Energy Conversion System Based on Permanent Magnet Synchronous Generator

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Abstract

Wind is one of the most abundant renewable sources of energy in nature. Wind energy can be harnessed by a wind energy conversion system (WECS) composed of a wind turbine, an electric generator, a power electronic converter and the corresponding control system. The most advanced generator type is perhaps the permanent magnet synchronous generator (PMSG). This paper describes the control of power which is flowing from generator to grid in variable speed wind energy conversion system (WECS). PMSG is connected to the power network by means of a fully controlled frequency converter which consist of a Space vector pulse width modulation (SVPWM), an intermediate dc circuit. and a SVPWM Inverter. Based on the Speed of Wind Effective MATLAB/Simulink based simulation results are presented.

Key words— PMSG, WECS, SVPWM, Controlled Rectifier, Voltage source inverter

Introduction

The continuously increasing energy demand, along with the necessity of higher reliability requirements, are driving the modern power systems towards distributed generation (DG) as an alternative source. Wind turbines, Fuel cells (FC), Photovoltaic (PV), Batteries, etc. are nowadays the most common available DGs for generation of power mostly in peak times or in rural area. Microgrids are combinations of DGs and load. To deliver high quality and reliable power, the microgrid should appear as a single controllable unit that responds to changes in the system. Microgrids should preferably tie to the utility grid so that any surplus energy generated within them can be channelled to the grid. Similarly, any shortfall can be replenished from the grid. As far as microgrid is concerned the loads may be unbalanced and non-linear in nature. Hence, microgrid should not inject harmonic and unbalanced currents into the grid. Harmonic currents and negative sequence currents (due to unbalance) will unnecessary increase the line currents flowing between microgrid and grid. Generally, harmonics increase losses in ac power lines, transformers and rotating machines. The load imbalance cause oscillatory torque leading to mechanical stress and malfunctions in sensitive equipment. Wind is one of the most abundant renewable sources of energy in nature. Wind energy can be harnessed by a wind energy conversion system (WECS) composed of a wind turbine, an electric generator, a power electronic converter and the corresponding control system. Based on the types of components used, different WECS structures can be realized to convert the wind energy at varying wind speeds to electric power at the grid frequency. The most advanced generator type is perhaps the permanent‑magnet synchronous generator (PMSG). This machine offers, compared at the same power level and machine size, the best efficiency among all types of machines with high robustness and easy maintenance due to slipring‑less and exciter‑less features. The inherent benefit of permanent magnet which supplies rotor flux in synchronous machines without excitation loss supports the wind power generation development. This thus results in the increasing use of PMSG.

II. 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

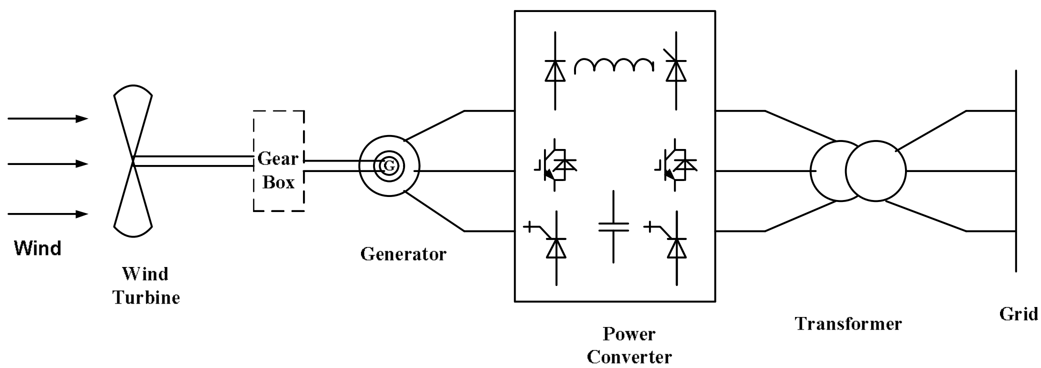

Fig. 1. Basic configuration of the contemporary WECS

The generator rotor is mechanically coupled with the wind turbine through the drive train, which can be either directly connected or through a gearbox. The gearbox works as a speed multiplier to step up the rotational speed of wind turbine to match that of the generator.

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.

III. 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]:

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

$$P_T = \frac{1}{2}C_P\left(\lambda,\beta\right)Av_w^3 \tag{2}$$

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

$$\lambda = \frac{\omega_T R}{v_w} \tag{3}$$

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

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

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).

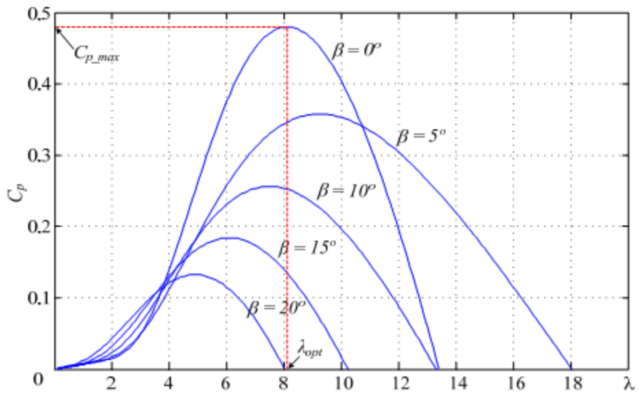

Fig. 2. Power coefficients over tip speed ratio at various pitch angles

IV. 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].

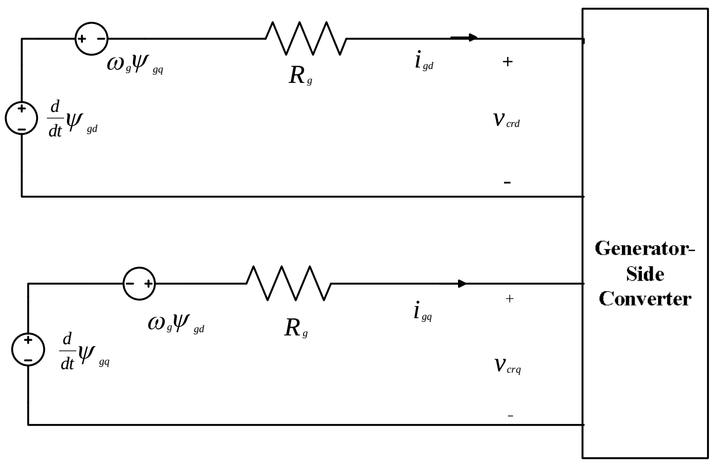

Fig. 3. Equivalent circuit of PMSG in synchronous frame

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)

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

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

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

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

V. PROPOSED SYSTEM CONFIGURATION

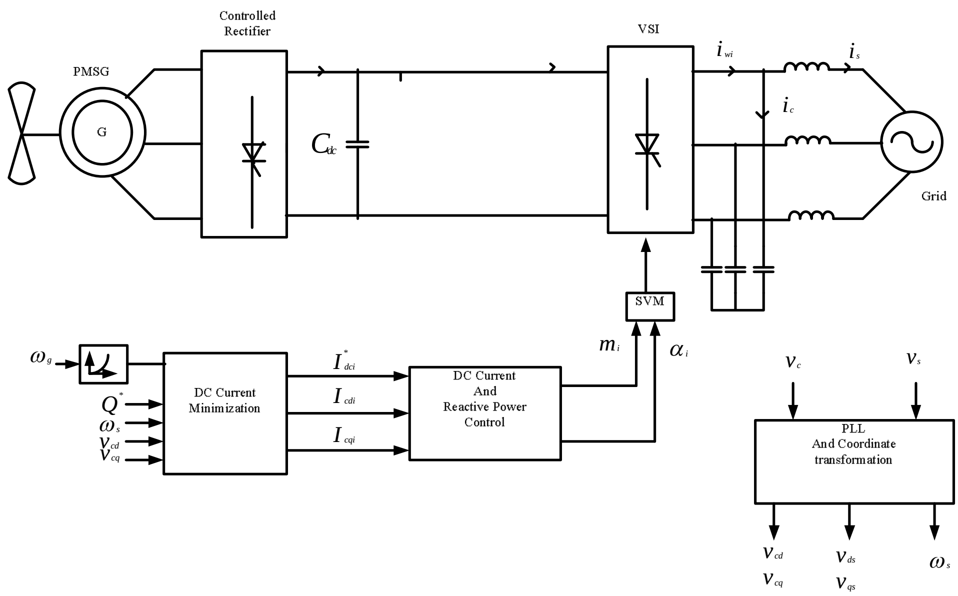

Fig. 5. Block diagram of the control scheme for the proposed system

VI. Overview Of The Control System

The block diagram of the control scheme for the system is shown in Fig. 5 The currents flowing through the DC link inductance and the switching devices are all defined by the DC link current

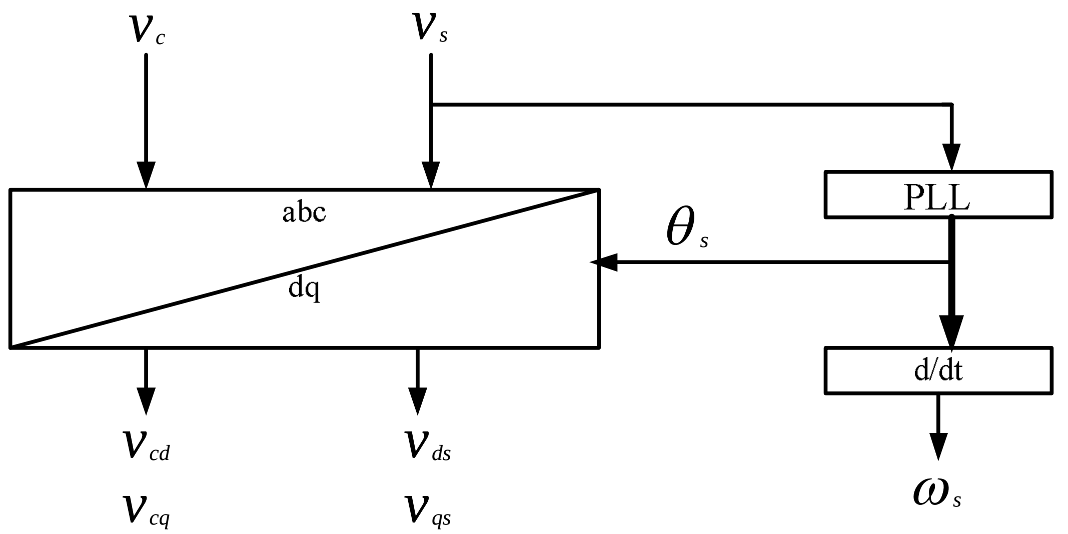

Fig.. 7. Grid voltage PLL and coordinate transformation

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

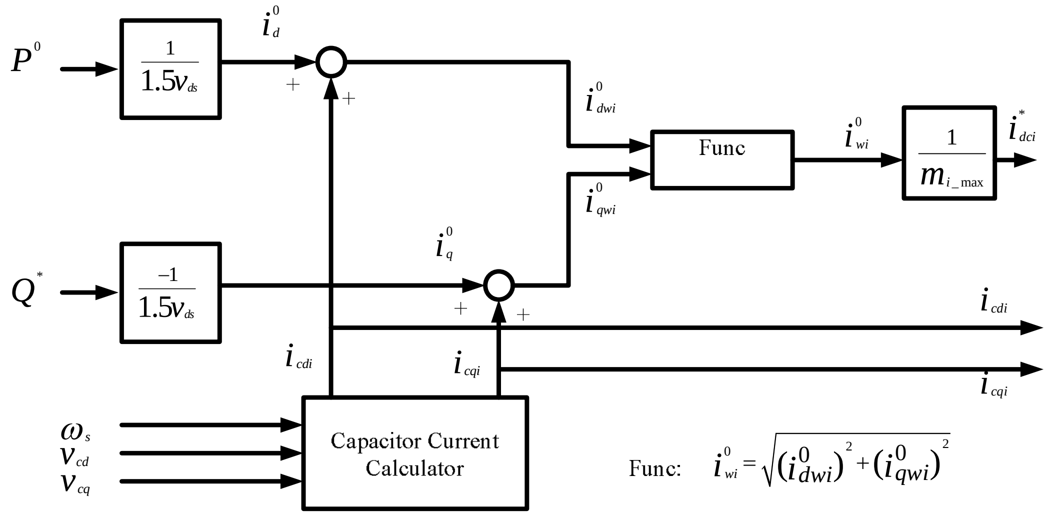

Fig. 8. DC voltage minimization

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 (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.

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

VII. GRID-SIDE MODEL

Today, large wind turbines are required to be connected to medium-voltage or high-voltage transmission lines. This normally requires a transformer at the output of the WECS to step up the generated voltage with relatively low magnitudes. A three-phase equivalent circuit reflecting the low-voltage side of the output transformer is illustrated in Fig. 4. 6. 1 The grid is assumed to be stiff and can be simplified as a voltage source with small source impedance (L_s and R_s). represents the sum of the line impedance and leakage inductance of the transformer, while R_s stands for the transformer and line losses.

The three-phase equation can be derived straightforwardly from the equivalent circuit.

$$\frac{d[i_s]_{abc}}{dt} = \frac{1}{L_s}\left([v_{ci}]_{abc} - [v_s]_{abc} - R_s[i_s]_{abc}\right) \qquad (4.\ 5\text{-}10)$$

The dq-axis equations based on the grid voltage oriented synchronous frame are,

$$\begin{bmatrix} v_{cid} \\ v_{ciq} \end{bmatrix} = \begin{bmatrix} v_{sd} + L_s \dfrac{di_{sd}}{dt} - \omega_s i_{sq} - R_s i_{sd} \\ v_{sq} + L_s \dfrac{di_{sq}}{dt} - \omega_s i_{sd} - R_s i_{sq} \end{bmatrix} \qquad (4.\ 5\text{-}11)$$

VIII. SIMULATION AND EXPERIMENT RESULTS

Table 1. 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

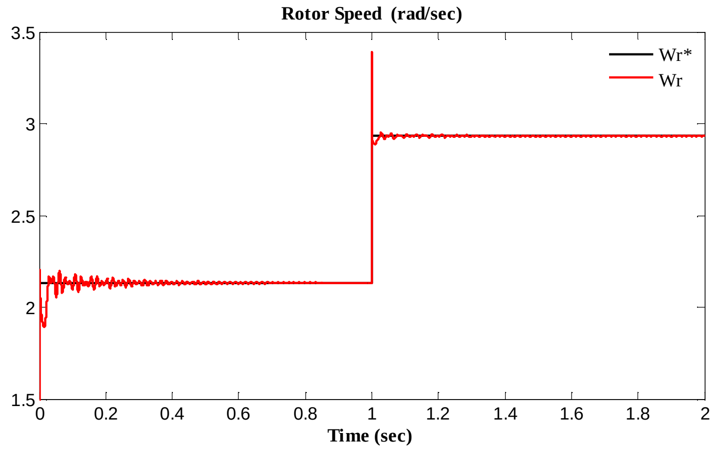

Fig. 6. 2 Rotor Speed of Generator

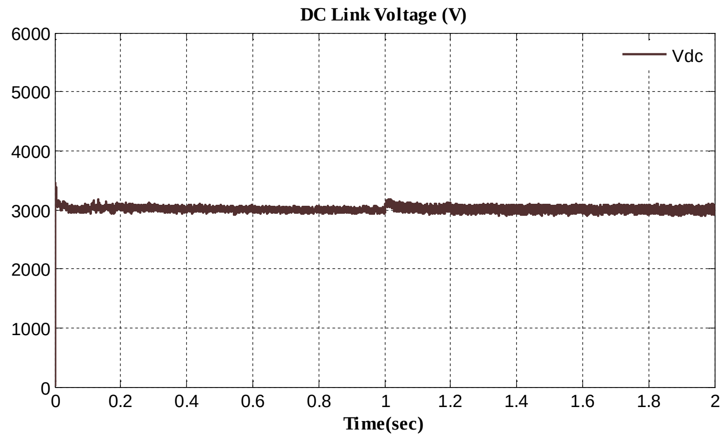

Fig. 6. 3 DC Link voltage

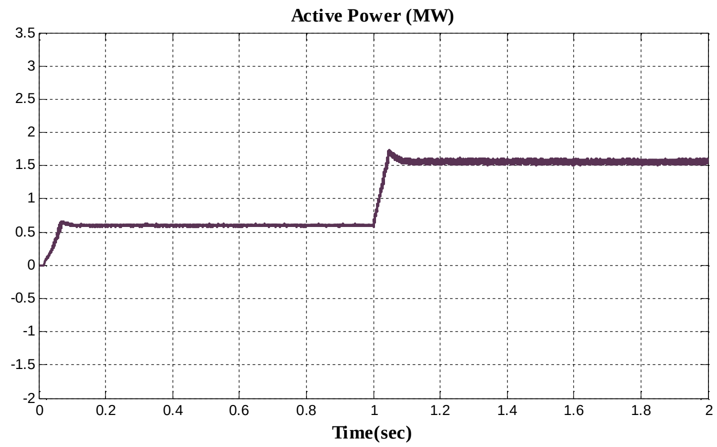

Fig. 6. 4 Active power

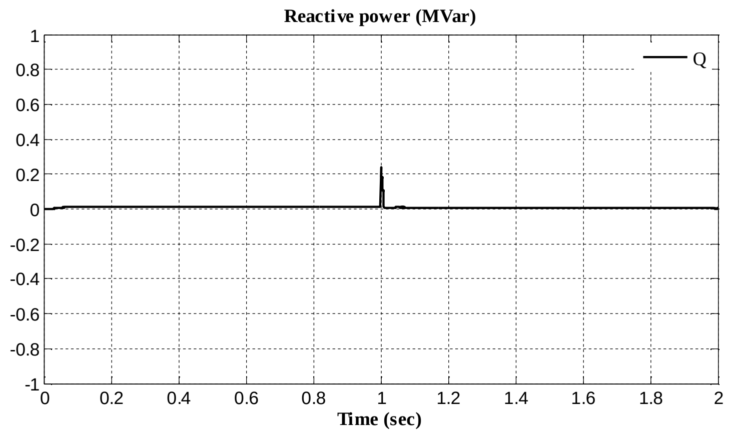

Fig. 6. 5 Reactive Power

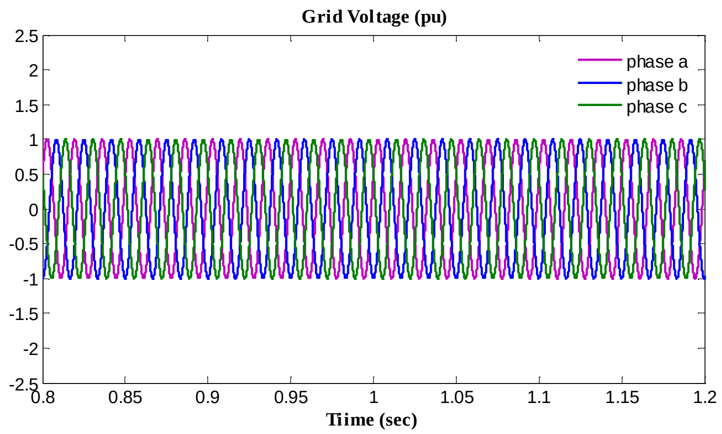

Fig. 6. 6 Grid Voltage

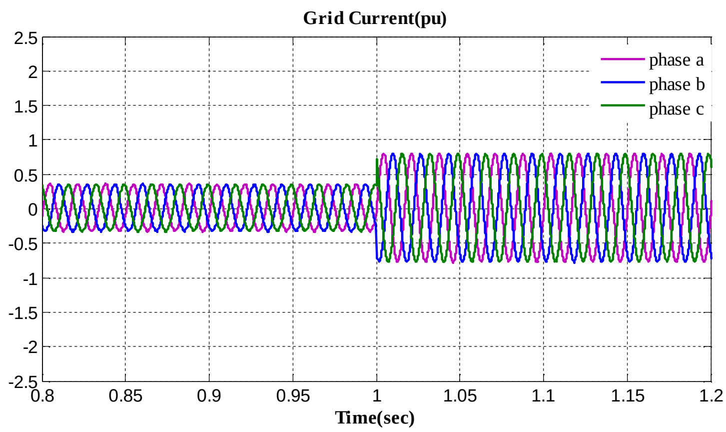

Fig. 6. 7 Grid Current

IX. CONCLUSION

The above work shows the performance of a direct-driven permanent magnet synchronous generator used in variable speed wind energy system. 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 voltage 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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