Analysis of a grid-connected wind energy conversion system based on complex simulation program

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Abstract— **The present paper details a complex simulation program designed in MATLAB/SIMULINK aiming at the analysis of a complete grid-connected wind energy conversion system. The model contains the wind turbine, a permanent-magnet synchronous generator, a back-to-back electronic power converter, and the grid, as load for the electric energy production unit. Also, the maximum-power-point-tracking strategy is considered in the control of the generator, in order to extract the highest power possible from the wind turbine. The results of the simulation emphasize the behaviour of the simulation program, flexible enough to be used at any power level and any wind or turbine speed.**

Keywords—wind energy conversion system, simulation program, back-to-back converter

I. INTRODUCTION

It is well known that, nowadays, there is a firm tendency regarding the use of renewable energy sources for electric power generation. Hence, wind turbines are worldwide installed for harvesting the wind power and producing nonpolluting electric energy.

Simulations are systematically used to study the behaviour of wind energy conversion systems in several operating conditions. Different control strategies can thus easily be tested, such as the maximum power point tracking (MPPT) to extract as much as possible power from the wind [1, 2].

There are many studies in the technical literature approaching the simulation of each part of the wind energy conversion system. However, only few papers have reported studies on complete simulation of the entire system, from the wind turbine with the MPPT control procedure, the electric generator, the back-to-back electronic converters delivering active power to the utility grid.

The aim of this paper is to develop such a complete simulation program comprising all the components of the wind energy conversion system. Hence, for each part, mathematical models are developed and all are then connected in one entire simulation program, able to emphasize the operation of the wind harvesting unit. All these mathematical models are implemented in MATLAB/SIMULINK, thus allowing their easier portability and handling.

The developed simulation program is structured around classical wind turbine, permanent-magnet synchronous generator (PMSG), connected to back-to-back power electronic converters with intermediate DC-link circuit. LCL-filter is used to decrease the harmonics injected into the utility grid by the grid-side power converter.

II. MATHEMATICAL MODELS

In order to implement the MPPT [3, 4] control strategy, it is necessary to define operational parameters of the wind turbine. These are listed in Table I. Hence, the power delivered by the turbine can be expressed by

$$P_t = \frac{1}{2}\rho A C_p v_w^3, \tag{1}$$

where ρ is the air density, A, the turbine's surface, C_p, the turbine's performance coefficient, and v_w, the wind speed. Turbine's performance coefficient depends on the tip-speed ratio (*TSR*), which is a function of the wind speed, the turbine speed ϖ_m and the radius of turbine-rotor blades:

$$TSR = \frac{r\varpi_m}{v_w}. \tag{2}$$

The functional dependence $C_p(TSR)$ is represented in Fig.1. At around TSR = 10, the wind turbine can reach its best performance. By using the MPPT control strategy, the turbine is forced to stay in the operating region, where the maximum power is extracted from the wind. Accordingly, the electric generator has to be controlled by imposing a certain value of the electromagnetic torque as

$$T = \frac{1}{2}\frac{\rho A C_p}{\omega_m}\left(\frac{r\omega_m}{TSR}\right)^3. \tag{3}$$

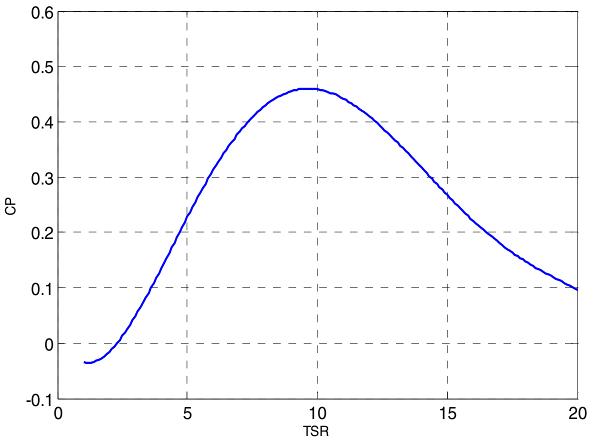

Fig. 1. Functional dependence $C_p(TSR)$.

The mathematical modeling of the PMSG is based on its *dq*- coordinate system equations [5]:

$$\begin{aligned}
u_{ds} &= R_s i_{ds} + L_s \frac{di_{ds}}{dt} - \omega_r L_s i_{qs} \\
u_{qs} &= R_s i_{qs} + L_s \frac{di_{qs}}{dt} - \omega_r \left(L_s i_{ds} + \lambda_{pm} \right) \\
T_e &= \frac{3}{2}\frac{p}{2}\left(\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds} \right) \\
P &= \frac{3}{2}\left(u_{ds} i_{qs} + u_{qs} i_{ds} \right) \\
Q &= \frac{3}{2}\left(u_{qs} i_{ds} - u_{ds} i_{qs} \right).
\end{aligned} \tag{4}$$

Since the outputs of the vector control scheme are the u_d and u_q voltages, these voltage values represent the inputs of the PMSG model. Accordingly, any distortion of the fundamental harmonic by the switching harmonic components is disregarded.

The generator-side power electronic converter injects into the DC-link circuit the apparent electric power *S*, so that the DC-link current can be computed as

$$i_{DC\_PMSG} = \frac{S}{U_{DC}} = \frac{\sqrt{P^2 + Q^2}}{U_{DC}}. \tag{5}$$

This current is responsible for charging the DC-link capacitors. Hence, if power is accumulated in the DC-link circuit, the voltage is continously increasing. To keep the voltage at a constant level, the grid-side converter needs to deliver power to the grid. The voltage is thus kept at a certain value, and any increase of it due to the power delivered by the PMSG is handled by injecting power (purposely, active power) into the grid.

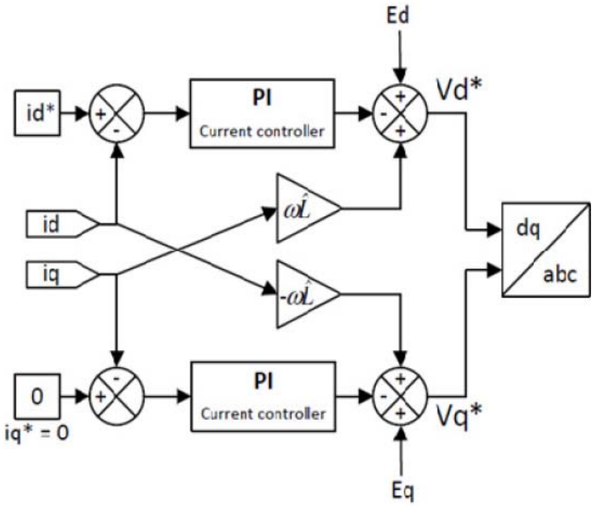

Fig. 2. Vector control scheme of the grid-side power converter.

The model of the DC-link circuit is based on the classical equations of capacitive circuit:

$$\frac{1}{2} C \frac{dU_{DC}^2}{dt} = S_{PMSG} - S_{grid}\,. \tag{6}$$

In order to model the DC-link voltage variation as a function of currents injected from the PMSG side and of those extracted on the grid side, the following equations are used:

$$\begin{aligned}
i_{DC} &= C \frac{dU_{DC}}{dt} + i_{DC\_pmsg} - i_{DC\_grid} \\
i_{DC\_grid} &= \frac{3}{2} \frac{U_{abc\_rms}}{\sqrt{3}} \frac{\sqrt{2}}{U_{DC}} i_{q\_pmsg}\ .
\end{aligned} \tag{7}$$

The i_{DC_grid} current component corresponds to the active power injected into the grid. As it can be seen, the DC-link circuit modeling is based only on the active current component. This is justified by the fact that in the model, no reactive power is delivered to the utility grid.

In the vector control strategy of the grid-side power converter, the phase-locked-loop (PLL) technique is used [6], as shown in Fig. 2. Depending on the considered PLL strategy, either *d*- or *q*-component of the current will be forced to zero for ensuring only active power delivery to the grid.

Fine tuning of the PI regulators with regards to the grid-side filter and the PWM frequency, enable increased performance and safety of the operating system [7], [8].

In Fig. 3, the vector diagram used to build the vector control scheme for the grid-side power converter is represented.

From the control loop, U_{d_grid} and U_{q_grid} voltage components are obtained, and further transformed in *abc* phase-coordinate components by means of Park transformation.

The model of the grid-side power converter is based on breeding a triangular-wave carrier, and comparing it with U_a ,

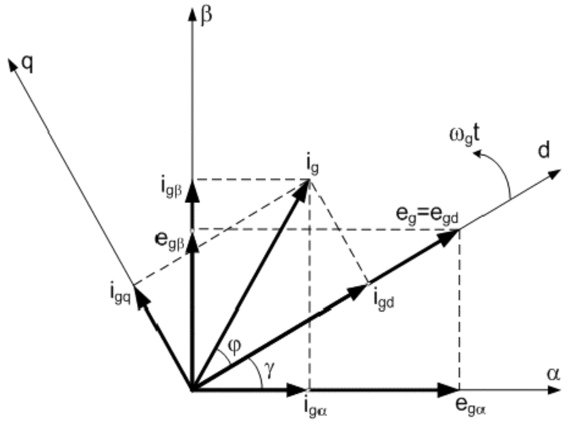

Fig. 3. Vector diagram on the grid-side power converter.

U_b and U_c voltage components. This is actually the PWM procedure that determines the firing instants of the power converter switches, which, in their turn, are simply modeled by multiplying the DC-link voltage by the resulting pulses for eventually obtaining the PWM-controlled voltage.

The LCL-filter serves in order to diminish the high-switching components from the current flowing into the grid. Actually, the LCL-filter components are added in the equations of the utility grid as

$$U_{grid} - U_{conv} = \left(R_c + R_g\right)i + \left(L_c + L_g\right)\frac{di}{dt} + \\ + \frac{1}{C}\int i(t)dt\ , \tag{8}$$

where *c*- and *g*-indexed parameters correspond to the converter side and grid side of the filter, respectively.

The grid is modeled using three sinusoidal signals connected to LCL-filter output, while voltage signals from the power converter are sent to the input of the filter.

III. SIMULATION MODEL

For the simulation program, MATLAB/SIMULINK environment was used to implement the mathematical models of each assembly of the wind energy conversion system. All the models are connected in order to obtain a unitary discrete-time simulation program.

The model of the wind turbine with the MPPT strategy is presented in Fig.4. The outputs are the speed of the turbine and the torque reference for the PMSG.

The control unit of the generator-side converter is shown in Fig. 5. There are two PI regulators for the control of the currents injected in the PMSG by imposing certain levels of voltages, and a third one for the speed controller of the wind turbine, which is built with an anti-windup loop.

The inputs of the MPPT control unit are the imposed wind speed and the actual PMSG speed.

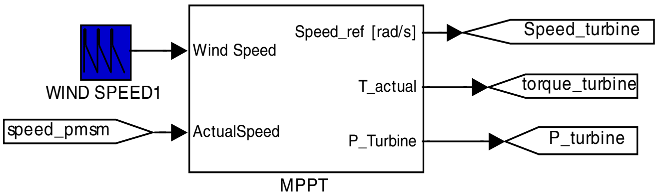

Fig. 4. MPPT control unit.

The main specifications of the considered wind turbine are listed in Table I.

TABLE I
WIND TURBINE MAIN SPECIFICATIONS

Radius	2.26 m
Air density	2.7 kg/m^3
Gear box ratio	3.57
Cp	0.4594
Ct	0.0479

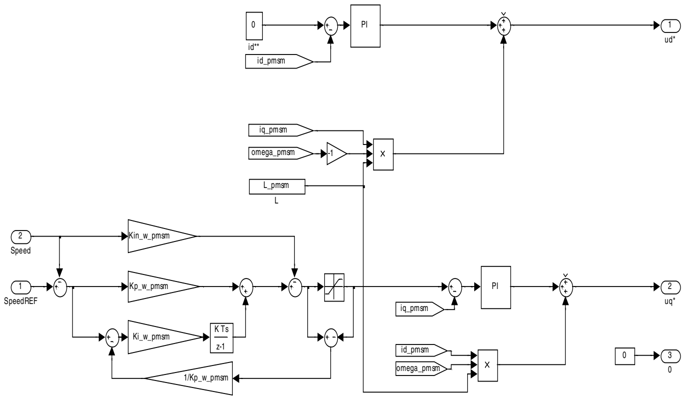

Fig. 5. Control scheme on the generator-side power converter.

In Fig. 6, the PMSG model is detailed, based on the *dq*-coordinate system equations (4). It contains both electrical and mechanical parameters needed for the complete model. In addition, blocks were designed to compute the active and reactive power, in *dq*-components, as well as PMSG torque and speed.

The model of the DC-link circuit is given in Fig. 7, and it is based on equations (7) and (8).

It can be seen that the inputs of the model are the generator-side power converter components and the *d-q* currents for the grid-side powering.

Thus, the current through the DC-link circuit is managed to increase/decrease the voltage on the capacitors. In Fig. 8, the grid-side converter control scheme is presented. Similarly to the control for the PMSG-side converter, there are current controllers, and, instead of the speed controller, there is a voltage controller, which ensures that the voltage on the DC-link circuit will not exceed certain peak values (i.e. 750 V cc).

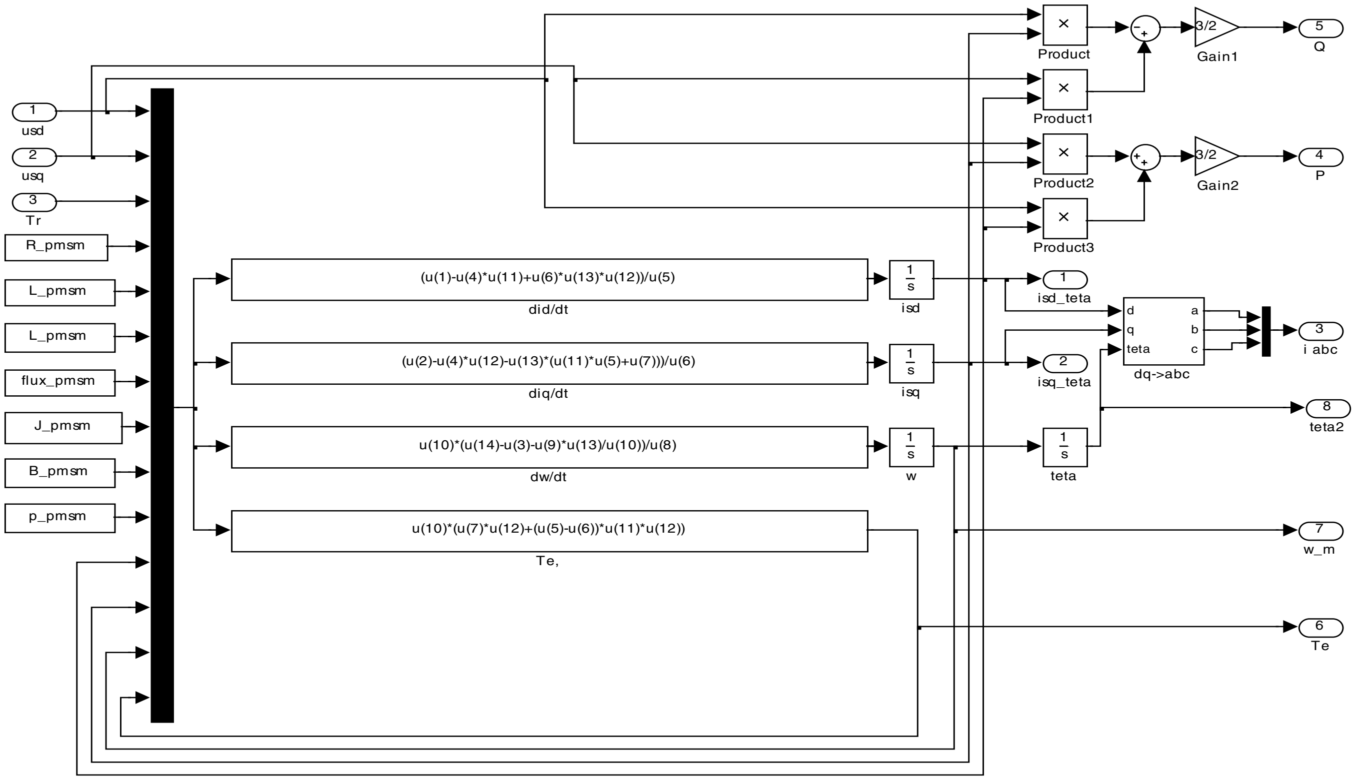

Fig. 6. PMSG simulation model.

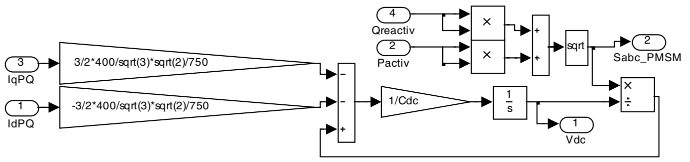

Fig. 7. DC-link simulation model.

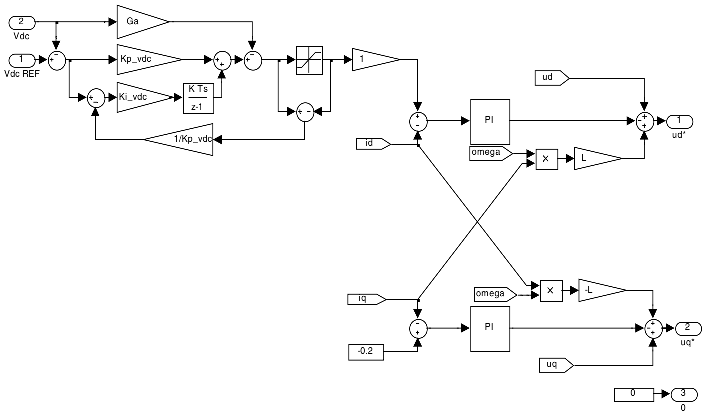

Fig. 8. Grid-side power-converter control scheme.

Control outputs are the *Ud* and *Uq* voltage components, which are further transformed into *abc* signals and sent to the PWM block to determine the firing pulses for the power converter switches.

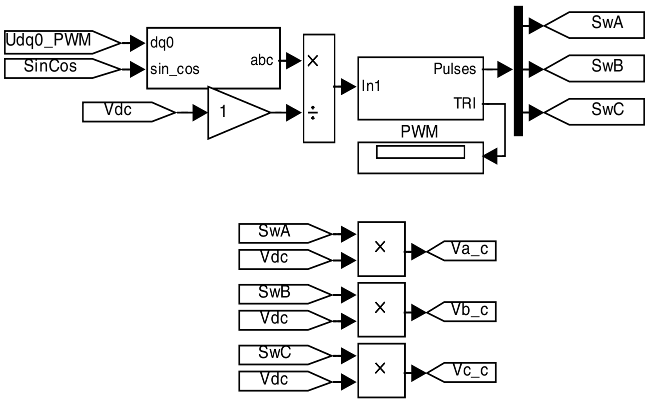

Fig. 9. Grid-side power-converter PWM generation and switched voltages

In Fig. 9, the simulation model of the grid-side inverter is represented with the switched voltages generated by multiplying the switching signals by the DC-link voltage.

The grid connection is accomplished by means of an LCL-filter, whose simulation model is shown in Fig. 10.

Fig. 11 presents the simulation model for the three-phase power grid. The simplest way to create three sources of correctly-shifted AC voltages is to use the Park transformation by imposing the wright pulsation and peak value of the voltage.

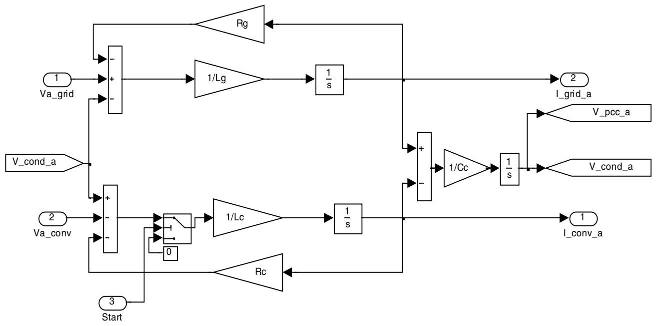

Fig. 10. LCL-filter simulation model.

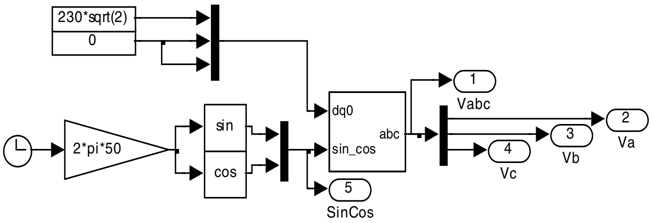

Fig. 11. Simple simulation model for the three-phase power grid.

IV. SIMULATION ANALYSIS RESULTS

In this section, simulation results are provided in order to prove the effectiveness of the program, and to highlight its easy use for wind energy-based electric power generation systems.

In order to have realistic simulations, the wind speed profile depicted in Fig. 12 was used for a registered time of 4.5e5 [s] and imposed to the simulation program.

Considering the MPPT control algorithm, the resulting wind-turbine developed torque is given in Fig. 13. This variation will represent input in the control strategy of the machine side inverter.

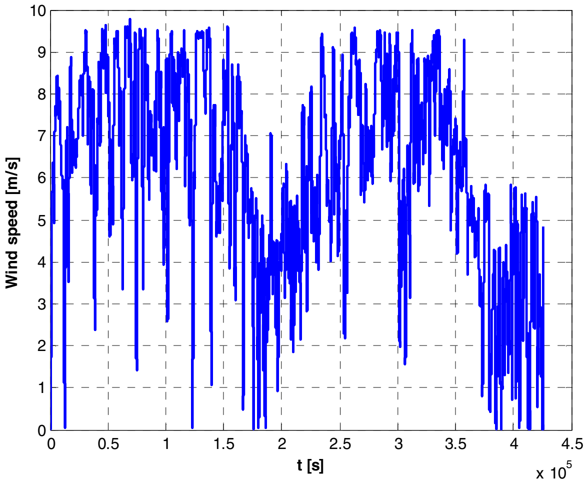

Fig. 12. Imposed wind-speed profile.

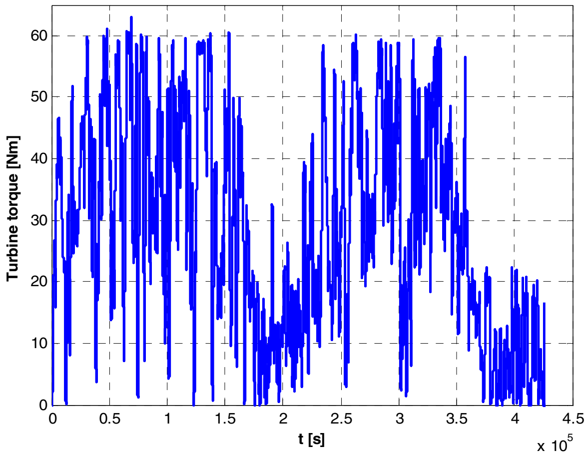

Fig. 13. Wind-turbine developed torque.

Active and reactive powers delivered by the PMSG are shown in Fig 14. It can be seen that

(i) the power of the wind turbine and the active power of the PMSG are very close; the reason for this fact is that the system used for the analysis is ideal;

(ii) there is a small flow of reactive power from the PMSG to the DC-link circuit that can be nullified if additional control loops are added for the PMSG-side power converter.

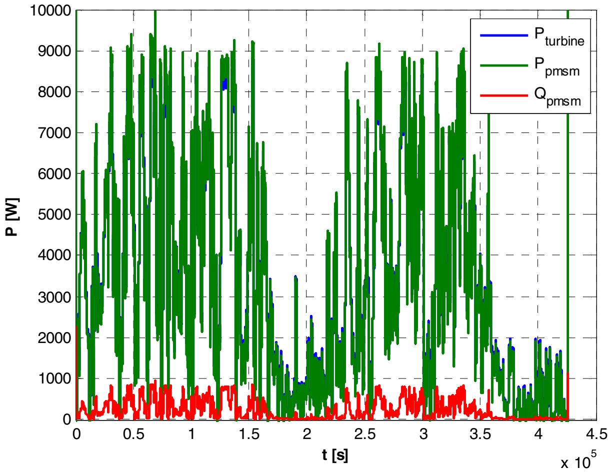

Fig. 14. Wind turbine power and PMSG active and reactive powers.

When power is delivered to the DC-link circuit, there is a tendency of voltage increase due to capacitor charging, but the grid-side inverter intervenes in order to diminish the voltage increase, and delivers active power to the utility grid to discharge the overload of the DC-link circuit.

As revealed by Fig. 15, there is only small variation of the DC-link voltage due to the power flow, meaning that the grid-side power converter is adequately controlled. The DC-link voltage is fixed at 750 V to make sure that there is no power transfer from the grid through the reverse diodes of the grid-side inverter.

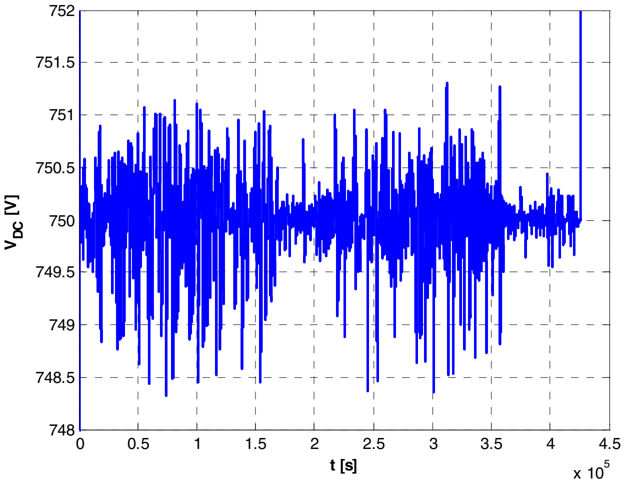

Fig. 15. DC-link voltage during power flow.

As clearly shown in Fig. 16, the reactive power injected in the grid is almost null, while the active power delivered to the utility grid follows closely the wind speed variation.

These results prove that the simulation program operates properly, fulfilling the imposed requirements, i.e. extracting maximum power from the wind turbine and delivering only active power to the utility grid.

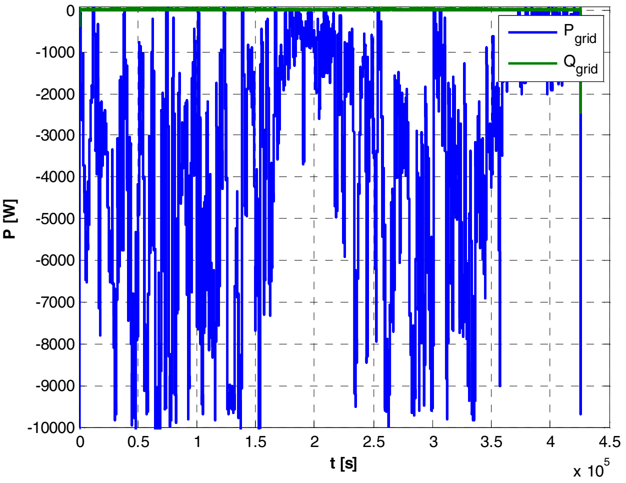

Fig. 16. Active and reactive powers delivered to the utility grid.

V. CONCLUSIONS

The paper has proposed and developed a complete simulation program, built in MATLAB/SIMULINK environment, for the analysis of a wind energy conversion system, consisting of wind turbine with MPPT strategy, vector-controlled PMSG, back-to-back converters with their control, grid-side LCL filter and utility grid.

Details of mathematical and simulation models for all these components have been developed, providing simulation tools for performance analysis and control design of any kind of installed wind energy-based electric power generation systems.

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