

Simulation analysis of a grid-connected wind energy conversion system

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Abstract—This paper describes a complex simulation program built in MATLAB/Simulink environment for the analysis of a grid-connected wind energy conversion system. Hence, it contains the simulation models based on electrical equations of the wind turbine with maximum-power-point-tracking (MPPT) control procedure, the permanent-magnet synchronous wind generator, the back-to-back converter, the DC-link circuit and the utility grid. Simulation results are provided in order to prove the effectiveness of the developed simulation program, and to highlight its easy use for wind energy-based electric power generation units.

Index Terms—wind energy conversion system, simulation models, analysis, control

I. INTRODUCTION

The wind-energy conversion task is nowadays one of the main research field in the electric power distributed production. Small- and high-scale power units are already implemented in the global system proving the benefits of non-polluting solution for generating electric energy. Many research laboratories all over the world are focused on creating solutions for developing optimized systems for wind power conversion, based on many types of turbines, electric generators and power electronics for the grid connection. All the studies start at the lowest level of development, at the simulation phase. Taking advantage of the simulations, several control procedures can be implemented, e.g. for maximum-power-point-tracking (MPPT) control, to increase as much as possible the efficiency of the overall system [1], [2].

There are many papers in the literature treating the problem of simulations in wind energy conversion systems, but there are few dealing with the entire system, composed of the wind turbine with the MPPT control procedure, the electric generator, the back-to-back converters delivering active power to the utility grid.

This paper is intended to contribute to the actual study in the field of simulation software for grid-connected wind energy conversion systems. Hence, for each component of the system, a mathematical model based on electrical equations is developed. In the next step, these mathematical models are coupled together in order to describe and analyze the behavior of the entire system. For the sake of simplicity, a MATLAB/ Simulink program is created, allowing more transparent analysis and easier post-processing of results.

For this simulation analysis, a classical wind turbine is considered, coupled with a permanent-magnet synchronous generator (PMSG). To extract maximum power from the wind turbine, the MPPT control strategy was implemented. The generator is connected to the DC-link circuit via a vector-controlled rectifier. The generated power is delivered into the common DC-link circuit, which is connected to the utility grid through an inverter, controlled to inject only active power into the grid. LCL filter is used to decrease the harmonics injected by the inverter into the grid.

The remainder of this paper is organized as follows. The mathematical models for components of the wind energy conversion system are developed in Section II of the paper. Then, in Section III, the Simulink models are presented detailing the implementation strategies and specific considerations for each sub-program. Simulation results are provided in section IV of the paper, proving the good behavior of the overall system and the usefulness of such simulation programs when approaching studies of wind turbine-based energy generation units.

II. MATHEMATICAL MODELS

The MPPT model considers a wind turbine with the mechanical and geometrical parameters listed in Table I. The maximum power that can be extracted from the turbine is given by

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

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

$$TSR = \frac{r \omega_m}{v_w}. \quad (2)$$

For the considered wind turbine, the functional dependence $C_p(TSR)$ is given in Fig. 1. A maximum performance of the wind turbine can be obtained at a tip-speed ratio of about 10. Using the MPPT control algorithm, the turbine can be held at an operational point where the extracted power is always maximum. This can be obtained using vector control for the PMSG, imposing a certain torque for the machine in order to

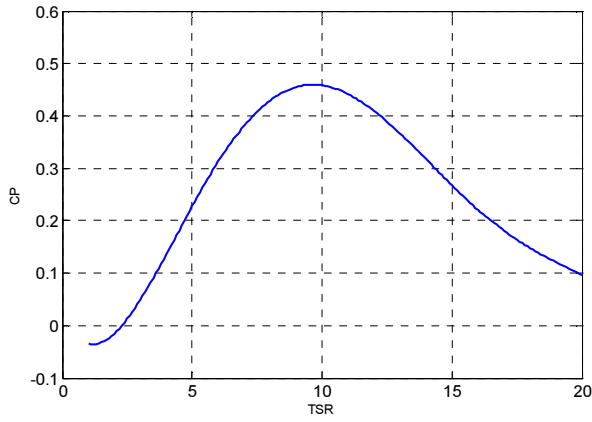


Fig. 1. Functional dependence $C_p(TSR)$.

set the turbine at the maximum-power-point operation, i.e.

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

The chosen PMSG is modeled based on the classical d - q equations for such machines:

$$u_{ds} = R_s i_{ds} + L_s \frac{di_{ds}}{dt} - \omega_r L_s i_{qs}$$

$$u_{qs} = R_s i_{qs} + L_s \frac{di_{qs}}{dt} - \omega_r (L_s i_{ds} + \lambda_{pm})$$

$$T_e = \frac{3}{2} \frac{P}{2} (\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds}) \quad (4)$$

$$P = \frac{3}{2} (u_{ds} i_{qs} + u_{qs} i_{ds})$$

$$Q = \frac{3}{2} (u_{qs} i_{ds} - u_{ds} i_{qs}).$$

As the output of the control loop for the vector-controlled PMSG is represented by the u_d and u_q voltages, these are directly imposed for the PMSG, thus ignoring the switching influence on the current waveform. The reason is that the high-frequency switching influence has to be treated mainly on the grid-side converter not on the generator-side one.

The power injected from the PMSG to the DC-link circuit is calculated based on the apparent power S :

$$S = \sqrt{P^2 + Q^2}$$

$$i_{DC_pmsg} = \frac{S}{U_{DC}}. \quad (5)$$

The current that charges the DC-link capacitors is determined as the ratio of the apparent power to the DC-link actual voltage. In order to keep the DC-link voltage at a certain imposed value, the grid-side converter is controlled to deliver active power to the grid by discharging the DC-link circuit.

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

$$\frac{1}{2} C \frac{dU_{DC}^2}{dt} = S_{PMSG} - S_{grid}. \quad (6)$$

In order to model the DC-link voltage variation as a function of currents injected from the machine side and of those extracted on the grid side, the mathematical model is based on the following equations:

$$i_{DC} = C \frac{dU_{DC}}{dt} + i_{DC_pmsg} - i_{DC_grid} \quad (7)$$

$$i_{DC_grid} = \frac{3}{2} \frac{U_{abc_rms}}{\sqrt{3}} \frac{\sqrt{2}}{U_{DC}} i_{q_pmsg}.$$

The i_{DC_grid} current component corresponds to the active power injected into the grid. The modeling of the DC-link circuit using only this active-power current component is justified by the fact that no reactive power is delivered to the grid.

As mentioned earlier, the grid-side inverter is controlled by vector control strategy to deliver active power to the grid by keeping constant the DC-link voltage.

To synchronize the inverter with the grid, Phase-Locked Loop (PLL) technique is used [6].

In Fig. 2, the vector control classical scheme for the grid-side inverter is shown. Depending on the PLL technique used, either the d - or the q -component of the control will be imposed to zero in order to ensure only active power delivery to the grid.

Correct tuning of PI regulators according to the grid-side filter and inverter switching frequency will ensure that the system operates well and fulfill its requirements [7], [8].

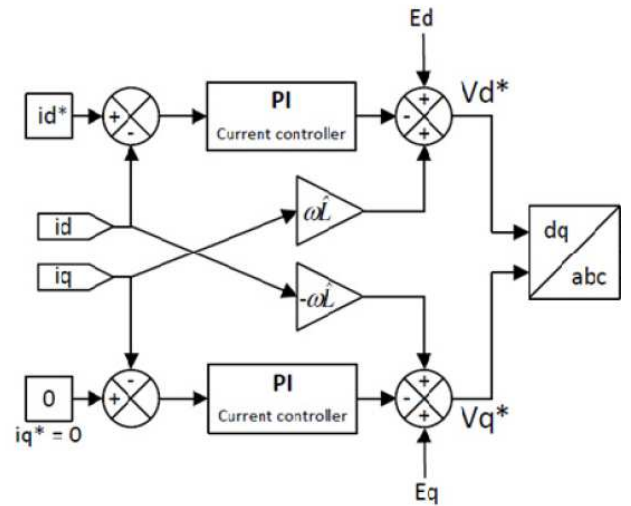


Fig. 2. Vector control scheme of the grid-side inverter.

In Fig. 3, the grid vector diagram is emphasized for the considered vector control scheme of the grid-side inverter.

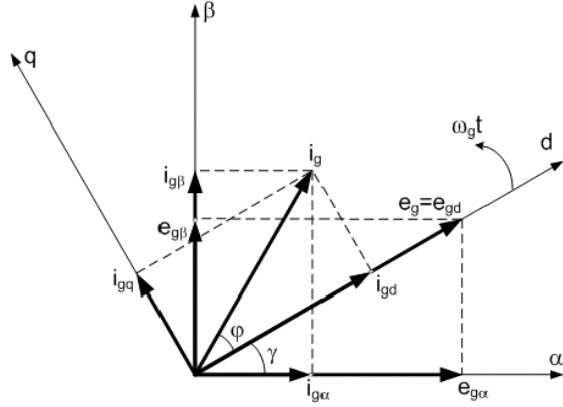


Fig. 3. Grid vector diagram for the grid-side inverter vector control scheme.

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

The model of the grid-side inverter is based on creating a triangular carrier, and comparing it with U_a , U_b , and U_c voltage components. This is actually the pulse-width modulation (PWM) procedure that determines the firing instants of the inverter power switches. These are simply modeled by multiplying the DC-link voltage by the resulting pulses, thus obtaining a PWM-controlled voltage.

The inverter is connected to the utility grid via an LCL filter that performs the filtering of current harmonics due to the inverter switching process.

For each phase, the model of the LCL filter is based on the following equation:

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

where the parameters with c and g index, respectively, correspond to the converter side and grid side of the filter.

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

III. SIMULATION PROGRAM

The simulation program is designed in MATLAB/Simulink. It is based on the electrical equations of each component of the wind energy conversion system, which are connected together to obtain a unitary discrete-time simulation software.

The model of the turbine with the MPPT control procedure (Fig. 4) is implemented in order to obtain the reference torque for the PMSG control.

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

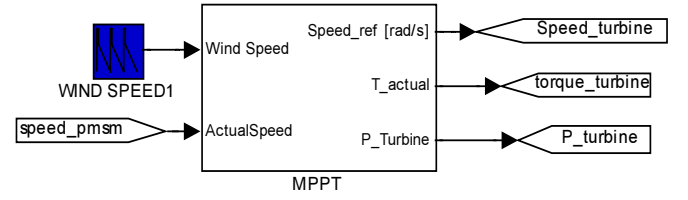


Fig. 4. MPPT control unit.

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
C _p	0.4594
C _t	0.0479

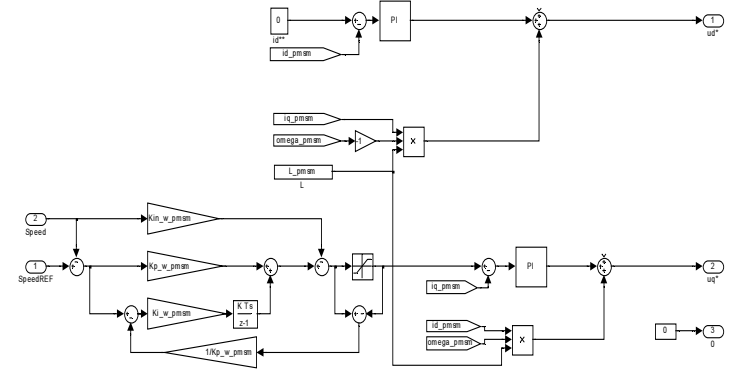


Fig. 5. Generator-side converter control scheme.

The generator-side converter control scheme is shown in Fig. 5. Correct tuning of PI regulators according to the grid-side filter and the inverter switching frequency ensures the correct operation of the overall system and the fulfillment of its requirements.

In Fig. 6, the PMSG model is depicted. It is based on the d - q equations, having as inputs the electrical and mechanical parameters of the machine, and as outputs the active and reactive power components, the d - q currents, as well as the computed torque and speed.

In Fig. 7, the Simulink model of the DC-link circuit, based on equations (7) and (8) is presented. It can be seen that the inputs of the model are the generator-side electric power 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.

The grid-side converter control scheme is shown in Fig 8. It contains a regulation part in order to keep constant the DC-link voltage by injecting currents into the grid for only active power delivering. Control outputs are the U_d and U_q voltage components, which are further transformed into abc signals

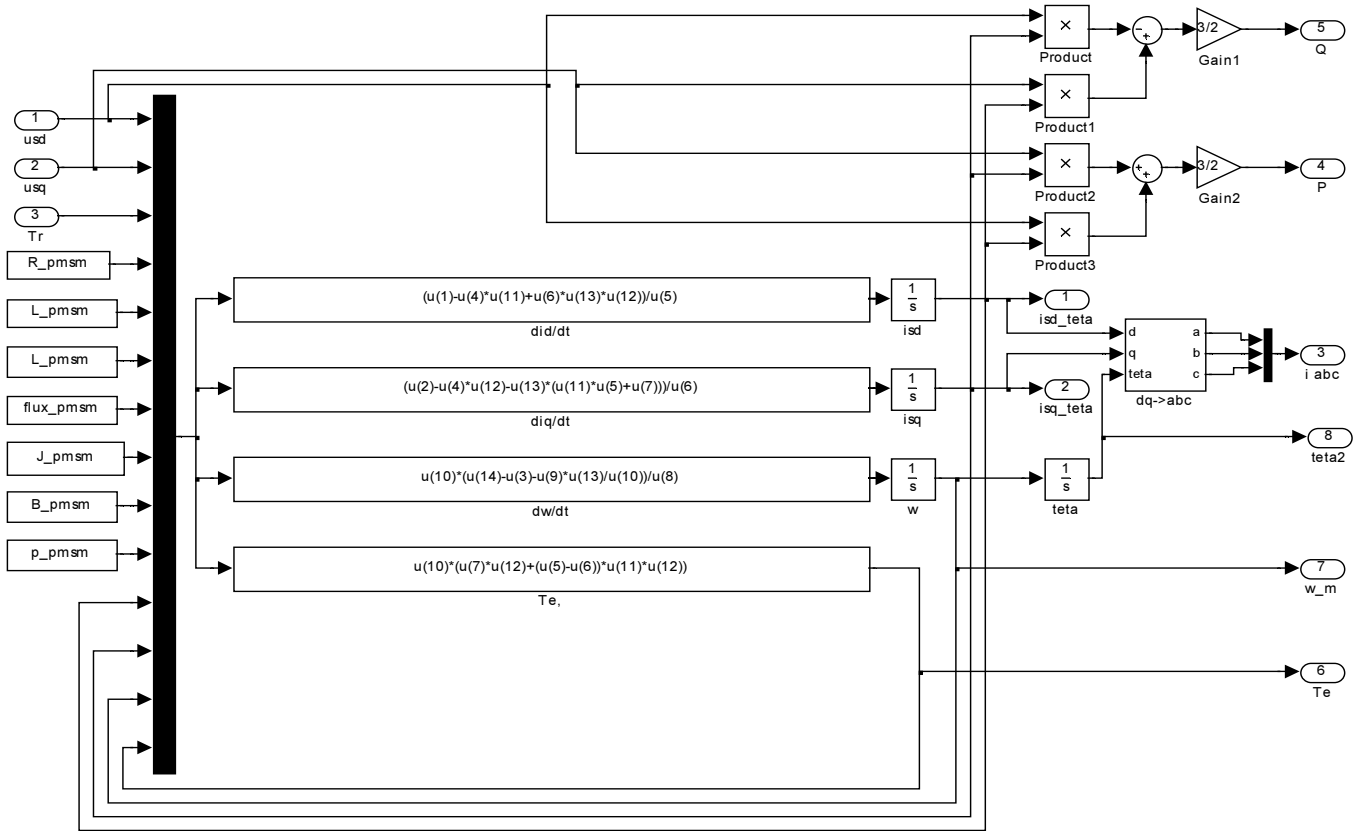


Fig. 6. Vector-controlled PMSG simulation model.

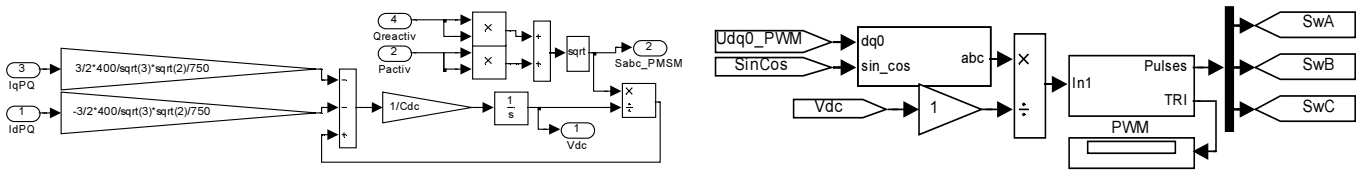


Fig. 7. DC-link circuit simulation model.

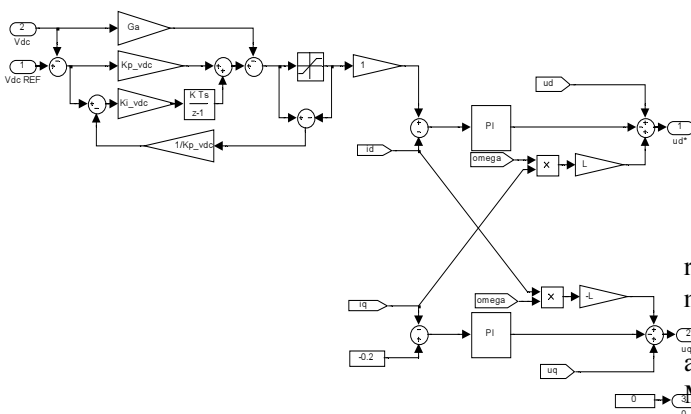


Fig. 8. Vector control scheme for the grid-side converter.

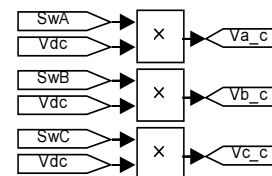


Fig. 9. Grid-side inverter PWM generation and switched voltages

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 connection to the grid is accomplished by means of an LCL filter. The simulation model implemented in MATLAB/Simulink environment is shown in Fig. 10.

In Fig. 11, the simulation model for the three-phase grid is presented. 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.

and sent to the PWM block to determine the firing pulses for the inverter power switches.

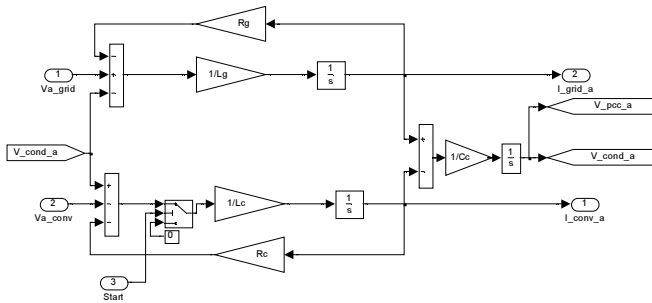


Fig. 10. LCL-filter simulation model for connecting the inverter to the grid.

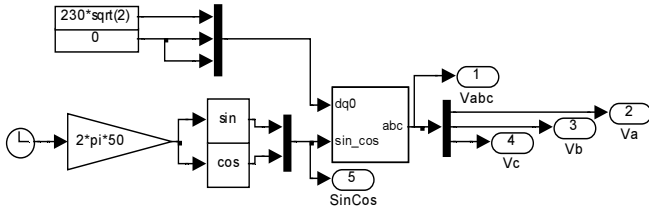


Fig. 11. Simple simulation model for the three-phase grid

IV. SIMULATIONS 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 units.

For the sake of simulation, a linear wind profile (Fig. 12) is imposed, in order to easily observe the power generated by the wind turbine and by the electric generator (PMSG), as well as the power delivered to the utility grid.

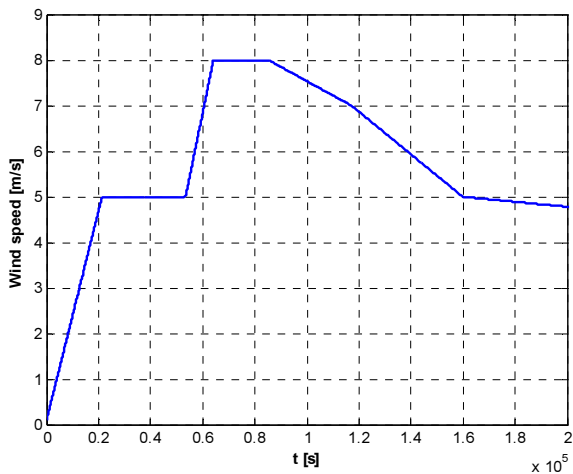


Fig. 12. Imposed wind-speed profile.

Considering the MPPT control algorithm, the resulting wind-turbine developed torque is given in Fig. 13. This torque has to be imposed in the vector-control loop for the wind generator (PMSG).

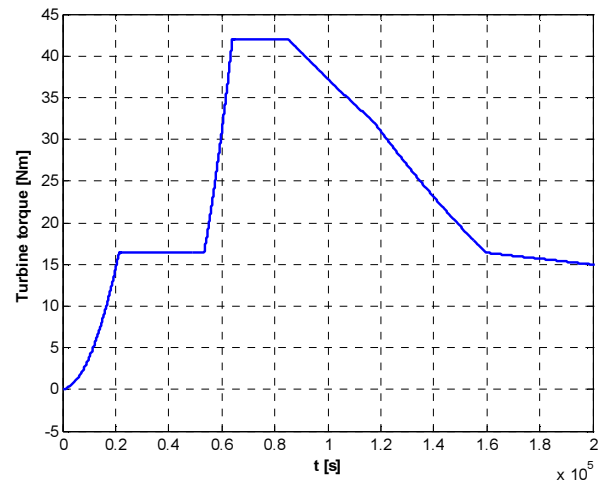


Fig. 13. Resulting wind-turbine developed torque.

The active and reactive electric powers generated 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 quite close; this is due to the fact that the analyzed wind energy conversion system is an ideal one;
- (ii) small amount of reactive power is delivered by the PMSG to the DC-link circuit; it can be reduced to zero, if a power control loop is added or if there is a marked difference between the PMSG $d-q$ voltage and current components.

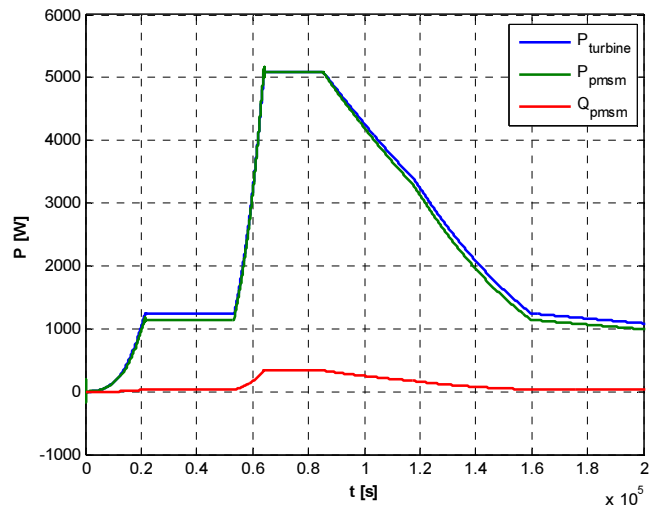


Fig. 14. Wind turbine power and PMSG active and reactive powers.

The power delivered to the DC-link circuit creates an increase of the voltage level. The grid-side converter control ensures that this voltage rise is diminished by discharging the DC-link capacitors into the utility grid.

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 converter is well controlled. The DC-bus 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.

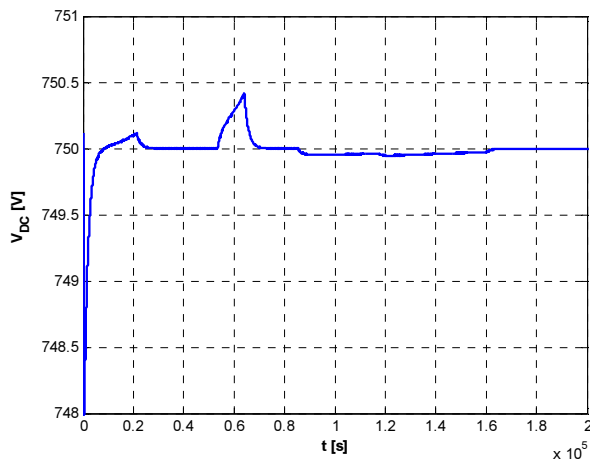


Fig. 15. DC-link voltage during power flow.

The currents through the LCL filter connected to the grid are shown in Fig. 16. It can be seen that the q -component of the current is null, i.e. no reactive power exchange with the utility grid, while the d -component varies in order to ensure active power delivery to the grid. The current is negative as the power flow direction is from the inverter via the filter to the grid.

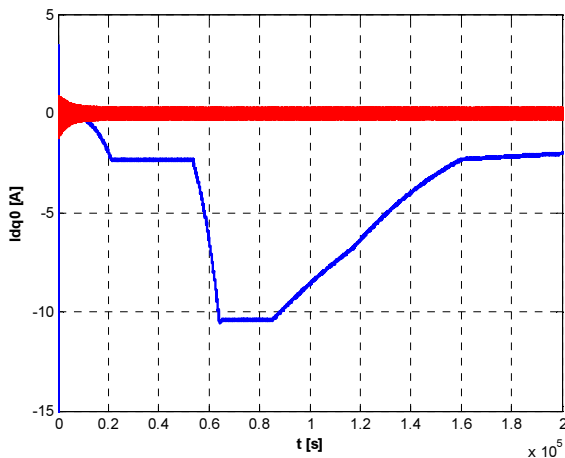


Fig. 16. Current d - q components through the LCL filter connected to the utility grid.

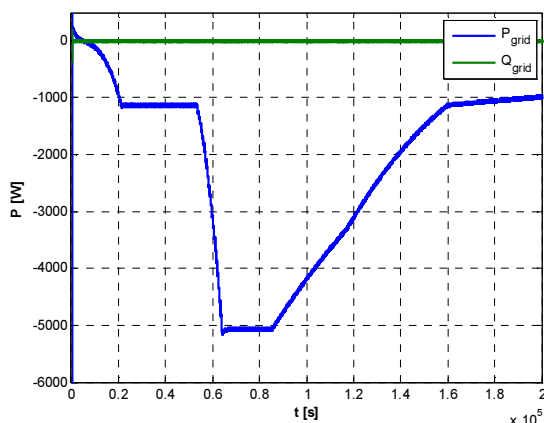


Fig. 17. Active and reactive electric powers delivered to the grid.

As clearly shown in Fig. 17, the reactive electric power injected in the grid is null, while the active electric power delivered to the grid follows closely the wind speed variation.

Overall, the simulation results prove that the simulation program operates well, fulfilling the imposed requirements, i.e. to extract maximum power from the wind turbine and, at the same time, to send only active electric power to the grid.

V. CONCLUSION

The present 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 given, providing to future users a simulation tool for performance analysis and control design of any kind of installed wind energy-based electric power generation units.

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