Investigation Bond Graph to control a variable speed wind turbine with Permanent Magnet Synchronous Generator

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Abstract—**In this paper a full detailed bond graph modeling and a new control scheme of a three phase grid connected wind energy conversion system (WECS) is described. This WECS uses a Permanent magnet synchronous generator and the power conditioning system is composed of a back-back (AC-DC-AC) power converter. The bond graph control system is used for identifying and extracting the maximum power from the wind energy system and transferring this power to utility. A three-level voltage source inverter (VSI) is used as interface with the AC power grid.**

Keywords—**Bond Graph, DC-DC Converter, Maximum Power Point Tracking, Permanent Magnet Synchronous Generator, Wind Energy Conversion Systems.**

I. INTRODUCTION

As concerns about climate change, rising fossil fuel prices and energy security increase, there is growing interest around the world in renewable energy resources. Since most renewable energy sources are intermittent in nature, it is a challenging task to integrate a significant portion of renewable energy resources into the power grid infrastructure. Traditional electricity grid was designed to transmit and distribute electricity generated by large conventional power plants. The electricity flow mainly takes place in one direction from the centralized plants to consumers. In contrast to large power plants, renewable energy plants have less capacity, and are installed in a more distributed manner at different locations.

The wind energy industry has developed rapidly through the last 20-30 years. The factories have developed from small workshops to mature industry, and technically the wind turbines have increased in size, the costs have been reduced, and the controllability developed. This places modern wind energy as a serious and competitive alternative to other energy sources [1].

The development has been concentrated on wind turbines for electrical power production, i.e. grid connected wind turbines. Grid connected wind turbines are a part of a power system, with which they interact. On one hand, the power system and its quality has an influence on the wind turbines

performance, lifetime and safety, and on the other hand, the quality and the reliability of the wind turbine power will influence the power system quality, stability and reliability [2]. Therefore, the integration of wind power into the power systems has become an important issue in development and research of wind power.

The scope of the present paper is the modelling and the control of wind turbine generation systems by bond graph approach for integration in power systems studies. The modelling of the wind phenomenon, the turbine mechanical system and the electrical machine, along with the corresponding converter and electrical grid is described. This paper presents an intelligent control method for the maximum power point tracking (MPPT).

II. LITERATURE REVIEW

The problem of the interaction between wind turbines and the electric grid has been treated by many authors. The reasons for predicting the power output from a wind turbine are various: the impact on the grid, the design of the wind turbine controller and stating the power quality standards are some typical examples.

Papers [3], [4] and [5] deal with predicting the power quality impact on the connected grid. Wind turbine models of different complexity were incorporated into a grid simulation program and conclusions regarding the requirements on the model complexity were drawn. These models incorporated the aerodynamic part of different complexities. The driving torque on the generator shaft was either calculated using a professional software package or, on the contrary, significantly simplified to a very rough approximation of reality.

Leithead has presented in [6], [7] and [8] a detailed description of the wind turbine mechanical parts. The structural dynamics of the whole drive train was thoroughly described and analyzed. The aerodynamic interaction between free wind and the turbine itself was incorporated into an overall model in the form of various filters applied to the free wind data.

[9] has also adopted the filter approach, mentioned above, and developed a model to be used, partly, in wind turbine control design and, partly, in power quality impact prediction.

The work presented by [10] has described a detailed analysis of induction machine dynamics. The induction machine models of different orders were presented and compared with laboratory measurements. The same author has presented in [11] and [12] measurements and analysis of the power quality impact by stall-regulated, fixed-speed wind turbines.

[13] and [14] have presented measurements of wind turbines' electrical performance. An analysis of the measured quantities was presented and conclusions regarding the power quality requirements for wind turbine installations were drawn.

III. PROCESS DESCRIPTION

The selected wind generator employs a permanent magnet synchronous generator directly coupled to the wind turbine and connected to the electric grid through a power conditioning system (PCS) [15]. The stator windings of the PMSG are straightforwardly connected to the PCS composed of a three-phase rectifier bridge, a DC-DC converter and a DC-AC switching power inverter, as shown in Fig. 1.
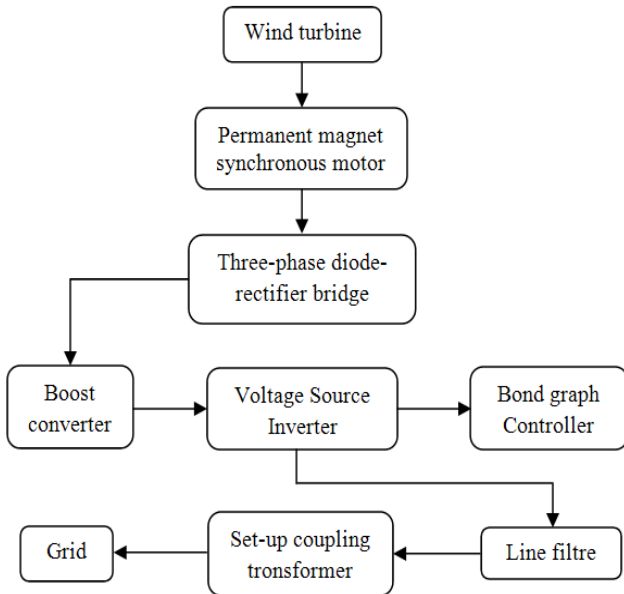

Fig. 1 General scheme of the proposed WECS

IV. BOND GRAPH APPROACH

Bond graph is an explicit graphical tool for capturing the structures among the physical systems and representing them as an energy network based on the exchange of power [16]. Others [17], [18] have extended the bond graph concept to represent Phenomena such as chemical kinetics and to extract causal models and control structures from the bond graph networks. Bond graph, a graphical modeling language, provides a model formalism that decomposes the system into subsystems that map to the physical connections. The resulting subsystems are essentially physical fields including

mechanics, electronics, hydraulics, and chemistry. The time granularity for these domains is usually distinct.

One of the advantages of bond graph method is that models of various systems belonging to different engineering domains can be expressed using a set of only nine elements: inertial elements (I), capacitive elements (C), resistive elements (R), effort sources (Se) and flow sources (Sf), transformer elements (TF), gyrator elements (GY), 0–junctions (J0) and 1–junctions (J1). I, C and R elements are passive elements because they convert the supplied energy into stored or dissipated energy. Se and Sf elements are active elements because they supply power to the system and TF, GY, 0 and 1 junctions are junction elements that serve to connect I, C, R, Se and Sf, and constitute the junction structure of the bond graph model.

A bond graph consists of subsystems linked to gather by lines representing power bonds. Each process is described by a pair of variables, effort e and flow f. Besides the effort and flow variables, two other types of variables are very important in describing dynamic systems; these variables, sometimes called energy variables, are the generalized momentum p as time integral of effort and the generalized displacement q as time integral of flow.

V. BOND GRAPH MODELLING

A. Variable-speed wind turbines

Wind energy has matured to a level of development where it is ready to become a generally accepted utility generation technology. Wind-turbine technology has under gone a dramatic transformation during the last 15 years, developing from a fringe science in the 1970s to the wind turbine of the 2000s using the latest in power electronics, aerodynamics, and mechanical drive train designs [19], [20]. In the last five years, the world wind-turbine market has been growing at over 30% a year, and wind power is playing an increasingly important role in electricity generation, especially in countries such as Germany and Spain. The legislation in both countries favors the continuing growth of installed capacity.

Various models of wind turbines have been developed. They have different purposes and, therefore, treat different features of the wind turbine system and they span, in fact, all the aspects relevant to such a device.

Wind turbines convert the kinetic energy present in the wind into mechanical energy by means of producing torque. Since the energy contained by the wind is in the form of kinetic energy, its magnitude depends on the air density and the wind velocity. The wind power developed by the turbine is given by the equation (1) [21], [22]:

$$P = \frac{1}{2} C_P \rho A V^3 \qquad (1)$$

Where C_P is the power coefficient, ρ is the air density in kg/m^3, A is the area of the turbine blades in m^2 and V is the wind velocity in m/sec. The power coefficient C_P gives the fraction of the kinetic energy that is converted into mechanical energy by the wind turbine. It is a function of the tip speed ratio λ and depends on the blade pitch angle for pitch-

controlled turbines. The tip speed ratio may be defined as the ratio of turbine blade linear speed and the wind speed

$$\lambda = \frac{R\omega}{V} \qquad (2)$$

Substituting (2) in (1), we have:

$$P = \frac{1}{2}C_P(\lambda)\rho A \left(\frac{R}{\lambda}\right)^3 \omega^3 \qquad (3)$$

The output torque of the wind turbine $T_{turbine}$ is calculated by the following equation (4).

$$T_{turbine} = \frac{1}{2}\rho A C_P V / \lambda \qquad (4)$$

Where R is the radius of the wind turbine rotor (m) there is a value of the tip speed ratio at which the power coefficient is maximum. Variable speed turbines can be made to capture this maximum energy in the wind by operating them at a blade speed that gives the optimum tip speed ratio. This may be done by changing the speed of the turbine in proportion to the change in wind speed.
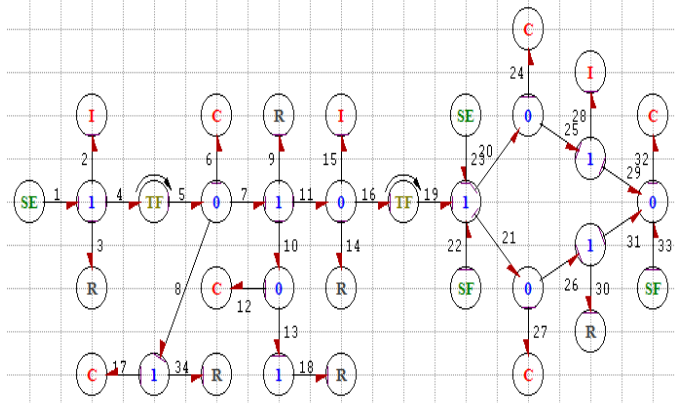
Fig. 2 Bond graph model of Variable-speed wind turbines

Figure (2) shows the bond graph model of the wind turbine and figure (3) shows how variable speed operation will allow a wind turbine to capture more energy from the wind.
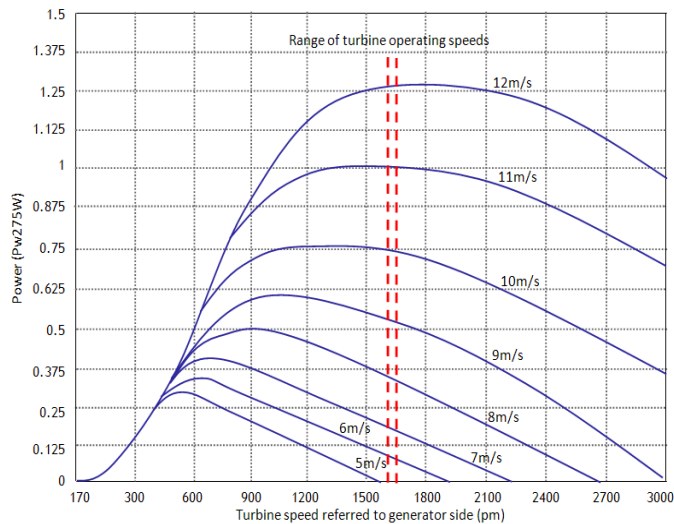

Fig. 3 Wind turbine characteristics

As one can see, the maximum power follows a cubic relationship. For variable speed generation, an induction generator is considered attractive due to its flexible rotor speed characteristic in contrast to the constant speed characteristic of synchronous generator. The bond graph model of wind turbine is shown in the following scheme.

B. Permanent magnet synchronous machine

To model the dynamical behavior of the permanent magnet synchronous machine, we will assume again the stator windings to be placed sinosuidally and symmetrical and the magnetical saturation effects and the capacitance of all the windings neglectable.

Taking as positive the currents flowing towards the machine, the relations between the voltages on the machine windings and the currents and its first derivatives can be written as [23]:

$$\upsilon_s^{abc} = r_s i_s^{abc} + \frac{\partial}{\partial t}\lambda_s^{abc} \qquad (5)$$

The following figure (Fig. 4) represents bond graph model of a permanent magnet synchronous generator by presenting some parameters held in account.

Rotor speed and the moment of inertia is modeled by I, resistance stator, rotor, frictions are modeled by R, the condensers, the mechanical structures are modeled by C, electromechanical transformation modeled by a gyrator GY and the electric source by Se.
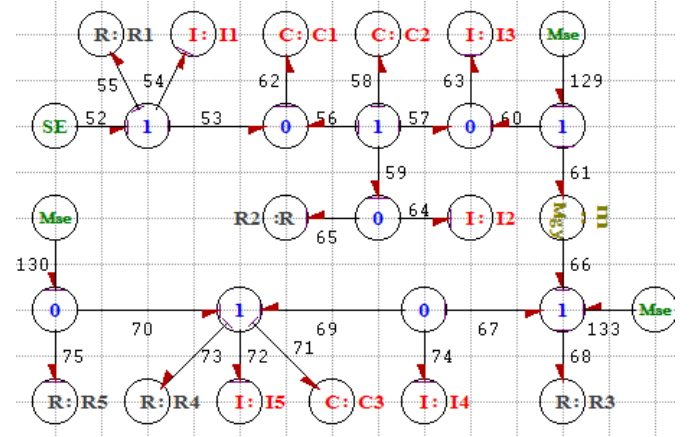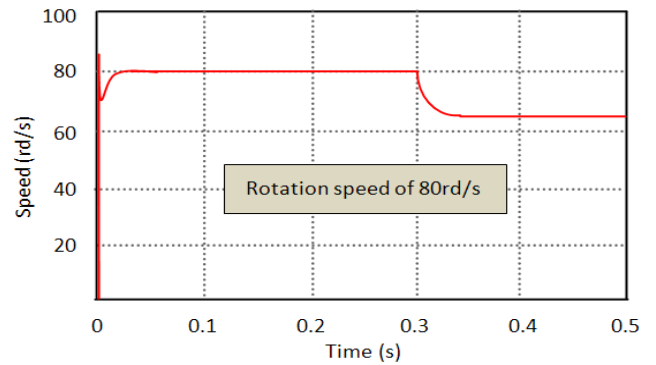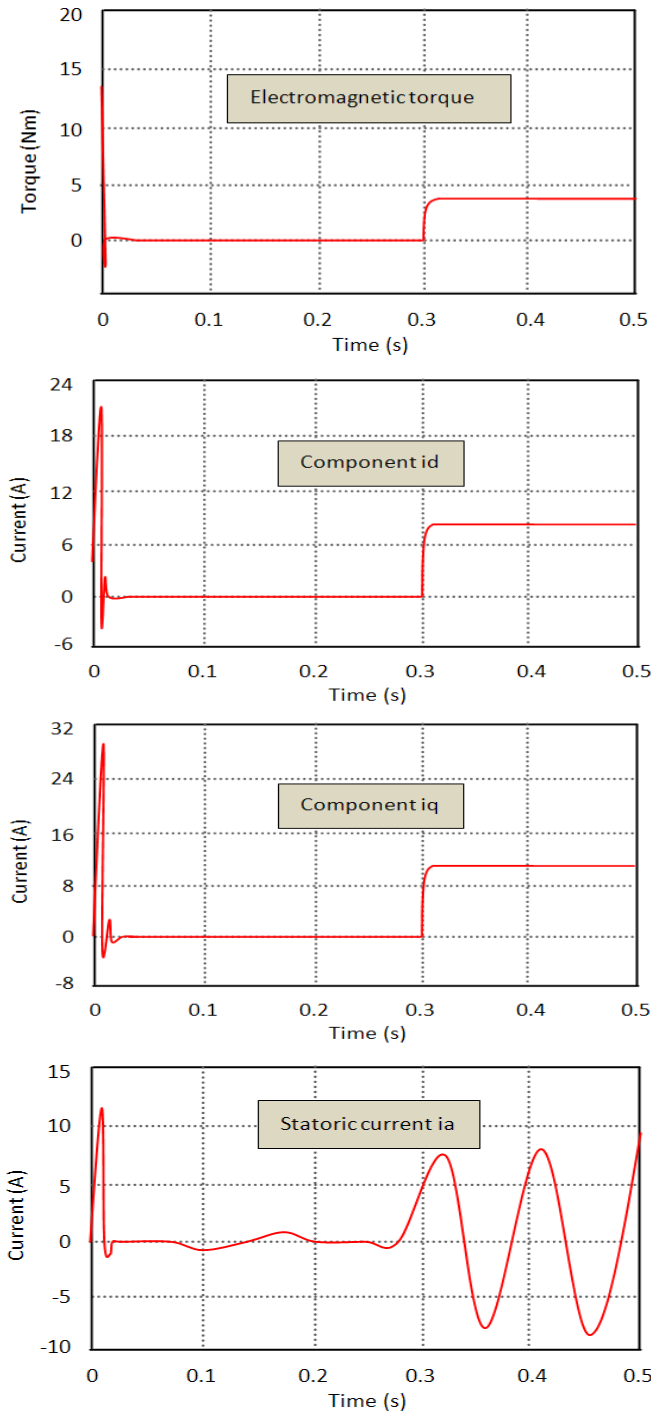

Fig. 4 Bond graph model of PMSG

Fig. 5 Simulation results of the synchronous permanent magnet machine model with the application of a load of 5 N.m to t=0.3 S in open loop.

The curves of the figure (5) represent the simulation results of the synchronous permanent magnet machine model.

During starting, a strong call of current appears and which is necessary to develop a couple for the machine and thus a rotational movement on its tree. This couple thus reaches a peak then is stabilized with a practically null value in steady operation with vacuum.

It should be noted according to these results, that the introduction of load couple causes a reduction number of revolutions

These results shows well the strong existing coupling between these various variables indicating the nonlinear character of the machine.

C. Power conditioning system

The most common converter topology used in variable speed wind turbines is the forced commutation voltage source back-to-back converter with insulated-gate bipolar transistors (IGBT). The structure of this type of converter is shown in figure (6).
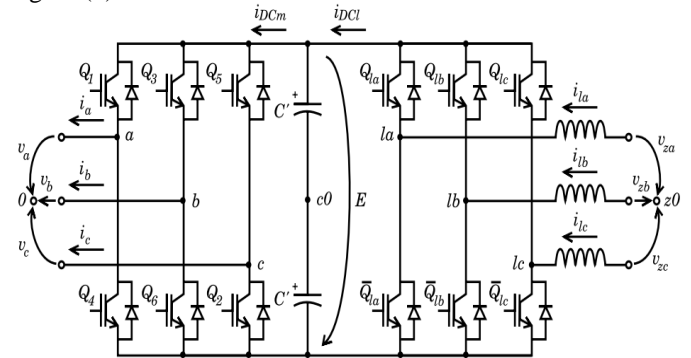

Fig. 6 The IGBT voltage source back-to-back converter

The AC side on the left, which we will call the machine side, is connected to the stator of the PMSG while the right AC side, grid side from now on, is connected to the wind turbine transformer.
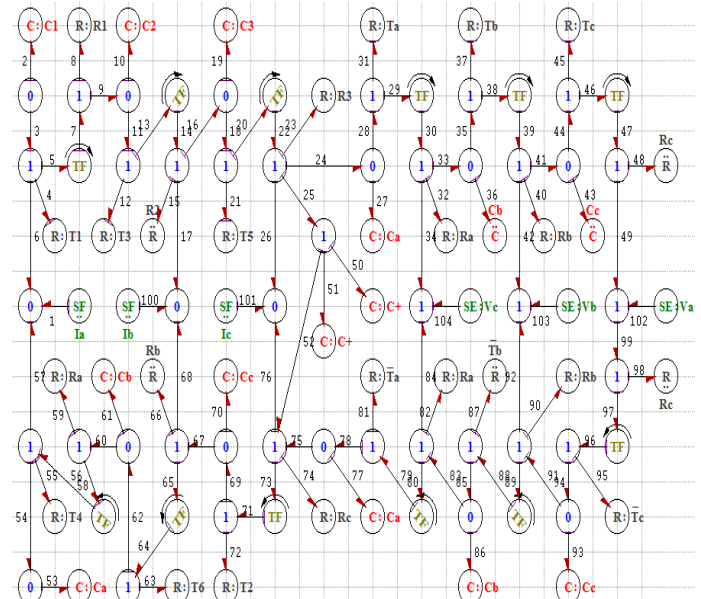

Fig. 7 The bond graph model of IGBT voltage source back-to-back converter

VI. CONTROL STRATEGY

D. MPPT Control Strategy

The characteristic of the optimal power of a wind is strongly non linear and in the shape of bell. For every speed of

wind, the system must find the maximal power what is equivalent in search of the optimal rotational speed.

An ideal functioning of the wind system requires a perfect follow-up of this curve. To approach of this goal, a specific control known by the terminology: Maximum Power Point Tracking (MPPT) must be used.

The strategy of this control consists in controlling electromagnetic torque in order to adjust the mechanical speed in order to maximize the generated electric power. So that the extracted power is maximal, we associate to the parameter λ its optimal value λ_{opt} corresponds to the maximum of power coefficient $C_{P_{max}}$.

The bond graph control scheme (BG-MPPT) for the three-phase grid-connected wind energy conversion system is depicted in figure (8).
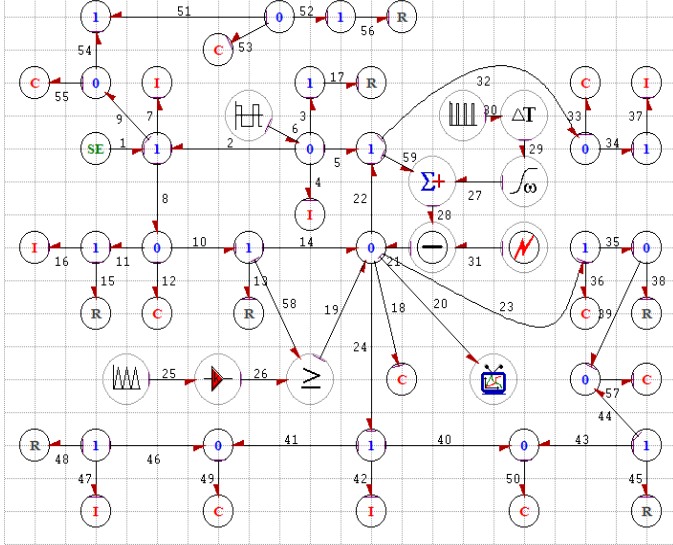
Fig. 8 The bond graph MPPT control of the global system

VII.   SIMULATION RESULTS

In order to investigate the effectiveness of the proposed models and bond graph control algorithms of the three-phase grid-connected WECS, time-discrete dynamic simulations were implemented using BondPad of Symbols environment. The wind speed varies in steps every 1 sec as described, producing proportional changes in the maximum power drawn from the WECS with a settling time of almost 0.4s.

Figure (10) shows power Vs rotor speed at various wind speeds and the bond graph method proves to be accurate in following the MPP of the WECS, for an optimum duty cycle perturbation step in accordance with the chopper dynamics. Figure (11) shows power co-efficient $\left(C_P\right)$ V$_s$ tip speed ratio (λ) for various pitch angles. The maximum value of C_P , that is $C_{P\,max} = 0.47$, is achieved for $\beta = 0^{\circ}$ and for $\lambda = 6.75$.
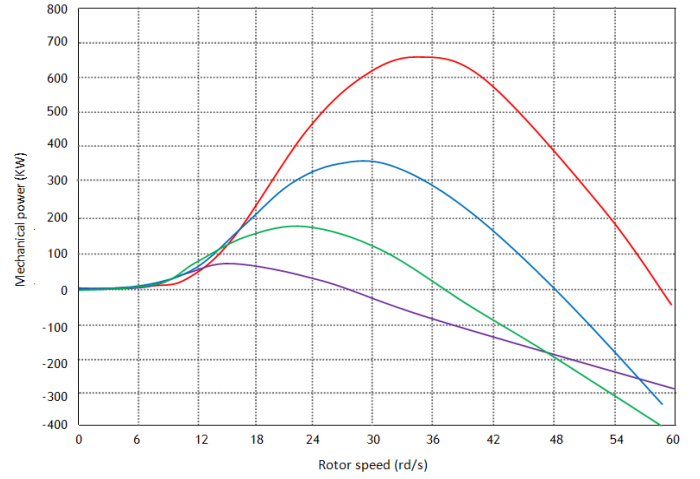
Fig. 9 Power versus rotor speed at various wind speeds

Figure (11) shows the gate pulse to the VSI obtained from the bond graph controller. Figure (12) shows the WTG output power with bond graph control method and a maximum WTG output power of 280W is obtained. Simulations depicted in Figure (13) show the case with only active power exchange with the utility grid, i.e. with APCM activated, for a typical 400W three-bladed horizontal-axis WTG connected to a 400V electric system.
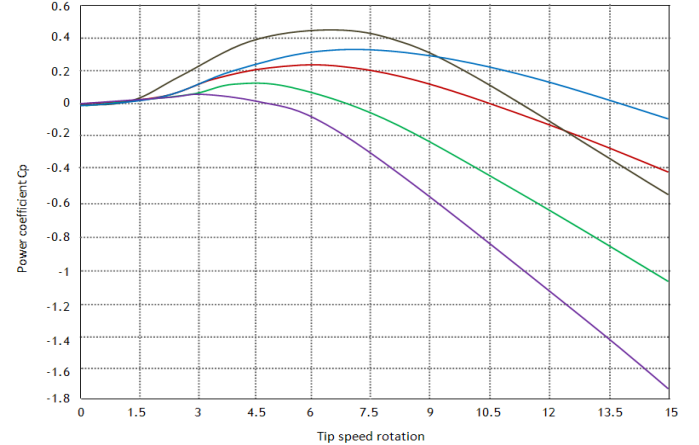
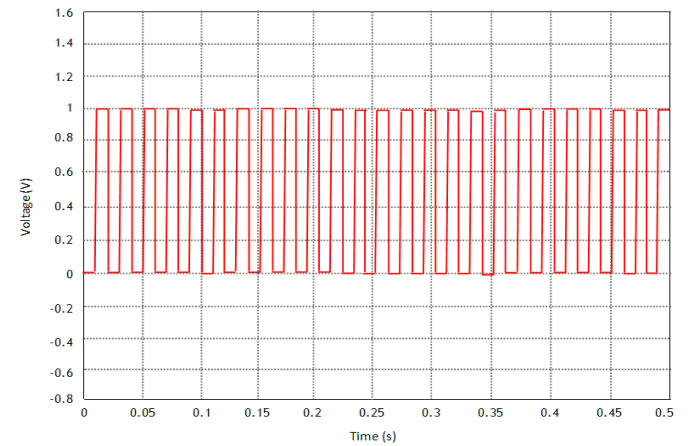Fig. 10 $C_P Vs \lambda$, for various pitch angles
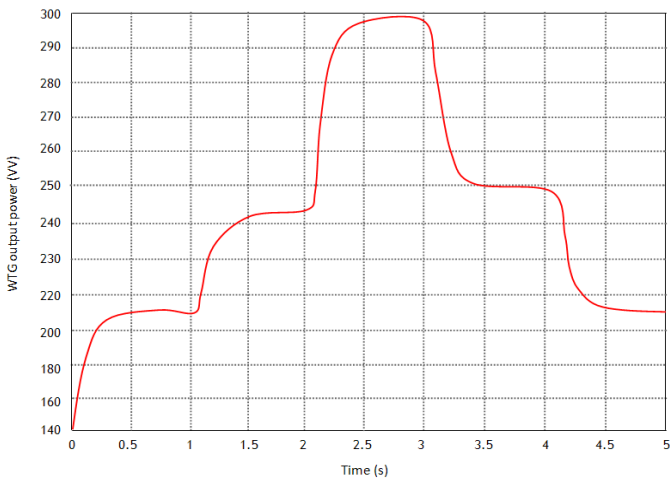
Fig. 11 VSI gate pulse

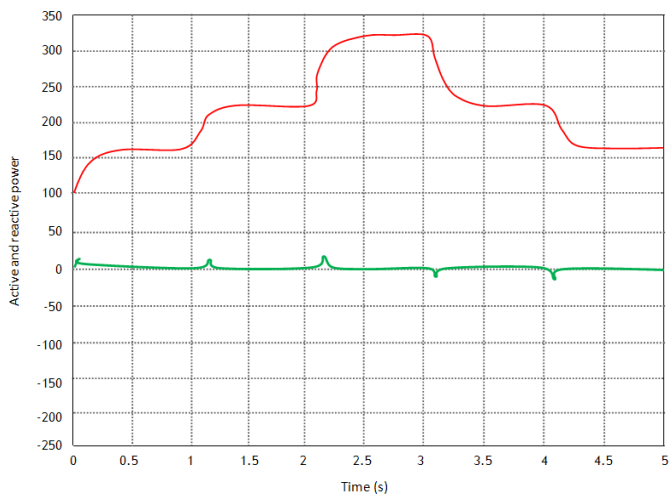Fig. 12 WTG output power with P&O control method

Fig. 13 VSI output active and reactive power

VIII. CONCLUSION

The work presented in this paper is devoted to modelling, control and simulation of a WECS using a permanent magnet synchronous generator connected to the grid. We have established a bond graph WECS model. The latter contains representations of a wind turbine, PMSG and the converters. A bond graph control approach of a three-phase grid-connected wind energy conversion system, incorporating a maximum power point tracker (MPPT) for dynamic active power generation jointly with reactive power compensation of distribution utility systems has been presented. The fast response of power electronic devices and the enhanced performance of the proposed control techniques allow taking full advantage of the WTG.

The obtained simulation results demonstrate the robustness of the control device whose objective is to maximize energy captured from the wind turbine for each wind speed and the control of the active power and reactive one injected into the grid via converters.

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