MODELING AND SIMULATION OF A PERMANENT MAGNET WIND GENERATOR BY USING SIMPOWERSYSTEMS OF MATLAB/SIMULINK

Gerardo A. Blanco*•, Marcelo G. Molina*†♦, Pedro E. Mercado*†, Walter I. Suemitsu‡

* Instituto de Energía Eléctrica (IEE) – Universidad Nacional de San Juan (UNSJ) – Argentina,

• German Academic Exchange Service (DAAD)

† Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET)

‡ Universidade Federal do Rio de Janeiro (UFRJ) – Brazil,
Instituto Alberto Luiz Coimbra de Pós Graduação e Pesquisa de Engenharia (COPPE)

♦ mgmolina@iee.unsj.edu.ar – http://www.iee-unsj.org

***Abstract* – This paper discusses the modeling and simulation of a grid-connected wind turbine generator (WTG). The model proposed of the wind generating system is based on a permanent magnet synchronous generator (PMSG). The detailed modeling approach is carried out by using SimPowersSystems of MATLAB/Simulink. Simulation analysis is performed for validating the methodology applied and components used. The main components of the WTG include the wind turbine, the synchronous generator and the power conditioning system (PCS) for connecting the device to the electric grid.**

***Keywords* – Detailed Modeling, Dynamic simulation, MATLAB/Simulink, SimPowerSystems, Wind energy, Wind turbine generator.**

I. INTRODUCTION

In 2005, the global wind energy sector registered a record year; a total of 11,531 MW of new capacity was installed in more than 30 countries. This represented a 40.5% increase on an annual basis and a 24% cumulative growth. At the end of that year, the worldwide wind power installed reached 59,084 MW.

Wind power is now established as an energy source in over 50 countries around the world. Those countries with the highest capacity installed are Germany (18,428 MW), Spain (10,027 MW), USA (9,149 MW), India (4,430 MW) and Denmark (3,122 MW). A number of other countries, including Italy, UK, Netherlands, China, Japan and Portugal have reached the 1,000 MW.

Although wind power industry has been previously mostly developed in the European Union countries, this trend has begun to change in the last decade. The United States and Canada are both experiencing a rapid emergence of the activity, while new markets are being opened in Asia and South America. In Asia, both China and India registered a record level of expansion during 2005[1].

Despite the fact that mayor wind power development has so far been on land, high demands of space and the attraction of greater productivity from a better wind regime have taken developers offshore. Thus, offshore wind farms are expected to contribute with an increasing proportion of global capacity, especially in northern Europe. The establishment of wind energy projects in the sea has opened new requirements, including the need for stronger foundations, long underwater cables and larger individual turbines [2].

The machine that converts wind energy into electric power is the wind turbine generator (WTG). Nowadays, existing WTGs combines and matches a variety of innovative concepts with proven technologies both for generators and for power electronics used to link the system to the utility grid. This work analyzes WTGs based on a variable-speed wind turbine, permanent magnet synchronous generators (PMSG), and connected to the electric distribution system through AC-to-DC-to-AC switching converters.

The application of a variable speed PMSG in the wind turbine can increase the energy capture from the wind, solve other problems such noise, and improve efficiency. For instance, if a gearbox is used in a wind turbine system, it produces noise, power losses, additional cost, potential of mechanical failure and other problems. The use of a variable speed PMSG could solve these problems.

The installation of these devices into the electric grid requires the prior realization of various dynamic performance studies in order to guarantee the operation security of the entire electric power system. Diverse simulation tools can be used to carry out this task, including PSCAD/EMTDC™, ATP/EMTP, and SimPowerSystems of MATLAB/Simulink among others.

The SimPowerSystems is a relatively recent computational tool that accompanies, in the form of a Blockset, the MATLAB/Simulink platform. This software has become quite popular in the academic environment due to its great flexibility and easiness of use. Simulink is a powerful platform for multi-domain simulation and model-based design for dynamic systems. It provides an interactive graphical environment and a customizable set of block libraries, and can be extended for specialized applications such as power systems and advanced control systems.

Based on above considerations, this work proposes to study the modeling and simulation of a grid-connected wind turbine generator based on a permanent magnet synchronous generator by using SimPowersSystems environment. Detailed modeling is proposed and simulations are carried out in order to validate the methodologies presented.

II. WIND TURBINE GENERATOR MODEL

In this section, the proposed models for simulation of the dynamic performance of a wind generator are presented. The selected wind generator utilizes a permanent magnet synchronous generator directly coupled to the wind turbine and connected to the electric grid through a power conditioning system (PCS) [3]. The stator windings of the PMSG are straightforwardly connected to the PCS composed of an uncontrolled rectifier, DC bus capacitors and a DC-to-AC switching power inverter, as shown in Figure 1.

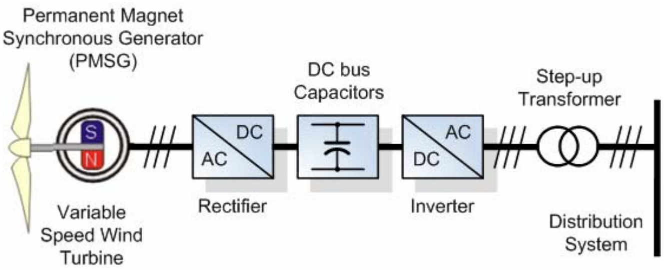

Fig. 1. General scheme of the wind generator.

The wind generator operates with variable rotation and includes control of mechanical power drawn from wind through the pitch control technology. In this way, when the wind speed and thus the power output becomes too high, the control scheme forces the blade pitch mechanism to immediately pitch (or turn) the rotor blades slightly out of the wind. Conversely, the blades are turned back into the wind whenever the wind speed drops again to safety values for the WTG [4].

A. Wind Turbine Aerodynamics Characteristics

The amount of mechanical power captured from wind by a wind turbine can be expressed as follows:

$$P_{mec} = \frac{1}{2}\rho\, A\, v_w{}^3 C_p(\lambda,\beta), \tag{1}$$

with,

$$\lambda = \left(\frac{R\omega_{wt}}{v_w}\right), \tag{2}$$

where:

ρ: Air density, 1.225 kg/m^3 at 15 °C
A: Swept area, in m^2
v_w: Wind speed, in m/s
C_p: Power coefficient of the wind turbine (dimensionless)
λ: Tip speed ratio (TSR)
β: Blade pitch angle, in degrees
R: Radius of the wind turbine rotor, in m
ω_{wt}: Angular speed of the wind turbine, in rad/s

Power Coefficient of the Wind Turbine

As can be derived from (1) the power coefficient C_p depends on the aerodynamic characteristics of the wind turbine (λ) and the blade pitch angle (β). The power coefficient $C_p(\lambda,\beta)$ is expressed as a bi-dimensional characteristic function.

Numeric approaches are usually developed in order to compute the parameter C_p for different values of λ and β. However, in this work the expressions proposed by [5] are applied, resulting in the following equations:

$$C_p(\lambda,\beta) = \frac{1}{2}\left(\frac{98}{\lambda_i} - 0.4\beta - 5\right)\exp\left(\frac{-16.5}{\lambda_i}\right), \tag{3}$$

with,

$$\lambda_i = \left[\frac{1}{(\lambda\ + 0.089)} - \frac{0.035}{(\beta^3 + 1)}\right]^{-1} \tag{4}$$

Figure 2 shows the representation of characteristic function C_p derived from (3) and (4). This curve will be used later for comparing to the one obtained from proposed model, for validating purposes [6].

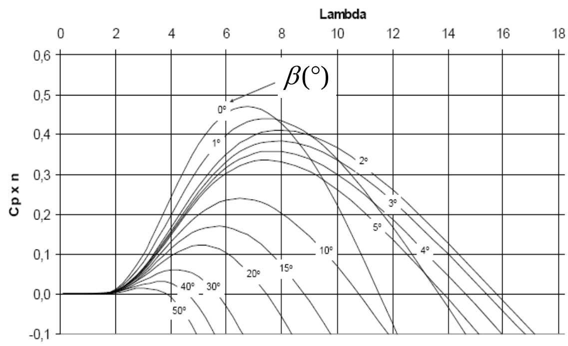

Fig. 2. Characteristic $C_p(\lambda,\beta)$ traced from applying (3) and (4).

According to [7], it is not necessary to develop different characteristics $C_p(\lambda,\beta)$ for various types of turbines. Differences among curves formats of commercial turbines are very small, so they can be neglected in dynamic simulations studies. Only in some cases, such as for estimating energy production, these variations are significant and have to be considered.

B. Mechanical Torque

The total wind turbine mechanical torque is modeled as an average torque with the addition of harmonic oscillations. The average mechanical torque (T_{m_mec}) can be expressed as stated in (5);

$$T_{m\_mec} = \frac{P_{mec}}{\omega_{wt}} \tag{5}$$

By combining (1) and (5) and computing the swept area, the general expression of the average mechanical torque produced by the wind turbine is obtained, represented in (6).

$$T_{m\_mec} = R^2 v_w{}^3 \rho\, \pi \frac{C_p(\lambda,\beta)}{2\omega_{wt}} \tag{6}$$

Tower shadow

In the three-bladed horizontal-axis wind turbine, the most common and largest periodic power pulsations occur at what is known as *3p* frequency. This is three times the rotor frequency, or the same frequency at which the blades pass in front of the tower. Then, the main effect added to the average torque is the effect of the aerodynamic shadow torque of the generator tower [8].

The aerodynamic shadow torque of the tower is the reduction of the aerodynamic torque taken place in the wind turbine blade when this passes in front of the tower of the wind generator. This happens due to the change in the glide of the air created by the tower (usually tubular). This effect is only manifested when the blades goes by the region of influence of the tower. This phenomenon is better modeled in the form of a sinusoidal function, as shown in (7) and (8).

$$T_{somb} = k_{somb}\left(\frac{1}{2}\cos(a) - \frac{1}{2}\right)T_{mec\_m}, \tag{7}$$

with,

$$a = f_{pos}(\theta), \tag{8}$$

where:

k_{somb}: Factor of reduction of the mechanical torque in function of the aerodynamic shadow.

θ: Rotor angle position of the wind turbine blade, measured between the blade and the tower. See Figure 4 for more details.

Function $f_{pos}(\theta)$ assumes the form presented in Figure 3.

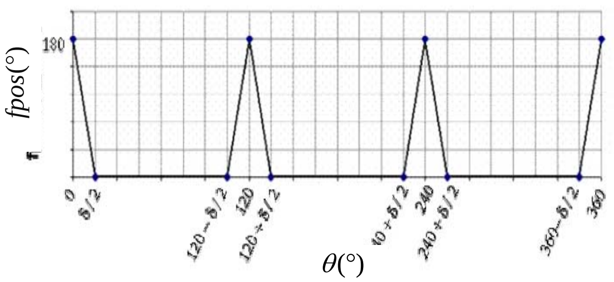

Fig. 3. Value assumed by function $f_{pos}(\theta)$.

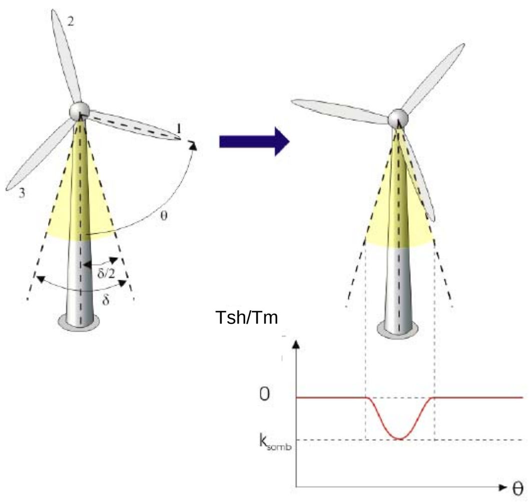

Fig. 4. Localization of the angles used in the calculation of the aerodynamic shadow torque.

The resulting mechanical torque is the sum of the average torque and the oscillation caused by the shadow torque, as expressed in (9):

$$T_{mec} = T_{mec\_m} + T_{somb} \tag{9}$$

The resulting torque shows a behavior according to the curve depicted in Figure 5, which will be later used for validation of the developed models that represent these phenomena.

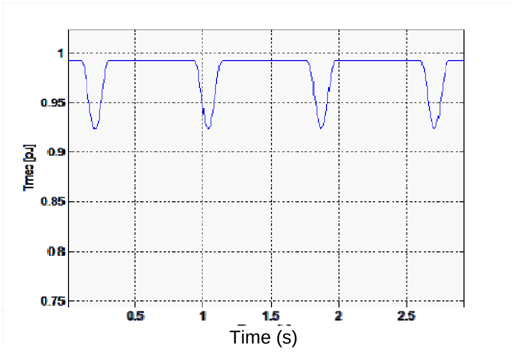

Fig. 5. Mechanical torque produced by the wind turbine.

C. Model of the Rotor

In order to make possible an effective analysis of performance of a wind generator, it is necessary that the models of used components are simple enough and representative of main dynamic behavior of the equipment.

When dealing with a variable speed generator, due to the effect of the disconnection between the generator and the electric grid, caused by the presence of the power electronics converters, the use of a simplified model is feasible. In this case, the aerodynamics of the axes can be neglected, being able to be used a model with a single mass and an equivalent inertia. It is necessary to stand out that this approach is only valid for wind generators that operate with variable rotation. A more accurate modeling of the rotor is required for wind generators that operate with constant speed, particularly for the verification of dynamic interferences, such as, for example, flickers.

D. Model of the permanent magnet synchronous generator (PMSG)

The model of the permanent magnet synchronous generator employed in this work is included in SimPowerSystems blockset of MATLAB/Simulink. The integration of this machine with the wind turbine model is straightforward.

E. Model of the power conditioning system

The power conditioning system of the wind turbine generator, consisting of an uncontrolled three-phase diode-rectifier bridge, a power inverter and the dc bus capacitors, is shown in Figure 6. The AC power generated from the PMSG is converted to DC power through a diode bridge which is simple, robust and cheap. Furthermore it does not require a control circuit. The output terminals of the rectifier are linked to a dc-bus, which is also shared with a three-phase power inverter. A pair of capacitors is used as energy storage device to interface both, the rectifier bridge and the power inverter. The connection of the inverter to the distribution utility system is carried out through a coupling step-up transformer in order to meet the voltage level requirements.

The presented inverter corresponds to a DC-to-AC voltage source inverter (VSI) using Insulated Gate Bipolar Transistors (IGBTs) [9, 10]. In the distribution voltage level, the switching device is generally the IGBT due to its lower switching losses and reduced size. In addition, the power rating of power devices is relatively low. As a result, the output voltage control of the VSI can be achieved through pulse width modulation (PWM) by using high-power fast-switched IGBTs.

The VSI structure is designed to make use of a three-level pole structure, also called neutral point clamped (NPC), instead of a standard two-level six-pulse inverter structure. This three-level inverter topology generates a more sinusoidal out-put voltage waveform than conventional structures without increasing the switching frequency. The additional flexibility of a level in the output voltage is used to assist in the output waveform construction. In this way, the harmonic performance of the inverter is improved, also obtaining better efficiency and reliability in respect to the conventional two-level inverter.

The connection to the utility grid is made by using low pass sine wave filters in order to reduce the perturbation on the distribution system from high-frequency switching harmonics generated by PWM control. The total harmonic distortion (THD) of the output voltage of the inverter combined with a sine wave filter is less than 5 % at full rated unity power factor load. Typically, leakage inductances of the step-up transformer windings are high enough to build the sine wave filter simply by adding a bank of capacitors in the point of common coupling (PCC). In this way, an effective filter is obtained at low costs, permitting to improve the quality of the voltage waveforms introduced by the PWM control to the power utility and thus meeting the requirements of IEEE Standard 519-1992 relative to power quality.

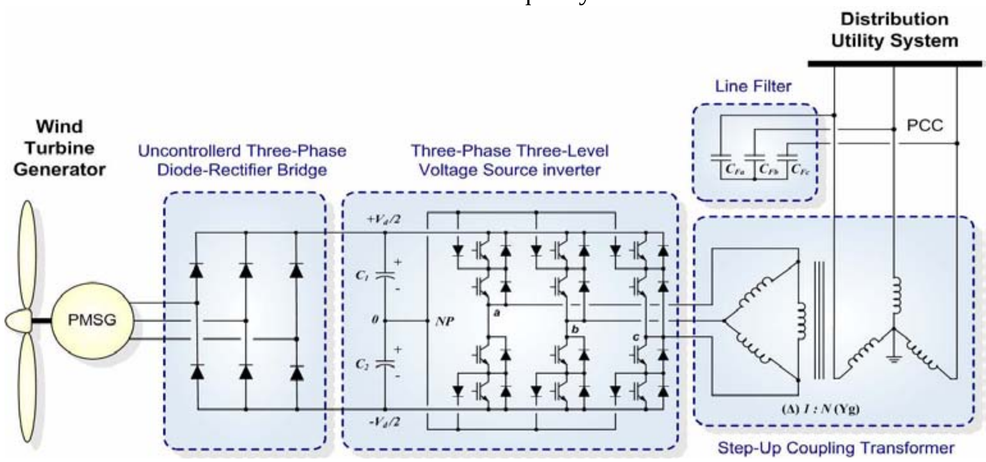

Fig. 6. Detailed model of proposed power conditioning system for wind turbine generator.

III. IMPLEMENTATION OF DYNAMIC MODELS OF THE WIND GENERATOR IN MATLAB/SIMULINK

A. Model of the isolated Wind Turbine

The full model of the wind turbine implemented in Matlab/Simulink is presented in Figure 7 [11]. This model is divided into several blocks which will be hereafter described.

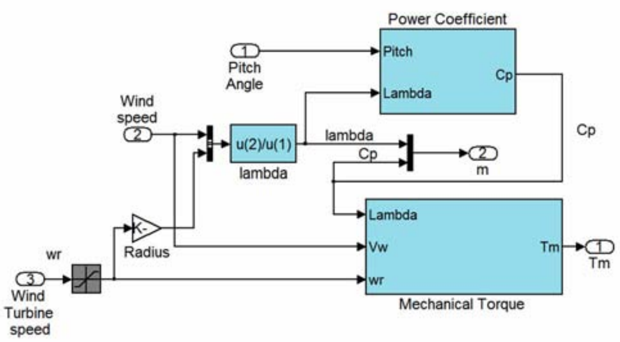

Fig. 7. Complete model of the wind turbine implemented in Matlab/Simulink.

1) Power Coefficient of the Wind Turbine

The power Coefficient C_p is implemented according to (3) and (4) [5]. Figure 8 depicts the diagram of the mathematical model of the Power Coefficient in Simulink.

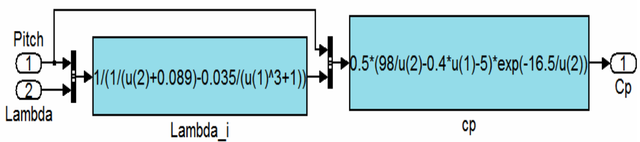

Fig. 8. Simulink Implementation of the power coefficient of the wind turbine.

From previous block, it is possible to trace the curves of C_p as a function of λ, for different values of the angle β, as illustrated in Figure 9. This is accomplished by linearly varying the value of the turbine rotational speed while maintaining constant the incident wind speed. A 40 m length was assumed as radius for the wind turbine blade modeled in this work, which is a typical value for a current medium scale turbine. The resulting curves obtained (Figure 9) clearly validates the present implementation of the power coefficient C_p when comparing to theoretical curves previously presented (Figure 2).

2) Mechanical Torque

The mechanical torque is implemented according to (9) as the sum of the average mechanical torque and the oscillating torque produced by the shadow one. Figure 10 depicts the blocks corresponding to the implementation in Simulink of the mechanical torque of the wind turbine.

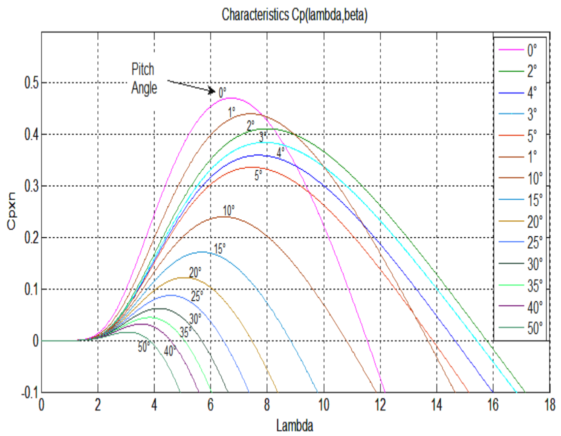

Fig. 9. Characteristic curve of the power coefficient obtained from simulations of the implemented model.

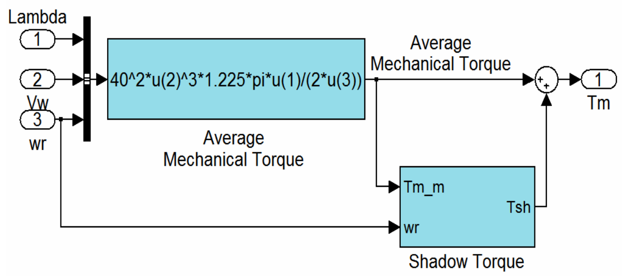

Fig. 10. Simulink implementation of the mechanical torque of the wind turbine.

The aerodynamic shadow torque of the tower is modeled in detailed form as formerly exposed in (7) and (8), and implemented by blocks shown in the Figures 11 and 12.

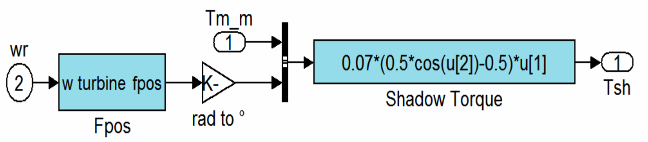

Fig. 11. Simulink implementation of the shadow torque of the wind turbine.

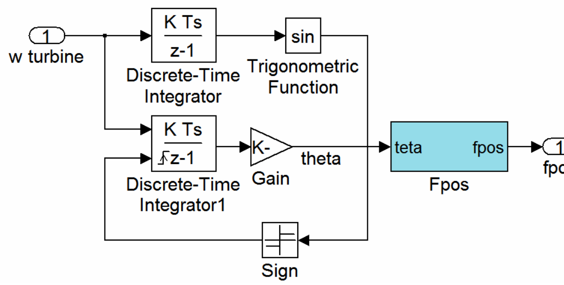

Fig. 12. Simulink implementation of the block f_{pos}.

Considering the reduction factor of the mechanical torque as a function of the aerodynamic shadow (k_{somb}), a 7% value was assumed. The function obtained as a result of a 3s simulation time is shown in the following figures.

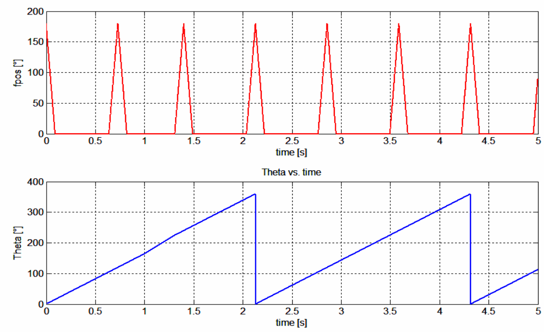

Fig. 13. Temporal evolution of function f_{pos}..

It can be noted from previous simulations that the shadow torque and the resulting mechanical torque behave as expected from analyzing experimental tests documented in the bibliography referenced in this work.

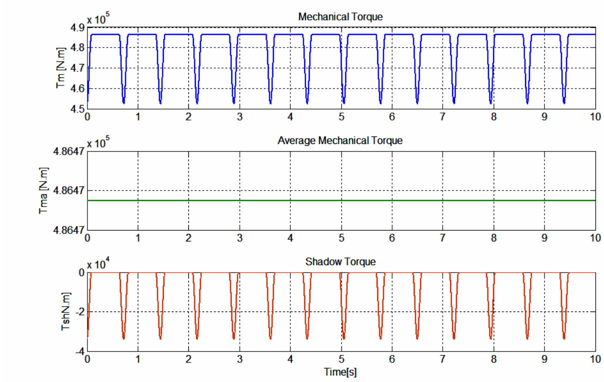

Fig. 14. Torque signals.

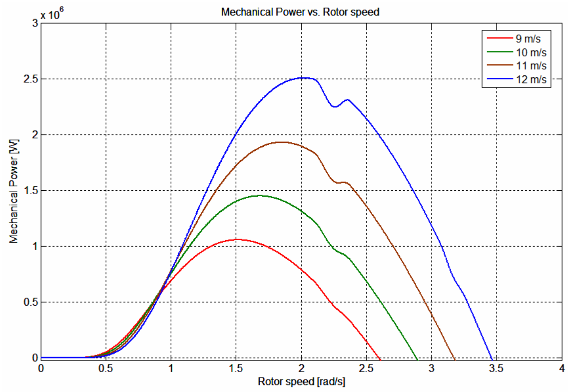

Fig. 15. Characteristic of the wind turbine mechanical power vs. angular speed of the rotor obtained from simulations.

As can be derived for the assumed model for C_p, the smaller speed of the wind the larger mechanical power is obtained. Furthermore, when overcoming the maximum mechanical power, there is a significant influence of the shadow torque.

B. Model of the Wind Turbine Generator connected to the Distribution Grid.

As previously mentioned, a model of a permanent magnet synchronous generator available in SimPowerSystems is employed for implementing the WTG. This block utilizes as input the mechanical torque signal from the model of the wind turbine. The rotational rotor speed of the generator is feedbacked as input to the wind turbine model. The electric output of the PMSG is connected to the utility system via the PCS described in section II.E. The power electronic system includes the rectifier linked to the VSI and the step-up transformer, as shown in Figure 16. The machine parameters are derived from [4].

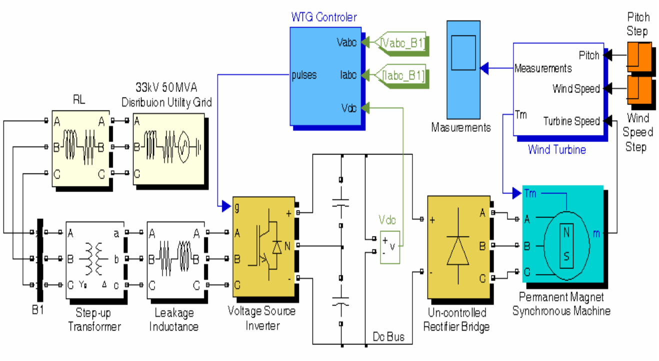

Fig. 16. Complete Simulink implementation of the wind turbine generator connected to the distribution grid.

IV. DIGITAL SIMULATION RESULTS

The performance of dynamic models is analyzed by computer simulation implemented in SimPowerSystems. To this aim, the effect of changes in wind speed and pitch angle of the WTG is studied.

Step variations of the wind speed and the pitch angle of the wind turbine are applied to the WTG proposed model in order to evaluate the acceleration effect in the angular speed of the rotor when the wind speed increases, which is counteracted by the braked effect of the increment of the pitch angle over the same rotational speed.

At t = 1 s, a step change of 2 m/s in the wind speed is applied to the WTG. The turbine tends to maintain constant the values of C_p and the deviation of the wind speed is reflected in the rotor angular speed almost entirely as a roughly proportional difference. This is reflected as an increment in the peak value of the output voltage and therefore in the DC/AC voltage.

This situation continues during 0.3 s, until a step change of 12.7° is applied in the pitch angle of the turbine. This perturbation influences in a reverse way to the previous perturbation in wind speed, reestablishing it to original values. These results can be clearly observed from the simulations of Figure 17.

V. CONCLUSION

This work presents a study about dynamic modeling and simulation of a wind turbine generator by using SimPowerSystems of MATLAB/Simulink. The WTG used is a permanent magnet synchronous generator. Simulation results obtained allow concluding that the dynamic models presented can be used with good precision for the performance analysis of a WTG. The use of SimPowerSystems allows developing, in a simple way, models that accurately simulate real complex equipments. Moreover, advanced control techniques can be included for performance studies, taken advantage of many other Simulink libraries.

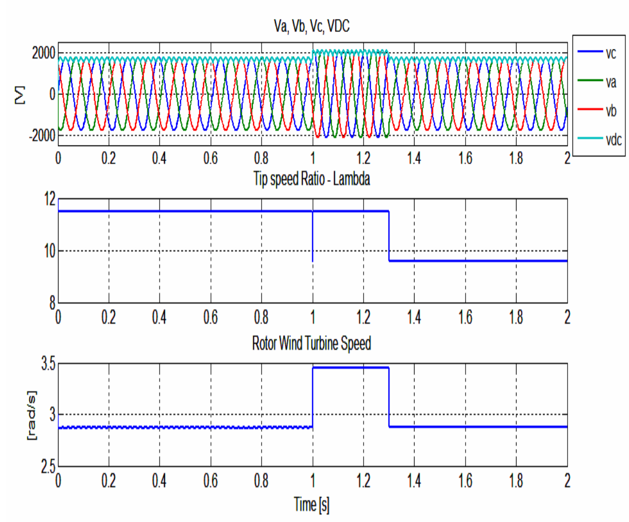

Fig. 17. Digital simulation results.

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