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Emulation of Wind Turbines

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Abstract

This chapter presents the modeling, simulation, and emulation for small wind turbine (WT) systems. The main objective of the emulation system is to reproduce the WT torque dynamic behavior in the generator shaft, which must be similar to one of real horizontal WTs used for distributed generation. The aerodynamic, mechanical, and electrical models for horizontal axis wind turbines (HAWTs) are presented in detail. The models are used for simulation analysis and emulation synthesis. The emulator consists a (i) computational platform, which is based on LabVIEW® environment and runs the model of the WT and (ii) an induction motor (IM) with AC power drive with torque control. The IM shaft is directly coupled with the real small wind generator and corresponding load. Experimental waveforms are also presented to demonstrate the functionality of the system.

Keywords: wind turbine, modeling, emulator, electrical generator, renewable energy, induction motor drive

1. Introduction

The increasing demand for electricity in addition to the need to minimize environmental problems such as global warming had led to the development of renewable sources for production of electricity in recent years. Among the alternative sources for power generation, wind-based generation is becoming increasingly common around the world, mainly due to government incentives and technological advances in recent years [1]. Thus, a worldwide growing number of large and small wind farms installed can be verified.

The design of wind to electricity conversion systems involves different kinds of generators, power electronics, and control, resulting in motivation for the development of numerous works. The analysis of the efficiency of a wind turbine (WT), based on an adequate simulation of its behavior, is an important step in the research and development of technologies for wind generation. A manufacturer needs tools and appropriate resources to test innovations and to evaluate their effects on the overall system. One possible and helpful tool uses a dedicated hardware and software that intends to emulate a real WT in a reduced scale. This tool is a so-called WT emulator.

A WT emulator uses a set of electrical machines (motor and generator) coupled by a shaft, driven by a converter, and controlled in real time by a computing environment in order to emulate different aerodynamic phenomena present in the rotor of a WT [2]. Therefore, using such a system, different control systems can be implemented and verified. In addition, WT emulators can be used as an educational tool in the study of the behavior of a real WT [3].

The emulation of a WT may be obtained by controlling the torque on the motor shaft. In reference [4], the reference torque for the motor is determined based on the wind speed applied to the turbine and on each mechanical shaft speed. This strategy has simple configuration and allows the validation of control strategies of converters connected to the generator side. However, the transient effects are disregarded, and only the steady-state conditions of the system are obtained.

There are several approaches for wind emulators that are used in different situations depending on the desired requirements. DC motors are used in the construction of wind emulators because of their great ease for implementation and due to their direct relationship between armature current and the torque produced by the machine, as shown in references [3] and [5]. However, they demand higher maintenance requirements and these are costly when compared to other electrical machines in the same power range. An emulation system based on an induction motor (IM) has a smaller size relative to the DC motor for a given power range and has lower cost. Emulators from IM are also described in references [6–8].

This chapter describes the development of an emulator of WTs. The emulator is composed of an IM coupled to the shaft of a permanent magnet synchronous generator (PMSG). The IM has an electrical drive system controlled in real time by a software developed in LabVIEW®. The interface between software and drive is performed by an instrumentation circuit and a data acquisition board PCI-2511. In the proposal, given the WT parameters and a specified wind speed the software module of emulator provides the necessary IM torque reference to emulate the desired turbine. A standard x86 personal computer with LabVIEW® executes the software module of wind emulator.

This chapter is organized as follows: Section 2 describes the mathematical modeling of WTs, including aerodynamic, mechanical, and electrical models. Section 3 presents a numerical analysis of horizontal axis WT using these models. Simulation waveforms are presented to show the turbine dynamics under typical wind conditions. Section 4 describes an emulator built using a LabVIEW® environment and IM drive system. The emulator experimental

evaluation is presented in Section 5. The waveforms of this evaluation are compared with simulation waveforms in Section 6, which concludes the chapter.

2. Mathematical model of wind turbines

A WT can be described using three mathematical models: aerodynamic, mechanical, and electrical model. The aerodynamic model is responsible to represent the energy conversion from a moving air mass at a certain speed, which creates the rotational movement of the turbine, into mechanical energy at the shaft of the generator. The mechanical power available reflects into the speed and torque of the shaft of the system. The electrical model describes the conversion of the mechanical torque into electrical energy at the generator output. This process is depicted in Figure 1.

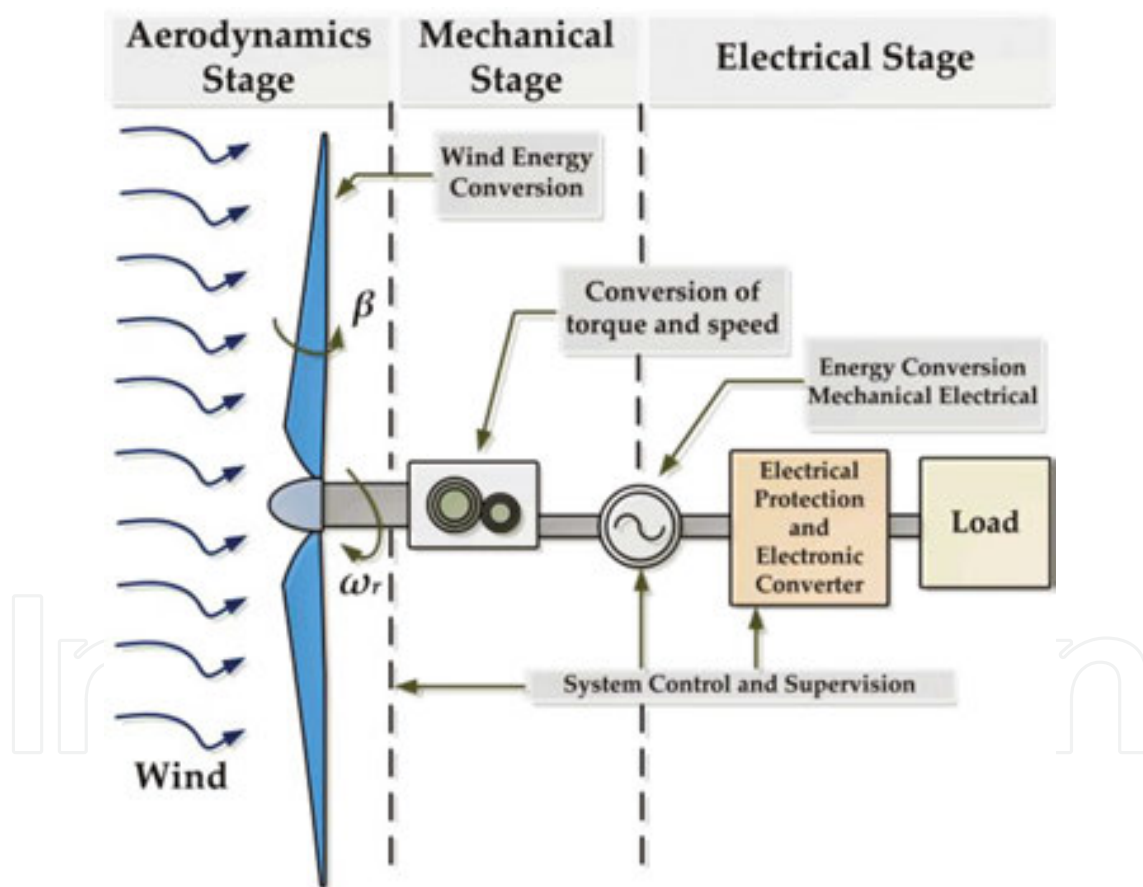


Figure 1. Energy conversion process for wind turbine.

In order to simulate/emulate a WT, it must obtain the three aforementioned mathematical models. From these models, given a wind profile, the mechanical torque and shaft speed that are used in the emulation stage can be obtained. The following topics present the mathematical modeling of a WT.

2.1. Aerodynamic model

The wind power that is converted into mechanical power at the turbine shaft is given by

$$P_T = \frac{\rho A V_w^3 C_p}{2} \quad (1)$$

where P_T is the mechanical power extracted by the wind turbine (W), ρ is the air density (1.225 kg/m³ at sea level), A is the swept area (m²), V_w is the wind speed (m/s), and C_p refers to the power coefficient. The aerodynamic characteristics and the orientation of a turbine relative to the wind flow result in its power efficiency. The value of C_p depends on the ratio speed of the blades and the wind. This ratio is known as tip speed ratio (TSR). Check reference [9] for more details of this conversion. The TSR is represented by λ and it is defined by

$$\lambda = \frac{\omega_r R}{V_w} \quad (2)$$

where R is the radius of the turbine swept area (m) and ω_r the angular velocity in the turbine shaft (rad/s).

For each WT model, the curves that relate C_p to different values of pitch angle (β) and TSR (λ) can be obtained from direct measurements of the turbine in operation. These curves are known as power curves, and they are useful in obtaining C_p for different points of operation of the turbine. The exact determination of C_p is not an easy task and demands complex mathematical models. Therefore, some approximations have been presented for the determination of C_p based on measurements of β and λ [10, 11]. An expression that is commonly used for determining C_p is

$$C_{p(\lambda, \beta)} = c_1 \left(c_2 \frac{1}{\lambda_i} - c_3 \beta - c_4 \right) e^{c_5 \frac{1}{\lambda_i}} + c_6 \lambda \quad (3)$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + c_7 \beta} - \frac{c_8}{1 + \beta^3} \quad (4)$$

where c_1, c_2, \dots, c_8 are constants that depend on the aerodynamic characteristic of the turbine.

The torque developed by the turbine can be expressed as a function of wind speed that strikes the blades V_w , the power coefficient C_p , and the physical characteristics of the blades. A mathematical relationship is given by

$$T_T = \frac{1}{2\lambda} \rho A R V_w^2 C_{p(\lambda, \beta)} \quad (5)$$

According to Eq. (5), the torque developed in the shaft of a WT has a direct relationship with the wind speed. Since the wind has a stochastic behavior, it is expected to produce a resultant mechanical torque also with the stochastic profile.

2.1.1. Oscillatory effects of torque on wind turbines

Power source fluctuations in wind power systems are due to both a stochastic process that determines the wind speed at different time points and heights and a deterministic process. Deterministic processes on WTs are usually related to two aerodynamic effects called wind shear and tower shadow.

The wind shear phenomenon describes the variation of the wind speed (V_{ws}) that occurs at different heights [12] and its interaction with the turbine due to the rotation of the blades. Wind shear can be represented by the following equation [13]:

$$V_{ws} = V_w \left[\frac{R^2 (\delta - 1)}{H} \frac{1}{8} + \frac{R^3 \delta (\delta - 1)(\delta - 2)}{H} \frac{1}{60} \cos \frac{\delta (\delta - 1)(\delta - 2)}{60} \cos 3\theta_b \right] \quad (6)$$

where H is the elevation of the rotor hub (m), δ is defined as an empirical coefficient of shear which varies in the range $0.1 < \delta < 1$, θ_b angular position to the blades (degrees) also called azimuthal angle.

The tower shadow effect is the change in wind speed due to the presence of the turbine tower [12]. Due to proximity between the blades and the tower of structure, wind flowing around the tower causes oscillations in the mechanical elements acting on the blades as well as on the mechanical torque developed on its axis. This effect can be modeled as presented in reference [13], that is,

$$V_{ts} = \frac{V_w}{3R^2} \sum_{b=1}^3 \left[\frac{a^2}{\sin^2 \theta_b} \ln \left(\frac{R^2 \sin^2 \theta_b}{x^2} + 1 \right) - \frac{2aR^2}{R^2 \sin^2 \theta_b + x^2} \right] \quad (7)$$

where a is the tower radius (m) and x is the average distance between the tower and the blade (m).

Therefore, combining both effects results in the equivalent wind velocity V_{eq} given by

$$V_{eq}(t, \theta) = V_{ws} + V_{ts} \quad (8)$$

Incorporating the shear and tower shadow effects, the total torque T_T developed by a WT is expressed by

$$T_T = \frac{\rho A R V_W C_{p(\lambda, \beta)}}{\lambda} \left(\frac{V_W}{2} + V_{eq}(t, \theta) \right). \quad (9)$$

In order to observe the impact of the aforementioned effects, consider two WTs with characteristics given in **Table 1**.

Parameters	Small turbine: 2.2 kW	Midsized turbine: 850 kW
Wind rated speed (V_W)	12 m/s	12 m/s
Mechanical nominal speed (ω_r)	630 rpm	26 rpm
Rotor radius (R)	1.23 m	26 m
Shear coefficient (δ)	0.1	0.3
Tower radius (a)	0.4 m	1.5 m
Tower height (H)	6 m	86 m
Blade tip away until half tower (x)	1.5 m	3.8 m

Table 1. Specifications of wind turbines.

The tower wind shear effect and the shadow effect for two turbines of different size are presented in **Figures 2** and **3**, respectively. Note that these effects are more pronounced for a midsized turbine, compared with the effects for a small one.

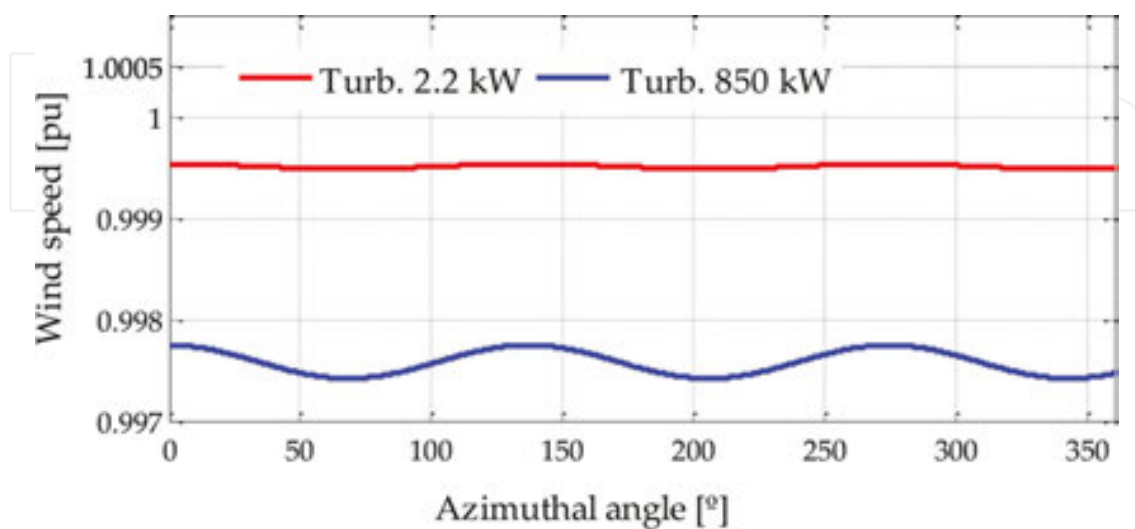


Figure 2. Wind shear effect of different wind turbines.

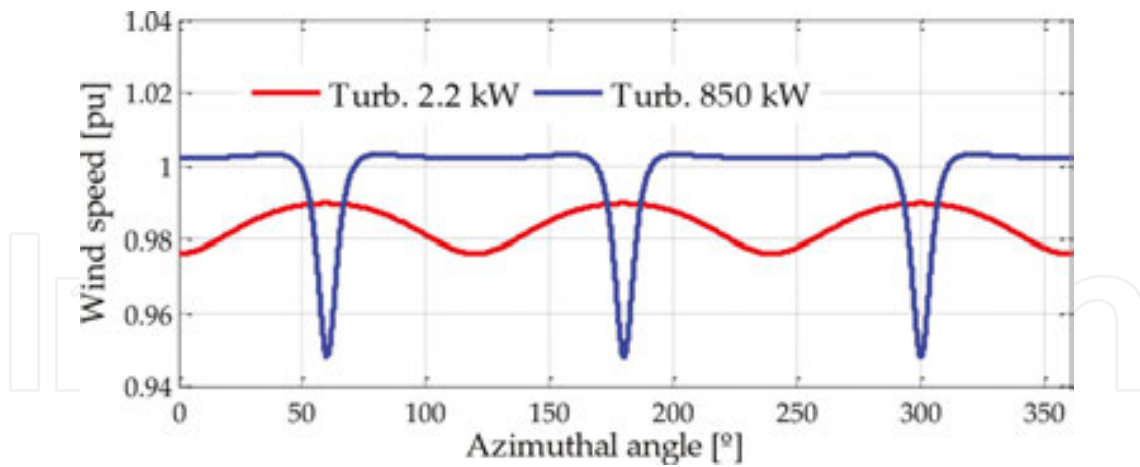


Figure 3. Tower shadow effect of different wind turbines.

The above-mentioned analysis shows that the tower shadow effect has greater impact on the resulting speed of the turbine than the wind shear effect. The tower shadow effect is responsible for an offset in the resulting torque. In addition, small turbines are less susceptible to oscillatory effects of wind than the midsize turbines.

2.2. Mechanical model

The mechanical dynamics of a WT can be modeled by two rotating masses, which represent the rotor of the WT and the generator shaft. The connection between them can be made with a gearbox or with direct coupling. Damping and torsion are also considered in the model as shown in **Figure 4**.

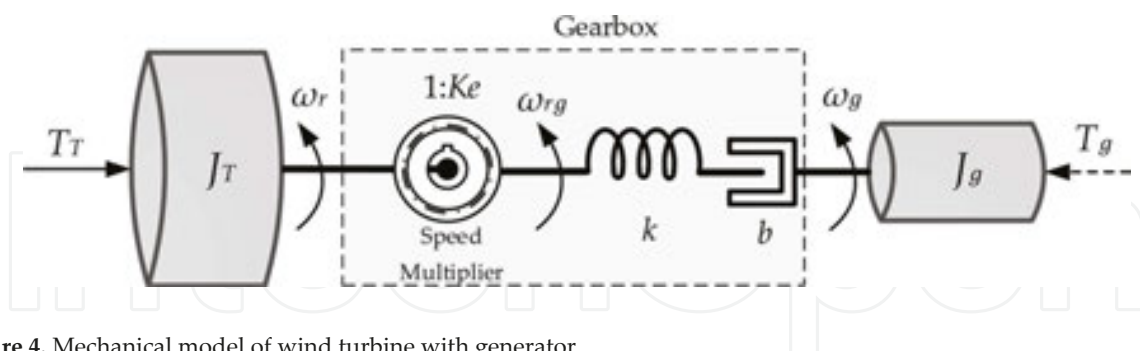


Figure 4. Mechanical model of wind turbine with generator.

The parameters presented in **Figure 4** are described below:

- J_T : Moment of inertia of the WT;
- J_g : Moment of inertia of the generator;
- T_T : Torque of the turbine, as a function of wind speed and power coefficient;
- T_g : Torque of the electrical generator, as a function of output electrical power;
- ω_r : Rotational speed of the turbine;

- ω_{rg} : Rotational speed of the turbine seen from the generator ($K_e \cdot \omega_r$);
- ω_g : Rotational speed of the generator;
- k : Torsion constant of the connection shaft;
- b : Damping coefficient of the shaft;
- K_e : Speed multiplication ratio.

Thus, the equations for the mechanical model of the WT are

$$\begin{aligned} T_{gT} &= K_e^{-1} \cdot T_T \\ \omega_{rg} &= K_e \cdot \omega_r \\ J_{gT} &= J_g + K_e^{-2} \cdot J_T \end{aligned} \quad (10)$$

where T_{gT} is the turbine torque seen by the generator and J_{gT} is the combined moment of inertia of the WT with the generator.

In most cases, for small WTs (that operate in a power range up to 10 kW) the dynamics of the axis are neglected, such as torsion and damping. In this situation, the equation regarding the mechanical model of the system becomes

$$T_{gT} - T_g = J_{gT} \frac{d}{dt}(\omega_{rg}). \quad (11)$$

2.3. Electrical model

Considering V_{dr} , V_q and I_{dr} , I_q as the voltages and currents of the stator of a PMSG represented in the synchronous reference frame [14], the electrical power of the generator is given by

$$P_e = \frac{3}{2} (V_d i_d + V_q i_q). \quad (12)$$

The electrical dynamic equations of the PMSG are expressed by

$$\begin{aligned} V_d &= R_s i_d - \omega_e L_q i_q + L_d \frac{di_d}{dt} \\ V_q &= R_s i_q + \omega_e (L_d i_d + \psi_{pm}) + L_q \frac{di_q}{dt} \end{aligned} \quad (13)$$

where ω_e is the angular velocity of the reference frame ($\omega_e = N_p \omega_g$), N_p is the number of pole pairs, L_d and L_q are the inductances of the stator winding in the synchronous reference frame,

R_s is the stator resistance, and ψ_{pm} is the flux constant of the generator rotor. The electrical torque (T_g) of the generator is expressed by

$$T_g = \frac{3}{2} \frac{Np}{2} (\psi_{pm} i_q + (L_d - L_q) i_d i_q) \quad (14)$$

3. Numerical simulation of the wind turbine

Based on the WT models presented in Section 2, an application was developed to simulate the behavior of a wind generator system. The simulator was developed in Matlab/Simulink® and was used for purposes of comparison with the waveforms of the emulator that was also developed for experimental analysis.

Figure 5 shows the block diagram that implements the dynamic behavior of a WT. The wind velocity and pitch angle are user inputs to the aerodynamic model. These inputs as well as the rotor speed are used to compute the power coefficient and the turbine torque. From the turbine torque and generator torque, the rotor speed is obtained. Then, the electrical model applies the load characteristic to obtain voltages, currents, and generator torque.

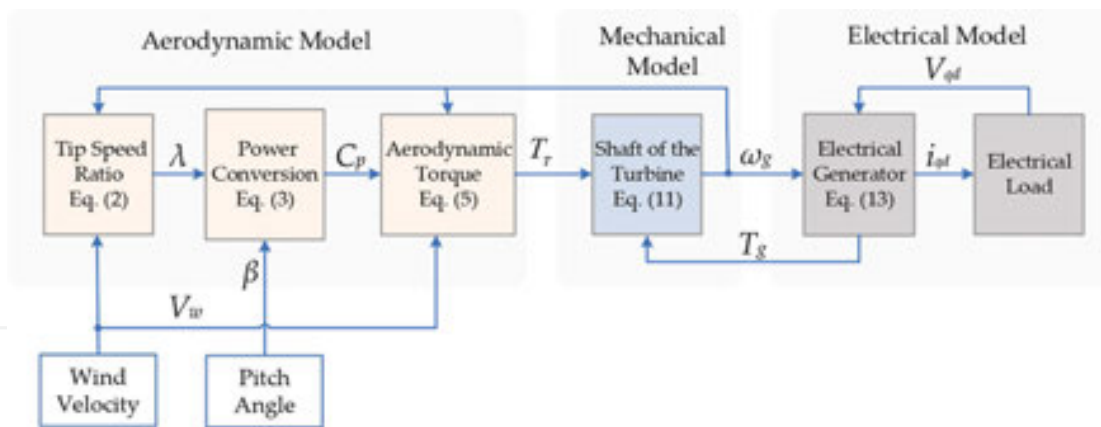


Figure 5. Block diagram of the wind turbine mathematical model for simulation implementation.

A 2.2-kW horizontal axis WT was considered as an example for the evaluation of dynamic behavior. The specifications of the aerodynamic model of the turbine are presented in **Table 1**, while the specifications of the mechanical model are given in **Table 2**.

Total turbine inertia (J_{gT})	2.29 kgm ²
Gearbox (K_e)	1200/630 = 1.9

Table 2. Parameters of mechanical model.

Due to the high-speed characteristics of the generator, the simulated WT incorporates a gearbox. The inertia of the turbine is obtained according to reference [15], and a resistive load used to terminals PMSG connected to “Δ”. Torsion and damping are neglected.

The generator used is a PMSG that corresponds to the machine used in the experimental setup. The parameters of the PMSG were obtained by experimental tests and are described in **Table 3**.

Rated power	2.2 kW
Speed rotation	1200 rpm (125.5 rad/s)
Number of pole pairs	3
Moment of inertia	0.0084 kgm ²
Stator resistance (R_s)	1.455 Ω
Axis inductance (L_d, L_q)	1.97 mH; 2.59 mH
Permanent flux (ψ_{pm})	0.205 Wb
Resistive load (R)	7.4 Ω

Table 3. Parameters of PMSG.

The system operates at variable speed without control for maximum power extraction. Therefore, the system will only provide maximum energy to the load at the nominal operation

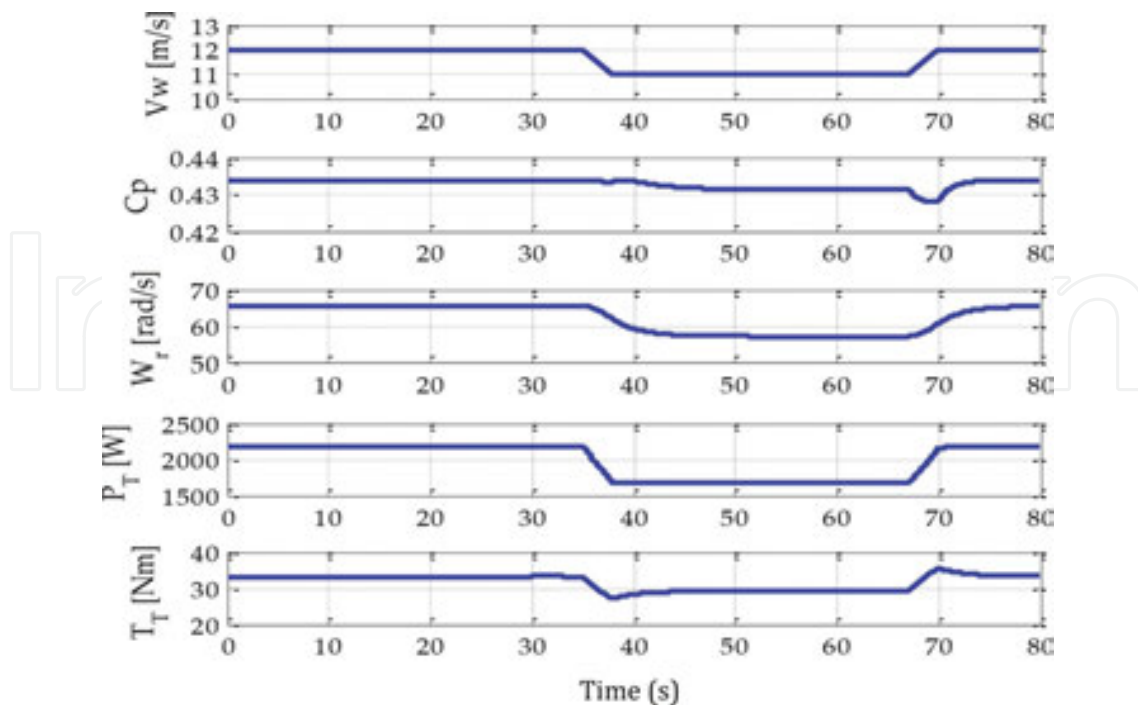


Figure 6. Aerodynamic quantities for a 2.2 kW turbine and wind speed changing from 12 to 11 and back to 12 m/s.

point. Thus, the analysis of the system starts at the nominal operating point with a wind speed of 12 m/s. After 35 s, the wind speed is reduced to 11 m/s using a ramp profile. At 67 s, the wind velocity is increased using a ramp profile up to the rated speed of 12 m/s. **Figure 6** describes the aerodynamic behavior of the simulated turbine.

In **Figure 6**, the variation in the wind speed results in a reduction of the mechanical power delivered to the generator around 25% (from 2.2 kW to 1.6 kW). The nominal torque of the turbine corresponds to 33.3 Nm. However, the torque seen by the generator is 17.5 Nm due to the gearbox speed ratio K_g . Due to the wind speed variation, the torque delivered to the shaft of the generator has a reduction of 9.7% (from 17.5 Nm to 15.8 Nm). The variation of the point of operation provides a small change in C_p value. The C_p changed from 0.434 to 0.431.

The turbine was also simulated at different points of operation that considered a variation in the wind speed from 12 to 10 m/s. The results are depicted in **Figure 7**.

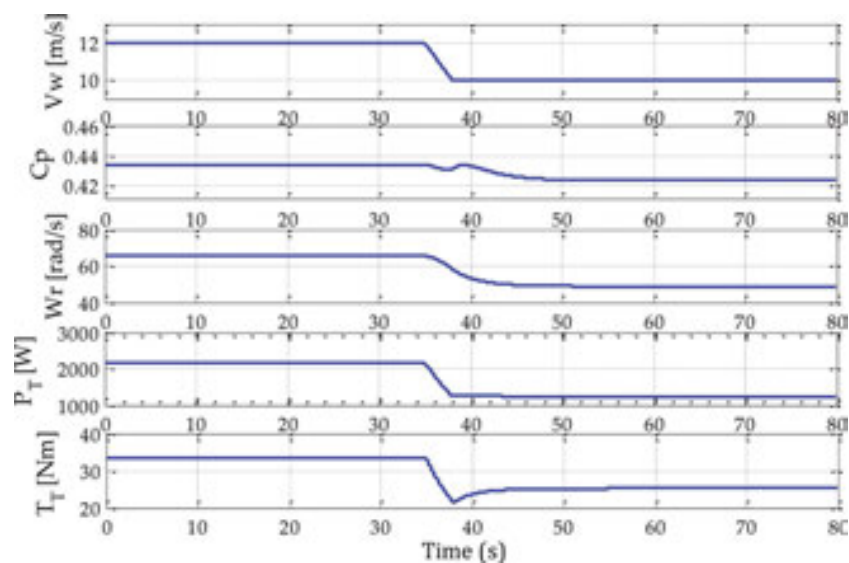


Figure 7. Aerodynamic quantities for a 2.2-kW turbine with a variation in the wind speed from 12 to 10 m/s.

As can be seen in **Figure 7**, even with a small wind speed variation of 2 m/s, the power coefficient is sensibly reduced. Moreover, the power absorbed by the turbine presents a larger reduction, around 40%. The simulation waveforms obtained in this section will be used to verify the emulator dynamics in the next section.

4. Emulation of the wind turbine

To develop a WT emulator, the setup is divided into two subsystems. The first one is a graphical user interface (GUI) running in a PC. The GUI was developed using LabVIEW® environment and uses an input-output card to communicate with the hardware setup. The second subsystem is an IM drive that emulates the WT following the dynamics evaluated by the software.

The software emulator developed in LabVIEW® incorporates the aerodynamic mathematical model presented in Section 2 and provides the necessary dynamic variables, such that the hardware is able to emulate the intended WT. Using the GUI, the user can provide parameters to the mathematical model. These input parameters include:

- Wind speed characteristics;
- Turbine parameters;
- IM parameters;
- Speed and torque signal specifications.

From input parameters, the software emulator acquires the rotational speed (ω_r) of the IM shaft to compute the turbine torque that must be developed on the shaft of the motor-generator set. The software converts both acquired IM torque and speed to the turbine nominal values (per-unit conversion) before using the aerodynamic emulator. After computing the turbine torque, the software converts it back to the IM nominal base, such that it is used as reference torque (T_T^*) by IM drive.



Figure 8. Emulator interface—wind turbine specifications screen.

4.1. Software implementation

The software has two tabs in the top of the main screen. The “Specifications” is the interface where the user inputs the parameters of the WT to be emulated. This screen is shown in Figure 8. The second tab, named “Signals Generated - Power – Torque” presents, graphically and in

real time, the dynamic characteristics of the emulated turbine. The dynamic characteristics are obtained from the model of the turbine. The mechanical quantities of the system are also shown. Torque and speed sensors installed on the experimental setup provide these quantities. To improve visualization, the quantities are presented in per-unit (pu) values. The user defines the base values in the “Specifications” tab. **Figure 9** shows the screen used to show the emulated variables in real time.

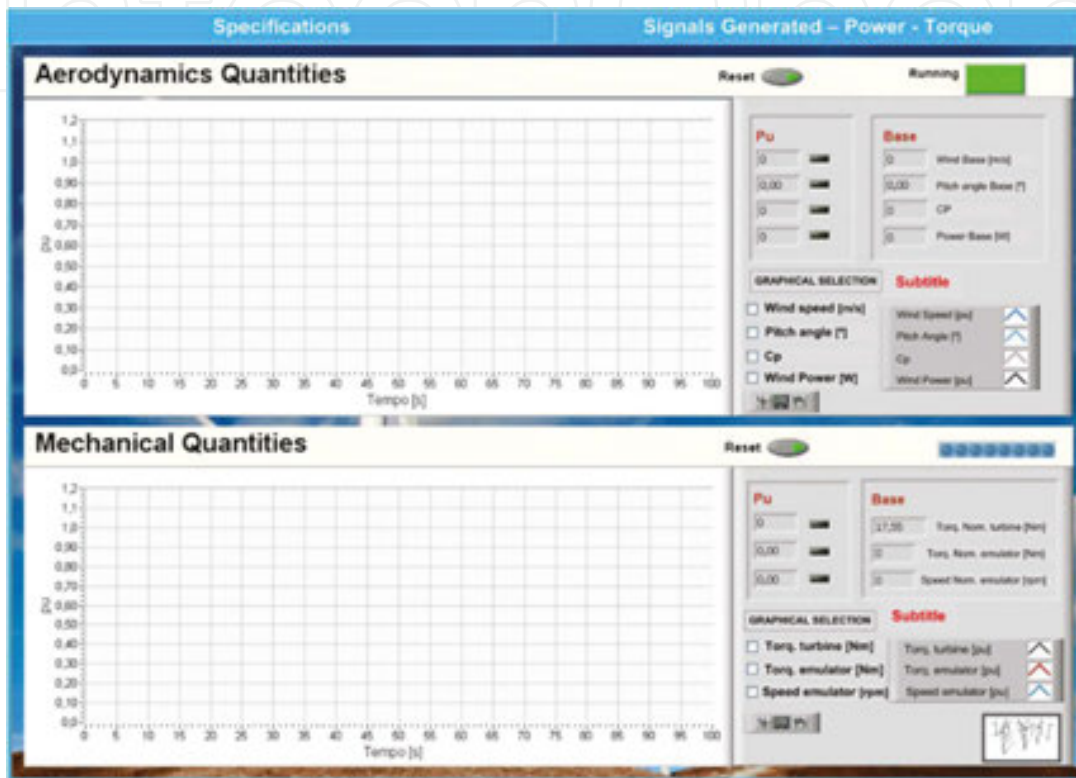


Figure 9. Emulator interface—screen used to present the generated signals.

4.2. Implementation of the drive system

The emulator drive is built using a motor-generator set based on IM-PMSG machines controlled in real time by the software platform. In addition, the drive can be designed to be flexible to receive future hardware upgrades or modifications and to be controlled by a high-level software. In this way, it is capable to emulate different WTs or even to use a new IM-PMSG set, such that it requires the user to inform the new parameters of the system in the GUI.

Since it is monitoring and controlling the system, a computing environment is responsible to provide the torque reference signal (T_T^*) according to mechanical speed (ωr) measure, and a wind speed to be emulated. The nominal torque (1 pu) to be emulated on the motor shaft corresponds to a load of 16.6 Nm. An acquisition board PCI-2511 performs the hardware-software interface circuit. Afterward, a digitally controlled PWM inverter is used as the IM drive. Moreover, to perform the drive, different approaches can be used. Either a commercial

IM drive system (CFW 11) or a DSP/microcontroller user programmable controller with a three-phase PWM inverter are possible choices.

The proposed emulator is a horizontal axis wind turbine (HAWT) with rated power of 2.2 kW. Hence, the nominal power of the IM-PMSG was defined as 3 kW. The IM has eight pole pairs, while the PMSG has four pole pairs. A torque transducer (T22WN) measures the mechanical torque signal developed in the shaft of the machines, which employs VK20A (commercial board) and TCB (user developed) conditioning boards to be read by PCI2511. An absolute encoder (AC58) measures the speed of the motor-generator shaft, which is read by the software through the PCI2511 and a SCB conditioning board (user developed).

Since the mechanical characteristics of the system are given by the IM-PMSG connection, the software obtains the real dynamic speed on the shaft of the machines. The rotational speed is one of the input variables for the aerodynamic model used to determinate TSR. The electrical system for wind system is composed of the real PMSG-load set. **Figure 10** shows the representation of the experimental emulator.

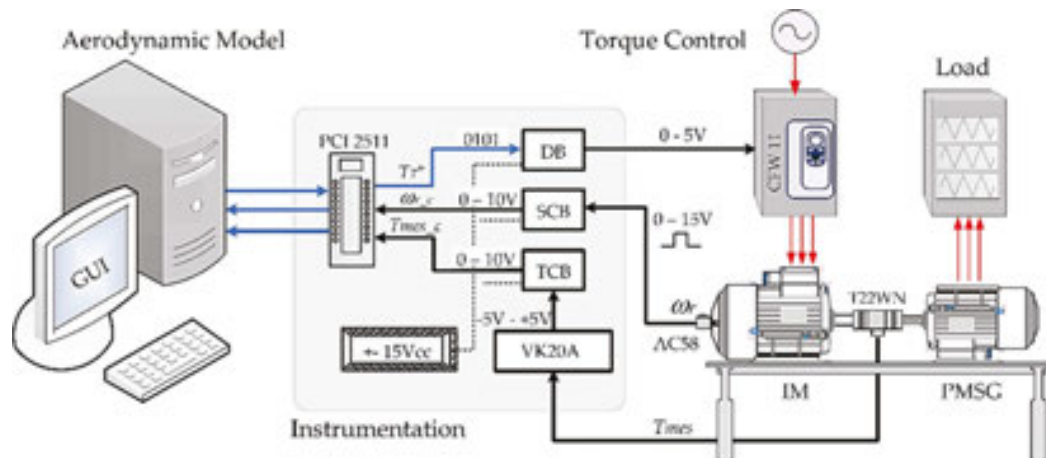


Figure 10. Representation of the wind turbine emulator experimental setup.

5. Emulator experimental evaluation

The emulator performance was analyzed considering two scenarios:

- Scenario 01: The emulation of the real system is carried out for different values of the operation curve of the WT, according to different wind speed profiles;
- Scenario 02: The emulation considers the wind turbulence, like steps and wind ramps.

Initially, the system is subject only to the aerodynamic conditions imposed by the wind speed changes. The emulator activation occurs after 20 s, due to torque control restrictions of the CFW11 drive. This drive requires the motor start at least 30% of its torque nominal. During the first 20 s, the setup operates in open-loop, in order to establish a constant speed in the shaft.

Then, the system starts to operate in closed-loop, where the mechanical speed dynamics feeds the WT model implemented in the computing environment.

In the first scenario, the analyzed operating points correspond to wind speeds of 10, 11, and 12 m/s. **Figure 11** shows the behavior of the WT for emulator running when the wind speed changes from 12 to 11 m/s at 43 s. After 94 s the variation of the wind speed occurs from 11 to 12 m/s, and at 135 s the execution of emulated system considers a wind step 12 to 10 m/s. As can be seen in **Figure 11**, when the wind speed V_w is reduced from 12 to 11 m/s, the power coefficient is not significantly affected (0.43), such that the absorbed power is reduced as V_w^2 and rotor speed and turbine torque are reduced as V_w . On the other way, when V_w diminishes from 12 to 10 m/s, the power coefficient also significantly decreases (under 0.4), and the absorbed power drops to 50%.

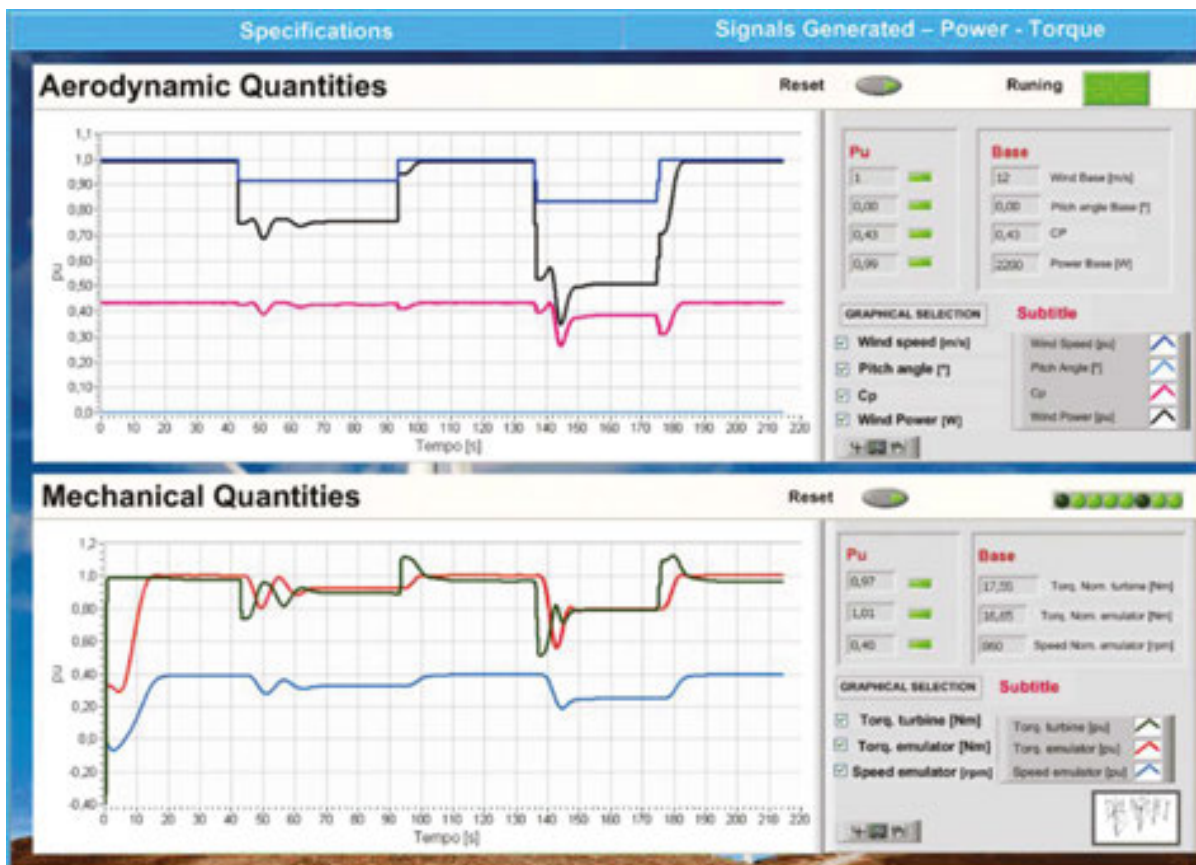


Figure 11. Operating dynamics for wind turbine emulation system.

Figures 12 and **13** show the waveforms of the real-time voltage and line current measured with a digital 1 GS/s oscilloscope in terminals of the PMSG for a resistive load. In these figures, the electrically generated quantities (voltage and current) vary according to the absorbed power when wind speed changes in **Figure 11**. A large transitory drop in generated quantities can be noted when wind speed changes from 12 to 10 m/s. This drop is due to the dynamics of the turbine torque reference and the IM drive (CFW 11) characteristics.

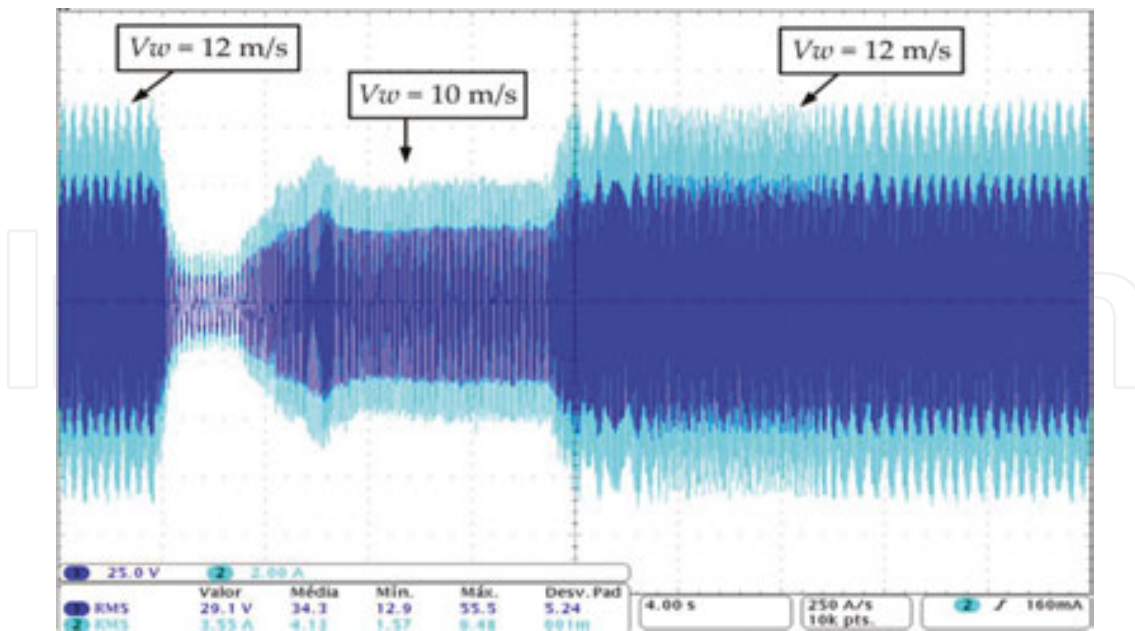


Figure 12. Voltage and electric current in the PMSG terminals for V_w changes from 12 to 10 m/s.



Figure 13. Voltage and electric current in the PMSG terminals for V_w changes between 12 and 10 m/s.

In order to check the response of the emulator in turbulence behavior within the nominal limits of the WT, the second scenario presents ramp conditions for wind speed. As can be seen in **Figure 14**, the setup exhibits high performance with significant variations in mechanical quantities, especially when drop variations occur in wind speed.



Figure 14. System emulator for the scenario with wind speed ramps.

It is possible to note the well working of system emulation considering consistent aerodynamic and mechanical quantities wind speed variation. In addition, due to the inertia of the turbine, rotational speed at the mechanical shaft does not respond instantaneously to changes in wind speed. The variation of the mechanical power available on the shaft of the turbine is 0.6 pu, corresponding to 1.3 kW. The C_p behavior shows greater variation during transitory, after the end of the wind ramp. After the transitory, C_p reaches its nominal value for 10 m/s wind speed. The variation of the mechanical torque on the turbine shaft is 0.4 pu, corresponding to 7 Nm. Since the mechanical torque in the shaft of IM-PMSG has also a variation of 0.4 pu, it features the same dynamics between the emulated system and the simulated one. Comparing the results from Simulink and LabVIEW is easy to note; the curves are very close. Small differences are present in mechanical torque since the simulator and the emulator drive applies different scales.

The performance analysis of the laboratory arrangement confirms that the emulator holds similar aerodynamic and mechanical dynamics to simulation models. In this way, the emulator can be used to design power converters as well as to check turbine dynamics in different generator/load arrangements.

6. Conclusion

This chapter presented the main steps for the implementation of a WT emulator through the torque control of an IM. First, it describes the simulation models and their verification. The simulator environment developed in Simulink/Matlab® can be used to analyze models and

check the emulator dynamics. Also, it presents the main concepts for building an emulator using LabVIEW, an IM drive, and an electrical generator.

An experimental evaluation presents emulator waveforms, which are compared with simulated ones in order to check emulator dynamics. Considering simulation and experimental waveforms for different wind conditions and their effects on several aerodynamic and mechanical variables, it is possible to validate the algorithm for WT emulation.

The described system permits a number of studies, such as

- design of power converters and correspondent control loops;
- implementation of the generator control to extract maximum wind power;
- implementation of computer platforms for other models of WTs, as well as for vertical axis WTs;
- an educational tool to teach main concepts of WTs and power conversion.

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