3 kW Wind Turbine Emulator Implementation on FPGA Using Matlab/Simulink

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Abstract- In this paper we present the interests of the hardware implementation of control algorithms for wind emulator based on DC-Machine. This work focus on modeling a horizontal axis wind turbine, a DC-Machine with independent excitation and its control via PI controllers and a fourth quadrant chopper by exploiting mathematical equations. Moreover, simulation results are analyzed and discussed using Simulink and XSG (Xilinx System Generator) showing the performance of our application. Through the tool XSG, algorithms are implemented on FPGA (Virtex-5 LX50T).

Keywords DC machine, FPGA, PI regulators, Control algorithms, XSG, Wind turbine emulator.

1. Introduction

The radical transformation of the way we use energy remains for researchers a futuristic vision. The exploitation of this energy is done through the conventional electric network to elucidate the perfect complementarities between energy production and distributed consumption. It is gradually transformed into a sophisticated and interactive smart model known as the smart grid concept. The use of renewable resources has been a great success in the industrialized countries and even in some developing countries since renewable energy sources are important parts of a power system. These energy flows are continuously regenerated by the rhythm of the sun and its derivatives. They are often expensive and sometimes inaccessible. So we proceed with emulators to work in an environment adapted to wind turbines and photovoltaic generators enabling the increase of research trial productivity. Various studies on control of wind turbine were performed [1,3]. Some authors [4,9] have used separate excitation DC machine to emulate the behavior of turbines. In [10] and [11], asynchronous machines controlled by IGBT converters have been also used as turbine emulator. The training of DC motor is easy to understand and the control of speed and torque is less complex than for asynchronous machines despite their low cost and mechanical robustness. For these reasons, and in order to have a more precise modeling of the turbine behavior by avoiding effects such as wind shear and inertia effect, we opt for a 3kW DC machine to emulate a wind speed turbine. Based on the established model, physical emulators have been built to test the interactions between the wind turbines and the power grid in real-time. Most of the wind turbine emulators require a torque controlled motor to represent the wind torque and turbine inertia and another to serve as the wind turbine generator [12], [4].

However, the context of these emulators requires the use of new methods for integrating control algorithms [13,15]. This is accomplished through digital circuits such as FPGAs targets or ASIC, microcontrollers and DSP. It is wise to rely on a more automated methodical approach to development, which solves the adequacy of control algorithm and architecture [15], [16].

This paper is organized as follows: The second section presents the description of the wind turbine emulator where wind, turbine, chopper and DC machine models are performed. The third section is devoted to study global wind emulator model using Matlab environment, including Simulink and XSG. Simulation results are presented and discussed in the fourth section and we finish with a conclusion.

2. Wind Turbine Emulator Description

Wind turbine emulator is a test device which offers a controllable environment of energy conversion system with variable speed. The general architecture of the chain of wind energy conversion is shown in Fig.1, which consists of three main blocks: the wind emulator, the generator and the converter. In fact, the wind emulator, including a wind turbine, converts kinetic energy into mechanical energy while the generator converts the mechanical energy recovered through the shaft of the motor into electrical energy. In this case, a converter is necessary as it provides the adaptation frequency of the electrical quantities coming from the generator and those networks.

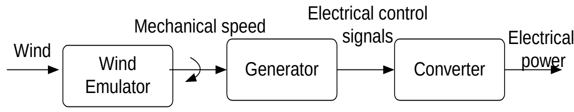

Fig. 1. General topology of wind energy conversion.

In order to make simulations and implementation of the emulator possible, several changes were made to the conversion structures to model and strengthen the control of their operations depending on weather conditions. The structure of wind turbine simulator is depicted in Fig.2.

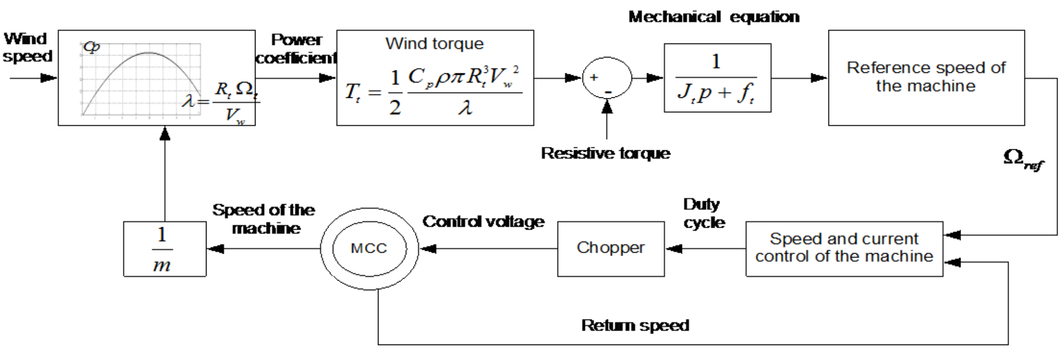

Fig. 2. Block diagram of the emulator.

2.1. Wind profile

Some studies [17] consider the wind as a stochastic quantity even if some of its features are deterministic. These studies decompose the wind in speed average component and high frequency fluctuations [18]. Other studies [19], [20] model the wind speed in determinant form of a sum of several harmonics. This is an excerpt from a sinusoidal model EDF France [20] field, given by the following equation (1):

$$V_w = 8.2 + \sin(\frac{2\pi t}{10}) - 0.875\sin(\frac{6\pi t}{10}) + 0.75\sin(\frac{100\pi t}{10}) - 0.625\sin(\frac{20\pi t}{10}) + 0.5\sin(\frac{60\pi t}{10}) + 0.25\sin(\frac{100\pi t}{10}) + 0.125\sin(\frac{200\pi t}{10}) \quad (1)$$

The wind energy is the input vector of a string conversion. Thus, dynamic properties are crucial for the study of the whole system. Sites are selected according to the speed and frequency of these winds. The behavioral model of wind is considerably simplified in order to validate the controls that we propose to design. It is modeled as a variable scalar function versus time [17] defined by the following equation (2):

$$\begin{cases} V_w = 4.1(1+2.t) & if \quad t < 0.5 \quad s \\ V_w = 8.2 & if \quad t > 0.5 \quad s \end{cases} \quad (2)$$

The result of both expression's simulation is represented by the following waveform as shown in Fig.3 and Fig.4.

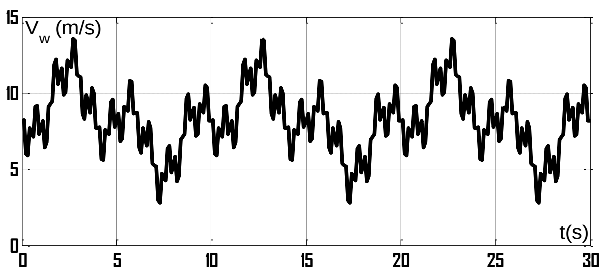

Fig. 3. Sinusoidal wind profile.

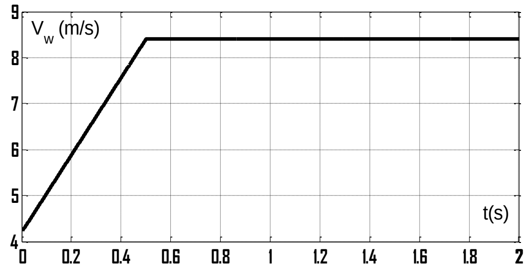

Fig. 4. Linear wind profile.

2.2. Power coefficient

The power contained in the form of kinetic energy through the wind increases with the cube of the wind speed and it is given by the following equation (3):

$$P_w = \frac{1}{2}\rho S\, V_w^3 \tag{3}$$

According to Betz 'law, this power can never be entirely removed. It is at most 59% of the kinetic energy of the mass of air flowing per second. The maximum power that can be collected by a wind turbine is equal to the Betz limit given by Eq. (4).

$$P_{\max} = \frac{16}{27} P_v = 0.59.P_v \tag{4}$$

We introduce the power coefficient C_p to calculate the power extracted. It expresses the aerodynamic efficiency of the turbine and its effectiveness in transforming the kinetic energy of wind into mechanical energy as given by Eq. (5).

$$P_t = \frac{1}{2}\rho\, \pi R_t{}^2 V_w{}^3 C_p \tag{5}$$

This coefficient is often expressed in terms of the angle of attack and the specific speed. It is a ratio of linear speed at the end of the turbine blades and the wind speed, defined by Eq. (6):

$$\lambda = \frac{R_t\, \Omega_t}{V_w} \tag{6}$$

Several expressions of C_p have been proposed and developed [21], we use two of them: the first one is a 3rd-order approximation which depends on λ. The second one depends on the pitch angle and the speed of wind turbine rotation. Thus, the first expression of C_p is modeled by a polynomial function Eq. (7):

$$C_p = -3.7e - 5\lambda^3 - 0.004834\lambda^2 + 0.1063\lambda - 0.02086 \tag{7}$$

The curve showing the variation of the variable C_p according to the reduced speed is illustrated in Fig.5.

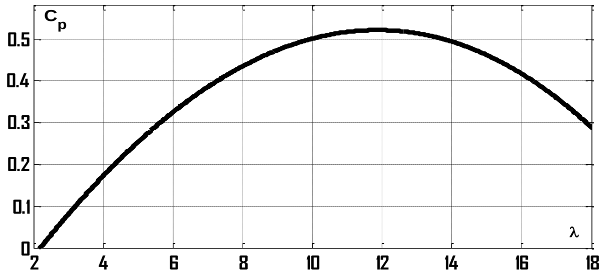

Fig. 5. C_p Characteristic depending on λ.

The second expression is given by the following equation (8):

$$C_p(\lambda,\beta) = \left[0.5 - 0.00167(\beta - 2)\right]\sin\left[\frac{\pi(\lambda + 0.1)}{18.5 - 0.3(\beta - 2)}\right] + 0.00184(\lambda - 3)(\beta - 2) \tag{8}$$

β is the angle of attack and control that can quickly retrieve the desired maximum power by the action on the electromagnetic torque and the turbine speed by adjusting the orientation of the wind blades despite fluctuations according to the direction and the speed of wind. Generally, for β=0, power coefficient is maximum [21]. The result of this equation is shown in Fig.6.

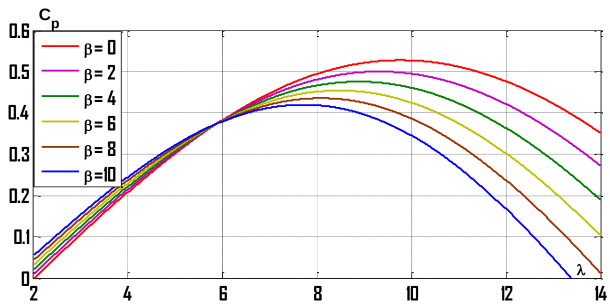

Fig. 6. Variation of power coefficient as a function of β and λ.

According to the two curves, it can be noticed that there is a maximum of 0.52 for a low speed of 10.2. So we can conclude that a turbine of radius R can recover a portion of the power contained in the form of kinetic energy of the wind.

On the energy front, several studies [22], [6], [11] have shown the value of the variable speed for wind turbine because the additional cost of the power electronics and the additional setting entrained by it is offset by the enormous electricity generation that it provides. Variable speed helps to smooth production through the enormous inertia of the blades.

The mechanical part of the turbine comprises three blades secured to a drive shaft rotating a velocity Ω_t which is connected to a gain multiplier m. This multiplier drives an electric generator. The aerodynamic torque of the turbine, by knowing its speed, is directly determined by Eq. (9):

$$T_t = \frac{P_t}{\Omega_t} = \frac{1}{2}\frac{C_p \rho S V_w{}^3}{\Omega_t} \tag{9}$$

By introducing specific speed λ in the previous relationship, the wind torque equation becomes as given by Eq. (10):

$$T_t = \frac{1}{2}\frac{C_P \rho \pi R_t^3 V_w{}^2}{\lambda} \tag{10}$$

Subsequently, we define the torque coefficient C_m by Eq. (11):

$$C_m = \frac{C_P}{\lambda} \tag{11}$$

Hence the expression of the turbine torque becomes in Eq. (12):

$$T_t = \frac{1}{2} C_m \rho \pi R_t^3 V_w{}^2 \tag{12}$$

According to the fundamental equation of dynamics, we can determine the evolution of the mechanical speed from the total mechanical torque T_{mec} applied to the rotor by Eq. (13) and Eq. (14):

$$J\frac{d\Omega_{mec}}{dt} = T_{mec} \tag{13}$$

$$T_{mec} = T_t - T_{em} - T_f \tag{14}$$

2.3. Electrical system

In this present work, we propose to develop the model of variable speed operation of 3 kW DC-Motor, 1500 rpm powered by a DC/DC converter. The renewed interest is due to the development of electronic components power and the appearance of the various structures of static converters. This orientation of choice is related to its structural simplicity and the ease of implementation of its equations. In fact, this machine has a great range of variation of the rotation speed, a good dynamic response and an excellent overload [23]. It is possible to define a general structure of a control system for electrical machines based on a reflection on the elements most commonly encountered in such systems [19].

3. The emulator implementation

3.1. Modeling with Matlab/Simulink

The purpose of modeling is to theoretically study the behavior of some parameters and optimize them within the constraints given by the system. Figure 7 shows the various blocks that constitute the emulator modeled with Matlab. After modeling the main blocs for wind turbine, the scheme developed with Simulink used for simulation is shown in Fig.8. It presents modeling C_p, the torque generation of the wind and the mechanical part of the turbine.

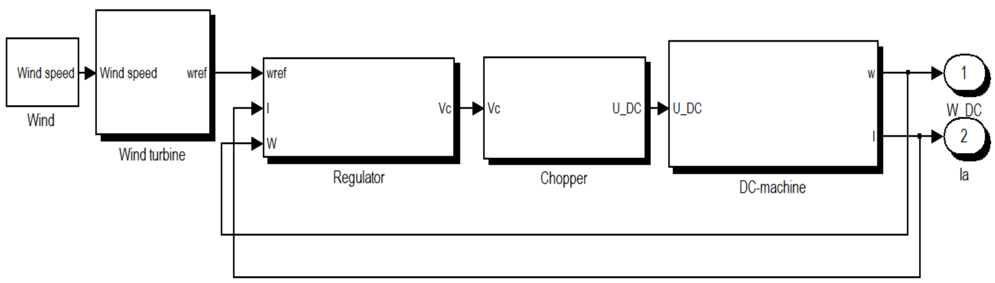

Fig. 7. Block diagram of global wind emulator model.

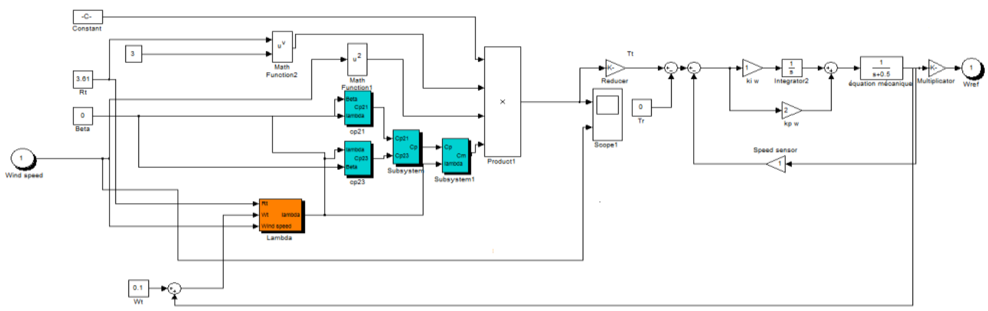

Fig. 8. Turbine implemented in Matlab/Simulink.

In the coming section, our interest is oriented to the control of speed in spite of the resistive torque and the armature current to synthesize the control law including the model of the machine and two control loops to describe the behavior of external signals to the system. Based on the principle of the multiple linear loop control in cascade, we propose to adopt proportional controller integrator (PI). It's modeling with Matlab/Simulink. The block diagram that models the DC machine controlled in closed loop allows us to visualize its speed and current as shown in Fig.9. The block diagram that models the DC machine controlled in closed loop allows us to visualize its speed and current as shown in Fig.10.

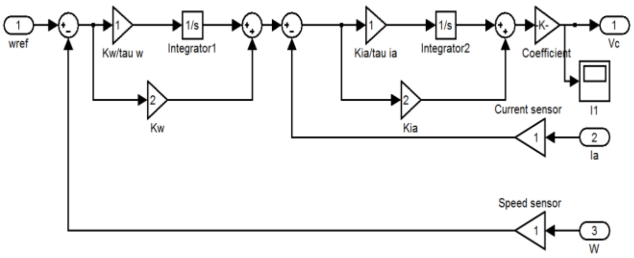

Fig. 9. Block diagram of the control loop.

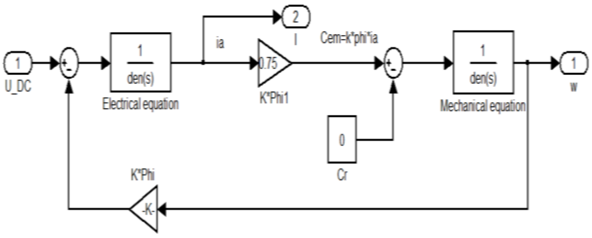

Fig. 10. Model of the separately excited DC motor.

3.2. Modeling with XSG (Xilinx System Generator)

With technological advancement in the field of microelectronics, new hardware design solutions such as FPGAs are reconfigurable and adaptable for operating control algorithms. In this section, we focus on the software implementation of wind power as well as control of the DC-Machine on FPGAs to take advantage from its performance in the field of digital control of rotating machines in real time to reduce investment emulator. The digital simulation is then an assessment strategy for process control systems. The performance of a control technique can be evaluated in respect with its ability to meet the basic requirements of control:

- Instant control must be precise enough.
- Robustness vis-a-vis the parametric variations and disturbances.
- The dynamic response must be rapid.

An integral methodology tools like (XSG), and Sim-Power-Systems (SPS) working in Matlab/Simulink provides a space for organic development that may change the direction of the research. These tools allow the development of this method, instead of their achievements in VHDL programming that requires pre-training, can avoid the costs and time for staff training necessary to learn VHDL programming. This tool provides rapid prototyping system to implement. It is much easier to analyze the results with Matlab than with the tools normally associated with VHDL as Modelsim. The XSG tool is used to produce a model that will immediately work on the equipment when completed and validated [24].

Initially, for the block modeling, we observe the existence of an integrator in the mechanical equation of the turbine as well as in regulators and since XSG library does not contain an integrator as in the case of Matlab/Simulink, then we are obliged to define the mathematical representation of a sampled integral to exploit in modeling the various system blocks as given by Eq. (15):

$$\int x dt \approx T_e \sum_{i=0}^{n} x_i \tag{15}$$

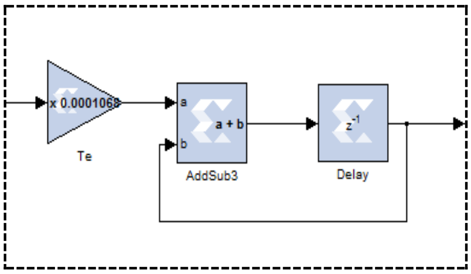

Fig. 11. Integral function using XSG tools.

As shown in Fig.11, we can ensure the desired result. First we try to test and simulate each block with XSG by comparing it with its reference model treated with Matlab/Simulink in a simultaneous manner as shown in Fig.12 since the error produced by a given function may affect the result of the command. Indeed, each block is a clearly defined function so that the model gives a confused result with it reference. Each block of this method requires a System Generator taken to be placed on the diagram, is not connected to anything, which is used to drive the process of implementation of FPGA and two blocks called "Gateway in" and "Gateway Out" define the limits of the FPGA from the simulation model Matlab/Simulink.

After checking the output of each block, the complete model is inserted to obtain the desired result. Fig.13 shows the blocks modeled with Matlab/Simulink and XSG. This speed is connected to block "regulators" to provide the control voltage of the chopper as shown below. The two inputs i_a and w are recovered by the speed sensor and the current sensor of DC Machine.

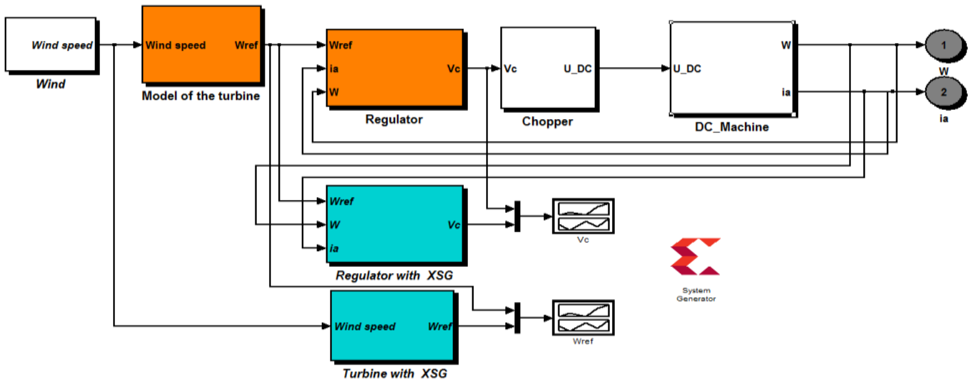

Fig. 12. Simultaneous simulation method.

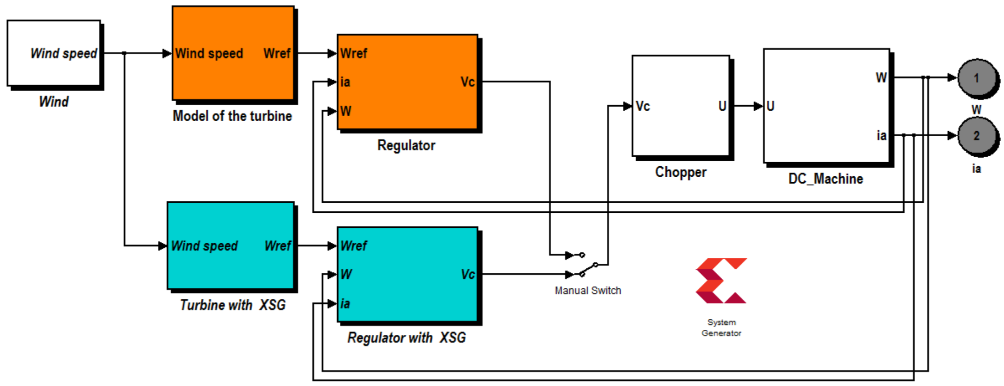

Fig. 13. Modeling of the turbine and the command using XSG.

4. Simulations and results

In this section, we present simulation results of the emulator outputs: C_{em} and Ω, using Matlab/Simulink and XSG tools. Results are obtained with respect to the turbine input according to Fig.3. Moreover, this particular case of constant wind speed is developed in order to verify results where the wind is rather dynamic. Using equations of section II, for V_w=8.2 m/s we obtain C_{em}=22 N.m and Ω =314 rad/s.

4.1. Simulation using Matlab/Simulink

Considering the wind speed waveform V_w, Fig.14 shows the time evolution of the turbine torque C_m and the DC machine torque C_{em}. Variation of the reference speed Ω_{ref}, current i_a and DC machine speed Ω are illustrated in Fig.15.

We note that the waveform of the emulated system speed Ω follows properly the wind speed fluctuation taking into account the equivalent mechanical inertia. The average value of Ω is about 320 rd/s, while the average value of V_w is about 9 m/s. This approximation deals with results obtained for the particular value of the wind speed presented above.

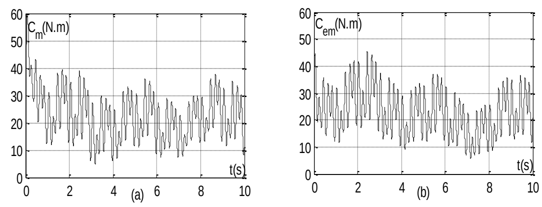

Fig. 14. Time evolution of the turbine torque (a: C_m) and the DC machine torque (b:C_{em}).

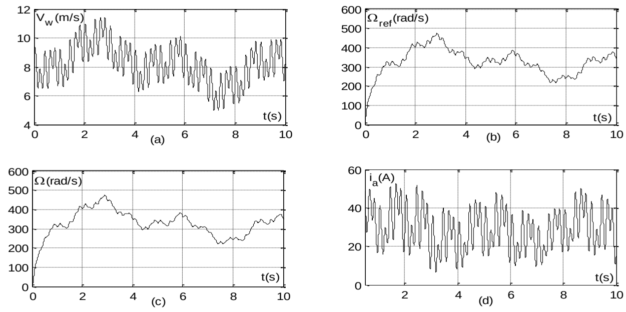

Fig. 15. Emulator outputs with variable wind speed (a:V_w), (b:Ω_{ref}), (c:Ω) and (d:i_a).

4.2. Simulation using XSG

In this section, we recorded the emulator response for constant and variable wind speed. Fig.16, Fig.17, Fig.18 and Fig.19 are results of simulation model using simultaneous method presented in Fig.12. Furthermore, Fig.20, Fig.21, Fig.22 and Fig.23 are given by the simulation of the model showed in Fig.13. Even though the algorithm and the simulation time are slow, we get a result very similar to the reference.

Comparing the simulation using Matlab/Simulink and XSG, we find that:

The simulation result of the wind turbine with Simulink and XSG shows that there's a slight difference due to the precision of the number of bits for each block that affect the final result. Furthermore, we have the control signal of the chopper coming in our application from the PI controller which varies from 0 to 10 V but with a variable wind, its value reaches up to 13 V.

According to Fig.21 and Fig.23, we note that the rotational speed of the machine increases rapidly with a no overflow until it stabilizes at a constant value almost equal to that of the reference (314 rd/s) with no resistive torque.

Concerning the electromagnetic torque, it has in transitory regime an increase oscillatory, and then it goes down almost instantly to its reference value of 22 N.m.

For the current, it is characterized by a high starting current which enables the engine to develop a maximum power to achieve the desired speed, then it stabilizes at its nominal value of 27 A. An expansion in the current during the steady state allows detecting a distortion lower.

Compared to the simulation using Mtalab/Simulink, we note that the XSG solution has less ripple in terms of variation of the current and speed, XSG solution gives the same results as Matlab/Simulink with an improvement in minimization level ripples.

It follows from the foregoing that the development method XSG is a real alternative to the method of VHDL programming to implement on FPGA. But after the simulation it is clearly noticed that this method has some differences compared to the reference due to the number of bits of accuracy and the use of the CORDIC algorithm for division, which provides a less satisfactory accuracy for its part and permits deviation of the signal. Also, its large size and limited execution speed may make it less attractive to a very complex application that already requires a lot of resources of the FPGA. The Mcode block supports a limited subset of MATLAB language which is useful for the implementation of arithmetic functions and the control logic.

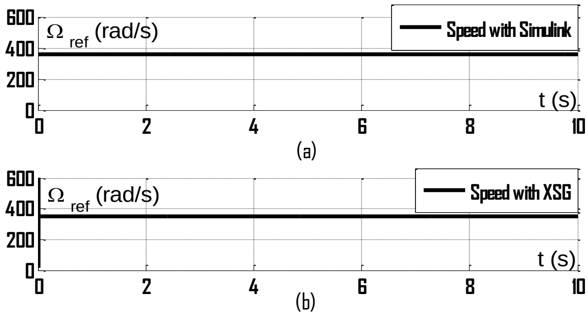

Fig. 16. Response of wind turbine at constant speed of wind.

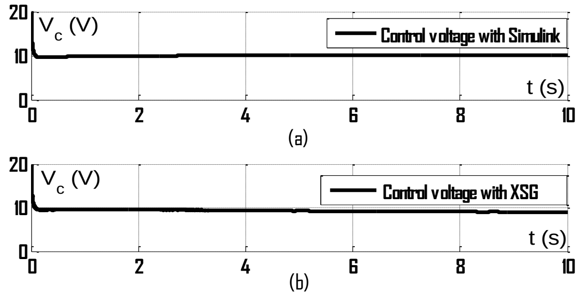

Fig. 17. Temporal evolution of the control voltage with constant wind.

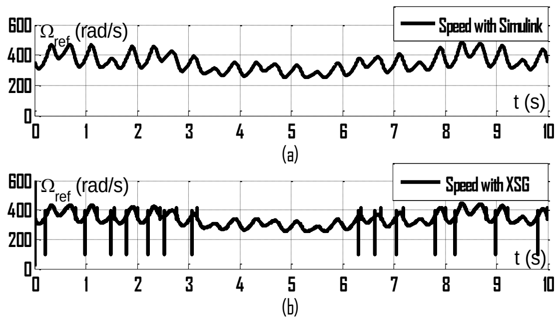

Fig. 18. Simulation of the turbine model at variable wind speed.

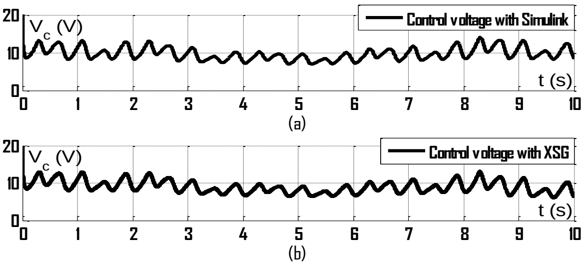

Fig. 19. Temporal evolution of the control voltage at variable wind speed.

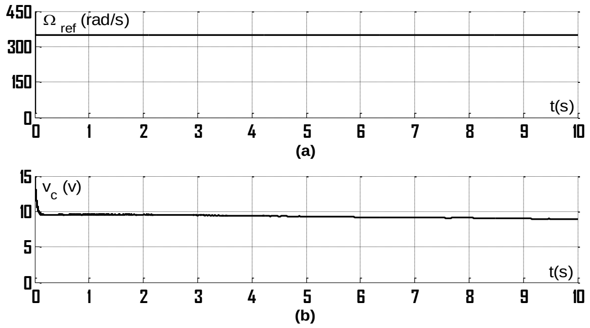

Fig. 20. Simulation of the emulator at constant wind speed with XSG (a: Ω_{ref}), (b:V_c).

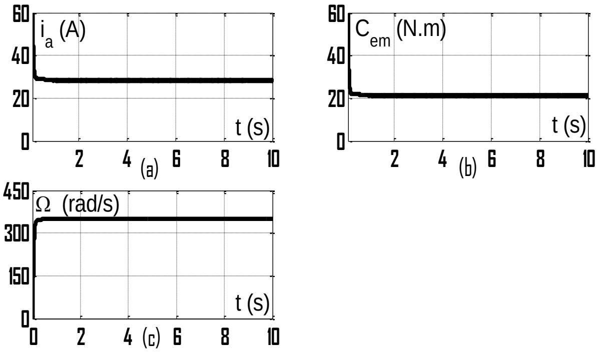

Fig. 21. Temporal evolution of various waveforms presented in the system: (a:i_a), (b:C_{em}), (c:Ω).

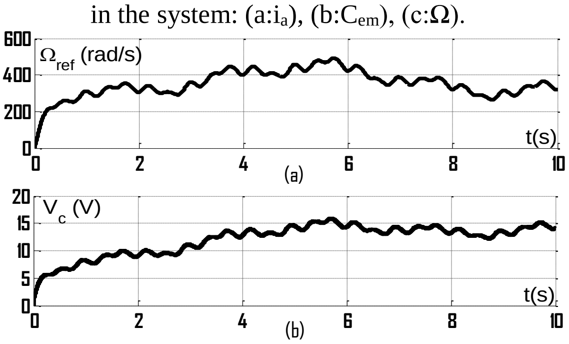

Fig. 22. Simulation of the emulator at variable speed of wind with XSG (a:Ω_{ref}), (b:V_c).

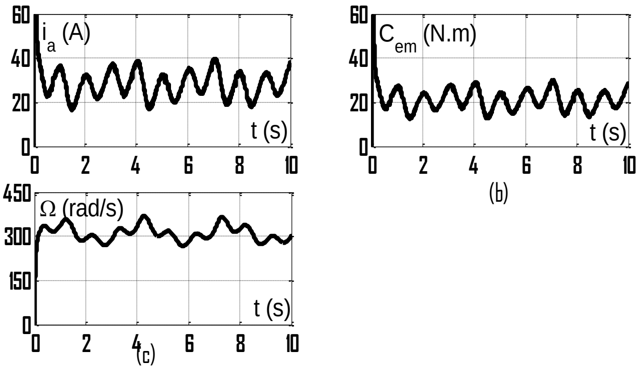

Fig. 23. Waveforms presented in the system of (a:i_a), (b:C_{em}), (c:Ω).

4.3. Hardware Co-Simulation

The use of FPGAs configured soft processor remains a very attractive choice for implementing many systems and application development since users can run their applications in two parts one such as software and the other as custom hardware implementation. We propose a hardware co-simulation of high level based on Matlab/Simulink environment for developing applications on FPGA. This tool integrates simulation capability with a hardware implementation to verify functionality of the system. Figure 23, Fig.24 and Fig.25 show the simulation result of this method. After the simulation is completed the results should be displayed as shown in Fig.24. We can verify the results by comparing the simulation output to the expected output.

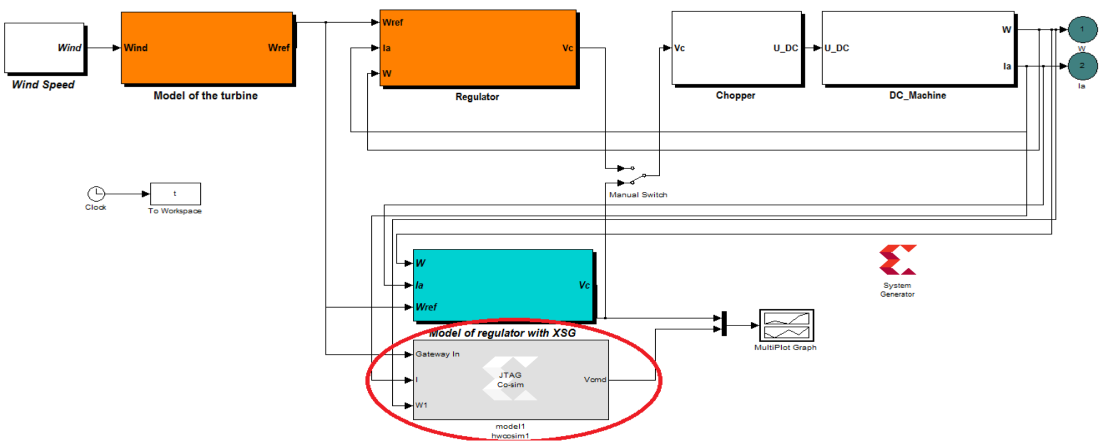

Fig. 23. Simulation and verifying the result for HW/SW Co-Simulation.

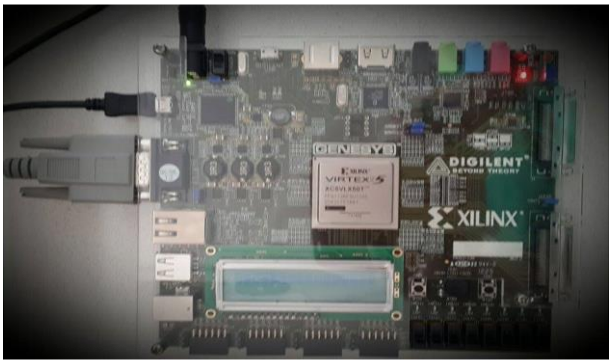

Fig. 24. Implementation of algorithm on FPGA.

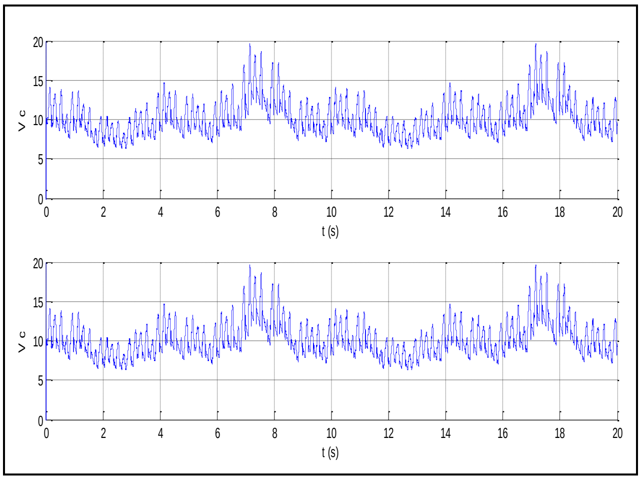

Fig. 25. Simulation of V_c with Hardware Co-Simulation.

5. Conclusion

The importance of renewable resources resides in its power to meet the world's energy needs as they evolve rapidly. Wind energy and solar energy are proven economic sources. Their use suffers from the high cost of wind turbines and solar cells, the low yield, and power fluctuation due to atmospheric conditions.

This work proposed a complete model of wind turbine simulator. We present here a structure based on 3 kW DC machine entrained by a wind turbine model. In fact we are interested in implementing algorithms on FPGA in terms of control of the machine. In order to reduce the complexity of the VHDL programming, a systematic approach, XSG, used in Matlab/Simulink.

The simulation results show that wind turbine simulator modeled with Simulink and XSG reproduces the turbine behavior. The development of this platform will allows us to perform our experimental test bench which is a wind–photovoltaic hybrid emulator.

Acknowledgements

Wind turbine data: $R_a = 1.086\ \Omega$, $L_a = 0.01216$ H, $R_e = 180\ \Omega$, $L_e = 71.74$ H, $J = 0.04251$ kg.m^2, $f = 0.003406$ N.m.s^{-1}, $n_p = 2$, $K_e = 0.75$, $\Omega = 1500$ tr/min.

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