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Wind Turbine Emulator Development Using Labview FPGA

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ABSTRACT

The paper presents a Hardware in the Loop (HIL) emulator for a wind turbine system, developed for the laboratory testing of a PMSM generator and the associate power electronics and control integrated in a microgrid laboratory. The emulator includes: a Lab View real time model of the wind turbine, an induction machine drive with direct torque control (the wind turbine mechanical system equivalent) coupled with the real generator and the corresponding load. Experimental results are also presented to validate the wind turbine emulator.

Keywords: Emulator, wind turbine, FPGA, real time target, Hardware In the Loop

INTRODUCTION

Hardware in the loop or HIL is relatively new strategy for testing software for control of real world applications. HIL is a development process which is centered around a system model, from requirements capture and design to implementation and test. During the development of the control system the controller is developed using a generation of system design processes on the of graphical models developed in specialized software to design, analyse, and implement the software that models process performance and behaviour. One of the steps of Model Based Design is Processor-in-the-Loop. During the processor-in-the-loop (HIL) phase the control algorithm is compiled and downloaded into an embedded target processor and communicates directly with the plant model via standard communications such as Ethernet, Modbus Etc.

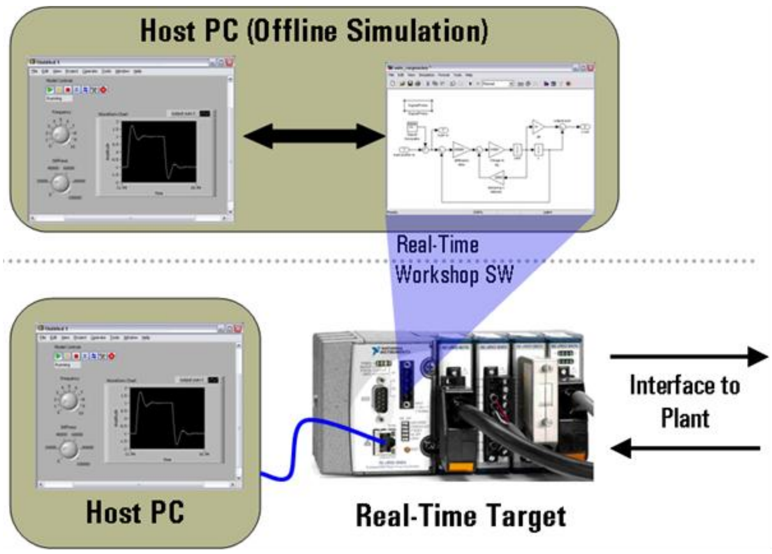

Figure1. *HIL concept for emulation*

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The plant model however is modelled using a high degree of fidelity using either Matlab/Simulink, C++, or any other modelling language. In this case, no I/O devices are used for the communication and the controller operates in purely virtual plant. The advantages of this method is that it can provide a real world controller to be test in a many scenarios configurations without requiring the presence of the real plant. In this paper we present the development of a emulation for wind turbines emulation using the national Instruments CRIO platform.

There a many real-time hardware platforms to implement a prototype HIL. In this paper we consider the use of National instruments Compact RIO platform. Compact RIO is ideally suited due to its packaging, ruggedness, and flexibility. The Compact RIO embedded system includes a real-time processor that can execute control algorithms deterministically, perform data logging, serve up Web pages, etc. Compact RIO also has integrated in the chassis an FPGA, which provides the flexibility and performance for high-speed signal acquisition and generation. The NI cRIO 9068 is relatively new platform hardware/software development platform launched in 2008, which is based on the Zynq-7010 All Programmable SoC.(system on a chip)

The NI cRIO features 8 RIO (reconfigurable I/O) and the platform is based on a mix of discrete processors, FPGAs, and pluggable I/O modules. The addition of an FPGA into the NI RIO platform permits large performance improvements, on the order of 10x or more. This provides a significantly better performance in process-control loops for control applications based on the cRIO platform.

Figure2. *NI RIO 9068 Real time FPGA control*

REAL TIME EMULATION OF WIND TURBINES

In the renewable energy systems very often is required to face some design issues. The effective design of wind turbines relies on detailed knowledge of several distinct subject areas which are briefly summarised below

First the conceptual design problem of the blades in very complex since it is important to have the means of expressing the efficiency of a wind turbine. Fundamentally, the efficiency is the ratio of the actual power production of the machine to the total energy available, and gives a dimensionless power coefficient, CP, whose basic formula is given by Eq. 1.

$$C_p = \frac{P_{out}}{\frac{1}{2}\rho U^3 A} \qquad (1)$$

where ρ is the density of air (1.225 kg/m3)

U is the wind velocity (m/s)

A is the circular area swept by the turbine blades (m2)

$$\lambda = \frac{\Omega R}{U} \tag{2}$$

In the formula for CP, the maximum possible value is 0.593, known as the Betz limit. Because the Betz limit is derived from theoretical principles rather than with reference to any particular turbine design, it provides a fixed upper bound for the efficiency of any turbine. The actual value of the power coefficient is affected by the geometry of the rotor blades and also varies with wind speed[]. The interaction of these quantities can be captured with reference to another proportional characteristic known as the tip speed ratio, λ.

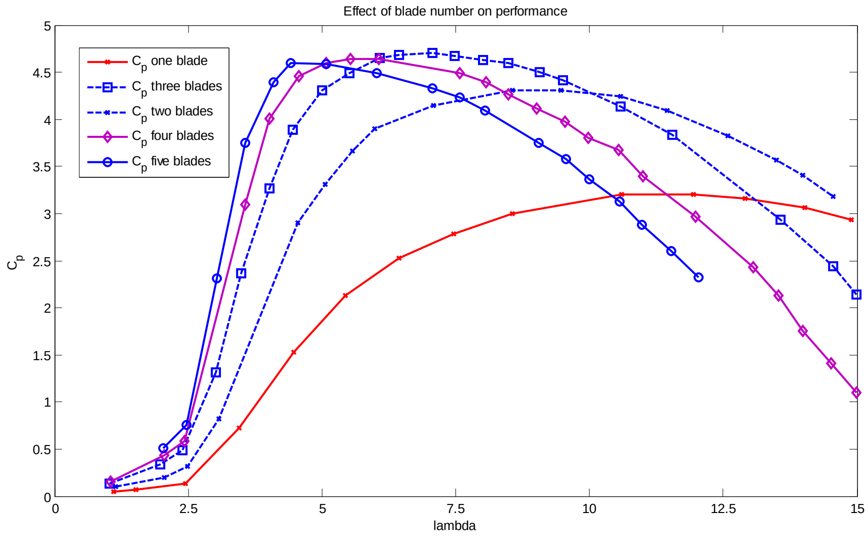


Figure3. *Power curves charatacteristic*

The power coefficient can be plotted against tip speed ratio for a given turbine design to give a characteristic performance curve wich can be used in real time emulation of the turbine. Figure 3 shows this curve for turbines with different numbers of blades. One may observe that fewer blades produce a broad, flat curve where C_P remains roughly constant over a wide range of λ, but the maximum value of C_P is low. More blades give a higher maximum value for C_P, but the curve has a narrow peak making the design sensitive to changes in λ. A design with three blades produces the highest maximum CP, but a two bladed design gives more consistent performance over a wider range of λ.

An very important performance indicator is the torque coefficient, C_T. the torque coefficient can also be calculated by dividing the power coefficient by the tip speed ratio for a given wind speed. This can be useful in determining instantaneous torque T using Eq. 3

$$T = \frac{1}{2}\rho \pi R^3 U^2 C_T \tag{3}$$

Another very important factor is the aerodynamic construction of the blades determines the torque generated by turbine, however the mathematical models used here are complex and require expert knowledge. In practice, the torque developed by a rotor is typically calculated on the basis of empirical measurements[].

The characteristic shape of the CP-λ curve for a turbine with a fixed blade pitch (see Figure 2) indicates that maximum efficiency is only achieved at a particular tip speed ratio.

By adjusting the pitch angle, however, a turbine can be made to maintain its rated power output at wind speeds higher than rated. Active pitch regulation requires that additional mechanical features to allow each blade to rotate about its own longitudinal axis. This necessarily includes a shaft and bearings for each blade, but the selection of individual or central actuator is a function of detailed turbine design

Finally the dynamic behaviour of the turbine can be represented by a simple two mass model (Figure 4) and equation 4:

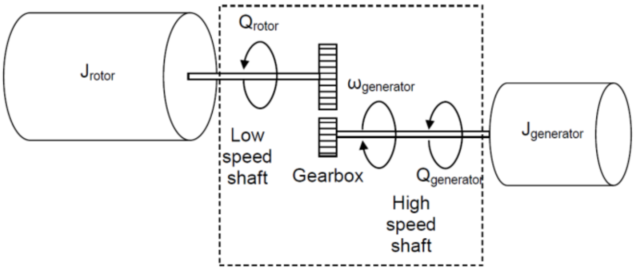


Figure4. *Two mass model of the wind turbine drive train*

$$\frac{T_{mech}}{n} = \left(\frac{J_{rotor}}{n^{2}} + J_{generator}\right)\frac{d\omega_{generator}}{dt} + T_{generator} \qquad (4)$$

where Tmech is mechanical torque

n is the gear ratio

J_{rotor} is the rotor inertia

$J_{generator}$ is the generator inertia

$\omega_{generator}$ is the rotational speed of the generator

$T_{generator}$ is the generator torque

the type of generator and the requirement for other electrical components depends on the detailed turbine design.

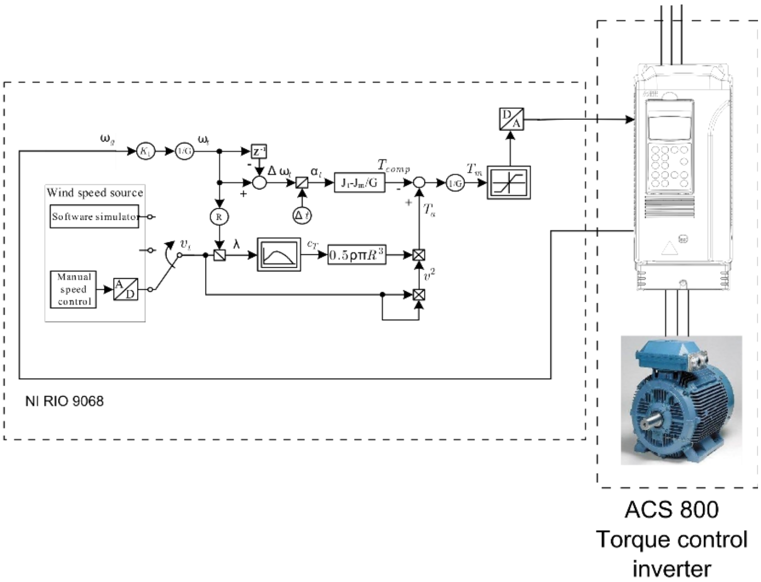


Figure5. *Proposed wind turbine emulator*

Using the previous equations a complete model of wind turbines can be assembled. The comple wind turbine model is presented in figure 5.

IMPLENTATION OF THE WIND TURBINE MODEL IN LABVIEW

The NI 9068 employes an Xillinx Artyx 667 MHz dual-core ARM Cortex-A9 processor, with 1 GB nonvolatile storage, 512 MB DDR3 memory. The architecture is hibrid since it incorporates two dual core ARM proceeesors and a FPGA. In our aplication the control task is performed by the FPGA and the comunication and data transfer is performed by the RT OS based on linux running on the ARM cortex processor.

Using the mathematical equations of the turbine the model was implemented in the real time NI RIO 9068 controler at the FPGA logic level. We have considered that if we use the model based on fpga logic we can take advantage fron the computational power of the Zynq core. Since the FPGA has a naturally a parallel data processing we can implement in this way a a micro wind farm emulator by using several emulation loops in paralel.

In Figure 6 is presented main FPGA Main VI. The VI contains a control loop running in parallel with an RT watchdog loop.

- The RT Watchdog Loop checks for a periodic comunication from the RT Main VI to ensure communications between RT and FPGA are maintained.

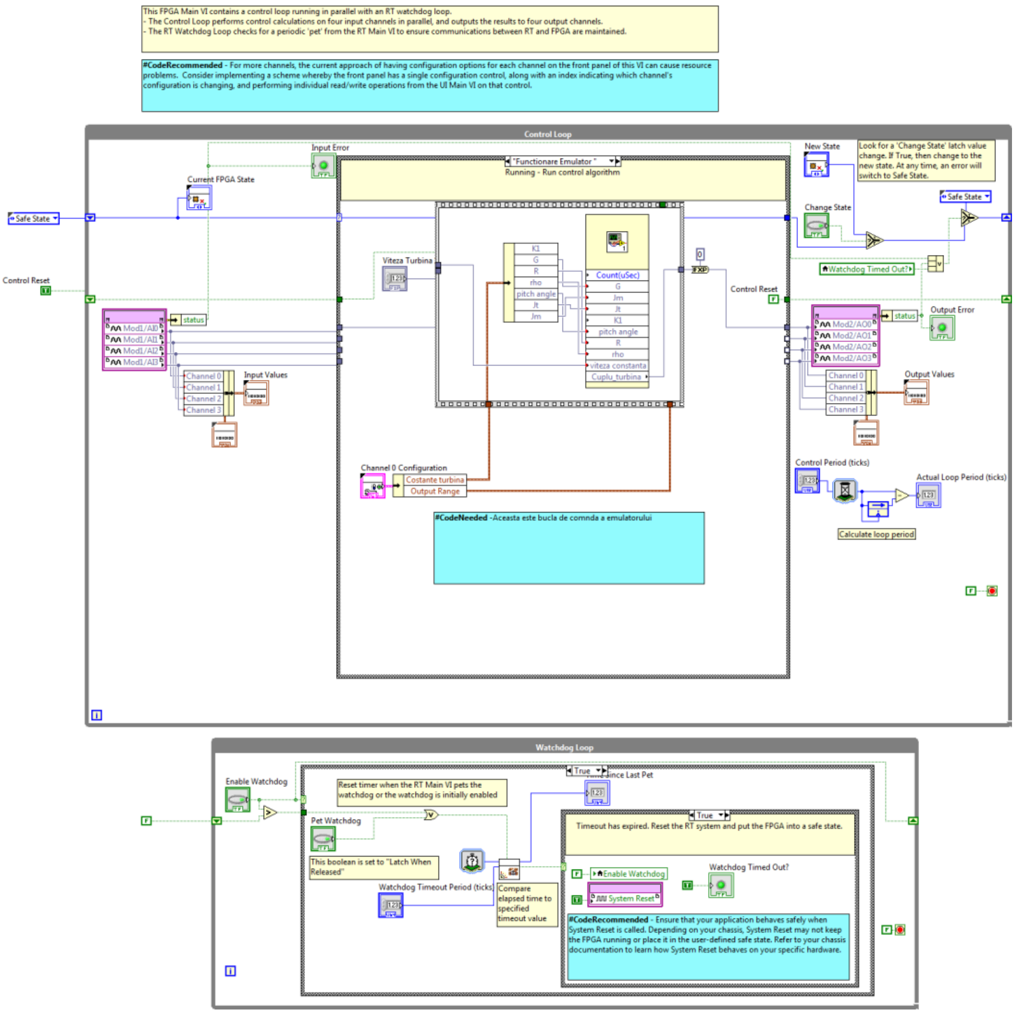


Figure6. *FPGA code for emulation*

- The Control Loop performs control calculations on four input/emulation channels in parallel, and outputs the results to four analog output channels.

The images above show the front panel and block diagrams of the example emulation algorithm. There are four analog inputs to the controller: reference wind speed, and speed are the measured torque and speed from the AC drive. The torque and speed can be measured from a dedicated torque or speed transducers or it can be obtained from the estimated torque/speed from the drive converter.

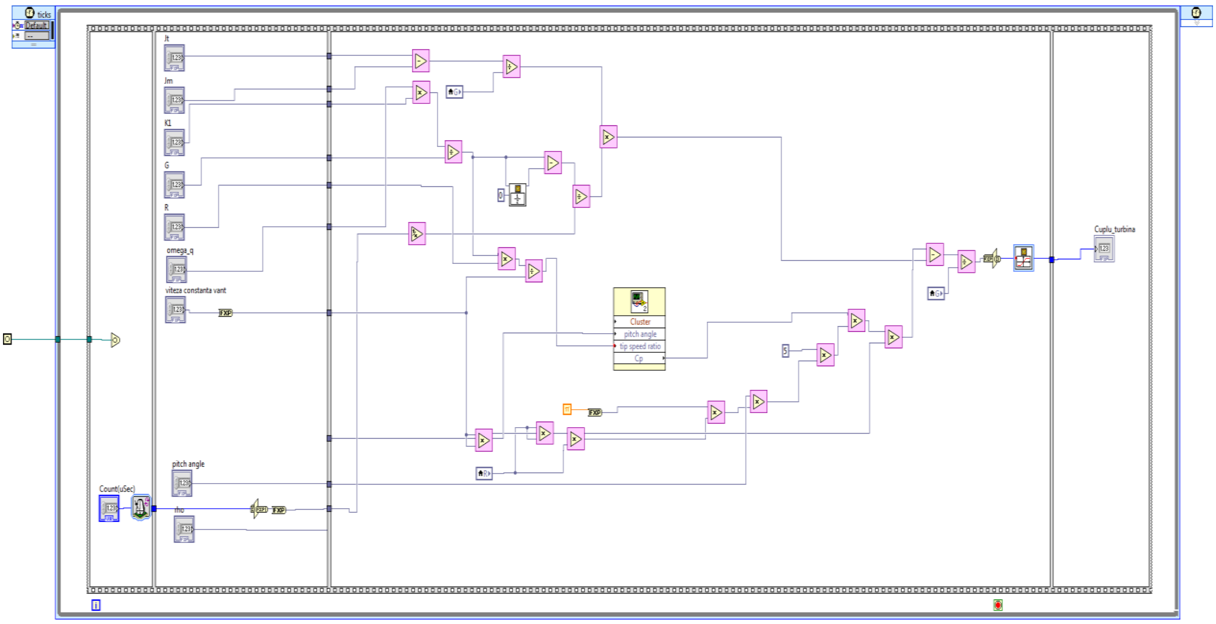


Figure7. *Wind turbine model with a parameterized* C_P

The charateristic curve of the wind turbine was implement in VI using a parametrized model.

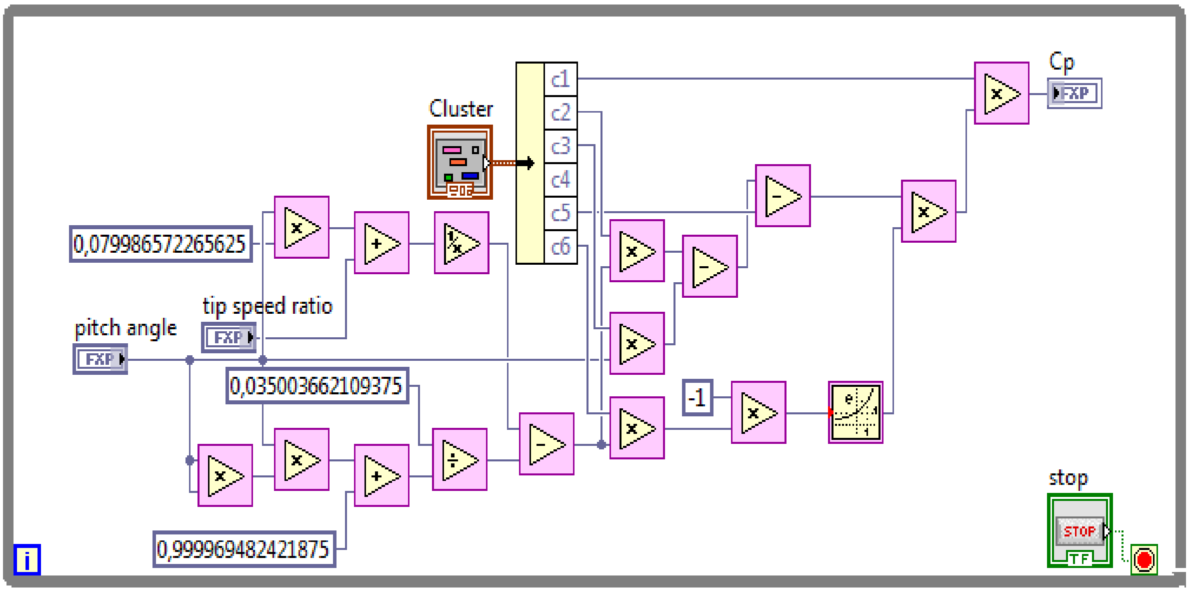


Figure8. *Power coeficient computation in labview using characteristic coffieicnts*

USER AND DATA PROCESSING INTERFACE

In figure 7 the RT VI comunication with the FPGA is presented. The comunication wit the RT host is realized using TCP/IP comunication. This way the sistem can be operated through internet remotelly.

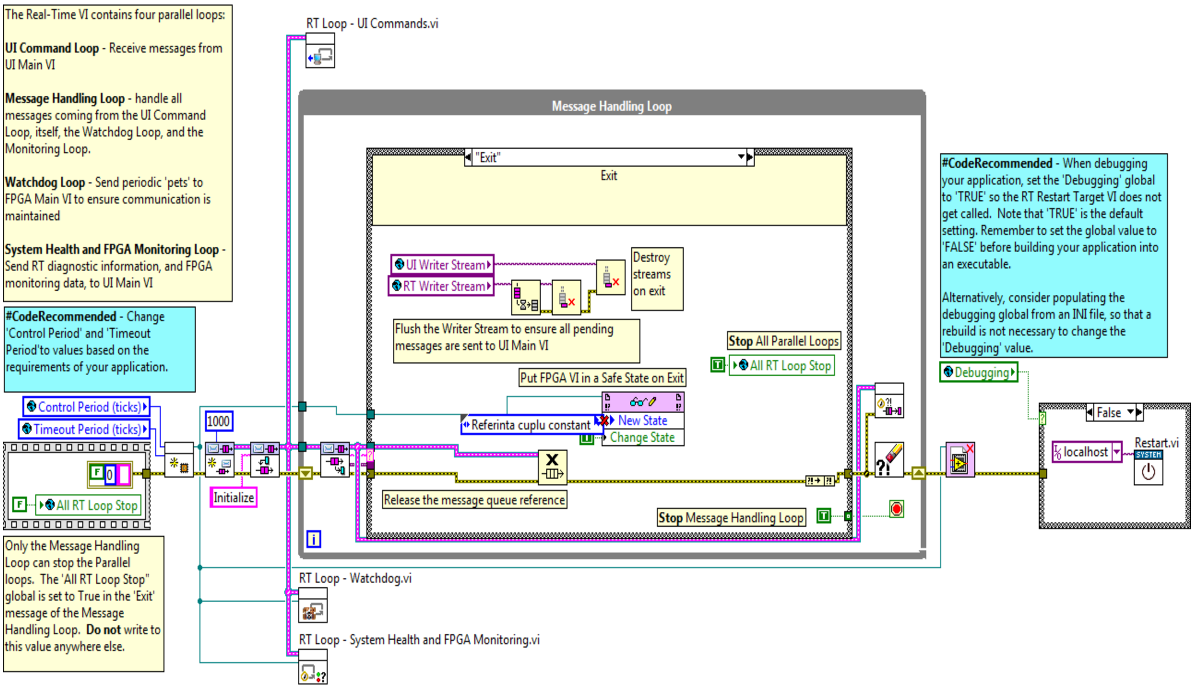


Figure9. *Real time code used for communication with the FPGA target*

The turbine simulator can perform satisfactorily under steady state wind profile and turbulence. The system could provide all necessary parameters of the wind turbine system such as wind speed, output torque, torque coefficient, output power, power coefficient, and tip speed ratio.

Theta is defined as the angle of the rotor, and is initialized so that theta = 0 at the rising edge of hall effect sensor . The speed setpoint is defined by the user, and the speed in RPMs must be calculated from hall sensor information, encoder sensor feedback or some other method of feedback.

Results and Discussion

The parameters of the emulator test bench are presented in table 1:

Table 1

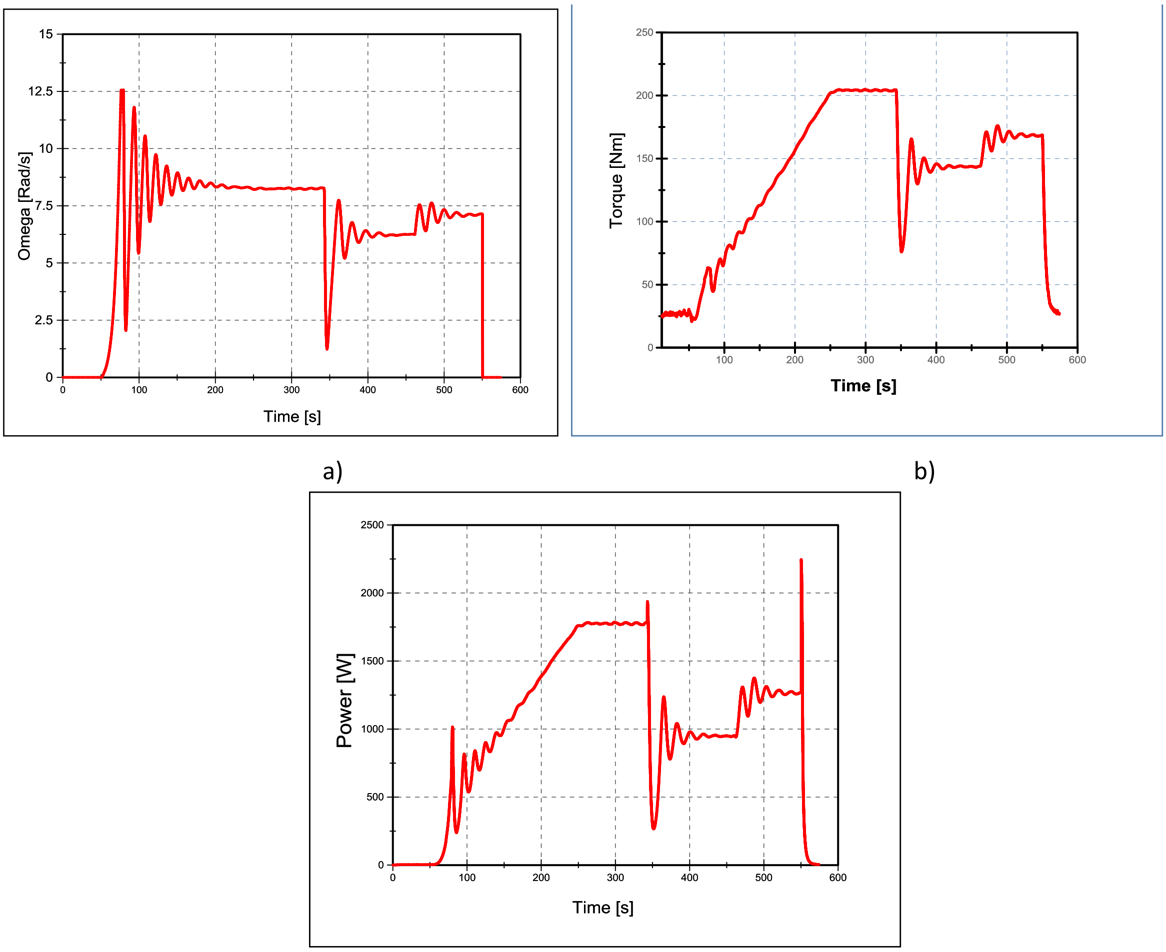
Rated power	Pn = 5.5 [kW];
Rated wind speed	v0 = 11 [m/s];
Maximum speed	n = 126 [rpm];
Pole pairs	pp = 16;
Rated power of the IM	PIM = 7.5 [kW];
Rated IM speed	nIM = 715 [rpm];
Turbine inertia	Jwt = 140 [kg·m2];
PMSG inertia	Jg = 1.05 [kg·m2];
IM inertia	JIM = 0.156 [kg·m2];
Hardware part of the emulator inertia	Jem = 6.68 [kg·m2];
Gearbox coefficient,	n = 6.03;
Blade swept area,	A = 19.6 [m2];
Radius of the turbine blade	R = 2.5 [m];
Maximum coefficient of power conversion	Cp = 0.42;
Nominal tip-speed ratio	
Constants for the nominal tip speed ratio	
a	$a = 0.0986$
b	$b = 0.0113$
C_{M0}	$C_{M0} = 0.0222$
Specific density of air	$\rho = 1.225$ [kg/m3]

The test generator was connected with a PVI-Wind Interface 4000 rectifier and PVI-12.5-TL-OUTD-W grid inverter [9] operating as load to the generator (Fig. 7).

a) b)

Figure10. *Experimental Setup: a) NI CRIO control board and the ABB PVI-12.5-TL-OUTD-W Wind Inverter[9]; b) IM, GB and PMSG.*

The behavior of the wind power system was studied by considering a step variation of the wind speed between 0 and 8 [m/s], with a time period of 100 sec.flowed by a drop off at 6 [ms] and an increase at 7 [m/s] , as it is shown in Figure . 11. The corresponding shaft speed, wind turbine torque and power are presented in Fig. 11 a, b and c.



a) b)

c)

Figure11. *The wind turbine shaft speed a), turbine torque b) and power c) measured from the wind turbine emulator.*

The good dynamic performance can be observed from the experimental results, which validates the good accuracy of the emulator. The system responses were tested considering a rectangular wind speed shape which is the most difficult regime that is never meet in real situations.

CONCLUSIONS

The development of the complex wind turbine emulator for multiple wind turbines power plant testing is presented. The developed simulator was implemented by a high-performance FPGA system controller developed by Lab view language. Wind speed can be easily programmed based on the wind power spectrum, or from recorded wind speed data or from manual set-up. The advantages of the simulators are that various wind profiles and wind turbines can be incorporated as desired in the control software and it includes the data acquisition to verify the control algorithms and display the parameters. The experimental results confirmed that the wind turbine emulator is operating accordingly to the expected performances.

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