WIND TURBINE EMULATOR DEVELOPMENT USING NI CRIO9068 AND ABB ACS 800 DRIVE

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Abstract: *The paper presents a Hardware in the Loop (HIL) emulator for a wind turbine system, developed for the testing in the microgrid laboratory of a PMSM generator and the associate power electronics and control. The emulator includes: a LabVIEW 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.*

Key words: *hardware-in-the loop, wind turbine systems, conversion control, direct torque control.*

1. Introduction.

Hardware in the loop or HIL [1] is relatively new strategy for testing complex systems for control of real applications. HIL is a development process, focused on a realistic process model, starting from requirements capture and design to implementation and test. During the development the controller, a plant model is realized using dedicated software capable to design, analyze, and implement the plant models with good dynamic performance and accurate behavior. After the control development the algorithm is compiled and downloaded into a real embedded target processor and communicates directly with the plant model via standard communications such as Ethernet, Modbus etc. The plant model however is modeled using a high degree of fidelity using Matlab/Simulink, C++, or any other modeling language. In this case, the I/O devices are used for the communication and the controller operates in purely virtual plant. The advantages of this method are 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 steps for an emulation system used for the evaluation of small power wind turbines (less than 10kW) using the National Instruments CRIO platform and ABB ACS 800 drive. The overall schematic is presented in Fig. 1. The structure comprises the software for emulating the wind turbine running on a real time controller NI cRIO 9068 programmable automation controller, a induction machine (IM) and electric drive from ABB respectively ACS 800. Using the real inputs from the drive (actual speed and torque of the IM) the resulting wind turbine torque and reference speed is obtained after the real time calculation of turbine parameters. The ACS 800 [8] provides the estimated load torque and actual shaft speed obtained from the reference IM model used in DTC control which is special feature implemented in advanced ABB drives. The reference model it is used as an estimator and its states and variables are computed every 10^{-4}s. The shaft speed is then imposed as a reference for the ABB ACS 800 induction motor drive which is in fact the executing element of the loop. The system components are presented in detail in the following paragraphs.

2. Emulation platform description

There a many real-time hardware platforms to implement a prototype HIL: PLC, real time embedded systems with microprocessor, DSP controlled systems, etc [3, 4]. For our system we considered the use of National Instruments CompactRIO platform (cRIO). The National Instruments CompactRIO 9068 is ideally suited due to its packaging, ruggedness, and flexibility for the control of industrial systems, motion control, data logging, signal processing [5].

The CompactRIO 9068 embedded system includes a dual core (Cortex A9) real-time processor that can execute control algorithms deterministically, perform data logging, operating a webserver etc [5,6]. CompactRIO also has integrated in the chassis an FPGA, which provides the flexibility and performance for high-speed signal acquisition and generation. However the usage of the FPGA architecture is very much eased since the FPGA core usage is accessible using the corresponding LabVIEW FPGA graphical programming module [7].

The NI cRIO 9068 is relatively new platform hardware/software development 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 based on a mix of discrete processors, FPGAs and pluggable I/O modules.

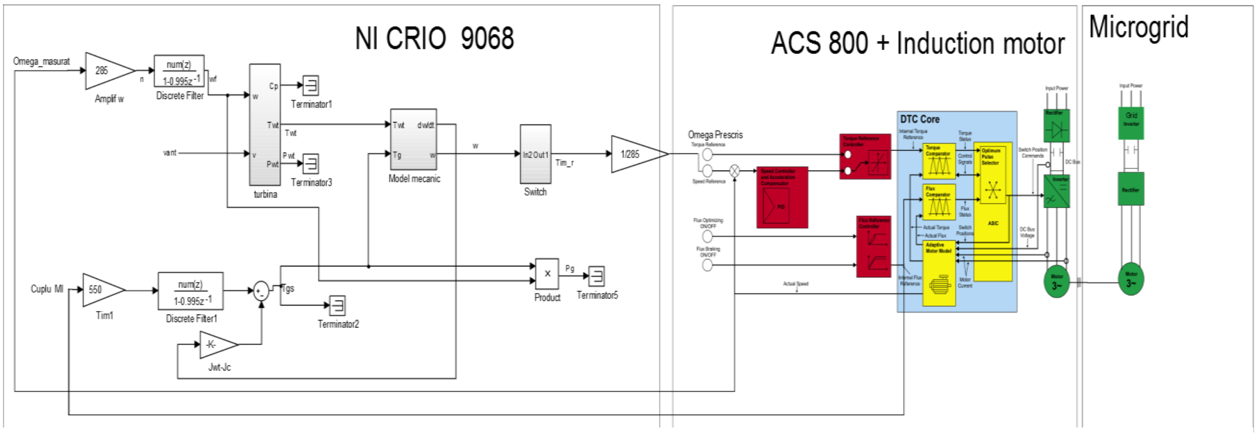


Fig. 1 HIL wind turbine emulator using NI CRIO and ABB ACS 800 drive.

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.

The development language is NI LabVIEW but it can integrate also VHDL or C++ code by means of specialized wrappers. The code developed is compiled and the downloaded to the real time target.

The benefit is that in an HIL application, the NI cRIO is capable to simulate/emulate a plant to be controlled with the same input/output and behavior so that the test can be performed safely providing information about many other parameters which cannot be easily measured [7].

3. Real time emulation of wind turbines using ABB ACS 800 DTC controlled drive.

The emulation system requires a high performance electric drive to be used capable perform an accurate response both in speed and in torque [8]. Among the possible solutions we have considered DTC an (direct torque control) controlled drive consisting in a ABB ACS 800 drive and a 7.5 kW squirrel cage induction motor. The reason for using ABB ACS drive is that this industrial drive uses DTC control algorithm to control torque and speed of the induction motor. Using the DTC control no tachometer or encoder is needed to feed back a speed or torque signal since this parameters are directly obtained from control algorithm. The motor state calculations are updated by the high speed digital signal processor at 40,000 times a second in the advanced motor software model Fig. 2. In DTC control the torque and flux are motor parameters that are being directly controlled, so there is no need for a modulator, as used in PWM drives, to control the frequency and voltage.

leading to a very good speed accuracy of 0.01 percent.

For emulation of electromechanical systems it is important also the dynamic speed accuracy represented by the time integral of speed deviation. Time integral of speed deviation is determined when a nominal (100 percent) torque speed is applied. For the ABB ACS 800 DTC dynamic speed accuracy is between 0.3 to 0.4% sec. close to the 0.1% sec. which represents servo drives performance [8].

4. Wind Turbine model development

The dynamics of the wind turbine can be described using the relationships [10-12],

$$T_{wt} - T_g = Jd\frac{\omega_r}{dt} \qquad (1)$$

$$P_{wt} - P_g = \omega Jd\frac{\omega_r}{dt} \qquad (2)$$

$$P_{wt} = 0.5C_p(\lambda)\cdot\rho\cdot Av^3 \qquad (3)$$

$$\lambda = \frac{R_m\omega}{v} \qquad (4)$$

where T_{wt} —wind turbine mechanical torque;

T_g —generator load torque;

v —wind speed;

A —sweeping area of the turbine rotor;

$C_P(\lambda)$ —turbine performance coefficient;

The turbine's $C_p(\lambda)$ curve can be obtained by field tests or from design computation [13];

λ —tip-speed ratio;

ω_r rotating speed [rad/s];

R_m —maximum radius of the turbine rotor;

The speed of the induction machine is not fed directly to the generator. Between the generator and the induction machine we have a gear box in order to adjust the speed to the necessary value for the generator.

In steady-state (neglecting the gearbox efficiency):

$$\frac{T_{IM}}{T_{wt}} = \frac{\omega_r}{\omega_{IM}} \qquad (5)$$

The control output signal (torque reference T_{IMref}) is send to the DTC inverter, which returns the real (estimated) IM torque (T_{IM}) and the drive (estimated) rotating speed (ω_{IM}). The wind turbine torque and power results from the wind turbine characteristics:

$$T_{wt} = \frac{1}{2} C_M \rho v^2 AR \qquad (6)$$

where C_M is the wind turbine torque coefficient. The expression was obtained from the wind turbine test in the form of:

$$C_M = C_{M0} + a\lambda - b\lambda^{2.5} \qquad (7)$$

where: a, b, C_{M0} are the constants for the nominal tip-speed ratio λ_0.

The power of the turbine is:

$$P_{wt} = T_{wt}\omega_r \qquad (8)$$

The inertia of the wind turbine system is composed by [13]:

$$J = J_{wt} + J_g \qquad (9)$$

where:

J_{wt} : inertia of the wind turbine [kg·m^2];

J_g : inertia of the PMSG generator [kg·m^2];

The hardware part of the emulator has itself the inertia Jem, composed by:

$$J_{em} = J_{IM} + J_{GB} + J_g \qquad (10)$$

where:

J_{IM} : inertia of the IM [kg·m^2];

J_{GB} : inertia of the gearbox [kg·m^2];

Because J_{em} is different than J, it is necessary to introduce compensation inertia in the emulator control J_c:

$$J_c = J - J_{em} \qquad (11)$$

The PMSG shaft torque T_{gs}, as emulator output, is:

$$T_{gs} = T_{IM}\frac{\omega_{IM}}{\omega_r} - (J_{wt} - J_c)\frac{d\omega_r}{dt} \qquad (12)$$

5. LabVIEW model of the wind turbine

The wind turbine equations were coded in LabVIEW graphical development environment. The LabVIEW Control Design and Simulation Module was used since it offers both hardware and software integration. It can use the integration of NI hardware and software to easily move from the design/simulation space to adding real-world data – both inputs and outputs. This feature is important for HIL applications where quick iteration between the simulated algorithms and real-world signals is crucial. The emulation algorithm requires deploying a simulated system in real-world conditions. The LabVIEW Control Design and Simulation Module have the ability to run in real time for increased performance and enhanced flexibility. The code is then deployed (without code generation) using LabVIEW Control Design and Simulation to the industrial NI CompactRIO hardware controller.

The virtual instrument diagram for the turbine under investigation is presented in Fig. 2. This VI is developed in Control and Simulation Module from National Instruments [6]. This module allows the usage of a similar blockset to the model developed in Matlab Simulink without the need to implement a full scale solver for the model. Hence it can access several build-in solvers like Euler or Runge-Kutta within the LabVIEW diagram. The complete model of the wind turbine is presented in Fig. 5.

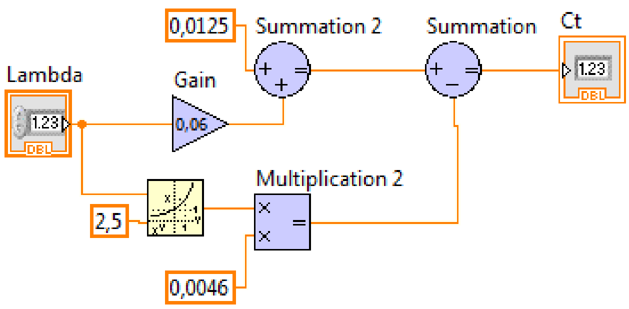


Fig. 2 The power coefficient Cp implemented build with in LabVIEW control and simulation module

The resulting model of the wind turbine is presented in Fig 4. The model is developed using a subroutine for calculating the C_p parameter (Fig. 3) and it has two inputs the rotational speed ω_r and the wind speed v.

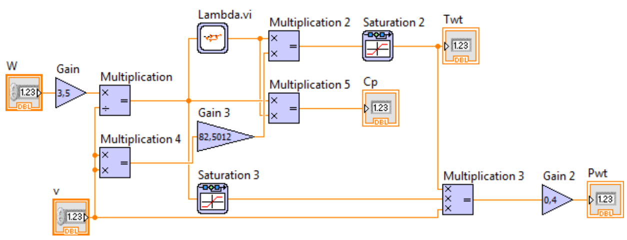


Fig. 3 Wind turbine model virtual instrument.

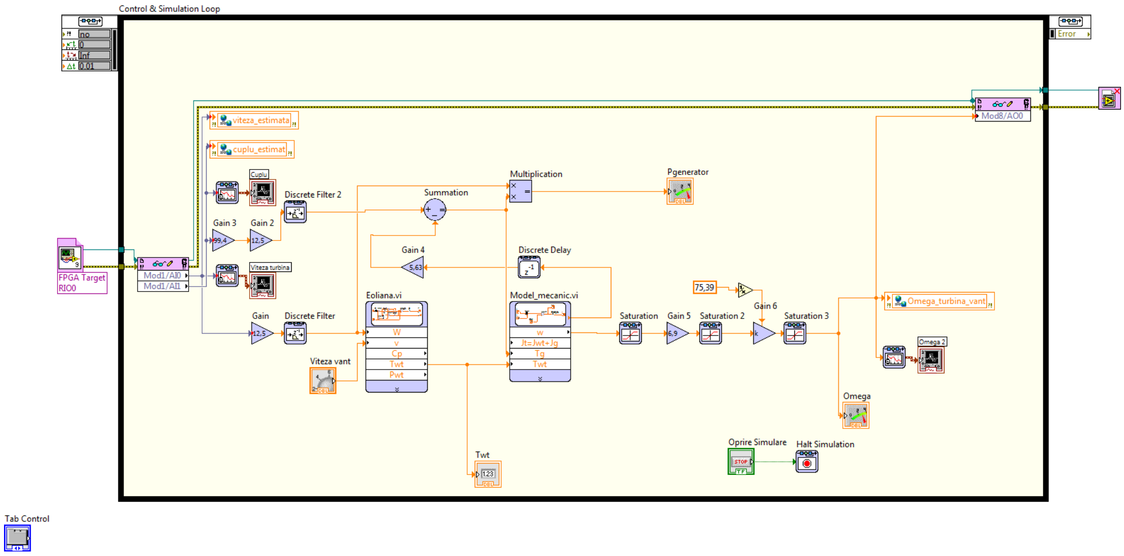


Fig. 4 The real time target virtual instrument representing the wind turbine emulator build in LabVIEW

The model diagram which is built in Control and Simulation Module needs to be processed in a special timed loop. This loop actually calls the solver for the processing of the model and deploying the simulated system to run on the real time target execution. The model is directly deployed (without code generation) using the code resulted from LabVIEW Control Design and Simulation diagram to the real-time target. However this solution is good for models which do not require a process speed above 1 kHz [7]. For applications were more computational speed is required the FPGA is needed to be used. In our case the time constants of the system and the complexity relatively small do not require a time step smaller then 0.02s. In order to operate correct the loop need to be synchronized with a clock source. This way the real time processing is enforced and the input and outputs of the model can be integrated with the other hardware models. We have used the 1 kHz clock of the real time target for this.

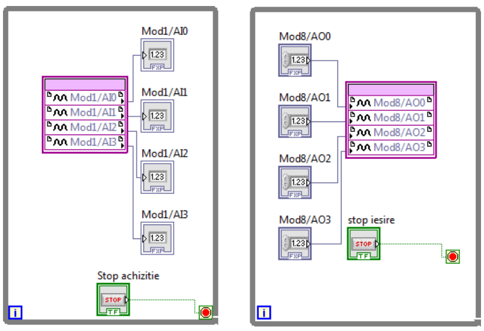


Fig. 5 LabVIEW FPGA virtual instrument diagram for signal acquisition and generation.

To test the control software in the experimental setup, the FPGA module of the NI cRIO 9068 must be programmed. However programming is done in a similar way to the build of a LabVIEW diagram using a special toolbox called FPGA module. In our case we have programed the module using two loops operating in parallel (the FPGA can do that with no time penalty) accessing two modules from the cRIO 9068: one analog input 9215 and one analog output 9263. The virtual instrument corresponding the data acquisition and signal generation is present in figure 5.

6. Experimental results

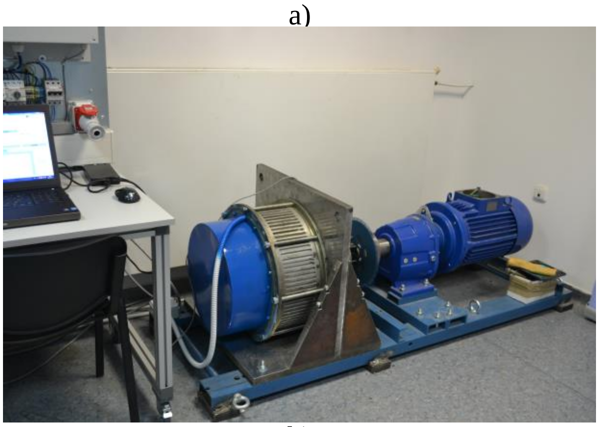
The parameters of the emulator test bench are presented in Table 1:

Table 1

Rated power	*Pn = 5.5 [kW];*
Rated wind speed	v_0 *= 11 [m/s];*
Maximum speed	*n = 126 [rpm];*
Pole pairs	p_p *= 16;*
Rated power of the IM	P_{IM} *= 7.5 [kW];*
Rated IM speed	n_{IM} *= 715 [rpm];*
Turbine inertia	J_{wt} *= 140 [kg·m2];*
PMSG inertia	J_g *= 1.05 [kg·m2];*
IM inertia	J_{IM} *= 0.156 [kg·m2];*
Hardware part of the emulator inertia	J_{em} *= 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	C_p *= 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	$\rho = 1.225\ [kg/m^3]$

The test generator was connected with a PVI-Wind Interface 4000 rectifier and PVI-12.5-TL-OUTD-W grid inverter produced by ABB operating as load to the generator (Fig. 6a and b) [9].

a)



b)

Fig. 6. Experimental Setup: a) NI CRIO control board and the ABB PVI-12.5-TL-OUTD-W Wind Inverter [9]; b) induction machine IM, gear box (GB) and permanent magnet synchronous generator PMSG.

The behavior of the wind power system was studied by considering a constant mean wind speed variation generated according to the recommendations in IEC 61400-3 concerning offshore turbines. The spectrum used is the Kaimal spectrum described by the following equation:

$$S_k(f)=\sigma_k^2\frac{4\frac{L_k}{U}}{\left(1+6f\frac{L_k}{U}\right)^{\frac{5}{3}}} \qquad (13)$$

where L_k is velocity component integral scale parameter, f is the frequency in Hertz, k denotes the velocity component, U is the hub height mean wind speed and σ_k is the variance determined by the turbulence intensity, T_i , given by

$$\sigma_x=T_i\left(\frac{3}{4}U+5.6\right) \qquad (14)$$
$$\sigma_y=T_i\left(0.8\sigma_x\right)$$

Lateral v_x and longitudinal v_y components of the wind speed fluctuations are obtained by relation

$$v_i(t)=\sqrt{2}\sum_{k=1}^{m}\sqrt{\left(S_k(f)\Delta n\right)}\cos(2\pi t+\beta) \qquad (15)$$

with $i=x,y$ (lateral, longitudinal direction), m is the harmonic (frequency) order, Δn is the frequency spacing and β a random phase angle. The wind profile is computed offline and it is used as time based look up table for the wind speed reference.

The mean value of the wind speed is around 6 [m/s], with a time period of 200 sec. A turbulence is simulated with a drop off at 3 [m/s] at 70 s from start as it is shown in Fig. 7. The corresponding shaft speed, wind turbine torque and power are presented in Fig. 7, 8, 9, and 10.

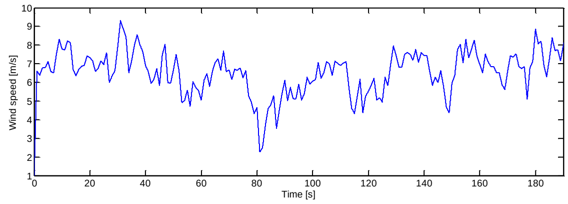


Fig. 7 Wind speed profile generated with Kaimal spectra

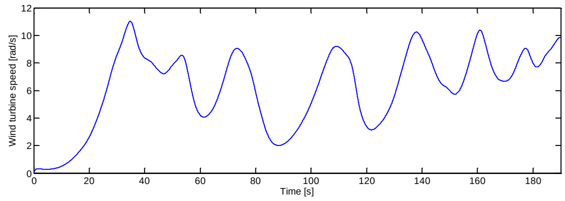


Fig. 8 Actual speed measured from generator/turbine shaft

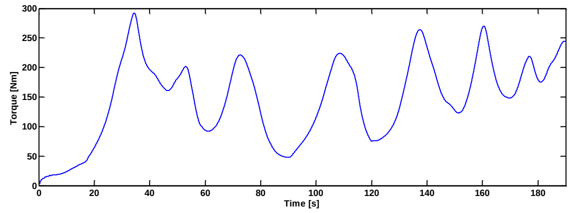


Fig. 9 Actual wind turbine torque

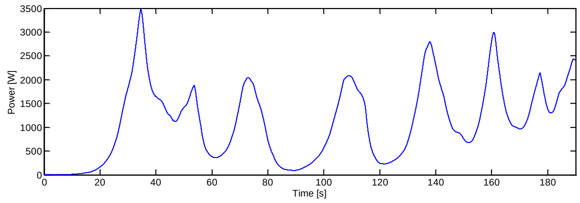


Fig. 10 Wind turbine power

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 real turbulent profile of the wind speed which is the most difficult regime that is found in real situations.

7. Conclusions

The development of the complex wind turbine emulator for multiple wind turbines power plant testing was presented. The developed simulator was implemented by a high-performance FPGA system controller and the algorithm is developed in LabVIEW graphical language. Wind speed can be easily programmed based on the wind power spectrum, or it can be taken from recorded wind speed data or it can be provided 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 also includes the data acquisition to verify the control algorithms and the dynamic display of the parameters for the wind turbine

The turbine emulator 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.

FPGA based emulation of electromechanical systems is a complex task but the NI LabVIEW graphical programming tools can provide a very fast solution. Also the ability to test/debug/validate LabVIEW code on the desktop using simulated inputs is a very useful feature during development stage. This can provide a confirmation that in all the situations the emulator works correctly providing matching results to the real time control results.

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