Experimental model of a wind energy conversion system

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Abstract. The renewable energy domain represents an important issue for the sustainable development of the mankind in the actual context of increasing demand for energy along with the increasing pollution that affect the environment. A significant quota of the clean energy is represented by the wind energy. As a consequence, the developing of wind energy conversion systems (WECS) in order to achieve high energetic performances (efficiency, stability, availability, competitive cost etc) represents a topic of permanent actuality. Testing and developing of an optimized control strategy for a WECS direct implemented on a real energetic site is quite difficult and not cost efficient. Thus a more convenient solution consists in a flexible laboratory setup which requires an experimental model of a WECS. Such approach would allow the simulation of various real conditions very similar with existing energetic sites.

This paper presents a grid-connected wind turbine emulator. The wind turbine is implemented through a real-time Hardware-in-the-Loop (HIL) emulator, which will be analyzed extensively in the paper. The HIL system uses software implemented in the LabVIEW programming environment to control an ABB ACS800 electric drive. ACS800 has the task of driving an induction machine coupled to a permanent magnet synchronous generator. The power obtained from the synchronous generator is rectified, filtered and sent to the main grid through a controlled inverter. The control strategy is implemented on a NI CompactRIO (cRIO) platform.

1. Introduction

Due to the increase in energy demand worldwide and environmental concerns, the world is going increasingly green (renewable energies) in its energy consumption. Use of wind energy for electricity generation purposes is becoming an attractive energy source. But, in order for wind power to compete effectively with fossil fuels as an electrical power generator in the market, the production cost must be comparable to that of fossil fuels. The initial capital investment in wind power goes to the machine and the supporting infrastructure. Any factors that lead to a decrease in the cost of energy (turbine design, construction or operation) are vital in making wind power competitive as an alternative energy source.

Hardware-in-the-loop (HIL) systems which replicate the behavior of the wind turbine are the main alternatives for laboratory-scale feeders. These provide a more cost-effective alternative to field testing [1]. In a HIL structure only one part of the process is actually used, the other parts are simulated in a controller board [2]. The controller board contains the mathematical representation of the real plant and all its related dynamic systems, being able, therefore, to simulate the complexity of the plant. The impact of the “missing” turbine components into the testing system is dependent on the exactness of the mathematical model. These mathematical representations are referred to as the “plant simulation” [3]. These modeled sources can be explicitly controlled and are not the whims of the weather and also
provide flexibility to change the characteristics of the sources as needed. By using such sources, the goal of this system is to use the given wind speed variations along with a software simulation of the turbine dynamics and related controllers to produce control signals that drive an appropriately sized motor and generator [4]. Wind, turbine and mechanical power train are emulated by a controlled induction motor to impose the dynamical behavior of the actual process on the generator shaft. Once connected to the feeder, the varying power produced by the generator will allow for a broader set of experiments dealing with the dynamic behavior of the wind turbine [4]. Such a methodology has been used in aeronautics, traction applications and electrical drives [2].

The advantages of this method are that it can provide a real world controller to be tested in many configurations without requiring the presence of the real plant.

This paper presents a Hardware-in-the-Loop (HIL) emulator for a wind turbine system, developed for the testing in a microgrid laboratory. The emulator includes: a LabVIEW real time model of the wind turbine running on a real time programmable automation controller, namely NI cRIO 9068, an induction machine (IM) drive with direct torque control (the wind turbine mechanical system equivalent), namely ACS 800, and coupled to an actual permanent magnet synchronous generator (PMSG) with the corresponding load [5].

2. Wind turbine

The wind turbine system is composed of a rotor that is connected to a permanent magnet synchronous generator [6]. These can be seen in Figure 1.

![Figure 1. The wind turbine main components](image)

The wind turbine output power varies with the wind speed:

\[ P_{\text{at}} = 0.5ApC_p(\lambda) = \rho v^3 \]  \hspace{1cm} (1)

where the speed ratio \( \lambda \) is defined as:

\[ \lambda = \frac{\omega R}{v} \]  \hspace{1cm} (2)

And the following denotations are considered:

- \( A \) : blade swept area [m²];
- \( \rho \) : specific density of air [kg/m³];
- \( v \) : wind speed [m/s];
- \( R \) : radius of the turbine blade [m];
- \( \omega_0 \) : rotating speed [rad/s];
- \( C_p \) : coefficient of power conversion.
The output power of a wind turbine is proportional with the cube of the wind speed. Larger rotors allow wind turbines to operate at higher wind speeds, increasing their output power. Because the area covered by the rotor is larger and so is the blades length, this leads to a large energy capture [7].

The mechanical part of the system is considered as a two-mass model, consisting of a large mass (corresponding to the wind turbine inertia $J_{wt}$) and a small mass (corresponding to the generator rotor inertia $J_g$). The dynamic equation is:

$$T_{wt} - T_g = J \frac{d\omega_r}{dt} \tag{3}$$

where:
- $T_{wt}$: wind turbine torque [N\(\cdot\)m];
- $T_g$: generator torque [N\(\cdot\)m];
- $J$: inertia of the wind turbine system [kg\(\cdot\)m$^2$]. This is composed of:

$$J = J_{wt} + J_g \tag{4}$$

where:
- $J_{wt}$: inertia of the wind turbine [kg\(\cdot\)m$^2$];
- $J_g$: inertia of the PMSG [kg\(\cdot\)m$^2$].

The corresponding power of the system can also be expressed as follows:

$$P_{wt} = T_{wt} \cdot \omega_r \tag{5}$$

From (1) and (5), the wind turbine torque has the following equation:

$$T_{wt} = 0.5 \rho \pi r^2 C_T (\lambda) \cdot v^2 \tag{6}$$

where $C_T$ is the wind turbine torque coefficient.

Expression (7) was obtained from the wind turbine test, where $a$, $b$, $C_{T0}$ are the constants for the nominal tip-speed ratio $\lambda_0$.

$$C_T = C_{T0} + a\lambda - b\lambda^{2.5} \tag{7}$$

The parameters of the considered wind turbine are presented in Table 1.

**Table 1.** The parameters of the considered wind turbine

| Parameter            | Value            |
|----------------------|------------------|
| Rated power          | $P_{r} = 5.5 \text{ [kW]}$ |
| Rated wind speed     | $v_0 = 11 \text{ [m/s] }$ |
| Maximum speed        | $n = 126 \text{ [rpm] }$ |
| Turbine inertia      | $J_{wt} = 140 \text{ [kg m}^2\text{] }$ |

As it was mentioned, one key component of the wind energy conversion system is represented by the electric generator. Most used is the permanent magnet synchronous generator (PMSG) due to its certain advantages:

- The rotor has no winding, containing only permanent magnets, and thus has no electric loss or thermal dissipation, increasing the generator efficiency.
- No need for electric circuit related to machine excitation system, reducing the control structure and increasing the overall reliability.
Due to the absence of the mechanical components such as brushes and slip rings, the friction and wearing is reduced, with benefits on the maintenance and reliability, also it lead to a decreased physical size, and a low moment of inertia [8].

The main disadvantage is related to the cost and availability of the permanent magnet.

It can be mentioned also the fact that the control is quite simple because the permanent magnet assures a constant excitation, and the generator output voltage is variable and directly influenced by the rotor speed [9]. This is not a real limitation since proper developed control strategies can assure desired performances.

The parameters of the considered PMSG are presented in Table 2.

| Parameter                | Value                  |
|--------------------------|------------------------|
| Rated power              | $S_n = 5 \text{ [kVA]}$ |
| Rated current            | $I_n = 12 \text{ [A]}$  |
| Rated speed              | $n_n = 120 \text{ [rpm]}$ |
| Rated frequency          | $f_n = 32 \text{ [Hz]}$ |
| Number of stator slots   | $N_c = 33$              |
| Pole pairs number        | $p_p = 16$              |
| PM flux                  | $\Psi_{PM} = 1.32 \text{ [Wb]}$ |

The wind turbine characteristics, representing the captured power versus the rotating speed, at constant wind speeds, have the allures as depicted in Figure 2.

![Wind turbine power characteristics](image)

**Figure 2.** Wind turbine power characteristics

It can be noticed a maximum power point for every wind speed at an optimum rotor speed, highlighted in the picture with the symbol “*”. Also the maximum torque point has its correspondent optimum value of the rotor speed as shown in Figure 3.

In order to provide the maximum power for the available wind condition, the wind turbine has to operate continuously in the maximum power point. This can be assured by using a maximum power point tracking algorithm (MPPT). As it can be noticed in Figure 2, for a constant wind speed, the provided power and angular speed increase until MPP is reached, and after that, the angular speed...
continues to increase while the provided power decreased based on the particular turbine specifications.

![Wind turbine torque characteristics](image)

**Figure 3.** Wind turbine torque characteristics

3. **Wind turbine emulator**

The wind turbine emulator consists essentially of two main components:

- **A software system** which implements the mathematical model of the wind turbine.
- **A hardware system** that provides the similar static and dynamic characteristics as the real studied system.

The software system includes a variable wind speed profile generator and a wind turbine aerodynamic model. The software system is deployed on the controller board, namely NI cRIO 9068. The wind turbine equations were coded in LabVIEW graphical development environment. The code is then deployed to the industrial NI CompactRIO hardware controller. The diagram of the program can be seen in Figure 4 and the front panel is depicted in Figure 5. The NI cRIO 9068 is represents a hardware/software platform for development of flexible applications of signal processing, data logging and industrial process control. The NI cRIO features 8 RIO (reconfigurable I/O) modules, however in this case, only 2 modules are used: one as an analogue input and another as an analogue output. CompactRIO also includes a dual core processor and an integrated FPGA, which provide the support for high-speed signal acquisition, assuring real time processing. The programming language is NI LabVIEW, but it can integrate also VHDL or C++ code by means of specialized wrappers. In [5] a similar system was programmed using a LabVIEW toolkit: Control Design and Simulation Module. This module permits 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. The disadvantage of this, which the current paper wants to highlight, is that with the Control Design and Simulation Module the primary reason of using LabVIEW, namely its superior quality in acquiring, processing and displaying signals, is not taken full advantage of it. MATLAB and its LabVIEW equivalent, the Control Design and Simulation Module, are better suited for calculus and operations that require high computational effort, whereas LabVIEW’s basic programming language G is more suited for real-time processing and control [10].
**Figure 4.** The LabVIEW software for the emulator - The block diagram of the .vi

**Figure 5.** The LabVIEW software for the emulator - The front panel
The model diagram needs to be processed in a while 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 [5].

The model is developed using 2 subroutines for calculating the parameters; one is based on the aerodynamic model of the turbine and another on the mechanical model. The program reads the torque estimated by ACS 800 and calculates the new rotating speed ($\omega_r$) based on the previous rotating speed and the torque calculated using the aerodynamic model of the turbine (6). The 1/6 gearbox is also accounted for in this step. Another method would be to read the rotating speed and calculate the torque, as can be seen in [6].

The mechanical component of the wind turbine is modeled as depicted in Figure 6.

![Figure 6. The mechanical model of the wind turbine](image)

The considered aerodynamic model of the wind turbine is presented in Figure 7.

![Figure 7. The aerodynamic model of the wind turbine](image)
In order to operate correctly 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.

The hardware system contains an ABB ACS 800 drive and a 7.5 kW three phase squirrel cage induction motor (IM) with a gearbox (GB) (the wind turbine equivalent) and a permanent magnet synchronous generator (PMSG) [6]. The generator is the same one used in the real turbine system.

![Figure 8. The emulator configuration](image)

The emulator control was implemented in LabVIEW and it runs in real-time on the NI cRIO board, as shown in Figure 8. The software system sends reference signals to the physical system during the real time simulation. The control output signal (angular speed reference) is send to the voltage source inverter ABB ACS 800 [6]. The role of ACS 800 is to drive a 7.5 kW/720 rpm squirrel cage induction motor (IM). The IM receives the shaft speed as a control signal from the ACS 800. ACS 800, in turn, computes the estimated load torque obtained from the reference model of the induction machine and feeds it back to the controller board.

4. Experimental results

The structure of the experimental setup for wind energy conversion system is presented in Figure 9.

![Figure 9. The complete structure of the experimental setup for a wind energy conversion system](image)
In the presented experiments, the wind condition has a profile as depicted in Figure 10. It can be noticed that the wind speed had an impulse varying from 5 to 6 m/s. In Figure 11 is presented the angular speed.

![Figure 10. Wind speed](image1)

![Figure 11. Angular speed](image2)

Measured torque variation is presented in Figure 12. As wind speed rise, the torque value increase, but due to the increasing load of the generator, as extracted power and angular speed increase, the torque decrease.

![Figure 12. Torque variation](image3)

![Figure 13. Power variation](image4)

The operating wind turbine power characteristic for the considered wind conditions is presented in Figure 13.

The wind turbine power characteristics achieved through simulations using the turbine model for various wind speed are presented in Figure 15.
Figure 14. Response to an impulse variation of the wind speed from 5 to 6 m/s

Figure 15. Wind turbine power characteristics $P(\omega)$, obtained by simulation

The wind turbine power characteristics obtained from emulator considering various wind speed are presented in Figure 16.
The main parameters determined experimentally are presented in Table 3.

| Wind speed | 5 m/s | 6 m/s | 7 m/s | 8 m/s | 9 m/s | 10 m/s |
|------------|-------|-------|-------|-------|-------|--------|
| Tg [Nm]    | 114.5 | 156   | 202   | 250   | 308   | 349    |
| Twt [Nm]   | 115.7 | 157   | 202.6 | 252.3 | 309.1 | 350    |
| P opt [W]  | 613.5 | 1101.5| 1747.5| 2575.6| 3620 | 4752   |
| \( \varphi \) opt [rad/s] | 5.3 | 7 | 8.6 | 10.2 | 11.7 | 13.6 |
| n opt [rpm] | 50.6 | 67 | 82.4 | 97.5 | 112 | 130.2 |
| Efficiency [%] | 46.454 | 57.557 | 65.236 | 70.080 | 73.922 | 71.927 |

It can be noticed that the wind turbine efficiency varies with the wind speed and angular speed. There are significant power losses at low values of the angular speed mainly due to the mechanical mechanism the coupling the induction machine, gearbox and PMS generator.

5. Conclusions
The paper presents a powerful and flexible setup for wind energy laboratory, useful for study and testing real equipment with real control strategies, without the necessity of a real wind turbine.

HIL systems has certain advantages in comparison with software simulators, due to the fact that there are certain factors (as different losses) that cannot be very accurate included in software simulation, but can be achieved by the physical system of the emulator [4].

The main advantage is the system flexibility, the number of wind turbines types with or without gearboxes that can be implemented and tested using the emulator is virtually unlimited – the only limitation is the knowledge of a good mathematical model combined with the characteristics of the used asynchronous motor.

Turbines can be simulated using real-time sampled data obtained from existing turbines. Thus, there is no need to spend money for expensive wind turbines or aerodynamic tunnel tests. A wide range of environmental conditions can be simulated: both regular wind conditions and special conditions (wind gust or extreme fluctuating wind), with any transient regime or successive steady-state regimes.

There is the possibility of testing different control loops, power converters, storage elements, electrical loads in real time.

All these facts can be used to optimize the turbine design and minimize the production costs, leading to decreased costs related to wind energy, and making it a viable energetic alternative [3].

The disadvantages are mainly related to the uncertainties regarding both the mathematical models and real parameters.

References
[1] Schkoda R, Fox C, Hadidi R, Gevorgian V, Wallen R and Lambert S 2016 Hardware-in-the-Loop Testing of Utility-Scale Wind Turbine Generators (No. NREL/TP-5000-64787), NREL- National Renewable Energy Laboratory, Golden, CO, United States
[2] Bouscayrol A, Guillaud X, Teodorescu R, Delarue P and Lhomme W 2006 Hardware-in-the-loop simulation of different wind turbines using Energetic Macroscopic Representation, IECON 2006-32nd Annual Conference on IEEE Industrial Electronics, Paris, France, November 6-10, pp 5338-5343
[3] Manyonge A W, Ochieng R M, Onyango F N and Shichikha J M 2012 Mathematical Modelling of Wind Turbine in a Wind Energy Conversion System: Power Coefficient Analysis, Applied Mathematical Sciences 6 4527-4536
[4] Hardy T and Jewell W 2014 Hardware-in-the-loop wind turbine simulation platform for a laboratory feeder model, *IEEE Transactions on Sustainable Energy* 5(3) 1003-1009

[5] Topor M, Muntean N and Sorandaru C 2014 Wind Turbine Emulator Development using NI cRIO 9068 and ABB ACS 800 Drive, *Journal of Electrical Engineering* 1-6

[6] Muntean N, Tutelea L, Petrila D and Pelan O 2011 *Hardware in the loop wind turbine emulator*, International Aegean Conference on Electrical Machines and Power Electronics and Electromotion, Joint Conference, Istanbul, Turkey, September 8-10, pp 53-58

[7] Petrila D 2013 *Energy Conversion And Storage Control For Small Wind Turbine Systems*, Timisoara, Romania, Doctoral Thesis

[8] Milivojevic N, Stamenkovic I, Schofield N and Emadi A 2008 *Electrical machines and power electronic drives for wind turbine applications*, Industrial Electronics, IECON 2008 34th Annual Conference of IEEE, Orlando, Florida, USA, November 10-13, pp 2326-2331

[9] Patrascu C, Muntean N and Hedes A 2016 *Microgrid Laboratory for Educational and Research Purposes*, IEEE International Energy Conference, Energycon, Leuven, Belgium, April 4-8

[10] Tasner T, Lovrec D, Tasner F and Edler J 2012 Comparison Of LabVIEW and MATLAB for scientific research, *Annals of the Faculty of Engineering Hunedoara* 10(3) 389-394