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Research paper

Design of a test bench for a small wind turbine emulator

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ABSTRACT

In this work, the authors present a small-scale wind turbine emulator that reproduces the steady-state performances of a wind turbine at various wind conditions. The proposed emulator is based on a three-phase induction machine powered by a variable-speed drive. The model of the emulated wind turbine comes from the PropID program, which permits an accurate modeling of its aerodynamic characteristics. In this study, the model of the Whisper100 wind turbine from Southwest Windpower is chosen for the test validation. The performances of the emulated Whisper100 wind turbine are examined by an experimental test bench under variable operating conditions. The theoretical results are compared with those obtained experimentally.

1. INTRODUCTION

In isolated sites where access to the electric power network is impossible or economically unprofitable, distributed generation systems based on renewable energy sources are frequently used (Alnasir & Kazerani, 2013; Idjdarène; Ion & Marinescu, 2013; Khare, Nema, & Baredar, 2016; Simoes & Farret, 2008). In particular, wind energy conversion systems (WECS) using small wind turbines with an output power rating of less than 10 kW have proved to be an attractive option to meet the load demands of stand-alone sites (Alnasir & Kazerani, 2013, 2016; Krishna, Sandeep, Murthy, & Yadlapati, 2022; Satpathy, Kishore, Kastha, & Sahoo, 2014; Singh & Sharma, 2014; Wood, 2011). However, to design an efficient WECS along with its control strategy for a stand-alone application, there is a need to study the aerodynamic performances of the wind turbine rotor by experimental tests or by numerical simulation (Hsiao, Bai, & Chong, 2013; Tahir et al., 2018; Wood, 2011). In addition, the wind turbine emulator (WTE) represents an interesting tool for the study of wind turbine behaviors before its use in real wind conditions. Indeed, by using a dedicated experimental test bench, the WTE allows a real-time

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physical simulation of the wind turbine in a controlled test environment for research and development purposes (Benzaouia et al., 2021; Dekali, Baghli, & Boumediene, 2019; Diana, Emerson, Jean, Rafael, & Carlos, 2016; Kojabadi, Liuchen, & Boutot, 2004; Martínez-Márquez et al., 2019; Moussa, Bouallegue, & Khedher, 2019; Neely et al., 2012; Satish Kumar, Chandrasena, & Victor Sam Moses Babu, 2022; Sokolovs, Grigans, Kamolins, & Voitkans, 2014). So far, apart from (Martínez-Márquez et al., 2019), the WTEs reported in the literature for simulating the torque of small power wind turbines are dedicated to education purposes only and do not incorporate models of real wind turbines, like ones existing in the industry. Whereas, to predict accurate wind turbine performances with a WTE, the tests must be performed with precise wind turbine models.

In the present research work, the model of the emulated wind turbine comes from the PropID computer program, which is a dedicated computer code for aerodynamic performance analysis and design of horizontal axis wind turbines (PROPID). In this study, the model of the Whisper100 wind turbine (Southwest_Windpower), is chosen for the experimental validation tests. On the other hand, since the components used in the proposed emulator are standard industrial components and no torque sensor (too expensive) is used, the proposed emulator can be qualified as a low-cost sensorless WTE. Indeed, the developed test bench consists of a variable speed drive (VSD) fed three-phase induction motor, which is mechanically coupled to a permanent magnet synchronous generator (PMSG). In addition, a programmable logic controller (PLC) is used to calculate the reference torque to be sent to the VSD through the RS-485 bus according to the Modbus communication protocol.

The objective of this paper is to detail the necessary steps for the real-time physical simulation of a wind turbine through an experimental test bench dedicated to small wind turbines. The study conducted in this work permits to examination of the performances of the emulated wind turbine under variable operating conditions.

2. AERODYNAMIC WIND TURBINE MODEL

The mechanical power extracted from the wind turbine is expressed in Eq. (1), where ρ is the air density in kg.m^{-3}, S is the surface swept by the turbine in m^2, V_w is the wind speed in m.s^{-1} and C_p is the power coefficient that links the extractable power of the wind turbine to the wind speed.

$$P_{ext} = \frac{1}{2}.\rho.S.V_w^3.C_p \tag{1}$$

The wind turbine power coefficient C_p is a nonlinear function of the tip speed ratio (TSR) λ, whose expression is given in Eq. (2), and of the blade pitch angle characterizing the aerodynamic behavior of the rotor blades. The C_p curve is specific to each wind turbine.

$$\lambda = \frac{R.w_t}{V_w} \tag{2}$$

Where: blade radius, w_t: wind turbine angular speed and V_w: wind speed.

On the other hand, to simulate the behavior of the wind turbine, it is necessary to determine the aerodynamic torque T_{aer} exerted on the mechanical shaft, which is calculated as follows:

$$T_{aer} = \frac{P_{ext}}{w_t} = \frac{1}{2}.\rho.S.V_w^2.R.\frac{C_p}{\lambda} \tag{3}$$

2.1 Modeling of the Whisper100 wind turbine

In this section, the aerodynamic performance analysis of the Whisper 100 wind turbine is examined with the PropID program for variable operating conditions. The Whisper100 wind turbine from Southwest Windpower has the following characteristics:

- The rated output power of approximately 900 W at a wind speed of 12.5 m/s.
- Rated rotational speed of 1000 rpm.
- The rotor diameter is 2.1 meters.
- The minimum wind speed required for the turbine to start generating power is 3.4 m/s.
- The maximum wind speed at which the turbine stops for safety reasons is 25 m/s.

2.1.1 Results obtained with PropID

The PropID program is a computer code based on the blade element momentum theory, where the geometry and aerodynamic characteristics of the blade profile are introduced to calculate the C_p curve of a given wind turbine as a function of the TSR (Hsiao et al., 2013; Tahir et al., 2018).

For the Whisper100 wind turbine, the rotor is made up of three blades with the aerodynamic profile fx63_137 (Airfoil). The lift and drag coefficients for the different angles of attack and the different Reynolds numbers are calculated by the open-source program (XFOIL). Subsequently, the aerodynamic characteristics of the blade profile are introduced into the PropID program to calculate the C_p curve of the Whisper100 wind turbine. The results are shown in Fig. (1). It can be observed that the optimum TSR is 5.7 corresponding to the maximum power coefficient of 0.42. The C_p curve shown in Fig. (1) is modeled by the following expression:

$$C_p = a_1 \sin(b_1 \lambda + c_1) + a_2 \sin(b_2 \lambda + c_2) + a_3 \sin(b_3 \lambda + c_3) \quad (4)$$

Where : a_1= 0.3655, b_1= 0.3346, c_1= -0.3782, a_2= 0.02195, b_2= 1.598, c_2= 0.6571, a_3= 0.06126; b_3= 1.018, c_3= -4.235

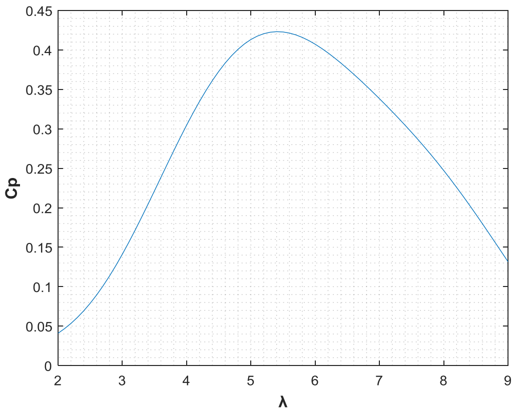


Fig. 1. Whisper100 wind turbine power coefficient

To theoretically predict the power-speed characteristics of the Whisper100 wind turbine, Equation (1) is used in conjunction with Eq. (4) to calculate the developed mechanical power for different rotational speeds and different wind speeds, as illustrated in Fig. (2).

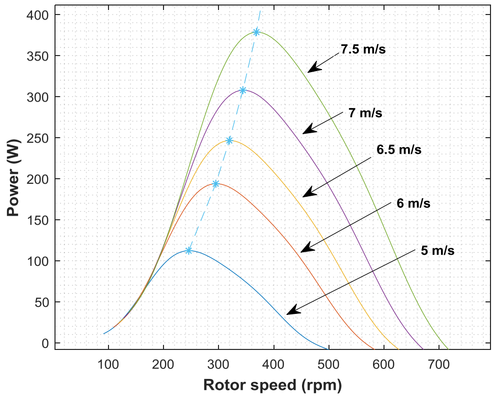


Fig 2. Mechanical power versus rotational speed for various wind speeds

3. PHYSICAL IMPLEMENTATION OF THE EMULATED WHISPER100 WIND TURBINE

3.1 Presentation of the experimental test bench

The laboratory test bench consists of a three-phase induction motor mechanically coupled to a permanent magnet synchronous generator (PMSG), which converts the mechanical energy into electrical energy and supplies a resistive load. The photograph of the experimental test bench is shown in Fig. (3). The parameters of the PMSG used in the tests are given in Table 1.

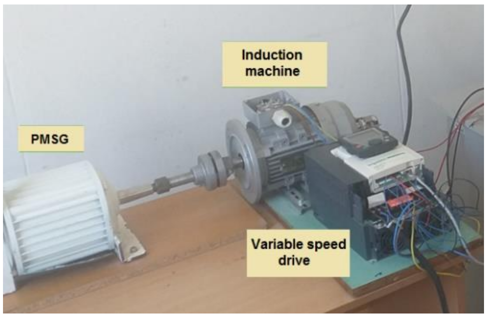


Fig 3. Photograph of the experimental test bench

Table 1. PMSG Parameters

Parameters	Values
Number of Phases	3
Rated power	1 kW
Nominal line-to-line voltage	80 V
Rated speed	500 rpm
Number of poles	10
Phase current	7 A
Phase resistance	0.5 Ω
Synchronous inductances	5 mH
Flux linkage	0.27 Wb

The induction motor is powered with a VSD from Schneider Electric (Altivar71), which is controlled via a programmable logic controller (PLC) from Modicon (M221). The synoptic diagram of the drive system is shown in Fig. (4). The PLC serves to accomplish the needed calculation for the reference torque as well as to exchange data and measured quantities with the VSD through the RS-485 bus according to the Modbus communication protocol.

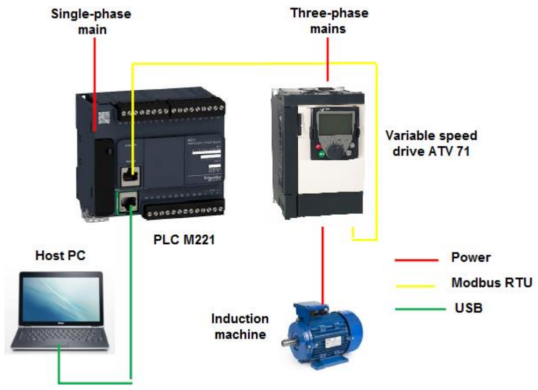


Fig 4. Synoptic diagram of the drive system

Depending on the VSD configuration, the motor can switch between speed regulation mode and torque regulation mode. However, for the physical simulation of the wind conditions, the VSD is configured to operate the motor in torque control mode. In this operating mode, the VSD is configured so that the motor operates at a reference torque, while the speed may vary within a configurable "deadband". When it reaches a lower or upper limit, the drive automatically reverts to speed regulation mode and remains at this limit speed. The regulated torque is therefore no longer maintained (see Fig. (5)). In addition, to protect the motor, a current and/or torque limitation is also established (Altivar71).

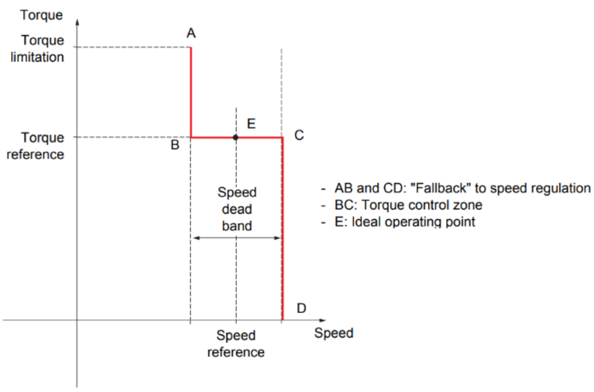


Fig 5. Torque control operating mode

3.2 Experimental validation

In this section, the necessary steps to experimentally determine the performances of the Whisper100 wind turbine are explained. To achieve the emulation of the Whisper100 wind turbine with the torque control of the induction motor, the mathematical model of the C_p coefficient of the Whisper100 (see Eq. (4)) is first implemented in the PLC, which permits to calculate the C_p value for given values of the wind speed profile and the TSR (see Eq. (2)). Then, taking into account the Whisper100 wind turbine dimensions (blade radius), the PLC allows calculating the aerodynamic torque for given values of the wind speed and the rotational speed (see Eq. (3)). This aerodynamic torque represents the reference torque value that the PLC sends to the VSD through the RS-485 communication bus.

On the other hand, it should be noted that to vary the rotational speed, the PMSG outputs are connected to batteries through a diode bridge and a step-down PWM DC-DC buck converter. Indeed, this converter makes it possible to vary the rotational speed of the PMSG through the control of the duty cycle of the PWM signal sent to the buck converter. The synoptic diagram of the test bench used in the experimental validation is illustrated in Fig. (6). In this study, the variation of the duty cycle of the PWM signal is accomplished by the PLC.

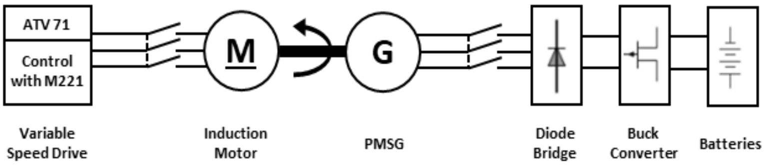


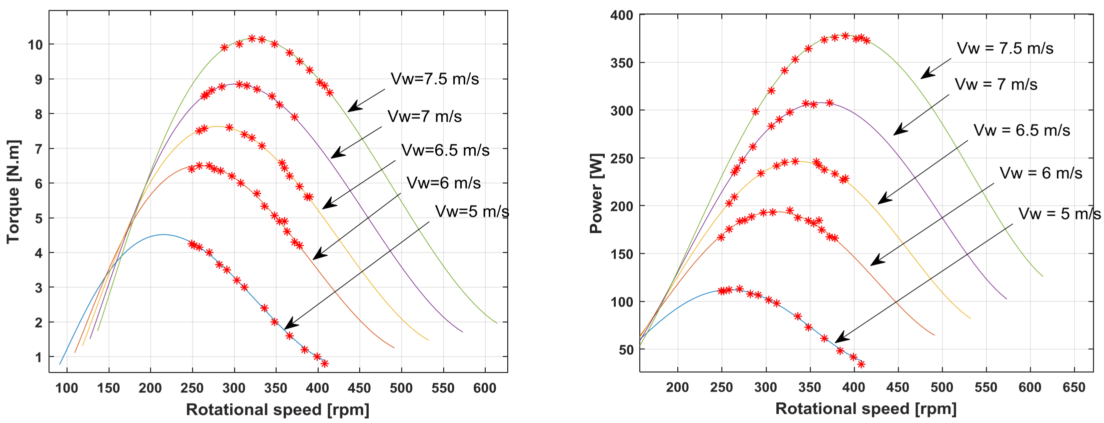
Fig 6. Synoptic diagram of the experimental test bench

3.3 Results and Discussion

In this section, the performance analysis of the Whisper100 wind turbine is given for variable operating conditions of rotational and wind speeds. The experimental validation is verified for five values of the wind speed: 5 m/s, 6 m/s, 6.5 m/s, 7 m/s, and 7.5 m/s. For all tests carried out, the speed rotation is maintained between 250 rpm and 450 rpm. This range of speed rotation makes it possible to have operating points close to the nominal conditions of the PMSG used in the tests. It should be noted that these tests can be carried out at speeds outside the previous variation range [250 rpm - 450 rpm]. However, the nominal quantities of the PMSG must be respected.

The obtained results for powers and torques against speed rotation are shown in Fig. (7). These results show good agreement between the results from the experimental readings and those obtained theoretically with the Whisper100 wind turbine model (see Fig. (2)). Thus, the proposed WTE makes it possible to physically implement the power-speed and torque-speed characteristics of the Whisper100 wind turbine.

Further, it should be noted that in these tests, the input voltage of the buck converter, which represents the speed image, is regulated through the control of the duty cycle sent to the converter. In addition, the input current of the converter, which represents the torque image, varies according to the operating point. Indeed, the current regulation is not established in the present study.



a) b)

Fig 7. Performance curves of the emulated Whisper100 wind turbine: (a) Torque, (b) Power

4. CONCLUSIONS

This research paper describes the steps required to develop an experimental test bench to emulate the behavior of a small-power wind turbine. The developed test bench essentially consists of a three-phase induction machine, a PMSG, a VSD, and a PLC. The proposed emulator allows to conduct research studies on wind turbine-driven power generation systems in a controllable test environment and at a low cost since no torque sensor is used. The originality of the proposed work lies in the use of the PropID calculation code. The results obtained from this computer code make it possible to reliably reproduce the performances of the emulated wind turbine (in this study: Whisper100) with the developed experimental test bench.

The objective of the proposed emulator, which consists of the physical implementation of the torque-speed and power-speed characteristics of the Whisper100 wind turbine, has been achieved. The future work involves the implementation of power control on the generator side to optimize power extraction from the wind turbine, this will permit the wind turbine to operate in the Maximum Power Point Tracking (MPPT) mode.

NOMENCLATURE

Cp	Wind turbine power coefficient	wt	Wind turbine angular speed [rad/s]
Pext	Extractable power of the wind turbine [W]	Vw	Wind speed [m/s]
R	Blade radius [m]	ρ	Air density [kg.m-3]
S	Surface swept by the turbine [m2]	λ	Tip speed ratio
Taer	Aerodynamique torque [W.s. rad-1]		

REFERENCES

Airfoil. WORTMANN FX 63-137 AIRFOIL, http://airfoiltools.com/airfoil/details?airfoil=fx63137-il [accessed 27 November 2023].

Alnasir, Z., & Kazerani, M. (2013). An analytical literature review of stand-alone wind energy conversion systems from generator viewpoint. Renewable and Sustainable Energy Reviews, 28, 597-615. doi: https://doi.org/10.1016/j.rser.2013.08.027

Alnasir, Z., & Kazerani, M. (2016). A small-scale standalone wind energy conversion system featuring SCIG, CSI and a novel storage integration scheme. Renewable Energy, 89, 360-370. doi: https://doi.org/10.1016/j.renene.2015.12.041

Altivar71. Guide de programmation, https://www.se.com/fr/fr/product/ATV71HD11M3X460/atv71-240v-11kw/ [accessed 27 November 2023]

Benzaouia, S., Mokhtari, M., Zouggar, S., Rabhi, A., Elhafyani, M. L., & Ouchbel, T. (2021). Design and implementation details of a low cost sensorless emulator for variable speed wind turbines. Sustainable Energy, Grids and Networks, 26, 100431. doi: https://doi.org/10.1016/j.segan.2021.100431

Dekali, Z., Baghli, L., & Boumediene, A. (2019, 25-27 Sept. 2019). Experimental Emulation of a Small Wind Turbine Under Operating Modes Using DC Motor. Paper presented at the 2019 4th International Conference on Power Electronics and their Applications (ICPEA).

Diana, M., Emerson, G. C., Jean, P. d. C., Rafael, C., & Carlos, M. O. S. (2016). Emulation of Wind Turbines. In A. Abdel Ghani & T. Ahmed (Eds.), Wind Turbines (pp. Ch. 8). Rijeka: IntechOpen.

Hsiao, F.-B., Bai, C.-J., & Chong, W.-T. (2013). The Performance Test of Three Different Horizontal Axis Wind Turbine (HAWT) Blade Shapes Using Experimental and Numerical Methods. Energies, 6(6), 2784-2803. doi:10.3390/en6062784

Idjdarène, K. Contribution à l'Etude et la commande de Génératrices Asynchrones à Cages Dédiées à des Centrales Electriques Eoliennes Autonomes. Thèse de Doctorat d’état en Electrotechnique, Université Abderrahmane Mira - Béjaia 2010.

Ion, C. P., & Marinescu, C. (2013). Three-phase induction generators for single-phase power generation: An overview. Renewable and Sustainable Energy Reviews, 22, 73-80.

Khare, V., Nema, S., & Baredar, P. (2016). Solar–wind hybrid renewable energy system: A review. Renewable and Sustainable Energy Reviews, 58, 23-33. doi: https://doi.org/10.1016/j.rser.2015.12.223

Kojabadi, H. M., Liuchen, C., & Boutot, T. (2004). Development of a novel wind turbine simulator for wind energy conversion systems using an inverter-controlled induction motor. IEEE Transactions on Energy Conversion, 19(3), 547-552. doi: 10.1109/tec.2004.832070

Krishna, V. B. M., Sandeep, V., Murthy, S. S., & Yadlapati, K. (2022). Experimental investigation on performance comparison of self excited induction generator and permanent magnet synchronous generator for small scale renewable energy applications. Renewable Energy, 195, 431-441. doi: https://doi.org/10.1016/j.renene.2022.06.051

M221. Guide Utilisateur, https://www.se.com/fr/fr/product/TM221CE40T/modicon-m221-contr%C3%B4leur-40e-s-pnp-port-ethernet+s%C3%A9rie-24vcc/ [accessed 27 November 2023]

Martínez-Márquez, C. I., Twizere-Bakunda, J. D., Lundback-Mompó, D., Orts-Grau, S., Gimeno-Sales, F. J., & Seguí-Chilet, S. (2019). Small Wind Turbine Emulator Based on Lambda-Cp Curves Obtained under Real Operating Conditions. Energies, 12(13). doi:10.3390/en12132456

Moussa, I., Bouallegue, A., & Khedher, A. (2019). New wind turbine emulator based on DC machine: hardware implementation using FPGA board for an open-loop operation. IET Circuits, Devices & Systems, 13(6), 896-902. doi: https://doi.org/10.1049/iet-cds.2018.5530

Neely, J., Glover, S., Finn, J., White, F. E., Loop, B., & Wasynczuk, O. (2012, 27-31 May 2012). Wind turbine emulation for intelligent microgrid development. Paper presented at the 2012 IEEE International Conference on Cyber Technology in Automation, Control, and Intelligent Systems (CYBER).

PROPID. PROPID for Horizontal Axis Wind Turbine Design,

https://m-selig.ae.illinois.edu/propid.html [accessed 20 November 2023]

Satish Kumar, P., Chandrasena, R. P. S., & Victor Sam Moses Babu, K. (2022). Design and implementation of wind turbine emulator using FPGA for stand-alone applications. International Journal of Ambient Energy, 43(1), 2397-2409. doi: 10.1080/01430750.2020.1736152

Satpathy, A. S., Kishore, N. K., Kastha, D., & Sahoo, N. C. (2014). Control Scheme for a Stand-Alone Wind Energy Conversion System. IEEE Transactions on Energy Conversion, 29(2), 418-425. doi: 10.1109/tec.2014.2303203

Simoes, M. G., & Farret, F. A. (2008). Alternative Energy Systems - Design and Analysis With Induction Generators: Boca Raton, FL: CRC Press.

Singh, B., & Sharma, S. (2014). Voltage and frequency controllers for standalone wind energy conversion systems. IET Renewable Power Generation, 8(6), 707-721. doi: 10.1049/iet-rpg.2013.0186

Sokolovs, A., Grigans, L., Kamolins, E., & Voitkans, J. (2014). An Induction Motor Based Wind Turbine Emulator. Latvian Journal of Physics and Technical Sciences, 51(2), 11-21. doi: doi:10.2478/lpts-2014-0009

Southwest_Windpower. Whisper 100 Owner’s Manual, https://www.technosun.com/descargas/SOUTHWEST-WHISPER-100-manual-EN.pdf [accessed 27 November]

Tahir, A., Elgabaili, M., Rajab, Z., Buaossa, N., Khalil, A., & Mohamed, F. (2018). Optimization of small wind turbine blades using improved blade element momentum theory. Wind Engineering, 43(3), 299-310. doi: 10.1177/0309524x18791395

Wood, D. (2011). Small Wind Turbines Analysis, Design and Application: Springer.

XFOIL. XFOIL Subsonic Airfoil Development System, https://web.mit.edu/drela/Public/web/xfoil/ [accessed 27 November 2023]