Development of a non-rotating wind turbine emulator

Phan Quoc Dung, To Huu Phuc, To Dinh Du and Pham Ngoc Thang

Abstract—**A Wind Turbine Emulator (WTE) is a equipment which closely imitates the dynamic characteristics of a wind turbine. It is developed for testing the performance and control algorithm power converter of a wind energy conversion system in a lab. The structure of this emulator is usually built on the basis of a rotating system which consists of two electrical machines coupling together. In this paper, the development of a non-rotating WTE is presented. The proposed WTE is built using hardware-in-the-loop method implemented on the dSPACE 1103 system and a buck converter. Experimental setup and results are shown to verify the validation of the proposed system.**

Index Terms—**Wind turbine emulator, wind energy conversion system, hardware in the loop.**

1 INTRODUCTION

In recent decades, wind energy conversion systems (WECS) became the fastest developing renewable technology, and power electronic converters play an important role in these systems. The converters are used to control torque, speed and power of the WECS to achieve high efficiency and high performance in power systems [1]. In addition, the wind turbine behavior is also significantly affected by the control strategy applied for the converters.

Phan Quoc Dung is with Ho Chi Minh City University of Technology, VNU-HCM (email: pqdung@hcmut.edu.vn)

To Huu Phuc is with Ho Chi Minh City University of Technology, VNU-HCM (email: thphuc@hcmut.edu.vn)

To Dinh Du is currently working toward the PhD. Degree in Electrical Engineering at Yeungnam University, Korea (email: dinhdubk@gmail.com)

Pham Ngoc Thang is with Schneider Toshiba Inverter Europe, France (email: ngoc.pham@schneider-electric.com)

In research and development of power converters for the WECS, a real-time wind turbine emulator (WTE) is important equipment because it helps to create a controlled environment to test the performance and control algorithm of the converters without relying on natural wind resources and actual wind turbines. Since the design of the power converters for WECS is highly dependent on the static and dynamic characteristics of the turbine, the output voltage and power of the WTE must be as close as possible to those of the real wind turbine generator.

In literature review, various studies on WTE have been conducted [2-9]. The common structure of WTE hardware consists of a motor as a prime mover coupled with an electrical generator. In this system, the motor is controlled by a variable speed drive so that the motor behavior must be similar to that of the wind turbine. Three main motor types used as prime movers are: (1) DC motor, (2) permanent magnet synchronous motor (PMSM) and (3): induction motor (IM). Separately excited DC motors have been used in [2-4] as their torque and speed can be controlled easily and accurately. However, this type of motor is usually expensive and required long-term maintenance of its brushes and commutator, making it unattractive. To eliminate these advantages, other works proposed the use of PMSM [5, 6] or IM [7-9] as prime mover.

An important requirement of the WTE is that the static and dynamic torque generated on the prime mover shaft must be similar to that generated by a wind turbine. To do this, the WTE system is usually set up via method of hardware-in-the-loop (HIL) and its general schematic is presented in Fig.1. In this system, the software simulator and the physical system are on-line communicated with each other. The simulator generates the reference signal to control the physical system based on the feedback measurements from this system. For a conventional WTE system, the simulator takes

wind speed pattern and wind turbine characteristics as well as feedback signals as inputs, and it calculates the reference torque (or speed) to control the motor.
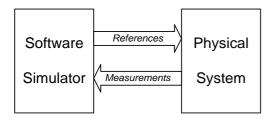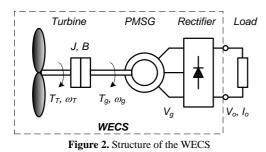

Figure 1. General structure of hardware in the loop system

Usually, the software simulator is implemented on a personal computer (PC) combined with a digital signal processor (DSP). In this system, the wind turbine model is developed by equations using high level programing language on PC, and the generated code is executed on the DSP board. Several rapid prototyping tools for this configuration has been used in the research, as DSP dSPACE in the SIMULINK environment [2, 9], FPGA card [4] or Data Acquisition Card [7] with MathWorks xPC Target, or DSP card with LabVIEW [5]. The physical system consists of the motor combined with a variable speed controller, the generator and sensors (torque, speed, etc.).

However, the aforementioned WTE systems are of rotating type, which usually requires two electrical machines coupling together, a variable speed drive to control the motor together with torque and/or speed sensors. Therefore the actual emulator system might be rather bulky and complex. In this paper, the authors will present the development of a non-rotating WTE using HIL technique, where all the rotating components such as the wind turbine and the generator are included in the software simulator, and the electrical output of the WTE is realized by a power converter. This WTE is implemented with the DSP board dSPACE DS1103 combining with a synchronous buck converter only. Experimental setup and results will also be presented to verify the validation of the system.

Figure 2. Structure of the WECS

2 MODEL OF WIND ENERGY CONVERSION SYSTEM

A WECS consists of two main components: a wind turbine to convert the wind kinetic to mechanical energy and a generator to convert this energy to electrical power. Fig. 2 shows the physical structure of the WECS studied in this paper. It is a variable speed wind turbine in low power range with permanent magnet synchronous generator (PMSG). For this generator type, there is no reactive power required as well as active power flows unidirectionally from the generator to the load, only a rectifier bridge needs be applied on the generator side. Thus the output voltage of this wind turbine system is of DC type. Further, in case the WECS is connected to a grid, the "load" on Fig. 2 may consists of a step-up converter at the rectifier side and an inverter at the grid side to control the torque and speed of the generator as well as the power injected to the grid [10]. However, such a system is beyond the scope of this research.

2.1 Model of the wind turbine

The wind turbine is the primary component of a WECS. The mechanical power extracted from the wind is given by [2, 3]:

$$P_T = \frac{1}{2} C_p (\lambda, \beta) \rho A v_w^{\ 3} \ (\text{W}) \qquad (1)$$

Where: ρ is the air density (kg/m^3), v_w is the wind speed to the turbine (m/s), A is the area swept by the rotor (m^2) ($A = \pi R^2$, being R the radius of the blade (m)), and C_p is the power coefficient of the turbine.

The power coefficient $C_p (\lambda, \beta)$ is defined as the ratio of the turbine power to the power of wind stream, and it is a function of the tip-speed ratio λ and the blade pitch angle β. The tip-speed ratio λ is defined as the ratio of the speed at the blade tip to the wind velocity as follows:

$$\lambda = \frac{\omega_T R}{v} \qquad (2)$$

Where: ω_T is the angular speed of the turbine rotor (rad/s) and v is the wind speed (m/s).

In modelling the wind turbine, a generic equation for $C_p (\lambda, \beta)$ is widely used [2-8] and it is described as follows:

$$C_p(\lambda, \beta) = c_1 (\frac{c_2}{\lambda_i} - c_3 \beta - c_4) e^{-\frac{c_5}{\lambda_i}} + c_6 \lambda \qquad (3)$$

Table I
The parameters of wind energy conversion system

WIND TURBINE PARAMETER	
Rated power	10 kW
Max power	15 kW
Cut-in wind speed	3 m/s
Cut-off wind speed	25 m/s
Rated wind speed	10 m/s

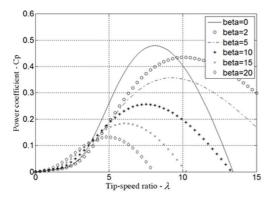| PMSG PARAMETERS	
Rated power	10 kVA
Number of pole pairs	12
Rated speed	250 rpm
Output voltage	150-450 VDC
Efficiency	95%
Total inertia J	0.065 kg.m^2
Viscous damping coefficient B	0.005 Nm.s^{-1}
Generator constant K_g	0.169

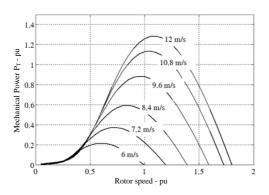**Figure 3.** The power coefficient $C_p(\lambda, \beta)$ curve

Figure 4. The turbine mechanical power versus rotor
speed at different wind speed

With:

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{1+\beta^3} \tag{4}$$

And the coefficients from c_1 to c_6 are:
$c_1 = 0.5176$, $c_2 = 116$, $c_3 = 0.4$, $c_4 = 5$, $c_5 = 21$,
$c_6 = 0.0068$.

The typical $C_p(\lambda, \beta)$ curves with various values
of pitch angle β are shown in Fig. 3. From these,
the mechanical power P_T of the investigated wind
turbine versus the turbine rotor speed ω_T and wind
speed v can be derived and plotted in Fig. 4.

The torque T_T developed on the turbine rotor is:

$$T_T = \frac{P_T}{\omega_T} \tag{5}$$

2.2 Model of the PMSG

The PMSG converts the mechanical power
received from the turbine rotor to the electrical
power and its model has been reported in many
works. However, to reduce the calculations of the
DSP in the developed WTE system, following
assumptions are adopted:

(1) The electrical time constants of the generator
are ignored as they are much smaller than the
mechanical time constant of the system.

(2) The generator efficiency is considered to be
unchanged with variations of generator output
power.

(3) The saturation effect in the generator is
neglected.

Neglected the losses in the rectifier and other
circuit to the WTE load, the electromagnetic
torque on the generator shaft is given by:

$$T_g = \frac{P_L}{\eta_g \omega_g} = \frac{V_o I_o}{\eta_g \omega_g} \tag{6}$$

Where: P_L is the load power (W) of the WTE,
V_o and I_o are respectively the WTE output voltage
and current, η_g is the generator efficiency and
ω_g is the generator angular speed (rad/s).

For the sake of simplicity, it is assumed that
there is no gearbox between the turbine rotor and
the generator, thus $\omega_g = \omega_T$, and the dynamic
equation for the generator speed is:

$$T_T - T_g = J\frac{d\omega_g}{dt} - B\omega_g \tag{7}$$

Where: J (kg.m^2) is the total inertia of the
turbine rotor and the generator rotor and B is the
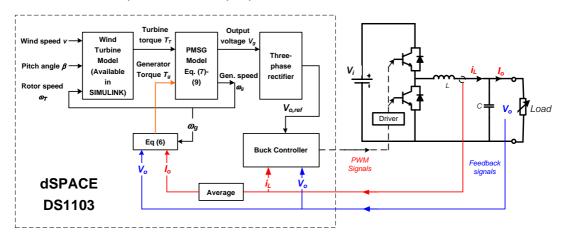viscous damping coefficient (Nm.s^{-1}).

Figure 5. Configuration of the proposed WTE system

As assuming in the above, the saturation effect in the PMSG is omitted, thus the phase voltage amplitude of the PMSG is proportional to the generator speed as follows:

$$V_m = K_g \omega_g \quad \text{(V)} \quad (8)$$

Where K_g is the generator constant (V.s/rad).

The three phase output voltages of the PMSG are given by:

$$v_a(t) = V_m \sin(2\pi f_g t)$$
$$v_b(t) = V_m \sin(2\pi f_g t - 2\pi/3) \quad (9)$$
$$v_b(t) = V_m \sin(2\pi f_g t + 2\pi/3)$$

Where f_g is the output frequency of the PMSG in according to the generator speed ω_g.

The parameters of the wind turbine and the generator are given in Table I.

3 CONFIGURATION OF THE WIND TURBINE EMULATOR

The WTE system in this paper is set up via HIL method mentioned in Section 1, and its block diagram is illustrated in Fig. 5. The software simulator includes the wind turbine model described in section 2.1, and the PMSG combined with the rectifier described in section 2.2. The

physical system is a synchronous Buck converter to realize the output of the WTE.

3.1 The software simulator

The control algorithm of the whole proposed WTE is implemented in MATLAB/SIMULINK and run in the real-time controller dSPACE 1103. This board is plugged into a personal computer (PC) and it can be programmed using MATLAB/SIMULINK software combined with Real-Time Interface (RTI) software developed by dSPACE.

The wind turbine model is implemented using the one available in SIMULINK, with its inputs consisting of wind speed v_w, blade pitch angle β and turbine speed ω_T. The PMSG block is modelled using equations (6) – (9). The inputs of this block consist of the turbine torque T_T and the generator torque T_g, and the block outputs are the generator speed ω_g and three-phase voltages. The rectifier is implemented using the model in SIMULINK, and its output voltage is used as the reference signal $V_{o,ref}$ to control the Buck converter to realize the actual electrical output of the WTE.
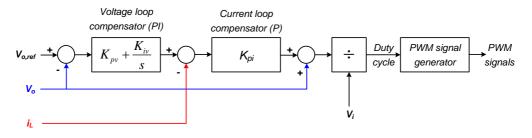

Figure 6. Structure of the Buck controller implemented in the dSPACE DS1103

3.2 The Buck converter

The synchronous buck converter in Fig. 5 is selected for the power stage of the emulator as it is simple to control and its output voltage ripple can be kept small with a proper design of its LC filter. The values of L and C are selected based on following equations:

$$L \geq \frac{V_i}{4\Delta I_{PP} f_{sw}} \text{ and } C \geq \frac{\Delta I_{PP}}{8 f_{sw} \Delta V_{PP}} \quad (10)$$

Where: V_i is converter input voltage, ΔI_{PP} and ΔV_{PP} are accordingly peak-to-peak ripple current and voltage, and f_{sw} is switching frequency of the converter. The parameters of this converter are given in Table II.

It is noted that the average output current I_o and the average inductor current I_L are equal:

$$I_o = I_L \quad (11)$$

The controller for this converter is of two-loop cascade type. It consists of an inner loop to control the inductor current i_L and an outer loop to control the converter output voltage V_o. The cut-off frequency of the inner loop is much higher than that of the outer loop, so that these two loops are decoupled.

The block diagram of the converter controller is illustrated in Fig.6. It is also implemented in the dSPACE 1103 with its input signals are the reference $V_{o,ref}$ from the inverter block and the real-time feedback signal V_o and i_L from the converter. The PWM signals to control the buck converter are generated from the PWM block in the Slave DSP of the dSPACE 1103. The proportional (P) compensator is selected for the inner current loop, and the proportional-integral (PI) compensator is designed for the outer loop. The parameters of the converter controller are given in Table II.

Table II.
The parameters of buck converter

THE CONVERTER	
Input voltage V_i	500 VDC
Switching frequency	20 kHz
Inductor L	3 mH
Capacitor C	100 uF
THE CONTROLLER	
Inner current loop	
Cut-off frequency	18,850 rad/s
K_{pi}	56.5
Outer voltage loop	
Cut-off frequency	1885 rad/s
K_{pv}	0.603
K_{iv}	355

4 EXPERIMENTAL RESULTS

To validate the proposed idea, the WTE system is implemented in the Power Electronic Research Laboratory (HCMUT). Fig. 7 shows the setup of the system in the lab, and Fig. 8 shows the user interface screen developed using the data acquisition software ControlDesk for dSPACE. This interface screen allows the user to monitor and change the system parameters while the emulator is operating.

Experiments have been performed at several values of wind speed: v = 5, 7 and 10 m/s and the pitch angle β = 2°. At every value of wind speed, the load of the converter is changed to survey the relationship between the actual load power and the simulated rotor speed. Fig. 9 compares the variation of simulated and actual load power with rotor speed. It can be seen that the actual curves are well matched with the simulated curves.

5 CONCLUSION

In this paper, the development of a wind turbine emulator (WTE) using only a DSP card DS1103 connected to a PC and a DC-DC converter is presented. Experimental results show that the emulator behavior is close to that of the simulated wind turbine generator system. This emulator is suitable for education purpose or for research and testing of power converters for small wind turbine systems whose output is of DC type.

As above mentioned, a simplified model of PMSG is used in this paper to reduce the calculation time of the DSP system. Further work to improve the proposed WTE has been conducting by using better model for the PMSG while maintaining the good response of the system. Another future work will be focused on developing a non-rotating WTE system with its output is of three-phase AC voltage, so it can be suitable to emulate actual high power wind turbine systems.
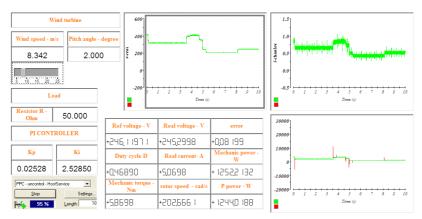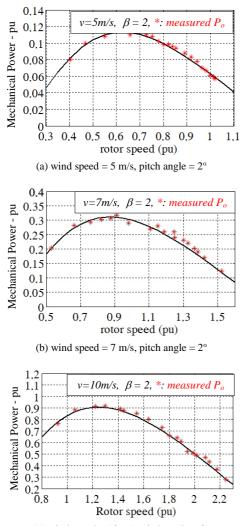

Figure 7. Experimental setup of the proposed WTE

Figure 8. User interface screen of the proposed WTE built with software ControlDesk for dSPACE

(a) wind speed = 5 m/s, pitch angle = 2º

(b) wind speed = 7 m/s, pitch angle = 2º

(c) wind speed = 10 m/s, pitch angle = 2º
Figure 9. Simulated power curves and experimental
results at different wind speed

REFERENCES

[1] Z. Chen, J. M. Guerrero, F. Blaajberg, "A review of state of the art of power electronics for wind turbines," *IEEE Transactions on Power Electronics.*, vol. 24, no. 8, August 2009, pp. 1859-1875.

[2] S. Kouadria, S. Belfedhal, E.M. Berkouk and Y. Meslem, "Development of real time wind turbine emulator based on DC motor controlled by PI regulator", *8th Int. Conf. and Exhibition on Ecological Vehicles and Renewable Energies (EVER)*, 2013.

[3] F.E.V Taiveros, L.S. Batos and F.B. Costa, "Wind Turbine torque-speed feature emulator using a DC motor", *Power Electronics Conference (COBEP)*, Brazil, 2013.

[4] I. Moussa, A. Boualleague and A. Khedher, "Design and implement of constant wind speed turbine emulator using Matlab/Simulink and FPGA," *9th International Conference on Ecological Vehicles and Renewable Energies (EVER)*, 2014.

[5] J. Yan, Y. Feng and J. Dong, "Study on dynamic characteristics of wind turbine emulator based on PMSM," *Renewable Energy*, vol. 97, pp. 731-736, 2016.

[6] S. Tammaruckwatana, K. Ohyama, "Experimental verification of variable speed wind powe generation system using permanent magnet synchronous generator by wind turbine emulator", *Proceedings of IECON 38th*, Annual Conference on IEEE Industrial Electronics Society, 2012.

[7] L. H. Chun and C. C. Le-Ren, "Use of wind turbine emulator for the WECS development," *Proceedings of International Power Electronics Conf. (IPEC)*, Sapporo, Japan, 2010.

[8] J. Castello, J. M. Espi and R. Garcia-Gil, "Development details and performance assessment of a wind turbine emulator," *Renewable Energy*, vol. 86, pp. 848-857, 2016.

[9] N. Muntean, L. Tutelea, D. Petrila and O. Pelan, "Hardware in the loop wind turbine emulator," *Proceedings of International Aegean Conference on Electrical Machines and Power Electronics (ACEMP)*, 2011.

[10] J. M. Carrasco, L.C. Franquello, J.T. Bialasiewicz and others, "Power Electronic Systems for the grid integration of renewable energy sources: a survey", *IEEE Transactions on Industrial Electronics*, vol. 13, no. 4, pp. 1002-1016, 2006.

Phan Quoc Dung is with Ho Chi Minh City University of Technology, Vietnam National University (email: pqdung@hcmut.edu.vn)

To Huu Phuc is with Ho Chi Minh City University of Technology, Vietnam National University (email: thphuc@hcmut.edu.vn)

To Dinh Du is currently working toward the PhD. Degree in Electrical Engineering at Yeungnam University, Korea (email: dinhdubk@gmail.com)

Pham Ngoc Thang is with Schneider Toshiba Inverter Europe, France (email: ngoc.pham@schneider-electric.com)

Phát triển bộ mô phỏng tuabin gió không sử dụng máy điện quay

Phan Quốc Dũng[1], Tô Hữu Phúc[1], Tô Đình Dự[2] và Phạm Ngọc Thắng[3]

[1]Trường Đại học Bách khoa, ĐHQG-HCM
[2]Trường Đại học Yeungnam, Hàn Quốc
[3]Công ty Schneider Toshiba Inverter Europe, Pháp
*Tác giả liên hệ: pqdung@hcmut.edu.vn; thphuc@hcmut,edu.vn

Tóm tắt – Bộ mô phỏng tuabin gió (WTE) là một thiết bị mô phỏng chặt chẽ các đặc tính động của tuabin gió. Nó được phát triển để thử nghiệm bộ chuyển đổi năng lượng hiệu suất và thuật toán điều khiển của hệ thống chuyển đổi năng lượng gió trong phòng thí nghiệm. Cấu trúc của bộ mô phỏng này thường được xây dựng trên cơ sở một hệ thống quay bao gồm hai máy điện khớp với nhau. Trong bài báo này, sự phát triển của WTE không sử dụng máy điện quay được trình bày. WTE được đề xuất xây dựng bằng phương pháp vòng lặp phần cứng được triển khai trên hệ thống dSPACE 1103 và bộ chuyển đổi buck. Thiết lập và kết quả thử nghiệm được hiển thị để xác minh xác nhận hệ thống được đề xuất.

Từ khóa – mô phỏng Tuabin gió, hệ thống chuyển đổi năng lượng gió, phần cứng trong vòng lặp.