

WIND TURBINE EMULATOR WITH DC MOTOR DRIVE

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Abstract: The paper presents the development of a simulation model of a wind turbine (WT) emulator. The emulator consists of a DC motor, electronic converter and controller. The mathematical modelling of a wind turbine and separately excited DC motor with electronic converter is performed in Matlab/Simulink environment. The WT performance characteristics are described by mathematical expressions and appropriate motor torque controller is developed. Thus the motor drive is made to behave as a wind turbine. The results from simulations using the created model of the WT emulator are also shown in the paper. The developed WT emulator model is a first stage of the development of a laboratory test bench for physical simulation of a wind turbine.

Keywords: DC motor, Matlab, simulation, wind turbine

I. INTRODUCTION

Wind energy has experienced great growth this last decade. This growth is partly due to the technological improvement of wind turbines, which has led to a significant decrease of wind power cost, allowing this energy source to compete with conventional generation methods. One of the important factors in the development of wind generators has been the transition from constant speed operation to variable speed. Variable speed operation increases the energy production and reduces the drive train torque and generated power fluctuations. Experimental examination of wind energy conversion systems (WECS) in a laboratory rises the problem of a mover that replaces the actual wind turbine. A wind turbine (WT) emulator would be a useful tool to add to a test bench for studying of electric generators and power electronic converters used in WECS in laboratory conditions. The emulator should drive the wind turbine generator in a similar way as a wind turbine reproducing the torque developed for a given wind velocity and rotational speed.

The fundamental aspects for modelling the behaviour of wind turbines are widely discussed in literature. The mechanical power and torque output of the turbine is represented as a function of wind speed, air density, turbine rotational speed and swept area. These relationships are the basis for the building of a WT emulator [1]. The most convenient way for emulating the behaviour of a wind turbine in a laboratory is the use of an electric motor drive directly coupled to the shaft of the generator. The drive can be based on a DC motor as it is shown in [2]-[6] or on AC induction motor [7]-[9]. Generally the DC motor is the better choice for a WT emulator as it can be controlled by the armature current that is directly

related to the torque produced by the machine. Besides, the DC motor is simply to control and its dynamic characteristics are very good [2]. Computer simulation models of WT emulators with DC motors are proposed in [1], [3]. Other authors have developed experimental setups [2], [5], [6]. Another alternative for an accurate torque control is induction motor drive using field oriented control or direct torque control [7], [8], [9].

The main goal of this research is to develop a simulation model of a wind turbine emulator based on a DC motor drive in the Matlab/Simulink environment. The model should be appropriate for further creation of a test bench for emulation of a WT in laboratory conditions.

II. GENERAL DESCRIPTION OF THE WIND TURBINE EMULATOR

The wind turbine emulator will be built using a 1.5kW separately excited DC motor supplied by an H-bridge transistor electronic converter with PWM. The block diagram of the proposed wind turbine emulator is shown in Figure 1.

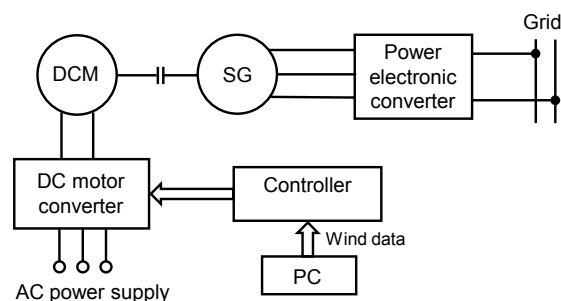


Figure 1. Simplified block diagram of the wind turbine emulator.

The main idea is to replace the wind turbine rotor and gearbox with a PC, controller,

power electronic converter and DC motor.

The DC motor is directly coupled to the generator shaft. In the particular case is used a synchronous generator that is connected to the electrical grid via second electronic converter. This converter is a combination of a diode rectifier and single-phase transistor inverter.

III. MATHEMATICAL MODELLING

1. Wind turbine model

The performance characteristics of the wind turbine have specific shape, which depends on the turbine geometry, wind speed, pitch angle etc. [2], [4], [5], [8], [9].

The turbine's mechanical output power P is expressed as

$$(1) \quad P = \frac{1}{2} \rho V^3 A C_P$$

where: ρ is the air density, V is the wind speed, A is the area swept by the rotor blades and C_P is the WT power coefficient.

The swept area is

$$(2) \quad A = \pi R_t^2$$

where: R_t is the turbine radius.

The aerodynamic torque of the wind turbine T_t is calculated as

$$(3) \quad T_t = \frac{P}{\omega_t}$$

where: ω_t is the angular velocity of the turbine.

After substitution of (2) in (3) the torque expression becomes

$$(4) \quad T_t = \frac{1}{2 \omega_t} \rho V^3 A \cdot C_P .$$

C_T is aerodynamic torque coefficient that relates to C_P by the tip speed ratio (TSR) λ

$$(5) \quad C_T = \frac{C_P}{\lambda} .$$

Based on (4), (5) and (2) the torque is calculated as

$$(6) \quad T_t = \frac{1}{2} \rho V^2 A R_t C_T .$$

The TSR is the ratio of the linear speed of the blade tip and the wind speed. It is given as

$$(7) \quad \lambda = \frac{\omega_t R_t}{V} .$$

The power coefficient C_P describes the energy conversion efficiency of a wind turbine. It is a nonlinear function of TSR λ and blade pitch

angle β characterizing the aerodynamic behaviour of the turbine

$$(8) \quad C_P = f(\lambda, \beta) .$$

The C_P value is different for each turbine type. Usually it is given by turbine manufactures as curve or in a look-up table.

For theoretical models of $C_P(\lambda, \beta)$ have been developed various analytical functions. One of the most appropriate functions is the following [2], [5], [8], [9]:

$$(9) \quad C_P = a_1 \left(a_2 \cdot \frac{1}{\lambda_i} - a_3 \cdot \beta - a_4 \right) \cdot e^{-\frac{a_5}{\lambda_i}} + a_6 \cdot \lambda$$

where:

$$(10) \quad \lambda_i = \frac{1}{\lambda + b_1 \beta - \frac{b_2}{\beta^3 + 1}} .$$

The parameters a_1 to a_6 depend on the aerodynamic characteristics of the turbine. For a typical three-bladed wind turbine these parameters are: $a_1=0.5176$, $a_2=116$, $a_3=0.4$, $a_4=5$, $a_5=21$, $a_6=0.0068$. These values are found in the literature [8] and used for the developed WT model in this study. The value of the pitch angle chosen for simulation is $\beta=0^\circ$ because the turbine is with fixed blades. The calculated C_P and C_T curves as function of λ are shown in Figure 2.

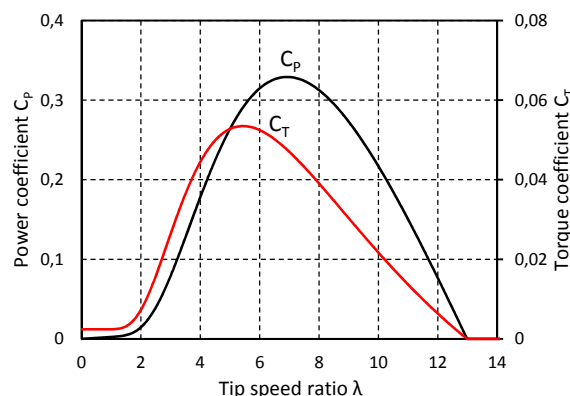


Figure 2. Turbine characteristics – power C_P and torque C_T coefficients as function of TSR.

Besides the characteristics shown in Figure 2 the wind turbine used for the simulation has the following parameters:

- Rated power 1.8kW;
- Rated wind speed 12m/s;
- Turbine diameter 2.6m.

As the electrical generator in the test bench has a rated speed 1500 rpm it is necessary to use a gearbox, which adjusts the speed and torque between the turbine and the generator. The

gear ratio is 1:2.4 and it is assumed that the efficiency of gearbox is 1 (no losses).

The block diagram of the wind turbine simulation model built according to equations (1) to (10) is shown in Figure 3.

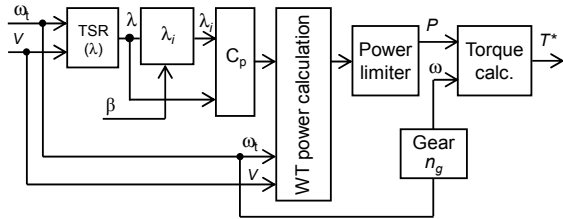


Figure 3. Wind turbine simulation model.

2. DC motor model

The motor used for the WT emulator is a separately excited DC motor. The mathematical model of the DC motor is given as follows. For the armature circuit

$$(11) \quad V_a = i_a \cdot R_a + \omega k_e \Phi + L_a \frac{di_a}{dt}$$

where: V_a is the armature voltage, i_a – armature current, R_a – armature resistance, ω – rotor angular speed; L_a – armature inductance; k_e – electromotive force constant and Φ – the main flux.

For the field circuit the equation is

$$(12) \quad V_f = i_f \cdot R_f + L_f \frac{di_f}{dt}$$

where: V_f is the field voltage, i_f – the field current, R_f – field winding resistance; L_f – field winding inductance.

The electromagnetic torque of the motor is

$$(13) \quad T_e = i_a k_e \Phi .$$

In the WT emulator the shaft of the DC motor is directly coupled to the shaft of the electric generator without any gearbox. Consequently the rotational speed of the generator is equal to this of the motor.

Mechanical part of the system is described by the equation of the motion

$$(14) \quad \dot{\omega} \cdot J + T_g = T_e - T_{loss}$$

where: J is the total inertia added to the motor shaft, T_g is the generator torque, T_{loss} – the torque due to the losses in the DC motor.

The torque on the DC motor shaft is

$$(15) \quad T = T_e - T_{loss} .$$

The motor losses are obtained from experimental testing and calculations. The loss

torque is represented as a straight line in function of the motor speed at constant excitation current as follows

$$(16) \quad T_{loss} = B\omega + T_0$$

where: B is the viscous friction coefficient and T_0 is the friction torque.

As the wind turbine and the gear box are replaced by the DC motor the relations between the turbine speed ω_t and torque T_t and those of the motor are as follows:

$$(17) \quad n_g = \frac{\omega}{\omega_t}$$

$$(18) \quad T = \frac{T_t}{n_g}$$

where: n_g is the gear ratio.

3. Controller model

The main purpose of the controller is to calculate and adjust the torque and the speed of the motor so as it reproduces exactly the torque-speed characteristics of the modelled wind turbine at given wind speed.

This goal is achieved by applying torque control of the DC motor on the basis of the reference wind velocity V and feedback signals for rotor speed n and armature current i_a . The torque control is performed by regulating the motor armature current via an inner current control loop.

The block diagram of the developed simulation model of the wind turbine emulator is shown in Figure 4. The wind velocity and rotor speed are fed to the turbine model where the motor reference torque T^* is calculated by equations (1) to (10) and (17) implemented in the model on Figure 3. As the turbine is small and it is with fixed blades (stall-controlled) the value of the pitch angle is assumed to be $\beta = 0^\circ$.

Reference torque is then used for calculation of the motor reference current I_a^* according to equations (13), (15), (16)

$$(19) \quad I_a^* = \frac{T^* + T_{loss}}{k_e \Phi} .$$

The current reference is an input for the current controller with PI structure. The output of the current controller is connected to the analogue input of the electronic converter which supplies the armature of the DC motor. This converter has a full-bridge structure with MOSFETs and operates with PWM frequency of 12.5 kHz. At this frequency the DC motor operates entirely in continuous current mode

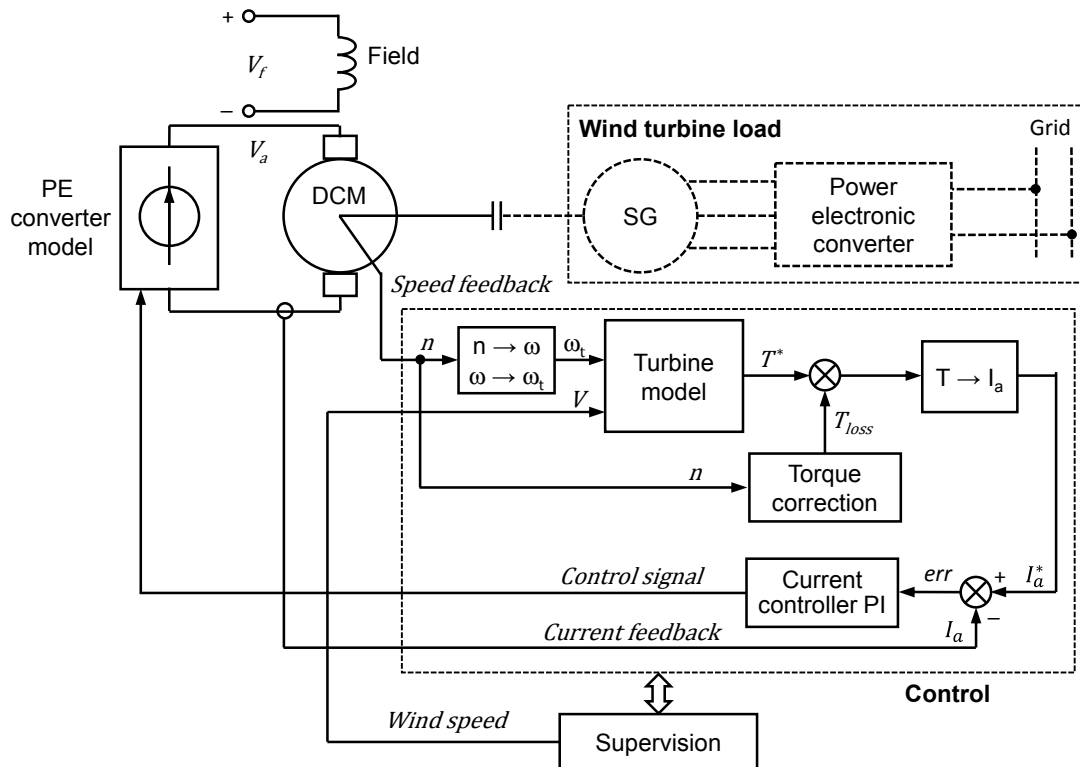


Figure 4. The block diagram of the developed simulation model of the wind turbine emulator.

(CCM) and has linear characteristics. That’s why in the Simulink an averaged model is adopted and the electronic converter is represented as a controlled DC voltage source (see Figure 4). The mechanical load of the WT emulator is the synchronous generator. In the model it is represented as a load torque applied to the motor.

III. SIMULATION RESULTS

Various simulations are performed with the developed model in order to validate its performance. The parameters used in the simulation models are listed in Table 1.

Table 1. DC motor parameters

Rated voltage	220V
Armature resistance, R_a	3.7Ω
Field resistance, R_f	354Ω
Armature inductance, L_a	53mH
Field inductance, L_f	30H
Electromotive force constant, $k_e\Phi$	1.1Vs
Viscous friction coefficient, B	0.0023Nms
Friction torque, T_0	0.418Nm

The total inertia added to the motor shaft $J=25e^{-3}kgm^2$.

In Figure 5 are shown the calculated power curves $P(n)$ of the emulated turbine at

different wind speeds. The maximum power curve is also shown.

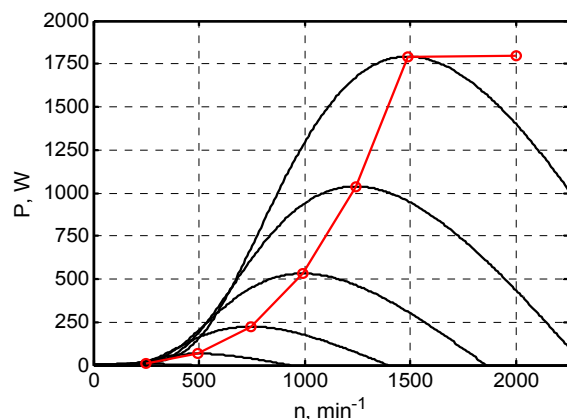


Figure 5. Calculated power curves and maximum power curve of the WT emulator.

Furthermore the emulator is tested with changing wind speed and constant torque of the generator. A pseudorandom wind profile was built as it is shown in Figure 6a.

The wind speed has values between 7 and 10m/s. The current controller operation is demonstrated with the armature voltage $V_a(t)$ and current $I_a(t)$ variations shown in Figure 6b, 6c. The turbine emulator torque $T(t)$, the shaft speed $n(t)$ and power $P(t)$, resulting from the wind input sequence, are also illustrated in Figure 6.

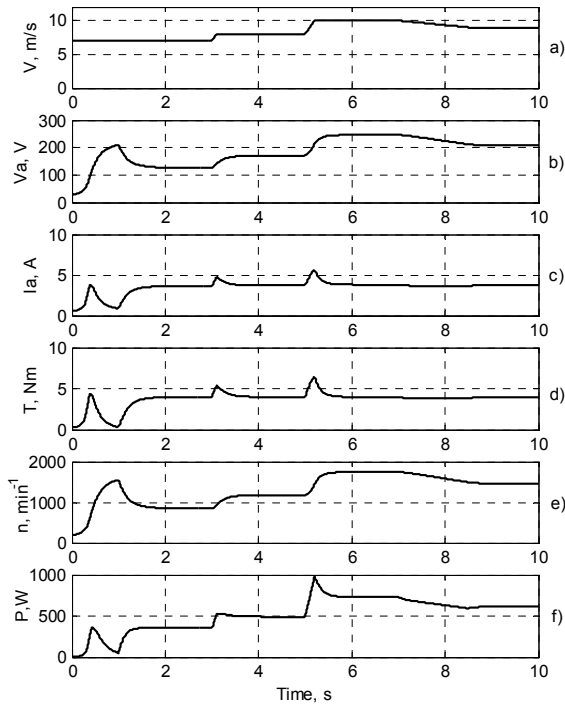


Figure 6. Turbine emulator operation at changing wind speed and constant load torque 4Nm.

Figure 7 displays the evolution of the operation point of the system in the plane (n, T) . The equilibrium operating points are the intersection points between the load torque line (characteristic of the generator) and the turbine characteristics. As can be observed, when a wind speed change occurs, the speed n evolves with the dominant mechanical time constant of the system, until a new equilibrium point is reached. So also does T , which progresses over the curve of the corresponding wind speed.

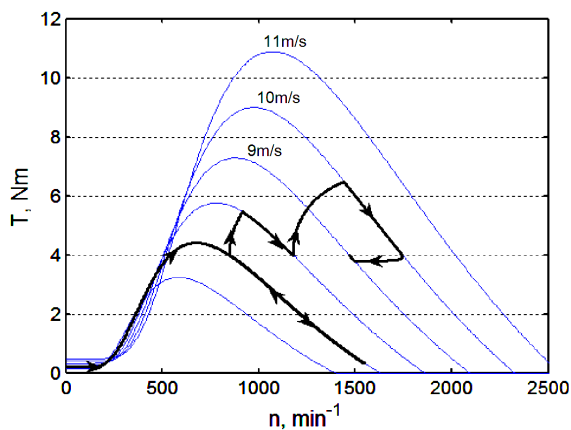


Figure 7. Trajectory of the working point in the (n, T) plane during the operation of the WTE.

Figure 8 shows the results from the simulation of the WT emulator at constant wind

speed $V=10\text{m/s}$ and changing load torque. The increase of the load torque leads to decrease in the turbine speed and increase in the produced power. This is because the operating point in this case is moving on the right side of the $T(n)$ characteristic of the turbine.

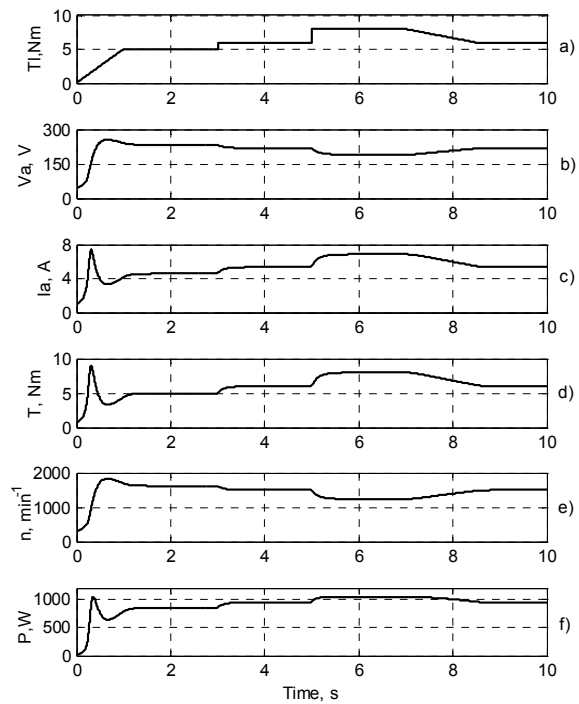


Figure 8. Turbine emulator operation at constant wind speed 10m/s and changing load torque.

In the real test bench there will be differences between the actual motor parameters and those used in the control program. Besides, the speed and the current will be measured with certain errors. All this will lead to not perfect reproduction of the reference turbine operating point that is issued by the turbine model.

In order to simulate this behaviour of the real system a Simulink model comprising a WT reference model and WTE model is created according to Figure 9.

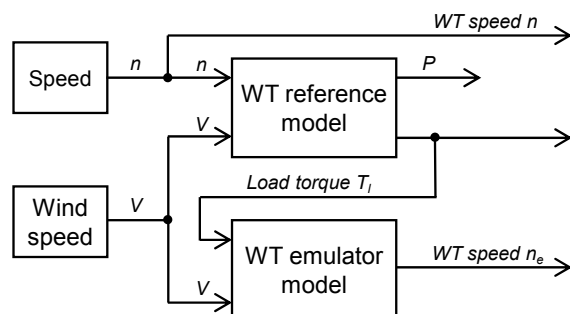


Figure 9. Simulink model for comparison of WT reference model and WTE model operation.

Some typical errors are introduced in the WT emulator model:

- Speed measurement error +1%;
- Current measurement error -4%.

The results from the simulation are shown in Figure 10 where $T(n)$ characteristics of the WT emulator are compared with those of the reference WT model.

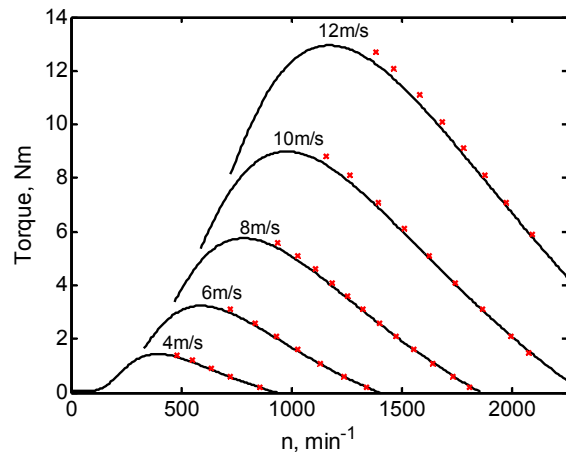


Figure 10. $T(n)$ characteristics of the WT model (solid lines) and WT emulator model (x marks).

As it can be seen the WTE operating points tend to deviate from the WT characteristics due to inaccurate measurements of the feedback quantities.

IV. CONCLUSIONS

A model of a wind turbine emulator has been designed to thoroughly reproduce the behaviour of a wind turbine using the wind profile as input. The WT emulator is based on DC motor drive with direct coupling with the electrical generator without gear box. The model is developed in Matlab/Simulink environment and gives the possibility to simulate the turbine operation under different conditions – variable wind speed, load torque and rotational speed.

The results of the simulation demonstrate that the chosen approach is good and the system has the capabilities to behave like a wind turbine subjected to exigent and repetitive wind conditions.

Further work will include a building of a real set-up of the proposed emulator, based on a DC motor and a microcontroller with appropriate software. By implementing the emulator on a test bench, it will be possible to validate and analyse different control strategies for wind energy conversion systems.

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