



## Technical note

## Open loop wind turbine emulator

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## ABSTRACT

A new wind turbine emulator (WTE) is presented, which is able to simulate the turbine power curves without using a closed loop control system. The state of the art emulators use DC or AC motors, closed loop controlled by processors with the turbine power curves recorded. The presented emulator has a DC voltage source, a power resistor and a DC motor with independent excitation. The motor power curve has a shape similar to a wind turbine power curve for a given wind speed; the wind speed variations can be emulated by the variations of the DC voltage source. The open loop emulator is completely different and new, because it works in open loop and does not require the presence of a processor.

The following elements are included: the theoretical foundations of the emulator, the emulator power curves adjustment procedure to simulate a commercial wind turbine and the experimental tests.

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## 1. Introduction

Wind turbines can be found in the market with outputs ranging from several tens of watts to several megawatts. Normally, up to 100 kW, they are called small wind turbines, and big turbines beyond that point. Small wind turbines are used in isolated applications, mini-grids and grid connections, while large turbines are usually used for grid connections grouped together to form wind farms.

Small wind turbines often have no pitch control of the blades or speed control. They mostly use permanent magnet generators and sometimes squirrel-cage induction generators.

The large wind turbines typically have control of the pitch angle and the rotation speed. The generators used are wound rotor induction and permanent magnets. In the first case, a gear box is needed to adapt the blade speed to the generator speed; while in the second case, the turbine rotor is directly coupled to the generator.

A power electronic converter is usually located between the electric generator and the load. With the permanent magnets generator, the converter used can be back-to-back or it may be a diode rectifier, a DC–DC converter and, optionally, a DC–AC converter for grid connection. With the squirrel-cage induction generator, a back-to-back converter is connected between the stator and the grid. With the double-fed induction generator a back-to-back converter connects the rotor and the grid [1].

To develop the electronic converters used in wind turbine control, wind turbine emulators are used to simulate their behavior

during laboratory tests. These motors are controlled by a computer or a processor that has the turbine power curves (Fig. 1) recorded. The closed loop control adjusts the motor variables to be as similar as possible to the turbine curves.

The DC motor is most frequently used for wind turbine emulators, using a control system (Fig. 2) where the input variables are the motor speed and torque. The motor torque can be measured, but in most cases, it is calculated from the motor current. These input variables are fed into a processor that has the curves of the turbine registered in its memory, and whose output is the DC motor reference torque. Here are some examples of practical realizations of such emulators. In Ref. [2], the emulation of the turbine is achieved by a DC motor fed by a thyristor rectifier. From the rotational speed and the wind speed, the turbine mechanical torque is calculated and introduced as a reference to the DC motor, which has a torque sensor. In Ref. [3], a commercial drive is used to control the torque of the DC motor. The turbine torque versus wind speed and turbine speed characteristics are recorded in a memory. The turbine torque is used as the torque reference of the DC motor drive. In Refs. [4,5], the DC motor torque is calculated from the current measurement and fed into the controller to emulate the power curve of the turbine. In Ref. [6], the DC motor speed is calculated and sent to the control system; a table is used for storing the power coefficient  $C_p$  versus the tip-speed-ratio (TSR)  $\lambda$  curves in the processor. In Refs. [7,8], the DC motors are controlled by means of LabView and a dSPACE controller, respectively. In Refs. [9,10], a model of the wind turbine that can emulate the change in pitch of the blades  $\beta$  is used. In Refs. [4,11,12], not only the static behavior of the turbine is taken into account, but also the dynamic behavior,

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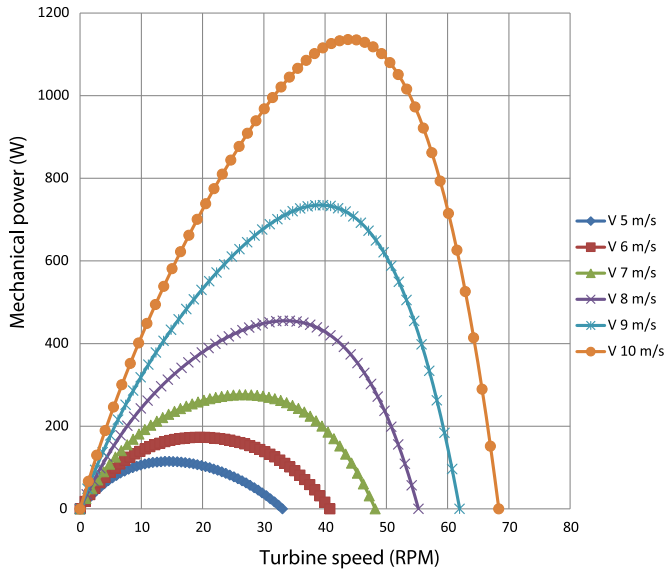


Fig. 1. Wind turbine power curves (courtesy of Kliux Energies).

including the greater inertia of the turbine and the shadow of the tower; while in Ref. [4], the difference in wind speed with increasing height is also taken into account, as is the elasticity of the drive train in Ref. [12].

There are wind turbine emulators that use AC motors, which can be of two types: squirrel-cage induction motors and permanent magnet motors. The turbine model (Fig. 3) sets the motor torque reference from the motor speed and wind speed. The control system of the AC motor is responsible for making the motor torque equal to the reference. Here are some examples of turbine emulators made with AC motors. In Ref. [13], an induction motor controlled from a commercial variable speed drive is used; the maximum torque is obtained from the power coefficient  $C_p$  versus the TSR curve and introduced into the drive as torque reference. In Refs. [14,15], an induction motor is used as the turbine emulator; the turbine torque is obtained from the wind and turbine speeds, and it is introduced as reference to the induction motor controller. In Refs. [16], an induction motor is controlled by a DSP processor, which has recorded the curve  $C_p$  (TSR,  $\beta$ ). From the  $C_p$  value, the induction motor reference speed is generated to emulate the behavior of the wind turbine. In Refs. [17], a permanent magnet motor with vector control is used to emulate the mechanical torque of the turbine. To feedback the torque, a torque sensor coupled to the shaft is used. The control is performed via the PC, and the

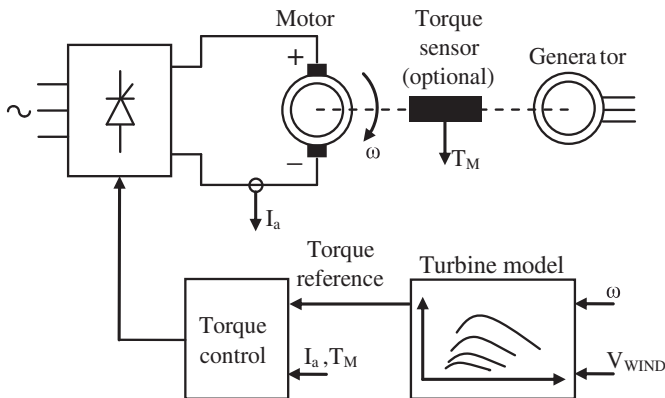


Fig. 2. Control scheme of the turbine emulator that uses a DC motor.

trigger signals are generated on an FPGA. The changes in wind speed from the base to the top of the turbine rotor, and the shadow of the turbine tower are taken into account.

All wind turbine emulators listed above use closed loop control. They feedback the speed and the torque of the motor that emulates the wind turbine, and generate a new motor torque reference using some type of processor or computer. This article presents a completely different and new wind turbine emulator, as it works in open loop and does not require the presence of a processor.

The new emulator presented consists of a DC voltage source, a power resistor and a DC motor. The emulator can operate in open loop because it inherently has power curves (Fig. 4) similar to those of a wind turbine, where the wind speed values have been substituted by the DC voltage values  $V_{DC}$ . The power curves that the emulator can generate are in an inverted parabolic shape, so they are not exactly equal to those of the wind turbine, but can be adjusted so that the difference is very small for a large range of wind speeds.

The article includes a detailed description of the fundamentals of the open loop emulator. The procedure for the emulator power curves to fit the turbine power curves is presented; the adjustment is performed for the case of the commercial wind turbine of Fig. 1. The article is structured as follows: Section 2 provides a theoretical introduction to the fundamental concepts of wind turbines, Section 3 includes the theoretical foundations of the emulator, Section 4 details the procedure to design and adjust the emulator, and Section 5 includes the experimental tests of the emulator.

## 2. Wind turbines

Wind energy is the kinetic energy of the wind. The power of the air passing through the wind turbine rotor is  $P_1 = 0.5\rho AV^3$ , where  $\rho$  is the air density,  $A$  is the area swept by the rotor blades and  $V$  is the wind speed. Only a part of this power can be converted into mechanical power  $P$ . The power coefficient of the turbine  $C_p$  is the relationship between the mechanical power and the wind power  $C_p = P/P_1$ . The mechanical power of the turbine, therefore, is

$$P = 0.5\rho AC_p V^3 \tag{1}$$

The power coefficient  $C_p$  has a theoretical maximum value of  $16/27 \approx 0.59$ , named the Betz limit, although, in commercial turbines, the maximum value is typically around 0.4. The power coefficient  $C_p$  is a function of the ratio between the speed of the blade tip and the wind speed,

$$\lambda = \frac{\omega R}{V} \tag{2}$$

where  $R$  is the radius of the rotor and  $\omega$  is the rotational speed of the rotor. The parameter  $\lambda$  is called “tip-speed-ratio” (TSR). In a fixed pitch turbine, the power coefficient  $C_p$  versus the TSR curve has the shape shown in Fig. 5. It has the maximum value  $C_{pmax}$  for the

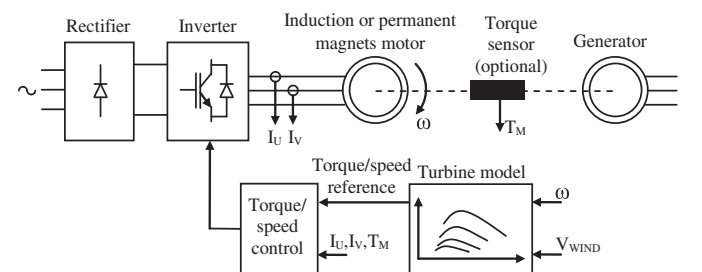


Fig. 3. Control scheme of the turbine emulator that uses an AC motor.

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