Fixed Pitch Wind Turbine Emulator using a DC Motor and a Series Resistor

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Keywords

Wind generator, wind turbine emulator.

Abstract

It is presented a novel emulator for fixed pitch wind turbines, allowing the laboratory testing of the generator control systems associated with the turbines. The emulator consists of the coupling in series of the following elements: a source of DC voltage, a power resistance and a DC motor. The modification of the input DC voltage has the same effect as the variation of wind speed in a fixed pitch wind turbine. It is included the theoretical foundation of the emulator, the simulations and the experimental results.

Introduction

Fixed pitch wind turbines have been used for a long time in power generation systems, from small to middle power. Nowadays, medium and high power systems use variable pitch wind turbines, and the use of fixed pitch turbines is limited to low-power applications. Wind turbines have power generation control systems to adapt them to changes in wind speed, and whose aim is to extract as much power as possible from the wind. In large turbines, the power extracted from the wind is controlled by means of the turbine speed and the pitch angle of the blades. When the turbines power range is smaller, the power is controlled by only one of the two systems; there are turbines that control the speed but not the pitch angle, and others that can change the pitch angle but not the speed [1].

The mechanical power curves of a fixed pitch turbine can be expressed as a function of wind speed as shown in Figure 1 [2] [3]. For each wind speed, the power curve has a maximum value that occurs at a different speed. A wind turbine emulator should be able to reproduce these power curves.

Turbines speed is controlled by a power electronic converter. This has a twofold mission, as well as controls the speed, is responsible for converting the AC voltage produced by the alternator into a DC. A second converter is responsible for transforming the AC voltage to be injected to the network.

When designing a power electronic converter application for wind energy applications, after performing the simulations fit, it is necessary laboratory tests, before making the final field tests using a wind turbine. In the intermediate stage of laboratory testing, it is required some sort of system that emulates the operation of the wind turbine. The designers of drives for wind turbines often use DC motors, squirrel cage induction motors or permanent magnets motors [4-11]. In all cases, the motor is controlled so that takes some power curves similar to those of a wind turbine. It uses a microprocessor-based control, which takes as input variables wind speed and turbine speed, and from them, provides the reference torque of the motor that emulates the turbine.

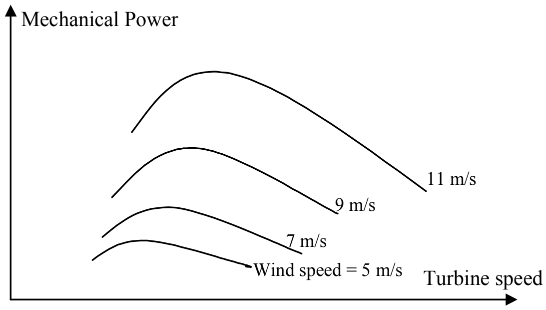


Fig. 1: Turbine power curves

The state of the art of emulation systems is such that the DC motor is the most frequently used [4-8]. It uses a control system (Figure 2), where the input variables are the speed and torque of the motor. Motor torque can be measured, but in most cases it is estimated from the motor current. These input variables are introduced into a microprocessor that has recorded the turbine curves and whose output is the torque reference of the DC motor. Here are some examples of practical achievements of this kind of emulators. In [4], the emulation of the turbine is achieved via a DC motor, fed by a thyristors converter. From the rotation speed and the wind speed, the turbine mechanical torque is calculated and is introduced as a reference in the DC motor drive, which has a torque sensor. In [5], a commercial drive of a DC motor with torque control is used. Turbine torque characteristics, depending on wind speed and turbine speed, are stored in a memory. This torque is used as the torque reference of the DC motor drive. In [6] and [7], the motor torque is estimated on the basis of the current measure, and it is introduced to the controller to emulate the power turbine curves. In [8], the DC motor speed is calculated and sent to the DC motor control system; a lookup table is used to store the power coefficient versus tip-speed-ratio (Cp-TSR) characteristic in the microprocessor.

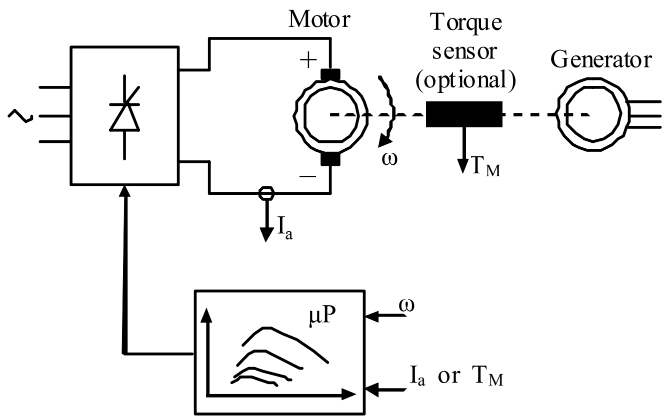


Fig. 2: Scheme of a turbine emulator control system that uses a DC motor

AC motors are also used in emulation systems [9-11]. The control system (Figure 3) sets the motor torque reference from the motor speed and the wind speed. The control system of the AC motor is responsible for establishing a torque equal to the reference. Examples of emulators made with AC motors, can be seen below. In [9], a permanent magnets motor with vector control is used to emulate the turbine mechanical torque. For feedback, it uses a torque sensor on the shaft. The control is done via PC and the driver signals are generated from an FPGA. It takes into account changes in wind speed from the bottom to the top of the turbine rotor, and the shadow of the turbine tower. In [10] and [11], an induction motor is used as turbine emulator. Based on wind speed and turbine speed, the turbine torque is obtained and is introduced as a reference to the induction motor regulator.

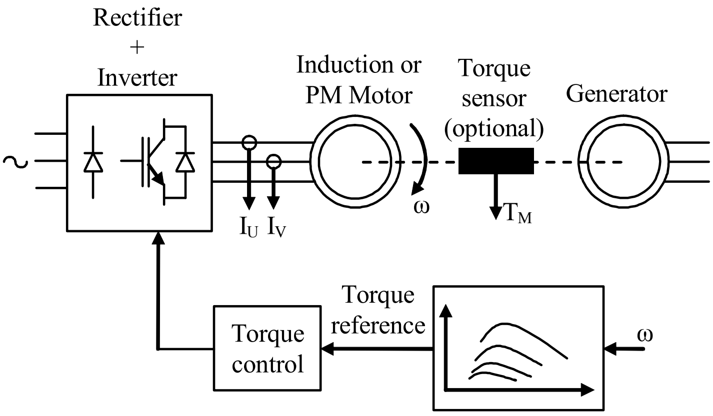
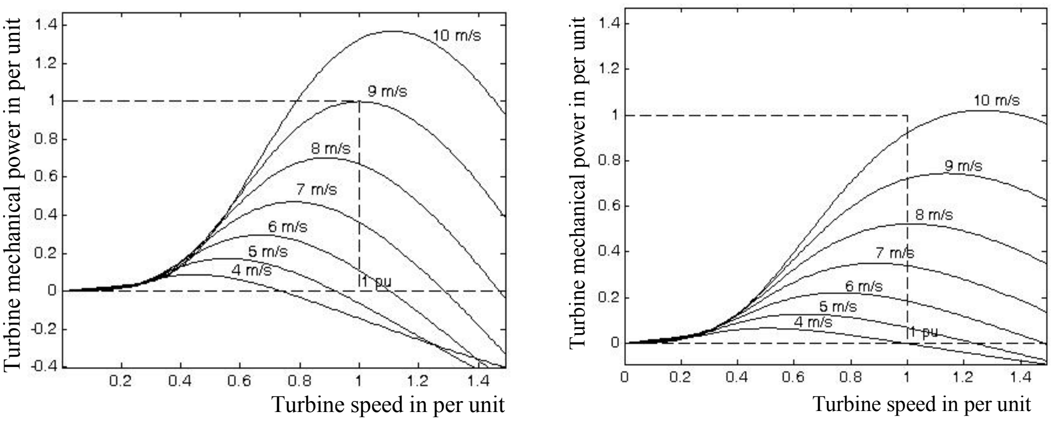


Fig. 3: Scheme of a turbine emulator control system that uses an AC motor

Proposed Emulator

The problem that seeks to remedy this paper is produced in the design phase of the generators control systems of wind turbines applications. The phases of the design would be, sequentially, simulation, laboratory tests and field trials. The first was conducted by computer, the latter using electric machines to emulate the wind turbine and the third using the wind turbine. In the laboratory tests are needed something that emulates the behavior of the wind turbine and, specifically, its power curves (Figure 4). The mechanical power of the wind turbine is a function of turbine speed and wind speed. For each wind speed, maximum power is generated for a different speed. The negative part of the mechanical power means functioning as a load, not as a generator.



(a) (b)

Fig. 4: Mechanical power curves of a wind turbine for different values of wind speed. Pitch angle of: (a) 0 degrees; (b) 5 degrees

We propose a way for solving the problem of emulating the mechanical power curves of the turbine, for carrying out laboratory testing. It consists of a DC motor controlled from the induced, a power resistance and a variable source of DC voltage, all linked in series (Figure 5). The variation of the DC voltage will be responsible for causing changes similar to those that produced the change of wind speed in a wind turbine.

The difference in our emulator with the state of the art is that our emulator reproduces the form of the turbine power curves in open loop, while the emulators currently working in closed loop. Our emulator has, so intrinsic, power curves similar to those in a turbine, so it is not needed the presence of a feedback system. The technique uses existing motors of several types (direct current, squirrel cage, permanent magnets), which work so intrinsic at constant speed, and that only by introducing a system to control the torque and speed, manages to reproduce the curves of the power turbine.

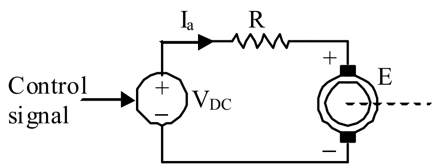


Fig. 5: Electrical diagram of the wind turbine emulator

Working in open loop, our emulator is a simpler system, has no problem of interaction between the two control loops (emulator turbine and generator) and is faster. The patent for this emulator is in process.

The system can simulate, by varying the DC voltage, variations in wind speed (as shown in Figure 4a) and changes in the blades pitch angle (as can be seen by comparing the graphic in Figure 4a and Figure 4b, which have a difference in the pitch angle of 5 degrees).

Detailed explanation of the emulator

The emulator consists of a variable source of DC voltage, a power resistor and a DC motor, all of them in series. It uses a DC motor with separate excitation. As is known, the power equations governing the behavior of the DC motor are:

$$E = K_E \omega \tag{1}$$

$$K_E = L_{af} I_f \tag{2}$$

$$T_E = K_T I_a \tag{3}$$

where:

E = motor e.m.f.
K_E = voltage constant
ω = motor speed
L_{af} = mutual inductance between field and stator
I_f = excitation current
T_E = motor torque
K_T = torque constant
I_a = stator current

The mechanical power of the motor, ignoring the losses in the motor resistance and the friction losses, is:

$$P_m = EI_a = E\left(\frac{V_{DC} - E}{R}\right) = \frac{K_E \omega V_{DC} - (K_E \omega)^2}{R} \tag{4}$$

The value of the voltage constant K_E must be constant. For this, excitation current I_f should be constant, so the excitation of the motor must be independent. The graphical representation of the motor power equation (1), for various values of the DC voltage, is shown in Figure 6 where there is equivalence with the curves of the wind turbine. The calculations used a motor with nominal power of 440 W and a series resistance of 50 Ω.

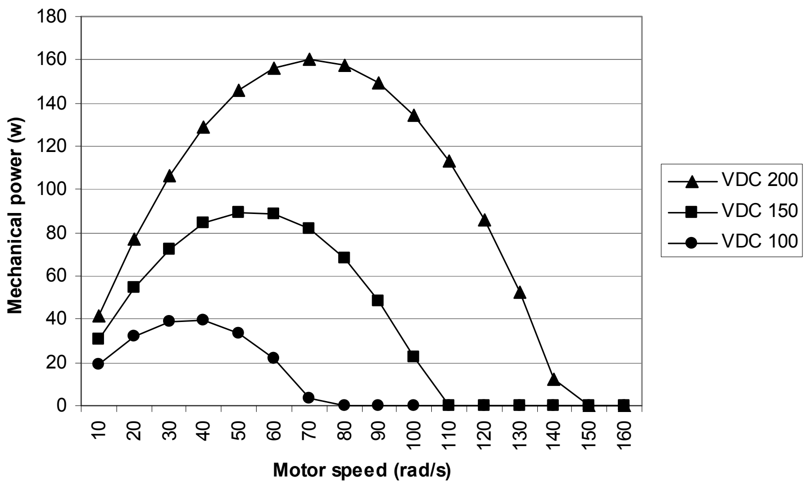


Fig. 6: Excel calculation of the emulator power curves, for different DC voltage source values

The series resistance R should permit a power dissipation of the same magnitude as the DC motor, because when the motor speed is low, the power dissipated in this resistance increases substantially, taking the following value:

$$P_R = I_a^2 R = \left(\frac{V_{DC} - E}{R} \right)^2 R = \frac{\left(V_{DC} - K_E \omega \right)^2}{R} \qquad (5)$$

In Figure 7, the power dissipated in the series resistance has been represented in the same case as Figure 6. It can be seen that the power is greatly increased in the resistance at low speed. This represents a limitation to the system, and calls for lower speed limit on the emulator.

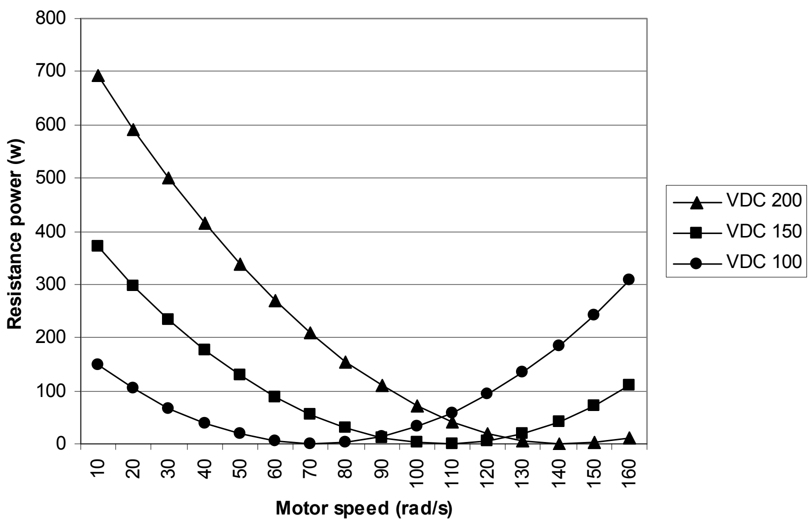


Fig. 7: Excel calculation of the series resistance power, for different DC voltage source values

Simulation Results

The wind turbine emulator has been simulated, using Simulink, to verify that it has mechanical power curves similar to those of a fixed pitch wind turbine. A 5 HP motor was chosen from Simulink libraries. The scheme is shown in Figure 8. The power curves of the DC motor, for various values of the DC voltage source can be seen in Figure 9, for R = 5Ω. For each value of the DC voltage source, there is a mechanical power curve for the motor, a form similar to those of a wind turbine. The voltage in the emulator can be considered equivalent to the speed of the real wind turbine.

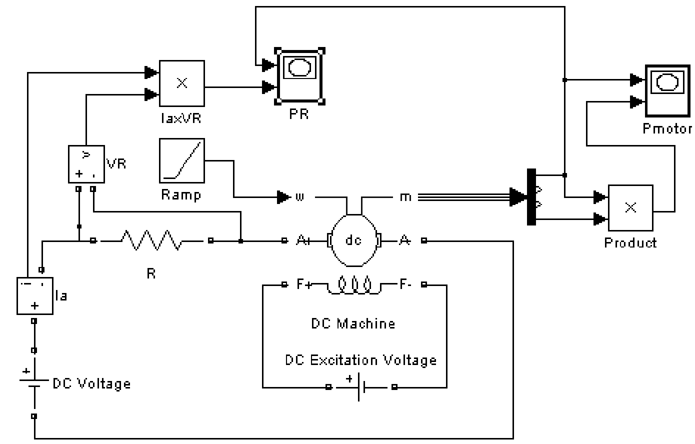


Fig. 8: Turbine emulator scheme simulated with Simulink

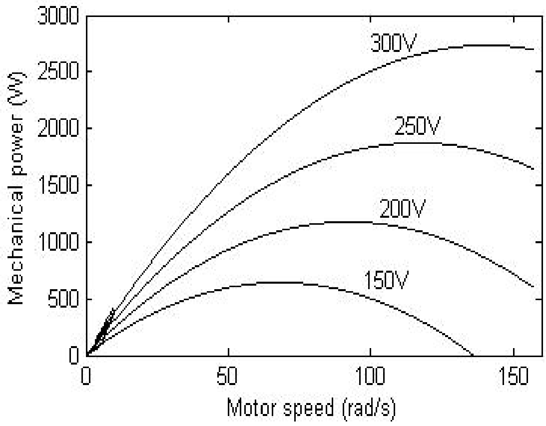


Fig. 9: Simulink simulation of the emulator power curves, for different DC voltage source values

Experimental Results

To obtain the experimental results, a set of two DC machines and a tachogenerator has been used. A DC machine has been used as a DC motor and the other as a DC generator (see Figure 10). The DC motor power is obtained from a single-phase half-controlled rectifier. The generator speed is controlled by a single-phase thyristor rectifier that works in inverter mode. The aim of the experiment is to obtain the mechanical power curves of the wind turbine emulator versus speed, for various values of DC voltage.

The characteristics of the elements used are shown in Table I. The characteristics of the DC motor and the DC generator are identical. The internal motor resistance is named R_M.

The mechanical power of the motor has been calculated as the difference between the electrical power and the losses in the internal resistance, as expressed by the following formula,

$$P_m = EI_a - R_M I_a^2 \tag{6}$$

The coupling of the two machines has been carried out softly, to avoid excess current. For this, first the generator voltage V_{DC2} has been established to 0. Then, the rectifier that feeds the motor has been switched on.

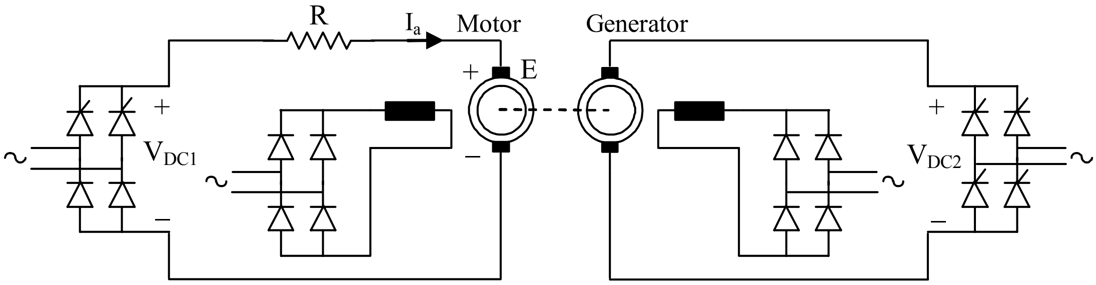


Fig. 10: Scheme used in laboratory tests

Table I: Parameters of the motor and the series resistance

R	50 Ω
Pmotor	440 W
Vmotor	220 V
R_M	9 Ω

Experimental results are presented in Figure 11. The voltage V_{DC1} is set by the motor rectifier firing angle. For each value of V_{DC1}, the speed variation is achieved through the generator rectifier voltage V_{DC2} (operating in inverter mode).

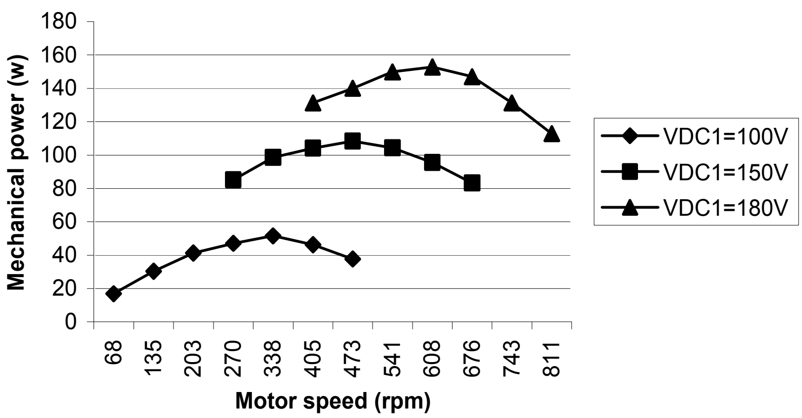


Fig. 11: Emulator mechanical power, obtained in laboratory tests

The voltage V_{DC1} must be adjusted for each speed, because this value is affected by the speed of the motor. The reason is that the electromotive force is proportional to motor speed.

It can be seen that the operation of the turbine emulator (see Figure 11) is as expected and as indicated by the simulations. For each value of the voltage V_{DC1}, the power curve has a maximum, which occurs at a higher speed when the value of V_{DC1} increases.

In Figure 12, the power dissipated in the series resistance is presented. As can be seen, its value increases greatly at low speed, which is a limitation on the proposed emulator. To avoid the resistance power takes an excessive value, it is necessary to limit the speed reduction, particularly for high voltages.

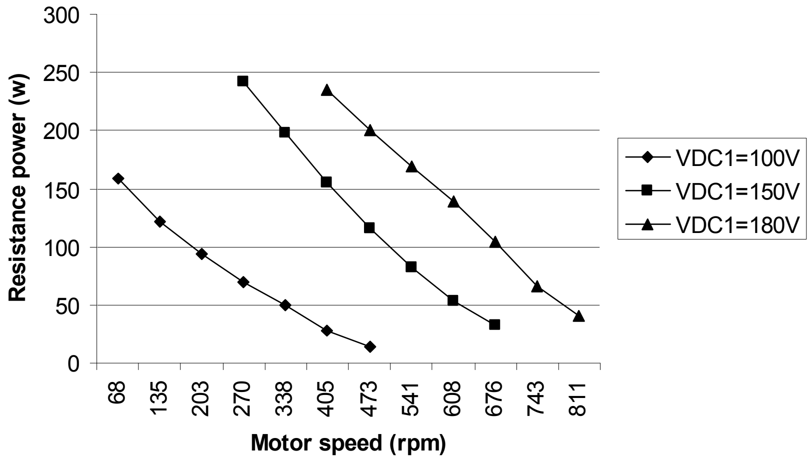


Fig. 12: Power dissipated in the emulator resistance, obtained in laboratory tests

Conclusion

It has been presented a novel system for emulation of fixed pitch wind turbines. It is useful for laboratory testing of power converters used to control the turbine generator. The emulator is composed by the series connection of a variable voltage source, a power resistance and a DC motor with independent excitation. It has been explained the theoretical foundation of the emulator, its behavior has been simulated and experimental tests have been performed. All has demonstrated the emulator can reproduce the power curve of a wind turbine, a quite rough.

The emulator shows the novelty of working in open loop, while the current emulators work in closed loop, so it has an intrinsic structure more like wind turbines.

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