# WIND TURBINE TORQUE-SPEED FEATURE EMULATOR USING A DC MOTOR

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***Abstract*—This paper presents the development of a wind turbine emulator to assist tests to be undertaken on wind energy conversion systems, which may include generator control, smart grid integration, stability analysis, among others. A DC motor delivers in its rotor the wind turbine torque versus speed characteristic. A dynamical model is used instead of steady state conditions, and typical values of wind turbine mechanical constants are presented. It is also investigated the adequacy of a thyristor six pulse three-phase rectifier for this application. The emulator has been designed to facilitate tests on wind energy systems under several wind speed conditions.**

***Index Terms*—Wind energy conversion systems, wind turbine emulator, two-mass model, DC motor**

## I. INTRODUCTION

Currently, researchers have been interested in renewable energy for electricity production such as wind power, solar cell, and fuel cell mainly because it is clean, renewable and economical for industry and government. Investments in research focusing on renewable sources of energy increased tenfold in the last decade, among them stands the wind generation, which is the fastest growing source, [1].

Many research laboratories have been focused on performance improvement in wind energy conversion systems (WECS), which directly impacts the efficiency and the costs of wind power setup. In order to achieve these improvements, WECS peculiarities and constraints are required to be overly investigated. Since it is not practical to study turbines operating in wind farms, it is convenient to emulate the turbine characteristics, drive train dynamics, and wind power fluctuations in the laboratory.

Emulators to represent WECS have been presented in the literature [2]-[10]. Most of them reproduce the behavior of fixed-pitch turbines in steady-state, but this solution lacks the flexibility required to emulate different wind turbines, like variable speed pitch-controlled [3]. This issue also limits dynamic conditions that can be emulated combined with the turbine mechanical power control, such as wind gusts or the torsional oscillation in the drive train.

This paper presents a wind turbine emulator (WTE) based on the power versus wind speed characteristic, which accurately emulates the instantaneous speed and torque developed by the wind turbine model, replacing typical turbine by a motor, allowing wind energy systems to be easily tested in the laboratory under different wind conditions and dynamical effects. To emulate the WECS, either DC or AC motors are usual choices to represent the torque-speed feature of the wind turbine. The DC motor is the most common option due to its simplicity of control. The adequacy of a three-phase thyristor ac-dc converter to drive the DC motor, regarding to low bandwidth and current ripple of the converter, is also investigated in this paper.

The paper is organized as follows: section II presents the system modelling, as well as the description of wind turbine model and DC motor model; section III shows the proposed emulator and the method to control the motor; section IV presents the simulation results obtained.

## II. SYSTEM MODELING

The development of the WTE requires a model that accurately describes how wind energy is captivated by the wind turbine.

### A. Wind Turbine Modeling

A wind turbine model consisting of a generator and the two mass model of a drive train is a compromised solution to provide a single wind turbine model for different types of control systems and power systems studies [1],[4],[5],[6].

*1) Developed Power:*

Theoretically, a maximum of 59.3% of the wind power can be captivated and converted by a turbine [5],[7]. However, actual turbines can harness around 35-45%, which characterises the power coefficient of the turbine ($C_p$).

The mechanical power $P_T$ captivated by a wind turbine is given by:

$$P_T = \frac{1}{2}\rho\pi r^2 v_w^3 C_p(\lambda, \beta), \tag{1}$$

where $\rho$ is the air density, $r$ is the blade length, $v_w$ is the wind speed, $\lambda$ is the tip speed ratio (TSR), and $\beta$ is the blade pitch angle in degree. The power coefficient $C_p(\lambda, \beta)$ can be obtained from the manufacturer data and depends on the wind turbine geometry and the TSR, which is given by:

$$\lambda = \frac{\omega_T r}{v_w}, \tag{2}$$

where $\omega_T$ is the wind turbine angular speed.

The torque developed by a wind turbine is then

$$T_T = \frac{P_T}{\omega_T} = \frac{1}{2\omega_T}\rho\pi r^2 v_w^3 C_p(\lambda, \beta), \tag{3}$$

and replacing the turbine angular speed according to (2), it becomes

$$T_T = \frac{1}{2}\rho\pi r^3 v_w^2 \frac{C_p(\lambda,\beta)}{\lambda}, \tag{4}$$

where $C_p(\lambda,\beta)/\lambda$ is the torque coefficient $C_T$. Therefore, the torque $T_T$ is a function of the wind speed, the pitch angle and the turbine speed; which characterizes the torque versus speed behavior of the turbine.

An example of the torque versus speed characteristic of a wind turbine under steady-state, fixed-pitch and constant wind speed operation is shown in Fig. 1 for several wind speeds [8], where the dashed line represents the optimal torque $T_{opt}$ for maximum power extraction.

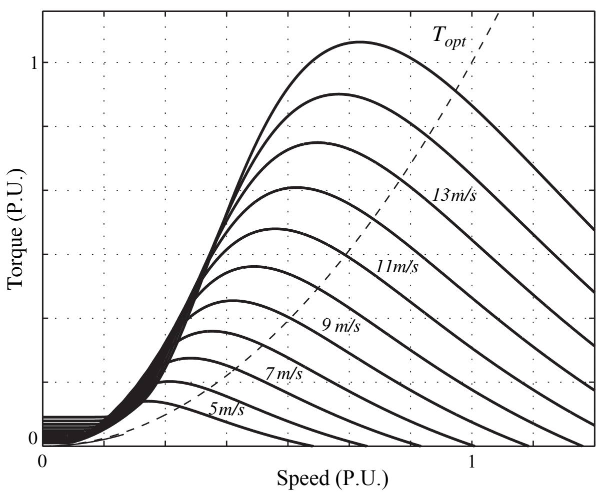


Fig. 1. Wind turbine per unit torque versus speed characteristic

A pitch-controlled wind turbine is designed to produce the rated power for wind speeds equal or greater than nominal operation speed. A computer checks the output power several times per second and adjusts the rotor blades accordingly. The pitch mechanism turns the blades few degrees every time that the wind changes in order to keep the optimum angle and maximize output. When the power output becomes too high, it pitches the rotor blades slightly out of the wind to protect the turbine from damages of excessive load [9].

Fig. 2 ilustrates the power developed by a pitch-controlled wind turbine as a function of the wind speed $v_w$. The wind generator starts to run and produces power at the wind speed connection $V_1$ (cut-in wind speed). As wind speed increases, the developed power also increases until the nominal wind speed $V_2$. For wind speeds greater than $V_2$, the pitch mechanism works in order to keep the turbine producing the nominal power and to reduce the mechanical stress on the turbine unity. When the wind reaches speed greater than cut-off speed $V_3$, the turbine is turned off to protect it from damages.

The power response to wind speed is usually obtained through experimental tests and it is usually provided by the turbine manufacturer. To represent a pitch-controlled turbine, the power

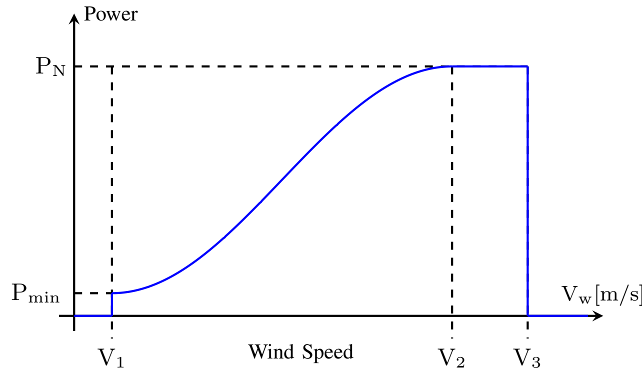


Fig. 2. Power curve of a wind turbine with pitch angle control

versus wind speed relation shown in Fig. 2 can be mathematically described as follows [5]

$$P_T = \\ = \begin{cases} \frac{P_N - P_{min}}{2}\left[1 - cos(\pi\frac{V_w - V_1}{V_2 - V_1})\right] + P_{min}, & V_1 \leq V_w \leq V_2 \\ P_N, & V_2 < V_w < V_3 \\ 0, & \text{otherwise} \end{cases} \tag{5}$$

where $P_n$ and $P_{min}$ are the emulated turbine nominal and minimal power, respectively.

### 2) *Drive Train Model:*

A two mass model is a compromised solution to provide a single wind turbine model, which is designed to represent the dynamics and the fundamental resonance frequency of the drive train [1],[9],[10].

Fig. 3 depicts the two mass model of the wind turbine drive train. In this model, the first inertia $J_T$ is made of the lumped inertia of the turbine, part of the gearbox, and the low-speed shaft. The second inertia $J_G$ consists of the generator rotor mass, the high-speed shaft including a disk brake, and part of the gearbox. The two inertias are connected to each other through a spring, which mainly represents the stiffness $K_s$ of the gearbox and the mechanical shaft. $D_T$ and $D_G$ are the friction coefficients and represent the mechanical losses by friction in the rotational movement. The shaft to which the turbine is connected is the low speed shaft, and the one which the generator is connected is the high-speed shaft.

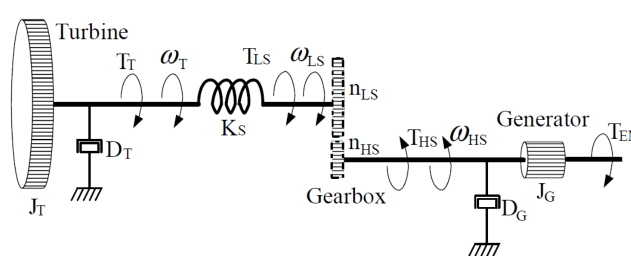


Fig. 3. Drive train structure of a wind turbine

The dynamical equations that represent the system of the two rotational masses and the ideal gear box are given by:

$$J_T \frac{d\omega_T}{dt} = T_T - D_T\omega_T - \underbrace{K_S(\theta_T - \theta_{LS})}_{T_{LS}}, \tag{6}$$

$$J_G \frac{d\omega_G}{dt} = T_{HS} - D_G\omega_G - T_{EM}, \tag{7}$$

$$\frac{T_{LS}}{n_{LS}} = \frac{T_{HS}}{n_{HS}}, \tag{8}$$

where $\omega_T$ is the angular rate of the turbine, $\omega_G$ is the angular rate of the generator rotor, $n_{LS}/n_{HS}$ is the gearbox ratio, $T_{LS}$ and $T_{HS}$ are the low speed and high-speed shaft torque, $\theta_T$ and $\theta_{LS}$ are the angle of the turbine shaft and the angle of the low speed shaft, respectively.

The drive train structure is represented in the per unit system in order to design the WTE. Thereby, one can represent several wind turbines based on typical per unit values of mechanical constants [11]. To apply the p.u. system to the rotating mechanical system, it becomes necessary to define base values for angular speed ($\omega_{base}$), angle ($\theta_{base}$), and power ($P_{base}$). From these base values, other quantities are also defined in p.u., as follows:

$$T_{base} = \frac{P_{base}}{\omega_{base}}, \tag{9}$$

$$K_{base} = \frac{T_{base}}{\theta_{base}} = \frac{P_{base}}{\omega_{base}\theta_{base}}, \tag{10}$$

and

$$D_{base} = \frac{T_{base}}{\omega_{base}}. \tag{11}$$

In p.u. systems, the inertia is generally represented by the inertia time constant ($H$) instead of a dimensionless quantity, as follows:

$$H = \frac{J\omega_{base}^2}{2P_{base}}. \tag{12}$$

For the WTE, the main base values are referred to the electrical angular speed and angle, $\omega_{base,el.}$ and $\theta_{base,el.}$, respectively, where the indice *el.* denotes the electrical system. From these base values, it is possible to derive the base values for both the high and low-speed shafts, depending on the generator number of pole pairs ($n_{PP}$) and the gearbox ratio ($n_{LS}/n_{HS}$), as follows:

$$\omega_{base,HS} = \frac{\omega_{base,el.}}{n_{PP}}, \tag{13}$$

$$\theta_{base,HS} = \frac{\theta_{base,el.}}{n_{PP}}, \tag{14}$$

$$\omega_{base,LS} = \frac{\omega_{base,el.}}{n_{PP}} \frac{n_{HS}}{n_{LS}}, \tag{15}$$

$$\theta_{base,LS} = \frac{\theta_{base,el.}}{n_{PP}} \frac{n_{HS}}{n_{LS}}. \tag{16}$$

Once defined the base values using (9)-(16), one can use the typical per unit values shown in Table I to represent a wide range of wind turbines [11].

TABLE I
TYPICAL MECHANICAL DATA (P.U. VALUES)

| Quantity | Range |
|---|---|
| Generator rotor inertia constant, $H_g$ (s) | 0.4 - 0.8 |
| Wind turbine inertia constant, $H_T$ (s) | 2.0 - 6.0 |
| Low-speed shaft stiffness, $K_{LS}$ (p.u.) | 0.35 - 0.7 |

### B. Wind speed

The representation of the wind speed model includes four components: constant speed ($V_c$), sinusoidal variations ($V_{sin}$), wind gusts ($V_g$), and random noise ($V_r$). The wind speed is defined by the sum of these components which makes possible the representation of numerous situations of wind [12], as follows

$$V_w = V_c + V_{sin} + V_g + V_r. \tag{17}$$

NOISE ???

The wind gust is mathematically described as follows:

$$V_g = \begin{cases} \frac{A}{2}\left[1 - cos(2\pi\frac{t - T_{g0}}{T_g})\right], & \text{if} \quad T_{g0} \le t \le T_{g0} + T_g \\ 0, & \text{otherwise} \end{cases} \tag{18}$$

where $t$ is the time in seconds, $T_{g0}$ is the initial time of the gust in seconds, $T_g$ is the duration of the gust, and $A$ is the peak of the gust. Fig. 4 shows an example of wind speed obtained from this model. The wind speed can also be real data from an anemometer.

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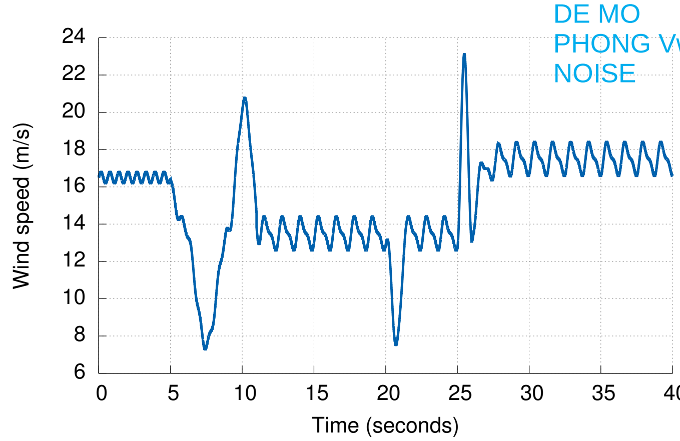


Fig. 4. Wind speed

### C. DC Motor Model

Due to its simplicity of control, a DC motor is a good solution to emulate the wind turbine model. The electrical model of a

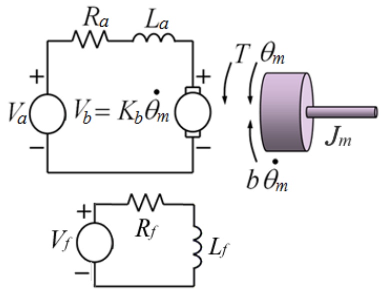


Fig. 5. DC Motor electrical model

DC motor is depicted in Fig. 5 and the parameters are presented in Table II.

The developed torque in a DC motor is a product of the armature current and the field current, as follows

$$T(t) = K_c L_f i_f(t) i_a(t), \tag{19}$$

where $K_c$ is a constant of the electrical machine.

The back electromotive force (BEMF) phenomenom is a product of the field current and the motor angular speed, given by

$$V_b(t) = K_f L_f i_f(t) \omega_m(t), \tag{20}$$

where $K_f$ is a coupling constant of the machine.

Assuming the field voltage $V_f$ as a constant, the field current $i_f$ is also constant in steady-state. Therefore, (19) and (20) can be rewritten as follows

$$T(t) = K_a i_a(t), \tag{21}$$

$$V_b(t) = K_b \omega_m(t), \tag{22}$$

where $K_a$ is the torque constant and $K_b$ is the BEMF constant.

TABLE II
DC MOTOR MODEL PARAMETERS

| Symbol | Parameter |
|---|---|
| $J_m$ | Motor inertia ( $\mathrm{kgm}^2$ ) |
| $D_m$ | friction coefficient ( $\mathrm{kgm}^2/\mathrm{s}$ ) |
| $L_a$ | Armature inductance (H) |
| $R_a$ | Armature resistance ( $\Omega$ ) |
| $V_a$ | Armature Voltage (V) |
| $I_a$ | Armature Current (A) |
| $L_f$ | Field inductance (H) |
| $R_f$ | Field resistance ( $\Omega$ ) |
| $V_f$ | Field Voltage (V) |
| $I_f$ | Field Current (A) |
| $K_a$ | Motor torque constant (Nm/A) |
| $K_b$ | Back-EMF constant (Vs) |
| $V_b$ | Back electromotive force (V) |
| $\theta_m$ | Rotor angular position (radians) |
| $\omega_m$ | Rotor angular speed (rad/s) |
| $T$ | Mechanical torque (Nm) |

The mechanical equation of DC motor with load is

$$(J_m + J_L)\frac{d\omega_m}{dt} = T(t) - D_m\omega_m(t) - T_{LOAD}, \tag{23}$$

where $J_L$ is the load inertia. The voltage law of Kirchhoff provides the following electrical equation:

$$V_a(t) = V_b(t) + R_a i_a(t) + L_a\frac{di_a(t)}{dt}. \tag{24}$$

The basic expressions which describe the model of the motor are (21)-(24).

## III. The Proposed Wind Turbine Emulator

The DC motor shaft connected to a generator is used to emulate the wind turbine torque versus speed characteristic in the laboratory. A mechanical diagram of the representative laboratory system is shown in Fig. 6.

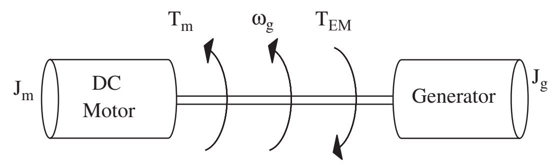


Fig. 6. Representative laboratory system of the WTE

The mechanical behavior of DC motor modeled in (23) is used to set a model equivalent to (7), which will dictate the torque that the DC motor will produce in response to a given wind, such that the effect of the turbine rotor inertia is emulated. The generator inertia $J_g$ in (7) is represented in (23) as the lumped inertia of the actual generator and the DC motor, representing a larger generator.

### A. Emulator Algorithm

In order to overcome the drawbacks of other turbine emulators, which require a fixed pitch steady-state model, this paper proposes an emulator algorithm where the dynamic feature of the two mass model is obtained based on the developed power, described in (5). In this way, the mechanical control of the turbine, such as pitch control or stall control, is built-in. Using this scheme any type of wind turbine can be represented if the respective power versus wind speed characteristic curve is given, limited only by the DC motor power rating.

The flowchart shown in Fig. 7 represents the wind turbine emulator, which is executed by the DC motor. This algorithm runs into a computer which controls the DC motor. The generator electromagnetic torque is estimated into the computer and fed back into the model in order to produce a realistic wind turbine response.

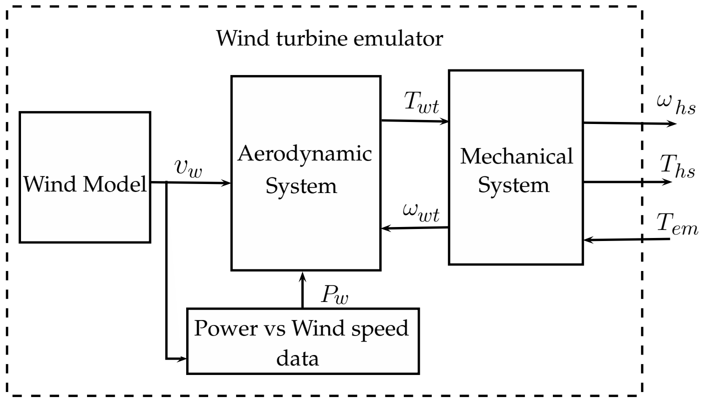


Fig. 7. Emulator flowchart

### B. DC Motor Control

The DC motor torque in (21) is proportional to the armature current. In order to ensure the equivalency of the laboratory system (23), and the high-speed shaft (7), the torque developed by the DC motor must be accurate with $T_{HS}$, and therefore, the armature current shall be accurately controlled [13]. Using (24), a PID controller is designed to track the current reference. A six-pulse, controlled thyristor bridge rectifier connected to a three-phase source is used to drive the DC motor. Fig. 8 depicts the DC motor current control system.

Low bandwidth and current ripple are well known constraints of this converter. Hence, it should investigate if a thyristor six pulse three-phase rectifier is suitable to this application, and verify if it allows a precise current control.

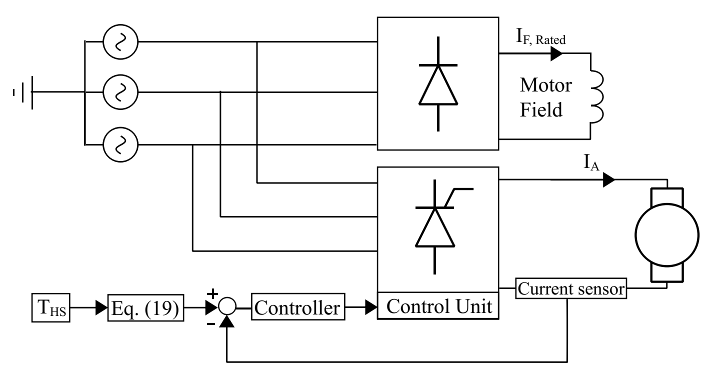


Fig. 8. DC motor control scheme

## IV. Results

This section presents the results obtained from PSIM® simulation for the wind speed signal shown in Fig. 4. Table III presents the parameters of simulated wind turbine and the DC motor used to the emulator.

For simulation purposes, the load torque is modeled proportional to the speed rotation squared, as follows

$$T_{EM} = k\omega_m^2, \tag{25}$$

TABLE III
Wind turbine and DC motor parameters

| Wind turbine parameter | Value |
|---|---|
| Diameter | 2.46 m |
| Rated Power at $V_{wind} = 16$ m/s | 2 kW |
| Start wind speed ($V_1$) | $V_{wind} = 4$ m/s |
| Nominal wind speed ($V_1$) | $V_{wind} = 16$ m/s |
| Rated speed | 180 RPM |
| Gear ratio | 1:10 |
| Generator rotor inertia constant, $H_g$ | 2.0 s |
| Wind turbine inertia constant, $H_T$ | 0.62 s |
| Low-speed shaft stiffness, $K_{LS}$ (p.u.) | 0.7 |
| **DC motor parameter** | **Value** |
| Rated speed | 1800 RPM |
| Rated Armature Voltage | 220 V |
| Rated armature current | 15 A |
| Rated field current | 2 A |
| Armature resistance $R_a$ | 0.5 Ω |
| Armature inductance $L_a$ | 0.01 H |

where the constant $k$ is obtained by using the rated value for angular speed and torque of the generator. This equation represents the maximum power extraction points for a given wind speed.

Fig. 9 depicts a comparison between the wind turbine emulator and the WECS high speed and low speed shaft models. The results are presented in the per unit system for comparison. The results of torque and speed developed by the DC motor compares well with the simulated reference signal of the WECS model. The torsional oscillation between the high speed and low speed shafts, as well as wind variation effects, produce fast speed variations in the wind turbine model, and the emulator demands the DC motor to produce such variations. Despite the ripples in torque waveform, which is mainly due to ac-dc converter, the DC motor tracked the speed reference.

Fig. 10 shows the obtained torque versus speed characteristic. For wind speeds below rated (dotted line), the pitch angle is set to maximum power extraction, and the torque-speed characteristic is consistent with Fig. 1. For wind speeds greater than rated (continuous line), the pitch mechanism controls the turbine power output to rated value and the curves intersect the trajectory of optimal torque at the point of rated power. According to Fig. 10, the emulator produced torque-speed feature very close to that of the emulated wind turbine.

Fig. 11 shows the voltage and current supplied to the DC motor by the thyristor ac-dc converter, and the graph zoom shows the current ripple. Although with approximately 1 A of current ripple, the converter was able to provide sufficient fast voltage to track the current reference.

## V. Conclusion

A methodology to model, design and emulate a wind energy conversion system has been proposed. The method is based on the power versus wind speed characteristics of the pitch-controlled wind turbine. A general mathematical description

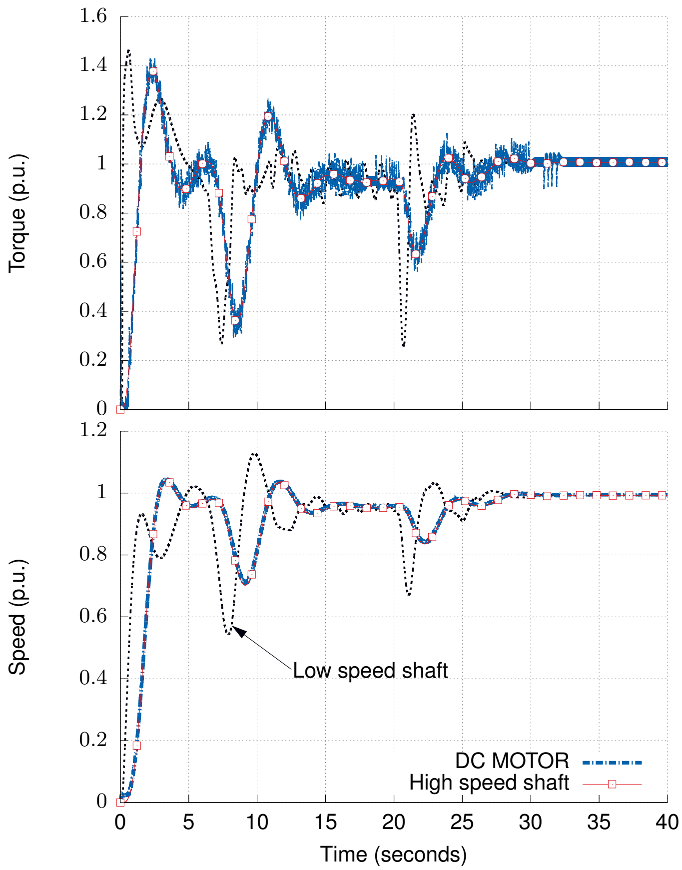


Fig. 9. Torque and speed results

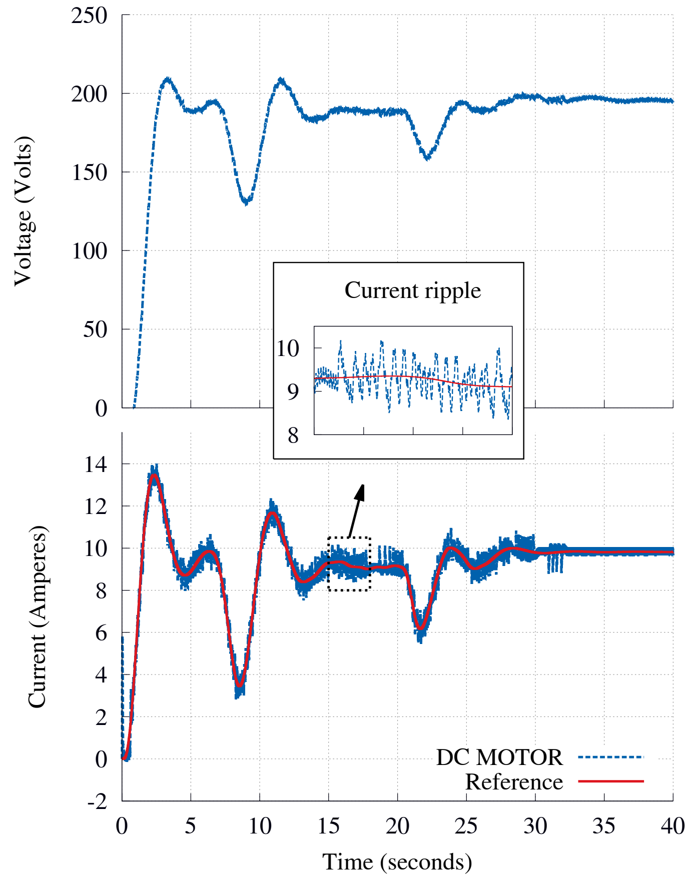


Fig. 11. DC Motor armature voltage and current

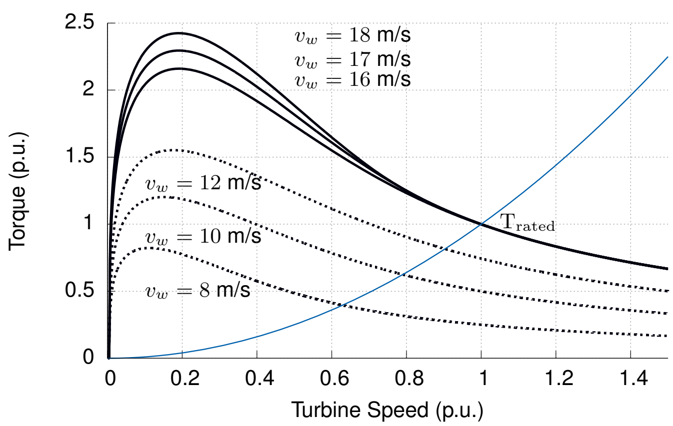


Fig. 10. Wind turbine emulator torque versus speed

for the power versus wind speed feature of the turbine, and per unit representation of drive train is used. Based on this description, the emulator can be used to emulate turbines with any type of power control, such as stall or pitch, if the respective curve is given. A system based on DC motor to emulate the WECS has been proposed and designed. The proposed wind turbine emulator presented satisfactory simulation result where the DC motor controlled by a thyristor six pulse ac-dc converter produced the instantaneous torque-speed characteristic very close to the wind turbine drive train model.

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