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Development details and performance assessment of a Wind Turbine Emulator

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ABSTRACT

This paper describes an experimental platform to emulate the static and dynamic behavior of real Wind Energy Conversion Systems (WECS). The Wind Turbine Emulator (WTE) consists of two coupled 1.5 kW squirrel-cage induction machines. The WTE calculations are performed on a PC and a DSP, both connected via USB. The total torque applied to the WTE motor is the difference of the scaled wind mechanical torque calculated on the PC, and the turbine inertia torque calculated on the DSP. An improved WTE shaft speed derivative has been used for the inertia torque calculation, which provides better results in terms of attenuation of the high-frequency harmonics present in the generator speed acquisition. The implemented WTE is used to compare different MPPT algorithms and to test power overrating and low voltage ride through procedures.

1. Introduction

During the initial steps of development and arrangement of power converters in a Wind Energy Conversion System (WECS), it is convenient to test their control and limitation strategies in the laboratory using a scaled real-time Wind Turbine Emulator (WTE).

A WTE is composed of two electrical machines mechanically coupled (see Fig. 1b), one acting as a motor (M_1) emulating the wind torque, and the other acting as a generator (M_2). Usually M_1 is controlled by a torque commanded driver, while the speed of the WTE shaft is controlled by the power converter connected to M_2. Motor M_1 is mostly implemented by a DC machine [1–6], or an induction machine [7–13] which is cheaper and require less maintenance.

In a WTE, the torque reference for M_1's driver has to be calculated as a function of the wind speed, shaft speed and turbine parameters. Moreover, when the moment of inertia of the turbine is emulated, the torque reference contains a term proportional to the shaft acceleration. If the acceleration is computed as the discrete derivative of the shaft speed, it must be filtered to limit the high frequency gain of the derivative operator.

Nearly all published WTEs use rapid prototyping tools to compute the torque reference, as dSPACE for Simulink [7,9,10,5,13], or a real-time software environment for MathWorks xPC target [1,2], or LabVIEW with a data acquisition board [3,8]. In all these solutions, torque reference equations are introduced in the PC using a high-level graphical programming language, and generated code is executed in the corresponding comercial target board or in the PC. Though these solutions are interesting in terms of prototyping time saving, they are expensive due to the software license and the comercial acquisition/DSP boards.

The aim of this paper is to give a description of how to implement a low-cost WTE with proprietary technology from scratch. The paper gives details on the specific hardware to use and software to be programmed in a PC and in the WTE's DSP. There are few references of WTEs implemented with own specific hardware and software [11,14,6] but none of these give enough details so that the reader can build its own WTE.

Regarding the inertia emulation, this feature is not always implemented in published WTEs. Among the papers that do model the inertia torque [2,11,1,7,6,14], only [1,7,6,14] mention the need for filtering the speed derivative term. In Refs. [7] [1], and [6], a first order filter, a moving average filter and a PLL respectively, are used, but none of these specify the filter design principles. Only [14] presents a design criterion for the filter cutoff frequency to ensure WTE stability, although implementation issues are not

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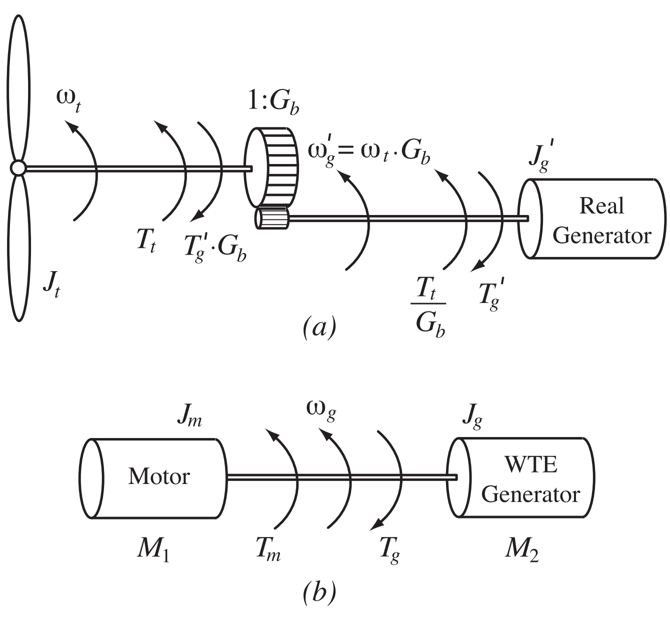

Fig. 1. a) Mechanical model of a wind turbine. b) Coupled motors in a WTE.

treated. In present paper, we propose a cascaded low-pass and high-pass filters to compute the shaft speed derivative at high sampling rates. The resulting second-order filtering combines an effective noise attenuation with a fast derivative dynamics.

From the point of view of the WTE application, though MPPT testing is addressed in the literature [10,9,15], there are no references in which the WTE is used to globally evaluate a grid-connected WECS. In this sense, the paper shows experimental results where the WTE is used to test WECS pitch angle and crowbar limitations against a power over-rating situation or during a low-voltage ride-through event.

2. Mechanical model of the wind turbine

Mechanical power extracted from the wind is given by Refs. [16,17].

$$P_t = \frac{1}{2}\rho\pi R^2 v^3 C_p(\lambda,\beta) \tag{1}$$

where ρ is the air density, R is the length of the blades, v is the wind speed and $C_p(\lambda,\beta)$ is the power coefficient, which represents the amount of kinetic energy captured by the turbine, and depends on both pitch angle β of the blades and on the tip-speed ratio λ, defined by,

$$\lambda = \frac{\omega_t R}{v} \tag{2}$$

being ω_t the rotational speed of the shaft. The power coefficient $C_p(\lambda,\beta)$ can be modeled by polynomial or exponential functions. In this work the following exponential function [16,18] was used

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

where

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

and c_1, c_2, c_3, c_4, c_5 and c_6 are constants that depend on the turbine characteristics.

Fig. 1a shows the mechanical model of a wind turbine, composed of the blades with inertia J_t, the gearbox with ratio 1: G_b and the electric generator with inertia J'_g. According to this figure, the mechanical equation expressed in the generator side is

$$\frac{T_t}{G_b} - T'_g = \left(\frac{J_t}{G_b^2} + J'_g\right)\frac{d\omega'_g}{dt} \tag{5}$$

where T_t is the mechanical torque on the wind turbine shaft, T'_g is the mechanical torque provided by the electric generator and ω'_g is the rotational speed on its shaft.

The goal of a WTE is to reproduce the turbine torque conditions of a real wind turbine (5) in the laboratory. For this, a motor M_1 controlled as a torque source, is mechanically coupled to the electrical generator M_2, as shown in Fig. 1b. In this case, the mechanical equation is

$$T_m - T_g = \left(J_m + J_g\right)\frac{d\omega_g}{dt}. \tag{6}$$

In order to emulate wind turbines of different power sizes and rotational speeds, the WTE must be able to perform both power and speed scaling [2]. The power scaling is given by

$$P_t = T'_g\omega'_g = nT_g\omega_g \tag{7}$$

where n is the power scaling factor. The speed scaling is given by

$$\omega_g = G_s\omega'_g \tag{8}$$

where G_s is the speed scaling factor.

Combining (5), (6), (7) and (8) the torque applied by the motor M_1 is

$$T_m = \frac{T_t}{nG} - J\frac{d\omega_g}{dt} \tag{9}$$

where $G = G_bG_s$ and

$$J = \frac{J_t}{nG^2} + \frac{J'_g}{nG_s^2} - J_m - J_g$$

is the equivalent inertia of the WTE.

3. WECS control strategies

WTEs are intended to test and tune algorithms in a WECS power converters, as control strategies, power and voltage limitations, MPPT algorithms, protections, etc.

Fig. 2 shows the overall scheme of the implemented grid-connected WECS with WTE. The MPPT algorithm seeks the generator speed reference ω_g^* that maximizes extracted power from a given wind speed. If wind becomes too strong, to preserve the wind turbine and the power electronics, the extracted power has to be reduced by increasing the blades pitch angle β. As seen in Fig.2, this is done either when wind power exceeds the maximum limit or when the dc bus voltage exceeds a given threshold.

In the proposed WTE, the torque reference for M_1's driver is calculated inside the control board of the generator-side converter, so that the DSP knows the accurate value of the generated electric