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Optimization of variable speed wind power systems based on a LQG approach ☆

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Abstract

This paper focuses on a control application of optimization in wind power systems. An optimal control structure for variable speed fixed pitch wind turbines is presented. The optimality of the whole system is defined by the trade-off between the energy conversion maximization and the control input minimization that determines the mechanical stress of the drive train. The frequency separation of the short-term and the long-term variations, adopted in the wind modelling, has resulted in a two-loop control structure. The optimal problem is treated within a complete linear quadratic stochastic approach, whose effectiveness was tested on an electromechanical wind turbine simulator.

Keywords: Power generation; Windmills; Linearization; Optimal control; Linear quadratic regulators; Performance indices

1. Introduction

The control problem associated with the wind energy conversion systems (WECS) consists essentially in optimizing the energy conversion, namely in maximizing the energy captured from the wind. Supposing that the energy of the moving air masses (wind) would be fully captured by means of a turning device (*turbine rotor*), normally disposed on the wind speed direction, the total power provided to the device would be $P_t = \frac{1}{2}\rho a v^3$, where ρ is the air density, a is the section area of the device and v is the wind speed. In fact, this power is partially transferred to the turbine rotor and transformed into mechanical power, which is further transformed into electrical power by means of an electrical generator.

The wind turbine harvests from the wind a mechanical power, P_{wt}, smaller than the total power, P_t, because of the nonzero wind speed behind the rotor. The expression of P_{wt} is obtained according to Rankine–Froude theory of propellers in incompressible fluids, reconsidered by Betz in 1919 (Burton, Sharpe, Jenkins, & Bossanyi, 2001):

$$P_{wt} = \frac{1}{2}\rho a v^3 C_p, \tag{1}$$

where C_p is the *power coefficient*, defining the aerodynamic efficiency of the wind turbine rotor. The power coefficient, C_p, is a function of the *tip speed ratio*, λ, defined as the ratio between the peripheral speed of the blades and the wind speed:

$$\lambda = \frac{\Omega R}{\overline{v}}, \tag{2}$$

where Ω is the rotational speed of the blades (the rotational speed of the low-speed shaft) and R is the blade length.

A typical performance curve for a horizontal axis wind turbine (HAWT) is given in Fig. 1. It presents a maximum for a well-determined tip speed, denoted by

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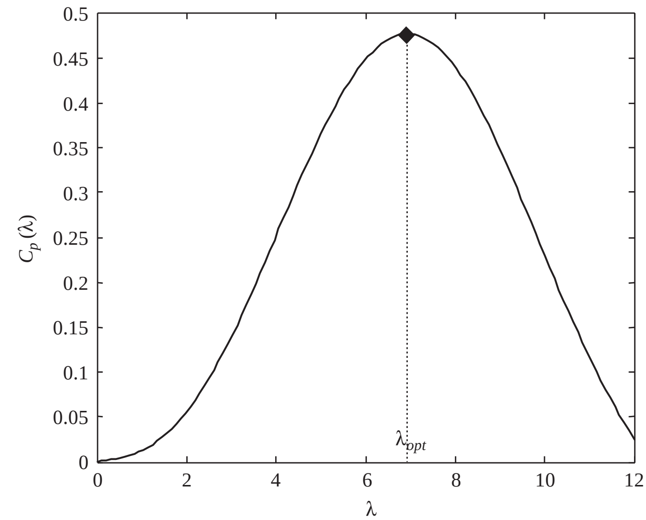

Fig. 1. The power coefficient versus the tip speed.

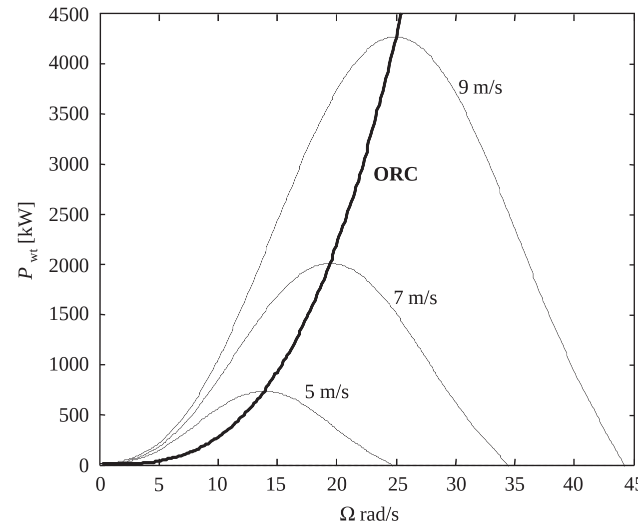

Fig. 2. The ORC.

λ_{opt} (Burton et al., 2001). According to relation (1), the power characteristics have the form of Fig. 2, having a maximum for each wind speed, corresponding to the maximal value of C_p. All these maxima determine the so-called *optimal regimes characteristic* (ORC), as in Fig. 2.

When the value of λ_{opt} is not known, the control objective is defined on the power characteristics (Fig. 2). The most common method used in this case is the so-called "Maximum Power Point Tracking" (MPPT), based on an on–off controller using minimal information from the system (Bhowmik & Spée, 1998). On the other hand, the operating point oscillates largely around the energetic maximum, which is harmful to the provided power quality and to the mechanical reliability. The fuzzy control techniques may be considered as an extension of MPPT (Simoes, Bose, & Spiegel, 1997), yielding more flexible but quite context-dependent controllers.

If λ_{opt} is specified by the wind turbine producer, the optimal control may be implemented by tracking the desired value of the shaft speed, $\Omega^{ref} = v\lambda_{opt}/R$, like in the approach of Miller, Muljadi, and Zinger (1997).

Some works have dealt with the sliding mode techniques for controlling the wind power systems (De Battista, Mantz, & Christiansen, 2000). Although intrinsically robust, this method is affected by chattering, which is specific to variable structure systems and could result in damaging oscillations.

All the above listed methods have as exclusive goal the maximization of the energetic efficiency, while ignoring the possible drawbacks related to the system's reliability, due to some large control input efforts. The reliability aspect, although important, has not been considered in the control of WECS but quite recently. The mechanical fatigue of the drive train can be reduced by imposing the minimization of the generator torque variations, $\Delta\Gamma_G(t)$ (Novak & Ekelund, 1994; Ekelund, 1997). Based upon the *linearization* of the system's model *around the optimal operating point*, Ekelund (1997) has expressed the antagonist demands of maximizing the energy conversion and minimizing the torque variations by a combined optimization criterion:

$$I = \underbrace{E\left\{\alpha(\lambda(t) - \lambda_{opt})^2\right\}}_{I_1} + \underbrace{E\left\{\Delta\Gamma_G^2(t)\right\}}_{I_2}, \tag{3}$$

where $E\{\cdot\}$ is the statistical average symbol. The optimization problem is thus defined as being *Gaussian linear quadratic* (LQ) (Levine, 1996). The functioning around the optimal regime is ensured by minimizing only the first component from (3), I_1, but with the price of some important torque variations, I_2. The positive coefficient α is introduced to adjust the trade-off between the two above-mentioned contrary requirements.

The dynamical system's parameters depend on the operating point chosen on the turbine's characteristic, and this latter depends on the average wind speed. For this reason, Ekelund (1997) proposed to solve off-line the associated Riccati equation in several optimal operating points and to use its solution in a gain scheduling adaptive structure, together with a Kalman filter for state reconstruction.

Starting from the frequency separation idea in the wind speed, presented by Cutululis, Munteanu, Ceangă, and Culea (2002), this paper develops a new optimal control structure, which optimizes the combined criterion (3) without using adaptive structures. This approach—named *the frequency separation principle*—relies upon separating the turbulence (high frequency) and the seasonal (low frequency) wind speed