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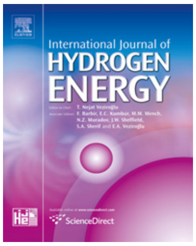

Control design for an autonomous wind based hydrogen production system

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ABSTRACT

This paper presents a complete control scheme to efficiently manage the operation of an autonomous wind based hydrogen production system. This system comprises a wind energy generation module based on a multipolar permanent magnet synchronous generator, a lead-acid battery bank as short term energy storage and an alkaline von Hoerner electrolyzer. The control is developed in two hierarchical levels. The higher control level or supervisor control determines the general operation strategy for the whole system according to the wind conditions and the state of charge of the battery bank. On the other hand, the lower control level includes the individual controllers that regulate the respective module operation assuming the set-points determined by the supervisor control. These last controllers are approached using second-order super-twisting sliding mode techniques. The performance of the closed-loop system is assessed through representative computer simulations.

1. Introduction

During the last decades, wind power has established itself as an economic grid-connected electricity production technology. However, the use of this environment-friendly energy source in autonomous systems has remained limited because of the lack of a suitable and economic long term energy storage technology [1]. In this context the study and analysis of wind based autonomous systems coupled to hydrogen generation through water electrolysis are receiving increasing attention [2]. Hydrogen is characterized by its high mass energy density and therefore it results very appropriate to be used as a long term energy carrier and storage substance. In this expanding scenery it has been established that together with other improvements, the incorporation of advanced control systems is one of the major technology changes that has translated into reduced costs of energy, turning the development of high-efficiency control strategies for renewable energy conversion systems into an essential R&D activity [3].

In the outlined context this paper deals with a two-level hierarchical control design for the autonomous wind based hydrogen production system shown in Fig. 1. The system is developed around a central dc bus whose voltage is imposed by a lead-acid battery bank, necessary to sustain the hydrogen production in scarce wind conditions. Using appropriate static converters, the dc bus links the wind energy conversion module (WECM) and the hydrogen production module. In particular, the former is built around a fixed-pitch three-bladed turbine directly coupled to a multipolar permanent magnet synchronous generator (PMSG). This machine is electrically connected to the dc bus through a rectifier and a half-bridge dc/dc converter. This particular configuration allows to control the turbine operation point and therefore its

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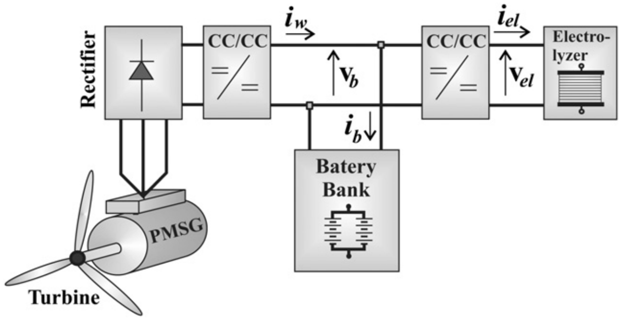

Fig. 1 – Autonomous wind based hydrogen production system.

power generation through the duty cycle of the dc/dc converter. On the other side, the hydrogen production module is composed by a von Hoerner alkaline electrolyzer electrically feed from the DC bus through a dc/dc buck converter.

2. Dynamic model of the autonomous system

2.1. *Dynamic model of the WECM*

In a *d-q* quadrature rotor-fixed reference frame the dynamic model of a PMSG with smooth airgap linked to a dc bus of voltage v_b through the structure shown in Fig. 1 can be expressed by [4]:

$$\dot{i}_d = \frac{1}{L_s}\left(-R_s i_d + \omega_e L_s i_q - \frac{\pi v_b i_q}{3\sqrt{3}L_s\sqrt{i_d^2 + i_q^2}}u_w\right) \tag{1}$$

$$\dot{i}_q = \frac{1}{L_s}\left(-R_s i_q - \omega_e L_s i_d + \omega_e \phi_{sr} - \frac{\pi v_b i_d}{3\sqrt{3}L_s\sqrt{i_d^2 + i_q^2}}u_w\right) \tag{2}$$

$$\dot{\omega}_e = \frac{P}{2J}\left(T_t - \frac{3}{2}\frac{P}{2}\phi_{sr} i_q\right) \tag{3}$$

where R_s and L_s are the synchronous resistance and inductance respectively, φ_{sr} the magnetic flux linked by the stator windings, i_d and i_q the direct and quadrature current components, ω_e the electric angular speed, P the number of poles of the generator, J the inertia of the rotating parts and T_t the propeller torque produced by the turbine blades, which can be written as:

$$T_t = \frac{P_t}{\omega_m} = \frac{1}{2}\rho A_w r C_t(\lambda) v^2 \tag{4}$$

where ρ is the air density, v the wind speed, A_w the swept cross area and C_t a power coefficient that specify the efficiency of the turbine. This coefficient is usually given in function of a variable $\lambda = r\omega_m/v$ called tip speed ratio, where ω_m is the mechanical angular speed of the shaft and r the blades length. Then, replacing (4) in (3), the dynamic model of the WECM can be expressed through (1), (2) and:

$$\dot{\omega}_e = \frac{P}{2J}\left(\frac{1}{2}\rho A_w r C_t(\lambda) v^2 - \frac{3}{2}\frac{P}{2}\phi_{sr} i_q\right) \tag{5}$$

It should be observed that this model is highly non-linear but affine with respect to the external control variable u_w and therefore it can be written under the structure $\dot{x} = f(x) + g(x)u_w$ with $x \in \Re^3$. It is important to remark that the turbine power conversion presents a unique maximum placed at $\lambda = \lambda_{opt}$, where the turbine extracts the maximum power from the wind. Then, the maximum energy capture is achieved by modifying the rotation speed as the wind speed varies, in order to maintain the tip speed ratio at λ_{opt}. Therefore, from (4) it is straightforward to determine the expression of the turbine torque corresponding to every optimal conversion point as:

$$T_{t_{opt}} = 2\rho\pi r^5 C_t(\lambda_{opt})^2 \omega_m^2 = K_{opt}\,\omega_m^2 \tag{6}$$

Fig. 2 shows in dashed lines the turbine torque curves as a function of the mechanical angular speed, parameterized in terms of the wind speed. The geometric locus corresponding to the points of maximum power conversion of the turbine is also depicted in dotted line. On the other hand, the torque curves of the PMSG in the considered configuration are presented in solid line, parameterized as a function of the PMSG terminal voltage, V_s. To complete the figure, a curve corresponding to a constant output power ($P_o = P_{ref}$) was included in dashed-dotted line, which intersects the maximum efficiency curve at $\omega_{mSW} = \sqrt{P_{ref}/K_{opt}3}$.

2.2. *Dynamic model of the battery bank*

The cost of the battery bank plays a fundamental role in the overall system cost, so its sizing must be done according to the local wind statistics and the predicted energy consumption of the electrolyzer. This is a critical reason to carefully operate the battery bank with the objective of extending its operative life. Many battery manufacturers recommend specific recharge cycles to recover 100% of the charge capacity and

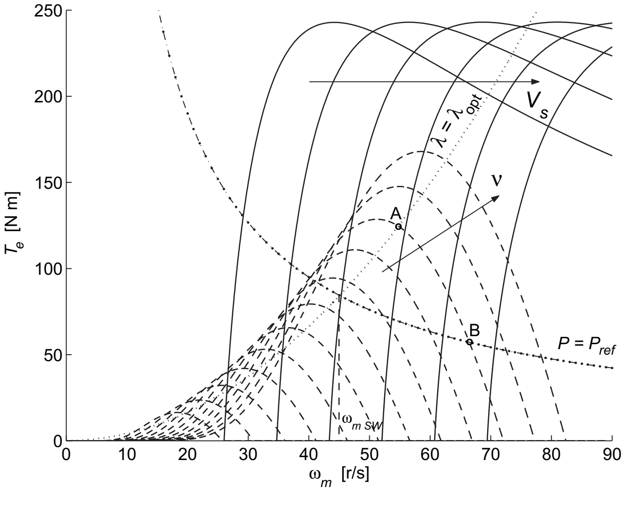

Fig. 2 – Turbine Torque and PMSG Torque.