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Extended SMC for a stand-alone wound rotor synchronous generator

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ABSTRACT

In this paper, a sliding mode controller for the stator voltage amplitude of a stand-alone wound rotor synchronous generator is presented. The standard *dq*-model of the electrical machine connected to an isolated inductive load is obtained. Then, the control law is designed using sliding mode techniques. The controller introduces a dynamic extension so that the stator voltage amplitude has relative degree one. As a result, a fast controller, robust to both machine and load parameters variations, is obtained. The control algorithm, that does not requires the knowledge of the parameters, is implemented and validated experimentally.

Introduction

Applications related with the production, transportation and consumption of electrical energy are widely studied. The increasing use of the electrical energy is due to the advantages of transmission possibilities, flexibility and control capacity among others. Electrical energy is mainly generated by interconnecting electric generators driven by prime-movers which are basically wind, hydro, steam turbines or internal combustion engines. Standard power generators are Wound Rotor Synchronous Generators (WRSG) connected in parallel setting up a theoretical infinite bus. Hence, this kind of machine is normally studied connected to an infinite bus called “power grid” [1]. The own grid determines the stator voltage and frequency, while the rotor voltage helps to improve the power factor and to compensate the reactive power at the connection point. Usually, the stator transients can be neglected [2].

A significantly different scenario is when the synchronous generator is isolated from the grid. This paper is focused on the stand-alone case of the wound rotor synchronous machine where neither amplitude nor frequency of stator voltage are fixed. For this isolated configuration, the mechanical speed determines the frequency, and the rotor voltage is used to set the stator voltage amplitude. This topology is used in many applications as isolated electrical power generation (for instance uninterruptible power supplies, UPS) with an internal combustion engine, aircraft electric systems [3], ship electrical power generation [4], wind turbines [5] or in propulsion systems for Hybrid Electric Vehicles [6,7].

Several examples can be found in the literature about the control of synchronous machines. The permanent magnet case (PMSM, Permanent Magnet Synchronous Machine) is the most studied. Examples for controlling PMSM include linear techniques [8], Model Predictive Controls [9], direct torque control [10], hybrid sensorless control [11] and, recently, nonlinear control techniques such as Passivity-based control [12], Optimal torque control [13], Fault-Tolerant Control [14] or Lyapunov-based designs [15] are also used for driving applications.

However, examples for the WRSG are not so extensive. The stator voltage regulation has been mainly studied using linear techniques. From classical approaches in [16,17] or a PID design [18], to a more sophisticated methods as pole assignment self tuning technique [19] or, more recently, using H_∞ algorithms [20] or Robust controllers [21]. Linear control methodology is usually insufficient for inherent nonlinear high-order multivariable plants such as AC machines where parameter changes caused by winding temperature variation, converter switching effect and saturation are well recognized and infrequently accounted for. Sliding mode control technique, with its distinctive features (order reduction, disturbance rejection and strong robustness with a minimum of implementation complexity [22]), had arisen the interest of many researchers in power electronics [23] and electrical machines.

The sliding mode control methodology has already been used for a generator in a stand-alone configuration. The design obtained in [24], valid only for static loads, includes a virtual high value

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resistances into the model to compute the voltages in the stator side. In this case, the controller results in a complex function which depends on both the machine and load parameters and requires the measurement of the whole state. A different approach, taking into account the load model, is presented in [25,26]. The result are simple and robust control algorithms but only valids for the resistive case.

The main contribution of this work is an experimentally tested sliding mode control algorithm for a stand alone wound rotor synchronous generator with resistive-inductive load. In this case, SMC cannot be directly applied, because the desired system output (the stator voltage amplitude) is relative degree zero. Instead, a dynamical extension of the system is proposed so that the output relative degree is one. SMC makes closed loop system robust to machine and load parameter variations and, moreover, local stability of the closed loop dynamics can be proved by using nonlinear techniques. The resulting controller, which only uses the stator voltage measurements and neither the machine parameters nor load knowledge are required, is easy to implement (with a low CPU use) and shows a good performance and a fast response as well.

The paper is organized as follows. Section 'System description' deals with the WRSM model, the control goals and the equilibrium points. The synthesis and analysis of a SMC are presented in Section 'Control design'. Section 'Hardware description and controller implementation' is devoted to a brief description of the hardware used for experiments which, in turn, are reported in Section 'Experimental results'. Finally, conclusions are drawn in Section 'Conclusions'.

System description

Fig. 1 shows the proposed scenario: a primary mover drags, at a constant speed, a WRSM which acts as a generator to feed a resistive-inductive isolated load. Is worth to mention that, due to the constant speed assumption, electric wind turbines (which require working with a variable speed range [27]) does not follow the proposed scheme.

As explained before, this system differs from the typical grid-connected systems in that, in the last case, the frequency and the voltage amplitude are fixed by the grid. For a stand-alone connection the frequency is determined by the mechanical speed, ω_m, (provided by the primary mover), while the voltage amplitude is set by the rotor field voltage. This configuration can be found in several scenarios, an example is the Series Hybrid Electric Vehicles in which the rotor power excitation is obtained from a on board battery pack [6].

Dynamic model

From the dynamic equations, in *dq*-coordinates [28], of a cylindrical-rotor WRSG[1] and the interconnection rules with an inductive load, the whole dynamical system is presented.

The electrical part of the wound rotor synchronous machine can be described as

$$L\frac{dx}{dt} = \begin{pmatrix} -R_s & \omega L_s & 0 \\ -\omega L_s & -R_s & -\omega L_m \\ 0 & 0 & -R_F \end{pmatrix} x + \begin{pmatrix} v_d \\ v_q \\ v_F \end{pmatrix} \tag{1}$$

where

[1] Since the mechanical speed is provided by an external prime-mover, and the electrical and mechanical time constant have different magnitude orders, the mechanical speed is considered constant and externally regulated.

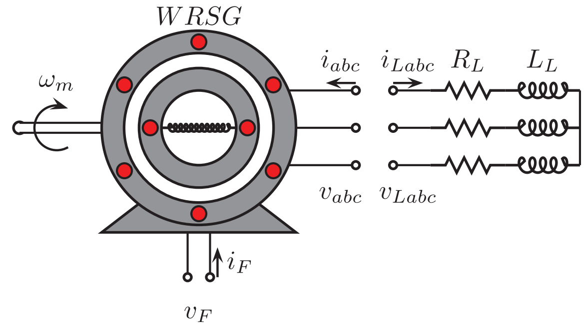

Fig. 1. Scheme of a stand alone wound rotor synchronous generator.

$$L = \begin{pmatrix} L_s & 0 & L_m \\ 0 & L_s & 0 \\ L_m & 0 & L_F \end{pmatrix}$$

is the inductance matrix, $x^T = (i_d, i_q, i_F) \in \mathbb{R}^3$ are the *dq*-stator and field currents, R_s and R_F are the stator and field resistances, L_s, L_m and L_F are the stator, mutual and field inductances, ω is the electrical speed ($\omega = n_p\omega_m$, where n_p is the number of pole pairs), v_d, v_q are the *dq*-stator voltages and v_F is the field voltage which will be used as a control input.

As a first approximation, the load is modeled by a pure resistive element, R_L, in series with a pure inductive element, L_L. All the possible variations (and complexities) of the actual load with respect to the simple RL load can be seen as derivations from the ideal model and, consequently, should be compensated by the robustness of the used controller. This can be appreciated during the experimental validation, when a realistic case of an induction motor as a load is presented. The load equation is given by

$$v_L = (R_L I_2 + \omega L_L J_2) i_L + L_L \frac{d}{dt} i_L, \tag{2}$$

where $v_L^T = (v_{Ld}, v_{Lq}) \in \mathbb{R}^2$ and $i_L^T = (i_{Ld}, i_{Lq}) \in \mathbb{R}^2$ are the *dq* voltages and currents, and

$$I_2 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \quad J_2 = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}.$$

According to Fig. 1, the interconnection rules are

$$v_s = v_L$$

$$i_L = -i_s. \tag{3}$$

Thus, putting together (1)–(3), the system can be written in an affine form as

$$\hat{L}\frac{dx}{dt} = Ax + Bv_F, \tag{4}$$

where $\hat{L}$ is a new inductance matrix,

$$\hat{L} = \begin{pmatrix} L_s + L_L & 0 & L_m \\ 0 & L_s + L_L & 0 \\ L_m & 0 & L_F \end{pmatrix}$$

and the homogeneous dynamics A and the input vector B are respectively given by

$$A = \begin{pmatrix} -(R_s + R_L) & \omega(L_s + L_L) & 0 \\ -\omega(L_s + L_L) & -(R_s + R_L) & -\omega L_m \\ 0 & 0 & -R_F \end{pmatrix}$$