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A sensor-less sliding mode control scheme for a stand-alone wound rotor synchronous generator under unbalanced load conditions

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ABSTRACT

This paper presents a sliding mode control for a wound rotor synchronous machine acting as an isolated generator connected to an unbalanced load. In order to simplify the control methodology, the standard dq-model of the machine is connected to a balanced resistive load. A switching function is defined in order to fulfill the control objective. From the desired surface, the standard sliding methodology is applied to obtain a robust and very simple controller. Then, the actual measured voltage of the machines is acquired and treated trough a frequency locked loop algorithm in order to extract the positive sequence and control it to guarantee a good definition of the park transformation. A phase locked loop algorithm is also used to avoid speed sensors. Numerical simulations and experimental results validate the control law and show good performance and a fast response to load and reference changes.

1. Introduction

The electrical energy is mainly generated by interconnecting Wound Rotor Synchronous Machines (WRSMs) which set up a theoretically infinite bus called "power grid" [1]. In this case, the WRSM stator transients can be neglected [2], the power grid determines the stator voltage and frequency while the WRSM, by means of the rotor voltage, helps to improve the power factor and compensate the reactive power at the connection point.

A different scenario is the stand-alone case, i.e, when the WRSM is isolated from the grid, where neither the stator amplitude nor the frequency is fixed. This paper focuses in this configuration, in which the mechanical speed determines the frequency, and the rotor voltage sets the stator voltage amplitude.

The Synchronous Machine (SM) has been controlled by using linear techniques [3] and hysteresis regulators [4]. However, decoupling methods [5] and modern control techniques, such as passivity-based control [6,7], sliding mode control [8,9], fuzzy control [10], neuro-fuzzy controllers [11] or optimal torque control [12], are also used for SM speed regulation.

In this paper, the WRSM is regulated in the sliding mode control framework. This technique is suitable for variable structure systems (VSS), such as power converters [13]. Even though electrical machines are not VSS, sliding mode control has been suggested as appropriate for their control [14,15] mainly because to the use of power converters when applying the electrical machine control voltages and the discrete values taken by control voltage. Its robustness and ease of implementation makes this approach particularly attractive.

The combination of sliding mode control and the block control approach [16] has been proposed for a WRSM connected to the power grid. This methodology was already used for a generator in a stand-alone configuration in [17–19]. In these control designs it is assumed a symmetrical machine interconnected with a balanced load or grid in order to fulfill the Park transformation requirements[1] [20]. But, in some applications it is not possible to guarantee a balanced system. In this case, the Park transformation is not defined, then, it is necessary to obtain a "virtual" symmetrical system by obtaining the positive sequence of the machine stator voltage. After that, one possibility is applying an adequate control scheme to regulate the amplitude of just the positive sequence voltage.

The positive sequence can be obtained by using a synchronization algorithm, which is one of the most important issues in the connection of power converters to the grid [21,22]. The grid

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[1] The Park transformation assumes a three-phase symmetrical system in which saturation and other nonlinear behaviors are neglected.

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voltage waveforms which are naturally sinusoidal and balanced under regular operating conditions, can easily become unbalanced and distorted due to the effect of grid faults and nonlinear loads.

Traditionally, for synchronizing the control system of power converters with the grid voltage, algorithms based on the implementation of phase-locked loops (PLL) have been used. This PLL algorithm is responsible of estimating the magnitude, $v^{\pm}$, frequency, ω, and phase angle, θ, of the positive and the negative sequence components of the grid voltage, respectively.

A PLL based on a Synchronous Reference Frame (SRF-PLL) [23] has become a conventional grid synchronization technique in three-phase systems. Nevertheless, the response of the SRF-PLL is unacceptably deficient when the grid voltage is unbalanced due to the appearance of a negative sequence component that the SRF-PLL is unable to process properly. In order to solve this problem, different advanced grid synchronization systems have been recently proposed [24–30]. However the dynamical response of these algorithms is very sensitive to phase angle jumps in the voltage at the point of common coupling (PCC) due the fact that the PLL is synchronizing with this variable. This is a serious drawback, as sudden phase angle changes are prone to happen due to the change in the network impedance, in our case, the load impedance.

In this paper, a frequency-locking presented in [31] instead of conventional phase-locking, will be presented as an effective solution for synchronization under adverse stator voltage conditions produced by unbalanced loads. This algorithm is used in order to obtain the positive sequence of the WRSM stator voltage. The used synchronization system (SOGI-FLL) is based on the basic operation principle presented in [32], on an Adaptive Filter (AF), implemented by means of a second order generalized integrator (SOGI), which is self-tuned to the grid frequency thanks to the action of a Frequency-Locked Loop (FLL).

The main contribution of this work is the combination of a sliding mode control algorithm for a stand-alone wound rotor synchronous generator with a frequency locked loop algorithm to guarantee the machine controllability and Park transformation definition. The control law is tested under simulations and experiments, and it performs well and responses rapidly.

The paper is organized as follows. In Section 2, the wound rotor synchronous machine model is introduced, control goals are described and the equilibrium points are computed. The sliding mode controller is designed in Section 3. Section 4 describes the synchronization system while Section 8 summarizes the simulation and experimental results. Finally, conclusions are drawn in Section 9.

2. System description

The proposed scenario is composed of a primary mover which drags a WRSM acting as a generator feeding an isolated load (Fig. 1). The convention of incoming positive current is adopted.

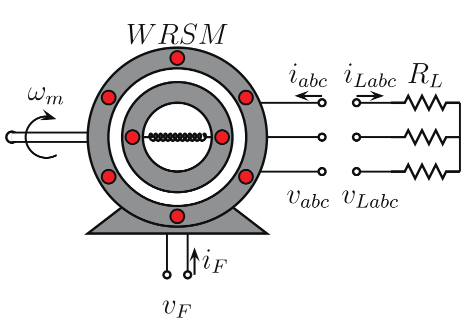

Fig. 1. Diagram of a stand-alone wound rotor synchronous generator.

In this islanded configuration, the frequency is determined by the mechanical speed, ω_m, and the voltage amplitude is set by the rotor voltage.

2.1. Dynamic model

The whole dynamic system is the interconnection of the WRSM[2] (in dq coordinates) with a pure resistive load. Then, the electrical system can be written in an affine form as

$$L\frac{dx}{dt} = Ax + Bv_F, \tag{1}$$

where

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

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

and

$$B = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix},$$

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

2.2. Control objective

As aforementioned, the system output is the stator voltage amplitude V_s, which must be regulated by the field voltage v_F. The stator voltage can be written in dq-coordinates as

$$V_s = \sqrt{v_d^2 + v_q^2} = R_L\sqrt{i_d^2 + i_q^2}, \tag{2}$$

where v_d, v_q are the dq-stator voltages.

2.3. Equilibrium points

From (1) and (2), where V_s was replaced by its desired value V_{ref}, the equilibrium point (i_d^*, i_q^*, i_F^*) and the control input v_F^* must fulfill

$$0 = -(R_s + R_L)i_d^* + \omega L_s i_q^*, \tag{3}$$

$$0 = -\omega L_s i_d^* - (R_s + R_L)i_q^* - \omega L_m i_F^*, \tag{4}$$

$$0 = -R_F i_F^* + v_F^*, \tag{5}$$

$$V_{ref}^2 = R_L^2(i_d^{*2} + i_q^{*2}). \tag{6}$$

Note that (3) and (6) can be interpreted as the intersection of a cylinder and a straight line.

3. Control design

In this Section, the sliding mode control technique is applied to regulate the stator voltage amplitude of a stand-alone wound rotor synchronous generator. This controller was designed in [19] and summarized as follows. The switching function is directly derived

[2] A cylindrical rotor type without damping windings is considered.