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Nonlinear observer-based control for PMSG wind turbine

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ABSTRACT

This paper introduces a mechanical sensorless control strategy to be used in variable speed wind energy conversion systems based on permanent magnet synchronous generators. The goal of the control strategy is to track the wind turbine maximum power point. With the proposed strategy, mechanical sensors are not needed to implement the control law. For this reason, electrical sensors -voltage and current sensors-are only needed to build the control law.

In order to obtain estimates of the mechanical variables, a nonlinear Luenberger-like observer is designed. This observer only uses measurements of the electrical variables. The estimates are fed back to the controller in order to build the mechanical sensorless control strategy.

The performance of the whole system is tested through simulations.

1. Introduction

Wind energy conversion systems (WECS) used in distributed generation must be able to inject energy in an efficient way. To this end, nowadays, the use of speed variable permanent magnet synchronous generator (PMSG) has increased a lot. It is mainly because PMSGs based WECSs have high efficiency and they reduce operation and maintenance cost, since this scheme does not employ neither gearbox nor slip rings. In addition, PMSGs based WECSs can be controlled for wind turbine maximum power point transfer (MPPT) operation, in a wide range of the wind speeds [1,2].

In order to transfer power from the generator to the grid, most of WECSs include Voltage Source Converters (VSCs). However, over the last few years, the use of topologies including Current Source Converters (CSCs) have increased a lot. This is because these topologies present several advantages [3,4]: 1) natural protection against shortcircuit 2) low dv/dt variations of the output voltage 3) high reliability of conversion and 4) regenerative capacity [5]. There are different configurations for WECS based on CSCs. One of the best, when it comes to power quality, consists of a current source rectifier (CSR) and a current source inverter (CSI) connected in a back-to-back configuration [6–8].

Many times, when the turbine power coefficient ($C_p(\lambda,\beta)$) is known, the power can be controlled to track the maximum power point. To this end, control algorithms for MPPT operation are implemented (see for instance, [9–12] and references therein). In such a case, the PMSG torque must be controlled [13–16] by setting the torque reference as a function of the mechanical variables. It is possible to measure mechanical variables to implement the control strategy. Nevertheless, in order to reduce cost and to increase the system reliability, sensorless algorithms can be used to estimate them. It can be mentioned that in Ref. [17], many of the problems that must be solved in order to obtain a more reliable and smart wind energy system were identified. There, optimum control strategies for PMSG wind turbine systems without mechanical sensors are mentioned. Some researchers have already proposed mechanical sensorless strategies. For instance, in Refs. [15,18] a PLL is used to estimate the turbine speed and the rotor speed. This strategy does not consider the acceleration in its prediction model. However, including the acceleration in the prediction model improves the estimator transient performance, and therefore, it is included in the proposal of this manuscript. In Ref. [19] a low-pass filter is used to estimate the stator flux, and then the mechanical speed is estimated via a recursive LMS algorithm. In Ref. [14] the stator flux and the rotor mechanical speed are estimated with a quasi sliding mode observer. In Ref. [20] a sliding mode observer estimates both the rotor speed and the rotor position. In other proposals these variables are estimated by using adaptive reference models (see Refs. [21,22]). Sliding-observers can be considered as linear high gain observers where the correction term introduces a

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constant high gain. These observers present chattering. For this reason, the estimated position is obtained from filtered EMF. The low pass filter used to filter the EMF deteriorates the system performance. Our proposal, introduces a correction term where a nonlinear gain is used to guarantee the convergence of the estimation error and improve the observer performance. In Ref. [23] the authors propose a method for wind speed estimation. The mechanical torque is approximated by using a neural network identifier. Our proposal uses a simple technique for the estimation of the mechanical torque. In Ref. [24] a sensorless control scheme for PMSG with diode bridge rectifier is presented. In this scheme, when parameters change, the system does not work in the maximum power point. For this reason, in Refs. [25], the authors analyze the system behavior under this undesirable condition. In our scheme, it is assumed that in order to obtain the maximum power transfer, the control strategy is calculated to track the maximum power point. In Ref. [26] an algebraic estimator is used. It must be noted that in this case, fast transients can make the system unstable. In our proposal, the dynamic model of the PMSG is considered in the design of the estimation algorithm. In Ref. [27] an unscented Kalman filter algorithm is proposed. This algorithm is based on Taylor's linearization technique. Our estimator design is based on a nonlinear technique. It is well-known that Taylor's linearization guarantees convergence in a small region around the equilibrium point. However, the PMSG model is highly nonlinear. For this reason is better to use a nonlinear technique to build the estimator, such as it is proposed in this work.

In this work a mechanical sensorless strategy for controlling a WECS consisting of a wind turbine, a PMSG and two CSCs connected in a back-to-back configuration is proposed. The control strategy is designed for MPPT operation by controlling the PMSG torque. The controller uses estimates of the rotor speed, rotor position and the PMSG electrical torque. The estimates are obtained via a nonlinear observer [28]. This observer uses the measurement of the electrical variables. The proposed nonlinear observer consists of two terms. The first term copies the system dynamics. This is the prediction term. A correction term is added to the prediction term. The correction term includes a nonlinear gain matrix. This paper contains a criterion for designing the nonlinear gain matrix. Simulation results are presented in order to show the performance of the whole system.

The rest of the paper is organized as follows. In Section 2, the system is described. The PMSG model and the nonlinear observer used to estimate the mechanical variables are introduced in Section 3. Section 4 contains a brief description of the wind turbine model and the MPPT control method. Different simulation tests for validating the system performance are included in Section 5. Finally, conclusions are drawn in Section 6, and the criterion for designing the observer's nonlinear gain matrix is presented in the Appendix section at the end of this paper.

2. System description

In Fig. 1 the WECS under study is shown. The turbine and PMSG axles are directly coupled (no gearbox is used), consequently both axles rotate to the same speed (ω_m). The wind power captured by the turbine is transformed into electrical power by the PMSG. Then, this energy is transferred to the grid via a power conversion system. This power conversion system consists of two three-phase current converters connected in a back-to-back configuration with a coupling inductor (L_{dc}) [29]. The generator side converter works as a CSR [1,29], controlling the power flux extracted from the turbine and transferred to the grid. The grid side converter works as a CSI [1,29], converting the energy stored in L_{dc}, in a three phase current synchronized with the grid voltage. Both converters operate with Space Vector Modulation (SVM) [1,29,30]; m_G and θ_G represent, the modulation index and the reference angle, respectively, used to control the CSR modulation. Whereas, m_R and θ_R represent the modulation index and the reference angle used to control the CSI modulation.

Since the current high frequency components flowing to the generator must be attenuated, the CSR and the PMSG are connected through an LC filter (LC_R in Fig. 1). The same concept is used for connecting the CSI and the grid (see LC_I). In order to implement the CSI controller, three phase grid voltage $v_{R_{abc}}$, three phase grid current $i_{R_{abc}}$ and DC-link voltage V_{dc} (in the rectifier side) are measured, as shown in Fig. 1. It must be remarked that the CSI control is not the focus of this paper. For this reason, a simple control scheme for injecting current satisfying unity power factor condition is used. However, it is possible to design another strategy. For instance, a strategy proposing to inject reactive power to the grid could be employed [1,29,31]. The three phase measurements are transformed into a two-axes reference frame $\alpha\beta$. The grid voltage, in this new reference frame ($v_{R_{\alpha\beta}}$), is transformed into polar coordinates and is represented by its magnitude $|v_R|$ and its angle θ_{v_R}. The CSI-SVM uses the modulation index $m_R = V_{dc}/|v_R|$ as reference [1].

It must be noted that the grid and inverter output currents are not in-phase, because the LC_R filter introduces a phase shift. In order to correct this deviation, CSI reference angle θ_R is calculated adding grid voltage angle θ_{v_R} and a PI controller output, whose input is the cross product between current and voltage vectors ($i_{\alpha\beta} \times v_{\alpha\beta}$). This product is equal to zero when the current and voltage are in-phase. A saturation block limits the PI output to $-\pi/2<\theta<\pi/2$.

The CSR controller uses the measurements of the generator currents and voltages (i.e. $v_{G_{abc}}$ and $i_{G_{abc}}$, respectively). The control law is to be calculated in the $\alpha\beta$ reference frame. For this reason, the measurements are transformed into the $\alpha\beta$ reference frame by using the Clarke's transformation. In this way, variables $v_{G_{\alpha\beta}}$ and $i_{G_{\alpha\beta}}$ are obtained.

The goal of the "MPPT Control" block is make the turbine operate on the curve corresponding to the maximum power point transfer (MPPT) [1]. To this end, PMSG electrical torque T_e will be controlled to achieve that the turbine axle rotates to the optimal speed, irrespectively of the wind speed value. In order to obtain a good performance, the following variables should be fed back to the MPPT controller: the PMSG rotor speed (ω_m), the PMSG rotor position (θ_m) and the PMSG electrical torque (T_e). Nevertheless, it is very important to remark that in our proposal, mechanical sensors will be avoided with minimal performance impact. To this end, estimated values of the rotor speed, the rotor position and the electrical torque ($\widehat{\omega}_m$, $\widehat{\theta}_m$ and $\widehat{T}_e$) will be obtained through a nonlinear observer [28], whose inputs are the electrical variables $v_{G_{\alpha\beta}}$ and $i_{G_{\alpha\beta}}$ (see block "Obs." in Fig. 1).

3. PMSG model and nonlinear observer

In $\alpha\beta$ reference frame, the non-salient pole PMSG model is described as [27]:

$$\begin{cases} \dfrac{\mathrm{d}i_{G_\alpha}}{\mathrm{d}t} = -\dfrac{R}{L}i_{G_\alpha} - \dfrac{\lambda_M}{L}P\omega_m\sin(P\theta_m) - \dfrac{1}{L}v_{G_\alpha}, \\ \dfrac{\mathrm{d}i_{G_\beta}}{\mathrm{d}t} = -\dfrac{R}{L}i_{G_\beta} + \dfrac{\lambda_M}{L}P\omega_m\cos(P\theta_m) - \dfrac{1}{L}v_{G_\beta}, \\ \dfrac{\mathrm{d}\theta_m}{dt} = \omega_m, \\ \dfrac{\mathrm{d}\omega_m}{\mathrm{d}t} = \dfrac{1}{J}T_m - \dfrac{1}{J}T_e - \dfrac{B}{J}\omega_m, \end{cases} \tag{1}$$

with