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Control by second order sliding modes for a double-fed induction generator for a wind turbine

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Abstract. In recent years, the consumption of electrical energy in the world has increased, increasing the construction of power plants that operate with fossil fuels, which emit a large amount of CO_2. Due to this polluting process, it is important to generate efficient alternatives. In this work the model of the double-feed induction generator for a wind turbine is exposed, to which the control by second order sliding modes will be applied to its state variables and these results will be compared with the classic proportional-integral-derivative technique of control. In this work it was found that the responses of the system with a second order sliding mode control compared to a control of the proportional-integral-derivative type, have a shorter establishment time and a slower behavior over time; in some cases the waveforms of the signals have a vibration effect at the moment of the response, but despite this, the response is not affected due to the wind speed to which the turbine is subjected, and reduces quickly system error at any instant of time. Whereas with a proportional-integral-derivative controller, some state variables can be highly dependent on wind speed.

1. Introduction

The consumption of electric power in the world has presented a great increase in recent years, increasing the construction of power plants that operate with fossil fuels, which emit a large amount of CO2. Taking into account that this process is highly polluting, it seeks to generate efficient alternatives that meet the necessary requirements of the electrical system such as efficiency, reliability and non-contamination, one of these alternatives is generation with wind turbines, which they have an inexhaustible, non-polluting source of free access. This alternative has grown in the last decades due to the technical advance that has allowed the decrease of the investment costs and the increase of the generation capacity per kilowatt hour (kWh) [1].

Bearing in mind that the main disadvantage of wind turbines is the fluctuation of wind speed, a control system is required that makes their efficiency reach an optimum point of performance. The control systems ensure that the operation of the system is correct as long as it works under normal conditions or disturbances occur, and the control implemented must guarantee greater efficiency in terms of generating electrical energy by discarding the speed of the turbine and adapting the speed from the rotor to variations in wind speed in order to achieve a greater amount of energy generated [2].

Currently, there are different control schemes such as the Proportional integral (PI) controller, linear quadratic gaussian (LQG) controller, robust H-Infinity controller, etc. One of the most used schemes in generation systems is the PI controller where algorithms are applied that optimize the generator performance, although it has the disadvantage of not receiving as much energy as possible from the wind. Therefore, in this document the technique of control by sliding planes of second order (2-MD) is proposed in order to bring the system to the desired state [3].

2. Control by sliding modes

The vast majority of mathematical systems that model physical phenomena are basically described by differential equations, which depend discontinuously on the current state of the system, that is, that the equations on the right side (inputs or excitations of the system) are discontinuous. These systems are known as variable structure systems (SEV), for which, at the end of the 50s, the first control ideas emerged taking advantage of this characteristic. As examples of SEV, we can highlight the electrical systems with electronic converters or switched sources, mechanical systems with the presence of friction forces, among others. For these SEVs and for some continuous systems, there is the possibility of designing variable structure control systems (CEV), which consist of the design of parameters for each of these structures using switching logic to achieve the performance of a SEV. The basic operation of a CEV is to design the control objective as a function of the states of the system, and then by switching ideally to infinite frequency, the system is led to follow the variation, this behavior is known as operation by sliding modes (MD).

2.1. Second order sliding modes

The 2-MD have different advantages over the 1-MD, among which two can be mentioned, the first in the reduction or elimination of the chattering effect and the second is the capacity of robustness for systems that present disturbances and uncertainties. About the synthesis of these 2-MD controllers, there is no unified design procedure available, since there are different 2-MD algorithms that represent particular situations that must be analyzed separately [4]. Considering a non-linear single input, single output system with the following restrictions (Equation (1)).

$$\begin{cases} \dot{x} = F(x, u, t) \\ u \quad : (t, x) \rightarrow u(t, x) \in \ U \subset \mathbb{R}. \\ \sigma \quad : (t, x) \rightarrow \sigma(t, x) \in \ \mathbb{R} \end{cases} \tag{1}$$

The main objective being the cancellation of σ, which may be of relative degree 1 or 2 with respect to u. In addition, we also want to cancel σ, and both conditions are met in a finite time. A large part of the design of the 2-MD algorithms depends on the functions that buy the second temporal derivative of σ. These first two derivatives are defined as [5,6] (Equations (2) and Equation (3)).

$$\dot{\sigma} = \frac{\partial}{\partial t}\sigma(x, t) + \frac{\partial}{\partial x}\sigma(x, t)F(x, u, t), \tag{2}$$

$$\ddot{\sigma} = \frac{\partial}{\partial t}\dot{\sigma}(x, t) + \frac{\partial}{\partial x}\dot{\sigma}(x, t)F(x, u, t) + \frac{\partial}{\partial u}\dot{\sigma}(x, t)\dot{u}(t). \tag{3}$$

2.1.1. Focus by Lyapunov. Using the stability theory of Lyapunov, one can test the convergence of the 2-MD algorithms by establishing conditions that guarantee the sliding regime on the surface; suppose that (Equation (4)).

$$\dot{y} = F(y), \tag{4}$$

Equation (4) is a system that contains the origin, with the origin being a system equilibrium point. If there is a scalar function $V(y)$, $V: D \rightarrow \mathbb{R}$, continuously differentiable in D such that (Equations (5) and Equation (6)).

$$V(0) = 0 \quad \text{and} \quad V(y) > 0 \quad \text{in } D - \{0\}, \tag{5}$$

$$\dot{V} \leq 0 \quad \text{in D}, \tag{6}$$

where $\dot{V}$ is the derivative of V on the trajectories of the system, then the origin $y = 0$ is a stable equilibrium point; if it is also verified, Equation (7); the equilibrium will be asymptotically stable [5,7].

$$\dot{V} < 0 \quad \text{in } D - \{0\}. \tag{7}$$

3. Control by sliding modes

3.1. Model

For the design of both controllers, a transfer function model is implemented, which will represent the plant in which the voltage control in the capacitor of the alternating current-direct current-alternating current (AC-DC-AC) converter, currents and voltages in the rotor of the induction machine will be used. to control the reactive power of the system and speed of the machine for the control of the active power. For each of the aforementioned controls, the analysis was performed, and a transfer function was obtained for each one. In the first instance, the objective is to keep the voltage in the capacitor constant, regardless of the magnitude and direction of the rotor power of the machine. The relationship between the three-phase voltages of the network and the three-phase voltages on the converter side will be (Equation (8)).

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = R \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + L \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} v_{a1} \\ v_{b1} \\ v_{c1} \end{bmatrix}, \tag{8}$$

where R and L are the resistance and inductance of the machine and the currents i_a, i_b, i_c, are the three-phase input currents to the converter. Using the transformation to reference dq you have (Equation (9)).

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = R \begin{bmatrix} i_d \\ i_q \end{bmatrix} + L \frac{d}{dt} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \omega_e L \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} v_{d1} \\ v_{q1} \end{bmatrix}. \tag{9}$$

With these estimates, it is possible to perform the analysis to express an adequate transfer function, which defines the system. Because the voltage on the capacitor can be controlled by means of v_d, i_d or by means of v_q, i_q the transfer function can be expressed as Equation (10) and Equation (11) [8,9].

$$H(s) = \frac{i_d(s)}{v_d(s)} = \frac{i_q(s)}{v_q(s)}, \tag{10}$$

$$H(s) = \frac{1}{Ls+R}. \tag{11}$$

This transfer function defines the plant that you want to control, to control the current i_d (Equation (12), Equation (13) and Equation (14)).

$$U = e^{-(R/L)Ts}, \tag{12}$$

$$UK_p = \frac{1-U}{R}, \tag{13}$$

$$H(z) = \frac{1-U}{(z-U)R}. \tag{14}$$

The voltage reference in the capacitor can be a step reference, with the desired amplitude value for the voltage in the element. The current Id leaving the controller will then be the reference current for the previous controller. To control the power generated by the machine, it is desired to maintain the power at its optimum point according to the level of wind present at the time. For this, it is intended to control the power from the control of the speed of the induction machine, which depends on a mechanical torque value given by the turbine; Equations (15) and Equation (16) show [8,10].

$$P_{opt} = K_{opt}\omega_r^3, \tag{15}$$

$$\omega_r^* = \sqrt{\frac{T_m}{K_{opt}}}, \tag{16}$$

where ω_r is the rotor speed of the machine, T_m is the mechanical torque delivered by the turbine and K_{opt} is a constant that depends on the wind speed, the density of the air, the area of the blades and a constant C_t defined as (Equation (17)).

$$C_t(\lambda) = \frac{c_1}{\lambda}\left(\frac{c_2}{\lambda} - 1\right)e^{-c_3/\lambda}. \tag{17}$$

With these defined values, the state space model is analyzed using the mechanical model of the system given by (Equation (18)).

$$\frac{d}{dt}\begin{bmatrix} \widetilde{\omega_r} \\ \widetilde{T}_{aux} \end{bmatrix} = \begin{bmatrix} 0 & \frac{1}{J} \\ 0 & 0 \end{bmatrix}\begin{bmatrix} \widetilde{\omega_r} \\ \widetilde{T}_{aux} \end{bmatrix} - \begin{bmatrix} \frac{3pL_m i_{ms}}{2J} \\ 0 \end{bmatrix} i_{qr} \quad \rightarrow \quad [\widetilde{\omega_r}] = [1 \quad 0]\begin{bmatrix} \widetilde{\omega_r} \\ \widetilde{T}_{aux} \end{bmatrix}. \tag{18}$$

The output of the state space model will be the predicted rotor speed, the system calculates the instantaneous power using Equation (15).

3.2. Controller design

The design of the controller will use the theory of sliding planes that says that the error is defined as (Equation (19)).

$$e = r - y. \tag{19}$$

With the error defined, the error and its respective derivative are chosen as state variables, depending on the order of the controller (Equation (20)).

$$z_1 = e,\ z_2 = \frac{de}{dt}, \dots, z_n = \frac{d^{n-1}e}{dt^{n-1}}. \tag{20}$$

With these state variables defined, the sliding plane is defined as the sum of the state variables multiplying each of them by a constant c_n, which does not necessarily have to be the same for all. Mathematically (Equation (21)).

$$s = c_1z_1 + c_2z_2 + c_3z_3 + \dots + c_nz_n = 0. \tag{21}$$

The constants c_n define the dynamics of the system in sliding mode. In this way, when the plane reaches the value of 0, each of the state variables is dependent on the others (Equation (22)) [10].

$$\dot{z}_1 = z_2 \quad \rightarrow \quad \dot{z}_1 = z_2 \quad \rightarrow \quad \dot{z}_{n-1} = z_n = -c_1 z_1 - c_2 z_2 - c_3 z_3 \quad \rightarrow \quad c_{n-1} z_{n-1}. \tag{22}$$

Once the plane and its state variables have been defined, a control signal must be selected that ensures the approach of the system to the sliding plane $s = 0$. For this it must be fulfilled that its derivative is of opposite sign so that the state variables tend to be on the plane, that is, the product of the plan and its derivative store at 0 [11]. Mathematically we have (Equation (23)).

$$s\dot{s} = 0. \tag{23}$$

For the fulfilment of this condition, the sign function is used on the sliding plane, which multiplied by a constant k will oscillate the control signal in such a way that it leads the variables to slide through the plane, and finally the signal Control will be defined by (Equation (24)).

$$u = k * \mathrm{sgn}(s) * e. \tag{24}$$

For the particular case of second order control, the state variables that will be chosen in this case will be the error and its respective derivative (Equation (25)).

$$z_1 = e \quad \rightarrow \quad z_2 = \frac{de}{dt} = \dot{z}_1. \tag{25}$$

The plane is defined as (Equation (26)).

$$s = c_1 z_1 + c_2 z_2. \tag{26}$$

4. Results

The simulation comprises the visualization elements and the representation of the sections to be controlled of the complete system, by means of transfer functions, which represent the model of the plant to be controlled in each particular case. It is important to note that each control is performed separately, but interconnected, because the output of one controller becomes the reference in the next [12]. The results of interest for the development of the simulation are:

- The voltage in capacitor terminals.
- The direct axis currents (i_{dr}) and quadrature (i_{qr}) on the rotor side of the machine.
- The direct-axis voltages (v_{dr}) and quadrature (v_{qr}) on the rotor side of the machine.

Each of the graphs of the aforementioned variables presents two graphs, one of them corresponds to the response of the system from the controller by sliding planes of second order, and the second shows the response of the system delivered by the discrete PID (Proportional integral derivative) controller.

Figures 1 and Figure 2 show the direct axis voltages on the rotor side, for both controllers you have to reach stability around 0:35 s, however the magnitude for the 2-MD controller is much smaller than the magnitude by PID, which is why 2-MD control is better. Figures 3 and Figure 4 show the voltage in the capacitor of the AC-DC-AC converter, where it can be seen that both controllers reach the reference value in a successful way, in this case the control by 2-MD is better than the PID since it does not present transient, in addition the control by 2-MD shows that it reaches the stability approximately in 0.2 s and the control PID reaches the stability approximately in 0.3 s, with what the control by 2-MD has a better response time.

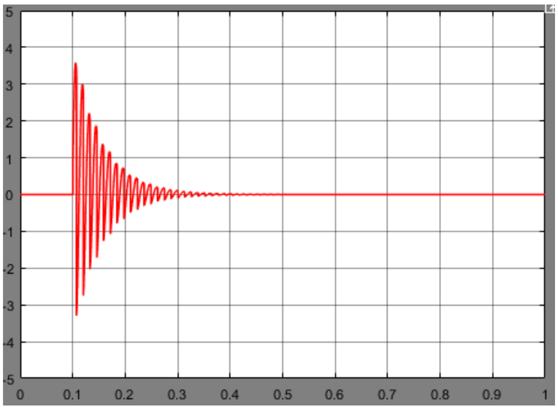

Figure 1. Direct axis voltages on the rotor side by 2-MD.

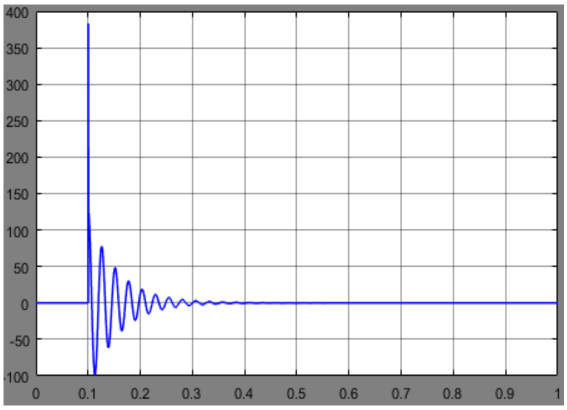

Figure 2. Direct axis voltages on the rotor side by PID.

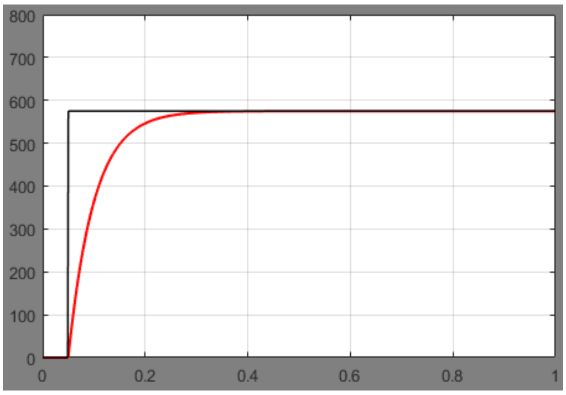

Figure 3. Voltage in the capacitor of the AC-DC-AC converter by 2-MD.

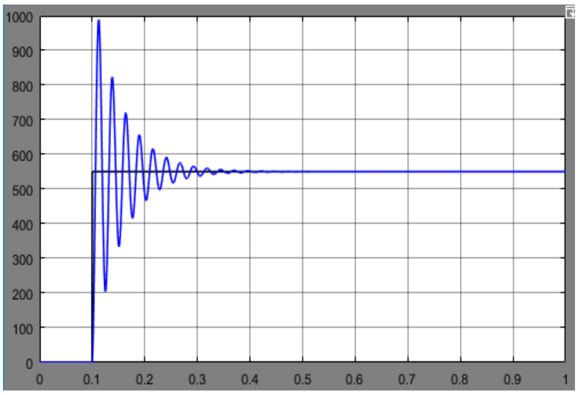

Figure 4. Voltage in the capacitor of the AC-DC-AC converter by PID.

5. Conclusion

The controller by sliding planes of second order applied to a wind generation system coupled to a doubly fed generator (DFIG) works optimally against any variation and intermittency of the wind. The behavior is stable despite the disturbances caused by the constant change of wind. The control by sliding planes allows the system to respond to any inconvenience, thus making the system sufficiently robust.

The control by sliding planes designed allows to have a great confidence in the system, since it is robust against any variation of the wind, which guarantees that in case of any disturbance the system will have a rather short transient state and the signal will return to its required state quickly. System responses with a second order slider mode control compared to a proportional–integral–derivative type control, have a shorter settling time, and a slower behavior over time; in some cases the waveforms of the signals have a chattering effect at the moment of the response, but despite this, the response is not affected due to the wind speed to which the turbine is subjected, and it rapidly reduces system error at any instant of time. While with a proportional–integral–derivative controller, some state variables can be highly dependent on wind speed because their response changes in proportion to the change in wind speed.

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