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Continuous Twisting apply to a nonlinear mathematical model of sinchronous generator

Continuous Twisting aplicado al modelo matemático no lineal de un generador síncrono

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Abstract

Electronic power systems are responsible for generating and supplying electrical power to society. It is necesary to keep suitable levels of current and voltage in order to achieve a good performance. This levels must be keep despite constant disturbances. The sinchronous generator is one device in charge of providing power to the system. In this paper we apply the Continuous Twisting Control Algorithm to provide power at a constant frequency giving robustness to the sinchronous generator robustness (insensitivity to parameter variations and disturbances and modeling errors) minimizing chattering. We take the control signal, time response and error magnitudes to verify the performance of the system. Besides, we use a normal form for the mathematical model of eigh states. Results show a correct performance of the proposed control verifying disturbances in mechanical torque and short circuit. The control signal si coninuous therefore we get a reducction of chattering.

Sincronous Generator, Twisting, Continuous Twisting

Resumen

Los sistemas electrónicos de potencia se encargan de generar y suministrar potencia eléctrica a la sociedad. Para el correcto funcionamiento de éstos sistemas, es necesario mantener niveles de voltaje y corriente estables y adecuados. Estos niveles deben cumplirse a pesar de las constantes perturbaciones a las que se encuentra sometida la red. Uno de los elementos encargados de proporcionar energía al sistema es el generador síncrono. En éste trabajo se aplica el algoritmo de control *Continuous Twisting* para garantizar una generación de potencia a frecuencia constante. Lo anterior, con el fin de proporcionar al generador la robustez característica del control por modos deslizantes (rechazo a perturbaciones acopladas al control, robustez ante cambios paramétricos y errores de modelado) minimizando el efecto *chattering*. Para lo anterior se toman en cuenta la señal de control, tiempo de respuesta y magnitudes de error. Para el diseño se utiliza una forma normal del modelo matemático no lineal de ocho estados del generador síncrono. Los resultados de simulación muestran la efectividad del control propuesto tomando en cuenta perturbaciones en el par mecánico y corto circuito. La señal de control es continua por lo tanto se obtiene una reducción de *chattering*.

Generador Síncrono, *Chattering*, Continuous Twisting

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I. Introduction

Much of the electricity generation is carried out by means of synchronous generators (Del Toro, 1992). These generators, with the aid of other devices such as photovoltaic panels, maintain a delicate balance between the generation and demand of electrical energy (Kundor, 1994). To achieve the above, it requires adequate operating margins, mainly in frequency and voltage. This has been achieved with the help of different control techniques applied to the synchronous generator.

For the control of the generator in an electrical network, the aid of linearisations has traditionally been used. These make decision making easier. However, when using simple control schemes, important dynamic characteristics are no longer considered (Kothari, 2008). To compensate for this loss of information, the operating margins of the generator are reduced. That is to say, due to the uncertainty, in the event of disturbances or critical variations in the demand for energy, it is decided to disable the operation of the generator. In such a way that, as a consequence, a considerable reduction in the robustness and capacity of the network is obtained.

Due to the above, the development of controllers applied to the synchronous generator has aroused the interest of many researchers. As a result, new control techniques have been obtained and applied, among them the direct method of Lyapunov (Machowski, 2000), linear techniques for feedback (Gao, 1992, Kazemi, 2007), diffuse control (Hiyama, 1997), neural networks (Shamsollahi, 1997), passivity (Xi, 2000), analysis of energy functions (Shen, 2005) and adaptive control (Rintoja, 2000). In addition to the previous methods, there is control by classic sliding modes (Huerta, 2009, Soto-Cota, 2006, Loukianov, 2011) which, due to their nature, in addition to presenting adequate levels of frequency and voltage, provides robustness against disturbances and parametric changes (Shtessel et al., 2014; Drazenovic, 1969).

A disadvantage of the application of sliding modes is that the first generations of these techniques, because the control signal is discontinuous at high frequency, present chattering (Slotine, 1983).

This effect causes low performance in the controller, high energy losses due to heat in electrical circuits and physical wear caused by mechanical movement (Utkin, 1993). Chatterign is one of the main reasons why new sliding control techniques have been developed (Levant, 1993).

One of the first techniques to reduce chattering is the application of a second-order or higher-order sliding mode algorithm (Shtessel, 1998). The first of this type is the second order Twisting (Shtessel, 2014), followed by Super-Twisting (Kamal, 2014) and Continuous Twisting (Torres Gonzales, 2016).

Each one with significant improvements in the control signal. In such a way that it is reduced, and in some cases, chattering is eliminated (Boiko, 2005). The Continuous Twisting control algorithm, in addition to providing a continuous control signal, compensates for disturbances, in such a way that it provides robustness to the system, in addition to ensuring convergence in finite time to the sliding surface and to its first and second derivatives..

The objective of this article is the application of a Continuous Twisting control to a synchronous generator to provide robustness against perturbations and unmodeled dynamics, decreasing the chattering effect resulting from the first generations of sliding modes. The above, in order to make improvements in the electric generation process, increasing the operating margins of the synchronous generator and guaranteeing the quality of frequency and voltage in adverse situations.

This article is structured as follows. Section II presents the mathematical model of the synchronous generator. In Section III, the control objective is clearly defined. In section IV a first control structure is proposed. In Section VI Continuous Twisting is applied through simulations, taking into account disturbances in the mechanical torque, parametric changes and short circuit. Finally, in section VI, the conclusions of the article are presented.

II. Mathematical model of the synchronous generator

This paper uses a non-linear mathematical model of eight states:

$$x = [x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_8]$$

where x_1 is the loading angle, x_2 is the angular velocity, x_3 is the flow link of the field winding, x_4, x_5 and x_6 are the flow link of the damping windings and finally x_7 and x_8 represent the stator currents in the direct axis and quadrature respectively (Soto, 2000). The mathematical model (Soto-Cota, 2006) is shown below:

$$\begin{aligned}
\dot{x}_1 &= \mathrm{x}_2 - w_b \\
\dot{x}_2 &= \frac{w_b}{2H}(T_m - T_e) \\
\dot{x}_3 &= \mathrm{b}_1 x_7 + \mathrm{b}_2 x_5 + \mathrm{b}_3 x_3 + w_b V_f \\
\dot{\mathrm{x}}_4 &= \mathrm{c}_1 x_8 + \mathrm{c}_2 x_6 + \mathrm{c}_3 x_4 \\
\dot{x}_5 &= \mathrm{d}_1 x_7 + \mathrm{d}_2 x_3 + \mathrm{d}_3 x_5 \\
\dot{x}_6 &= \mathrm{e}_1 x_8 + \mathrm{e}_2 x_4 + \mathrm{e}_3 x_6 \\
\dot{x}_7 &= \mathrm{h}_1 V_d + \mathrm{h}_2 V_f + \mathrm{h}_3 x_7 + \mathrm{h}_4 x_3 + \mathrm{h}_5 x_5 + \\
&\quad \mathrm{h}_6 x_2 x_4 + \mathrm{h}_7 x_2 x_6 + \mathrm{h}_8 x_2 x_8 \\
\dot{x}_8 &= \mathrm{k}_1 V_q + \mathrm{k}_2 x_8 + \mathrm{k}_3 x_4 + \mathrm{k}_4 x_6 + \mathrm{k}_5 x_2 x_3 + \\
&\quad \mathrm{k}_6 x_2 x_5 + \mathrm{k}_7 x_2 x_7
\end{aligned} \tag{1}$$

where w_b is the desired angular velocity, $\mathrm{T_m}$ is the mechanical torque, $T_\mathrm{e} = \mathrm{a}_1 x_3 x_8 + \mathrm{a}_2 x_5 x_8 + \mathrm{a}_3 x_4 x_7 + \mathrm{a}_4 x_6 x_7 + \mathrm{a}_5 x_7 x_8$ is the electromagnetic pair, $V_d = V \sin x_1$, $V_q = V \cos x_1$ and V represents the bus to which the generator is connected. V_f, which is generally a constant value in the order of the millivolts (Huerta, 2008), in this work it is considered as the control input, ie $V_f = u$.

The rest of the values represent parameters of the synchronous generator and are described in Annex 1.

III. Control objective

The control objective is to keep the synchronous generator providing power at a frequency of 60Hz. For this, it is necessary that the rotor rotate at synchronous speed w_b. The above, taking into account the stability of the voltage at the generator terminals. Therefore, an error function is defined $e = x_2 - w_b$ and it is taken as the sliding surface and its derivative is obtained,

$$s = s_1 = e = \dot{x}_1 = x_2 - w_b \tag{2}$$

$$\dot{s}_1 = s_2 = \dot{x}_2 = \frac{w_b}{2H}(T_m - T_e). \tag{3}$$

In this way, when the error is equal to zero $x_2 = w_b$.

IV. First control structure

It defines $q_1 = b_1 x_7 + b_2 x_5 + b_3 x_3$ and $\dot{x}_3$ is taken into account as the control channel from (1). The following control structure is proposed:

$$u = \frac{1}{w_b}(-q_1 + v_1) \tag{4}$$

where v_1 is the new control to be defined. In this way, replacing (4) in (1), $\dot{x}_3$ is defined as follows

$$\dot{x}_3 = v_1. \tag{5}$$

Calculating in $\dot{s}_2$, and taking into account (4), (5) and $\dot{x}_7$, that also presents the control signal explicitly, you get

$$\dot{s}_2 = -\frac{w_b}{2H}\{(w_b \mathrm{a}_1 x_8 + \mathrm{h}_2 q_3)\left[\frac{1}{w_b}(-q_2 - v_1)\right] + \mathrm{a}_1 x_8 q_1 + q_2 + q_3 q_4\} \tag{6}$$

where

$$q_2 = \mathrm{a}_3 \dot{x}_4 x_7 + \mathrm{a}_2 \dot{x}_5 x_8 + \mathrm{a}_4 \dot{x}_6 x_7 + \dot{x}_7(\mathrm{a}_3 x_4 + \mathrm{a}_4 x_6 + \mathrm{a}_5 x_8) + \dot{x}_8(\mathrm{a}_1 x_3 + \mathrm{a}_2 x_5 + \mathrm{a}_5 x_7)$$

$$q_3 = \mathrm{a}_3 x_4 + \mathrm{a}_4 x_6 + \mathrm{a}_5 x_8$$

$$q_4 = \mathrm{h}_1 V_d + \mathrm{h}_3 x_7 + \mathrm{h}_4 x_3 + \mathrm{h}_5 x_5 + \mathrm{h}_6 x_2 x_4 + \mathrm{h}_7 x_2 x_6 + \mathrm{h}_8 x_2 x_8.$$

Defining v_1 as follows

$$v_1 = -\left(\frac{2H}{w_b \mathrm{a}_1 x_8 + \mathrm{h}_2 q_3}\right) v. \tag{7}$$

Substituting (7) in (6) and taking into account (3) you get the following

$$\begin{aligned}
\dot{s}_1 &= s_2 \\
\dot{s}_2 &= v + q_5
\end{aligned} \tag{8}$$

where

$$q_5 = \frac{h_2}{2H} q_1 q_3 - \frac{w_b}{2H}(q_2 + q_3 q_4).$$

The control by sliding modes will be carried out taking into account (8). Being v the new control signal to be designed and it is assumed that $|\dot{q}_5| \leq q \in \mathbb{R}$.

V. Application of the Continuous Twisting control algorithm

To use this control algorithm surface information is required s_1 and its first derivative s_2, which, in turn, are equal to (2) and (3) respectively.

The control algorithm v has the following form:

$$v = -K_1\lceil z_1\rfloor^{\frac{1}{3}} - K_2\lceil z_2\rfloor^{\frac{1}{2}} + \eta \qquad (10)$$
$$\dot{\eta} = -K_3\lceil z_1\rfloor^{0} - K_4\lceil z_2\rfloor^{0}$$

considering the nomenclature $\lceil w\rfloor^{p} = |s_j|^{p}\operatorname{sign}(s_j), j = \{1,2\}$ y $p = \left\{1, \frac{1}{3}, \frac{1}{2}\right\}$.

The values of the gains were obtained assuming q = 3.011503. Earnings are adjusted according to (Torres Gonzales, 2016).

Which suggests that

$$K_1 = 1.109878\, L^{\frac{2}{3}}$$
$$K_2 = 1.341066\, L^{\frac{1}{2}}$$
$$K_3 = 0.033206\, L$$
$$K_4 = 0.016846\, L$$

Where L is given by the equation Lq = 0.002. Therefore L = 1505.751973. So the gains are like

$$K_1 = 145.8067188$$
$$K_2 = 40.127493$$
$$K_3 = 50$$
$$K_4 = 25.36589774.$$

This structure is stable and presents convergence to zero s_1 and s_2 in finite time. It also presents insensitivity to disturbances buffered to control. It should be mentioned that the control signal v is continuous.

VI. Simulation results of the controlled system with disturbances

To obtain the simulation results, the nominal parameters of a three-phase synchronous generator of 555 MVA are used, with 24 kV at a frequency of 60 Hz. The rotor has two poles, three phases and is considered an infinite bus. The parameters of the synchronous generated and the external network in values in per unit (Huerta, 2009). Figure 1 shows the external network of a synchronous generator connected to an infused bus. Inductance and line resistance are considered.

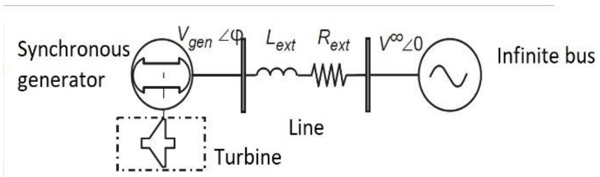


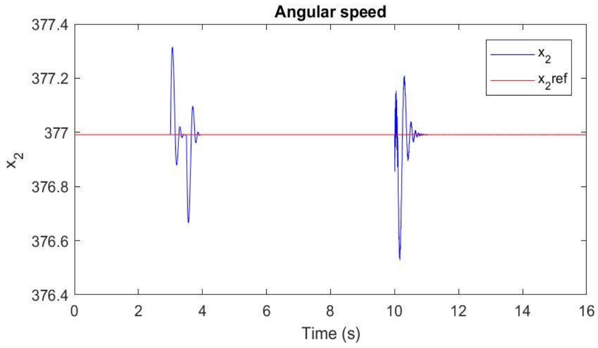
Figure 1 Synchronous generator connected to an infinite bus
(Soto-Cota, 2006)

To check the control of the plant in closed loop with the controller, it was subjected to perturbations in the electromechanical pair, short circuit and parametric changes. An increase in the mechanical torque of 0.2 pu was applied from the time t = 3 sec to the time t = 3.5 sec.

Parametric changes were made t = 6 sec at t = 6.5 sec, a change of 10% was introduced in the values b_2 and h_4, both in the control channel. The short circuit was applied for 0.1 sec, starting at t = 10 sec, to achieve this, the infinite bus voltage was brought to $V_{inf} = 0.7$ pu.

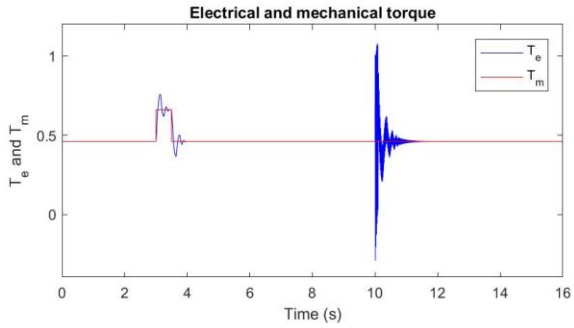
The results of the angular velocity (control objective), the electromechanical torque, the control signal and the voltage at the generator terminals are shown below. The values of the initial conditions are presented in Annex 2.

In graphic 1, the angular velocity shows convergence in finite time. This is to be expected because the sliding surface is designed so that the angular velocity is the synchronous speed.



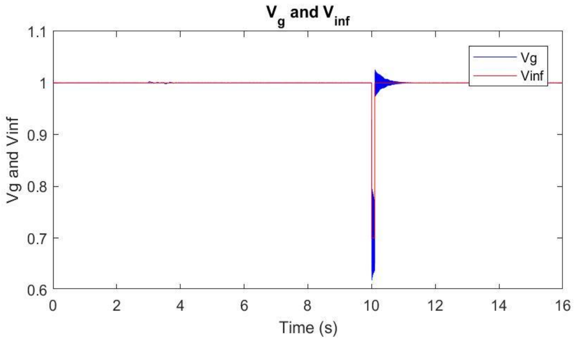
Graphic 1 Angular velocity
Source: Self Made

The important to note that parametric changes do not affect the control objective, the angular velocity. Graphic 2 shows how the electromechanical pair follows the electromagnetic torque despite being disturbed. Finite time convergence is also shown because it has a very close relationship with the first derivative of the sliding surface. In this graph it is possible to observe a small perturbation in the electromechanical pair during the parametric changes.



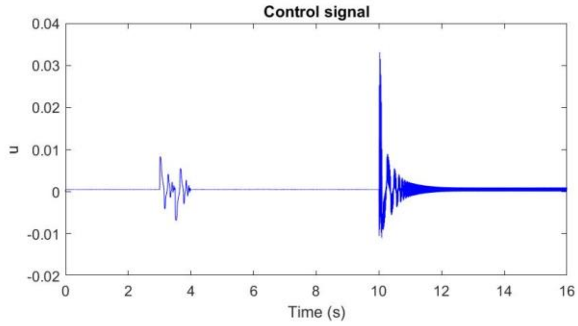
Graphic 2 Electromechanical torque and electromagnetic torque
Source: Self Made

Graphic 3 shows Voltage in terminals and the infinite bus voltage. The disturbance in the mechanical torque does not affect it much, however, the perturbation of the short circuit is more significant.



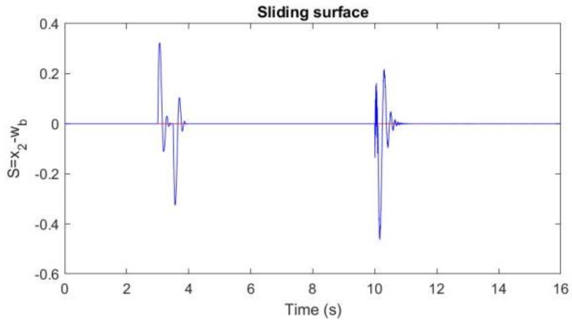
Graphic 3 Voltage in terminals and infinite bus voltage
Source: Self Made

The generated control signal can be seen in graphic 4, a continuous control signal is obtained as a result. Parametric changes generate a change in the control signal. The first is at the moment of detecting the change of the parameter with error of 10% and the second is to return to normal.



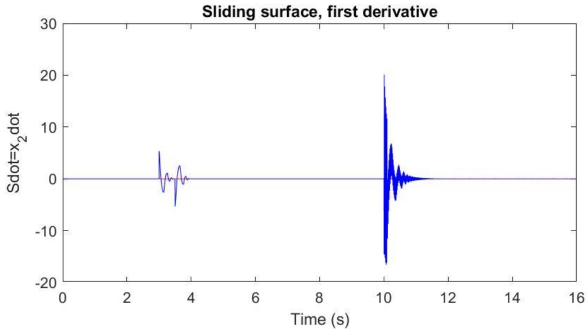
Graphic 4 Control signal
Source: Self Made

Graphic 5 shows the convergence to zero at the time of the sliding surface. In blue the surface is appreciated and in red the value zero. Note that the sliding surface is not affected by the parametric changes. This is because the disturbances were made on the control channel.



Graphic 5 Sliding surface
Source: Self Made

The derivative of the sliding surface is shown in graphic 6.



Graphic 6 Derived from the sliding surface
Source: Self Made

The derivative of the sliding surface, like the surface, has finite time convergence. In blue the surface is appreciated and in red the value zero. Note that the sliding surface is not affected by the parametric changes.

VII. Conclusions

The present work shows the application of a Continuous Twisting control algorithm with the help of a first proposed control structure. The resulting control signal is continuous therefore a chattering elimination is obtained. Unlike other algorithms by sliding modes that, due to the discontinuous nature of the resulting control signal, generate chattering.

The gains proposed in this work guarantee the stability of the system as long as the present conditions are met. The use of the first control structure can be applied to other algorithms such as Twisting and Super-Twisting, facilitating the comparison between them. For future work, it is recommended that an observer be used to estimate difficult-to-measure states and, thus, get closer to an implementation.

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Annex 1

The parameters of the synchronous generator obtained from the specifications given in the article are:

$w_b = 376.911$ $H = 7.05$
$T_m = 0.4610$ $V_f = 5.5305 \times 10^{-4}$
$a_1 = 0.6495$ $a_2 = 0.2$
$a_3 = -0.2628$ $a_4 = -0.5714$
$a_5 = 0.02$ $b_1 = -0.186$
$b_2 = 0.1329$ $b_3 = -0.2329$
$c_1 = -0.7757$ $c_2 = 1.4776$
$c_3 = -1.9061$ $d_1 = -11.6667$
$d_2 = 27.0609$ $d_3 = -33.3333$
$e_1 = -10$ $e_2 = 8.7609$
$e_3 = -14.2857$ $h_1 = -876.7235$
$h_2 = 569.3989$ $h_3 = -9.2142$
$h_4 = 12.2348$ $h_5 = -15.3032$
$h_6 = -0.6112$ $h_7 = -1.3289$
$k_1 = -837.758$ $k_2 = -16.5025$
$k_3 = 10.0116$ $k_4 = -17.2776$
$k_5 = 1.4432$ $k_6 = 0.4444$
$k_7 = -0.9556$ $V_{inf} = 1$
$V_d = V_{inf}\sin(x_1)$ $V_q = V_{inf}\cos(x_1)$.

Annex 2

The initial conditions calculated are:

$x_1 = 0.7565$ $x_2 = 376.9911$
$x_3 = 1.0815$ $x_4 = -0.635$
$x_5 = 0.7734$ $x_6 = -0.635$
$x_7 = 0.2988$ $x_8 = 0.3508$.