CHATTER-FREE NONLINEAR CONTROL OF DFIG POWER FOR WIND CONVERSION SYSTEM

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Abstract— In this paper, a robust nonlinear controller based on sliding mode control strategy is adopted for a variable-speed wind energy conversion system with a double-fed asynchronous generator (DFIG). Firstly, field-oriented control law based on PI controllers has been introduced. However, wind turbines components work as nonlinear systems where electromechanical parameters change considerably; thus, a SOSMC with a simple function to smooth control signals is introduced, the aim of the proposed controller is to contribute with some important features such as power fineness, minimize the chattering, ameliorate response time and deal with grid requirements. Matlab tests are introduced in an attempt to confirm the effectiveness of the proposed control.

Keywords— SOSMC, DFIG, SMC, wind turbines

1. INTRODUCTION

Nowadays, Wind energy is the brightest renewable source of electrical power generation for the future; it has been proved as one acknowledged potential source of energy. Compared with other clean energies like its cost efficiency and reliability [1- 5]. Thus, those factors became important topics in industry and research [6, 7]. Control strategies are necessary to attain maximum performance. The DFIG WT has been an attractive choice [8, 9] because of its independent power control plus its ability to deal with variable speed due to control of back-to-back converter scheme [10, 11], reduced mechanical stresses [2], recompense for power pulsations and torque [12] and improve power quality [2], the major feature of proposed generator is that the power converter is sized between “20–30%” of entire power which means the cost is reduced [13], still the generator response to voltage disturbances is critical, as expressed in [2, 14], to protect and remain connected to the network even with faults it is required to control the rotor converter. [2, 14-16], the control schemes are established with the vector control with the classical controller, but this controller can provide favorable performance restrictive under ideal voltage conditions. Furthermore, disturbances and parameter variations will leave us with imperfect performance. Therefore, papers have offered many control strategies for DFIG like Sliding Mode Control, smart control or adaptive algorithms [1, 17, 18], HOSMC [6, 15, 16, 19, 20]. SMC, despite robust, it suffers two main deficiencies. First, chattering phenomena which produced from the high-frequency switching that damage the performance and excites high frequency oscillations [21, 22]. In an attempt to overthrow these problems, many authors proposed to modify the SMC law [15, 19].

In this present paper, SMC is suggested to regulate the power swapped between the generator and the grid, to overcome its drawbacks many methods were proposed like

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approximating the sign function by a high gain saturation function [16], we decide to use SOMC because it has several features like:

- Robustness [22, 20].
- Subtraction of mechanical stresses and chattering [22].
- Easy to implement.

We propose an improvement to the 2SMC by adjusting the discontinuous control signal toward sliding surface and we used the three phase matrix converter because:

- Provides bidirectional energy flow
- Nearly sinusoidal input/output waveforms
- Controllable input power factor.

2. MODEL OF THE TURBINE

The power contained in kinetic energy form at a speed V_v , surface A_l , is expressed by

$$P_v = \frac{1}{2} \rho A_l V_v^3 \quad (1)$$

Where ρ is the air density.

The wind turbine can recover only a part of that power:

$$P_v = \frac{1}{2} \rho \pi R^2 V_v^3 C_p \quad (2)$$

Where: R is the radius; C_p is power coefficient [11], this coefficient is a related with the wind and wind turbine rotation pace and the pitch angle. The speed ratio λ introduced by

$$\lambda = \frac{R \Omega_t}{V_v} \quad (3)$$

Knowing the speed of rotation of the turbine, the mechanical torque C_t available on the slow shaft of the turbine can be expressed by:

$$C_t = \frac{P_t}{\Omega_t} = \frac{\pi}{2\lambda} \rho R^3 v^2 C_p \quad (4)$$

2.1. MECHANICAL SYSTEM: The mechanical model will be illustrated in Figure 1.

Fig. 1 Mechanical Model

Where: J_t : the turbine inertia, while J_m : generator inertia, G is the gearbox ratio. The generator speed and the fast shaft torque are given in:

$$\Omega_m = G\Omega_t \quad (5)$$

$$C_m = C_t / G \quad (6)$$

Next,

$$C_m - C_{em} = \left(\frac{J_t}{G^2} + J_m \right) \frac{d\Omega_m}{dt} + f_v \Omega_m \quad (7)$$

3. THE MATRIX CONVERTER MODEL

It can be considered as the simplest structure due to the lack of the dc link; it composed of a matrix of bidirectional switches linking two independent three-phase systems as shown in Fig. 2 shows the diagram of a matrix converter. S_{mn} is given by:

$$S_{mn} = \begin{cases} 1 & S_{mn} \text{ closed} \\ 0 & S_{mn} \text{ open} \end{cases} \quad m \in \{A, B, C\}, n \in \{a, b, c\} \quad (8)$$

The mathematical expression of the matrix converter can be written as:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} S_{Aa} & S_{Ab} & S_{Ac} \\ S_{Ba} & S_{Bb} & S_{Bc} \\ S_{Ca} & S_{Cb} & S_{Cc} \end{bmatrix} \begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} \quad (9)$$

$$\begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} = \begin{bmatrix} S_{Aa} & S_{Ba} & S_{Ca} \\ S_{Ab} & S_{Bb} & S_{Cb} \\ S_{Ac} & S_{Bc} & S_{Cc} \end{bmatrix}^T \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (10)$$

The input/output relationships of voltages and currents are related to the states of the nine switches and can be expressed as follows:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} k_{Aa} & k_{Ab} & k_{Ac} \\ k_{Ba} & k_{Bb} & k_{Bc} \\ k_{Ca} & k_{Cb} & k_{Cc} \end{bmatrix} \begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} \quad (11)$$

$$\begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} = \begin{bmatrix} k_{Aa} & k_{Ba} & k_{Ca} \\ k_{Ab} & k_{Bb} & k_{Cb} \\ k_{Ac} & k_{Bc} & k_{Cc} \end{bmatrix}^T \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (12)$$

With:

$$0 \leq k_{mn} \leq 1, \quad m = A, B, C, \quad n = a, b, c \quad (13)$$

k_{mn} are the duty cycles of the switches, these duty cycles must satisfy the three following constraint conditions to prevent a short circuit:

$$\begin{cases} k_{Aa} + k_{Ab} + k_{Ac} = 1 \\ k_{Ba} + k_{Bb} + k_{Bc} = 1 \\ k_{Ca} + k_{Cb} + k_{Cc} = 1 \end{cases} \quad (14)$$

The output voltage is given by:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} 1+2\delta \cos a & 1+2\delta \cos\left(a-\frac{2\pi}{3}\right) & 1+2\delta \cos\left(a-\frac{4\pi}{3}\right) \\ 1+2\delta \cos\left(a-\frac{4\pi}{3}\right) & 1+2\delta \cos a & 1+2\delta \cos\left(a-\frac{2\pi}{3}\right) \\ 1+2\delta \cos\left(a-\frac{2\pi}{3}\right) & 1+2\delta \cos\left(a-\frac{4\pi}{3}\right) & 1+2\delta \cos a \end{bmatrix} \begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} \quad (15)$$

Where:

$$\begin{cases} a = \omega_m + \theta \\ \omega_m = \omega_{output} - \omega_{input} \end{cases} \quad (16)$$

The running matrix converter with Venturini algorithm generates at the output a three-phases sinusoidal voltages system having in that order pulsation ω_m , a phase angle θ and amplitude $\delta \cdot V_s$ ($0 < \delta < 0.866$ with modulation of the neural).

Fig 2 The Matrix Converter

4. MATHEMATICAL MODEL OF DFIG:

We have chosen to use the double-fed induction generator because with the help of the bidirectional converter in the rotor it is possible to work in both sub-synchronous and super-synchronous. The electrical model of the machine obtained using Park transformation is given by the following equations:

Stator, rotor voltages:

$$V_{qs} = R_s I_{qs} + \frac{d\phi_{qs}}{dt} - \omega_s \phi_{ds} \quad (17)$$

$$V_{ds} = R_s I_{ds} + \frac{d\phi_{ds}}{dt} - \omega_s \phi_{qs} \quad (18)$$

$$V_{dr} = R_r I_{dr} + \frac{d\phi_{dr}}{dt} - \omega \phi_{qr} \quad (19)$$

$$V_{qr} = R_r I_{qr} + \frac{d\phi_{qr}}{dt} - \omega \phi_{dr} \quad (20)$$

5. THE DFIG VECTOR CONTROL:

In this section, the application of vector control DFIG is to achieve a decoupling between the quantities generating torque and flux. For this, we adjust the flux by (I_{ds} or I_{dr}), and torque by (I_{qs} or I_{qr}). Thus, the dynamics of DFIG will be reduced to that of a DC machine. This method can be outlined as shown in Fig 3.

Fig. 3 Analogy between the Vector Control of DFIG and the Control of a DC Machine

The doubly fed induction generator model can be described by the next equations in the synchronous frame whose axis d is aligned with the stator flux vector as shown in Fig. 4, ($\phi_{ds} = \phi_s$) and ($\phi_{qs} = 0$) [7, 21]. By neglect stator resistances voltage will be:

$$V_{ds} = 0 \text{ and } V_{qs} = V_s = \omega_s \phi_s \quad (21)$$

Fig. 4 Stator and rotor flux vectors

We driver to an uncoupled power control; where, I_{dr} controls the active power, and the reactive power is controlled by the direct component I_{ds} [13] as shown in Fig 5:

$$P_s = -V_s \frac{M}{L_s} I_{qr} \quad (22)$$

$$Q_s = \left(\frac{\phi_s V_s}{L_s} - \frac{M}{L_s} V_s I_{dr} \right) = \left(\frac{V_s^2}{\omega_s L_s} - \frac{M}{L_s} V_s I_{dr} \right) \quad (23)$$

The equations of the voltages according to the rotor currents are shown below (Fig. 5):

$$V_{dr} = R_r I_{dr} + L_r \sigma \frac{dI_{dr}}{dt} - L_r \sigma \omega I_{qr} \quad (24)$$

$$V_{qr} = R_r I_{qr} + L_r \sigma \frac{dI_{qr}}{dt} - L_r \sigma \omega I_{dr} + \frac{M}{L_s} \omega \phi_s \quad (25)$$

With:

$$\sigma = (1 - M^2) / L_s L_r \quad (26)$$

Where: V_{dr} , V_{qr} are rotor voltage; R_r is the rotor resistance; L_r , L_s are the rotor inductances; M is mutual inductance; σ is leakage factor.

6. THE SLIDING MODE CONTROL

The main advantage of this control is its simplicity and robustness in spite of uncertainties in the system and external disturbances and, on the other hand, it needs relatively less information about the system [15, 16, 19, 20]. The sliding mode control has three stages: Choice of surface, convergence condition and calculation of the control laws.

6.1. Second Order Sliding Mode Control

SMC is an interesting nonlinear method approach. Nevertheless, the biggest problem of this control is the chattering phenomenon which causes mischievous effects on the generator because of the discontinuous surveillance and that cause overheating and trigger unmodeled high frequency dynamics. SOMC is an attractive solution, it generalizes the sliding mode idea by going to a higher order time derivatives, which decrease chattering and avoid powerful mechanical efforts while maintaining advantages of the SMC [22], such as robustness under uncertainties. Aiming at achieving satisfactory tracking performance for P_s and Q_s , the switching functions given next are adopted.

$$\begin{cases} S_P = e_P + c_P \int e_P dt \\ S_Q = e_Q + c_Q \int e_Q dt \end{cases} \quad (27)$$

The integral terms c_P and c_Q are positive constant are added for steady-state errors elimination [6, 22]. The voltage applied represented in the equation below:

$$\begin{cases} V_{dr} = V_{dreq} + V_{dm} \\ V_{qr} = V_{qreq} + V_{qm} \end{cases} \quad (28)$$

The system in reach the sliding surface with the help of the switching control V_{dm} and V_{qm} ; V_{qreq} and V_{dreq} are the equivalent control terms, they make the system move along the sliding manifold and accelerate the response of the system while reducing the steady-state errors[21]. The equivalent control terms are derived by letting $\dot{S}_P = \dot{S}_Q = 0$, the voltage to be applied to the rotor are expressed as:

$$\begin{cases} V_{qreq} = -\frac{L_s L_r \sigma}{MV_s} \left(\dot{P}_{s_ref} + c_P (P_{s_ref} - P_s) \right) + R_r I_{qr} - g w_s L_r \sigma I_{dr} - g \frac{MV_s}{L_s} \\ V_{dreq} = -\frac{L_s L_r \sigma}{MV_s} \left(\dot{Q}_{s_ref} + c_Q (Q_{s_ref} - Q_s) \right) + R_r I_{dr} - g w_s L_r \sigma I_{qr} \end{cases} \quad (29)$$

Thus;

$$\begin{cases} V_{dm} = y_1 + B_1 |e_P|^{\frac{1}{2}} \text{sign}(e_Q) & \dot{S}_1 = B_2 \text{sign}(e_Q) \\ V_{qm} = y_2 - B_3 |e_Q|^{\frac{1}{2}} \text{sign}(e_P) & \dot{S}_2 = -B_4 \text{sign}(e_P) \end{cases} \quad (30)$$

Where B_1 , B_2 , B_3 and B_4 are constants.

7. SIMULATION RESULTS

In this section, simulation tests have been performed with the help of Matlab. A performance comparison with two different linear and nonlinear controllers "PI, SMC and SOSMC" will be introduced and discussed

Wind speed shown in Fig (5) in order evaluates the designed control.

Fig. 5 Wind speed

Fig. 6 Stator Active Power

Fig. 7 Reactive Active power

Fig. 8 Electromagnetique Couple

Fig. 9 Stator current components

Fig. 10 Stator current

Fig 6-7 represent the stator active and reactive powers and its reference profiles using PI and SMC, we can notice that the dynamic response under the PI control is much slower than SMC control while SMC tracks almost perfectly their references. However, the first order sliding mode controller includes an appearance of perturbations which presented through the chattering phenomenon after zooming. To guarantee a unity power factor at the stator side, the reactive power must be maintained zero.

The electromagnetic torque represented in Fig (8) is negative due to the generator operation. We can notice a great decoupling among the rotor and stator current components is obtained as shown in fig 9 which guarantee a decoupled powers control. Figure 10 displays the current waveform. It can be seen that the rotor is supplied with low variable frequency signals according to wind speed variations.

8. CONCLUSION

In order to ensure of the high performance, and to make the system insensible with the external disturbances and the parametric variations. A nonlinear controller has been developed for WT control. The proposed method was tasted and compared with other controllers. Simulation results show that the proposed controller provides a good efficiency, since it permits to track the optimum power quickly despite the speed wind changing. On the other hand, the stator power quantities provided show smooth waveforms, with good tracking indices. The chattering free improved performance of the SOSMC makes it superior to conventional SMC, and establishes its suitability for the system drive.

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