A New DTC Scheme using Second Order Sliding Mode and Fuzzy Logic of a DFIG for Wind Turbine System

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***Abstract*—This article present a novel direct torque control (DTC) scheme using high order sliding mode (HOSM) and fuzzy logic of a doubly fed induction generator (DFIG) incorporated in a wind turbine system. Conventional direct torque control strategy (C-DTC) using hysteresis controllers presents considerable flux and torque undulations at steady state period. In order to ensure a robust DTC method for the DFIG-rotor side converter and reduce flux and torque ripples, a second order sliding mode (SOSM) technique based on super twisting algorithm and fuzzy logic is used in this paper. Simulation results show the efficiency of the proposed method of control especially on the quality of the provided power comparatively to a C-DTC.**

Keywords—DFIG; wind turbine; DTC; SOSM; super twisting; fuzzy logic

I. INTRODUCTION

Among all kinds of renewable energy sources that are being developed recently in the world, wind energy source is the fastest growing one [1]. Currently, variable speed wind turbine system (WTS) employing DFIG is the most popular technology in presently installed wind turbines [2]. This is because DFIG presents many advantages compared to other generators used in WTSs such as reduced converter size, improved efficiency, and economic benefits [3].

Stator vector control with proportional-integral (PI) regulators is the usual strategy employed currently for WTS based on DFIG [4,5]. This strategy presents a good decoupling between the two current axes (*d* and *q*), therefore the model of the DFIG becomes simple and PI regulators can be employed. However, this method of control is highly depends on the accuracy of the machine parameters, employs diverse loops and needs a big regulation strength in order to ensures stability during the whole speed domain [6].

To avoid the disadvantages of the filed oriented control method, a novel DTC scheme has been discussed in this paper [7,4]. In the C-DTC strategy, torque and flux are directly regulated through switching table plus hysteresis regulators. However, some drawbacks brake the employ of these regulators, for example variable switching frequency and torque ripple [8,9]. In several research articles realized on DTC scheme, these undesirable problems are decreased by employing space vector modulation (SVM) technique, but the control robustness was immolated [10,11].

In recent years, sliding mode control (SMC) based on the theory of variable structure systems (VSS) has been extensively employed for nonlinear systems. It uses a particular version of on-off control, or discontinuous signal across the sliding surface, satisfying the sliding mode condition, to achieve a robust control. However**,** the SMC has a major inconvenience which is the chattering effect created by the discontinuous part of control. In order to resolve this problem, various adjustments to the usual control law have been discussed. The approach based on boundary layer is applied in almost all cases [12]. Another efficiency solution consists to substitute the discontinuous control signal by fuzzy logic one has also been used recently in some research works [13-15]. For the same goal the notion of HOSM control has also proven its competence in [16,17] for different applications.

Some useful solutions for sliding mode DTC with small torque and flux undulations, applied for induction motor (IM) controls are presented in [18,19]. In [20], the authors suggest the using of a DTC with SOSM controllers employed to IM drive.

In the aim to design an advanced DTC with very small torque and flux undulations and without chattering effect, in our article we suggest to employ a new DTC scheme based on SOSM and fuzzy logic functions for a DFIG-based wind turbine. This is for essential objects, including reducing mechanical stresses and improving power quality provided to the grid. The SOSM technique generalizes the basic SMC design by integrating second order derivatives of the sliding variable [21]. A few of such controllers have been discussed in the literature [22-25].

The rest of the paper is arranged as follows. In section 2, the modeling of the DFIG-based WTS is presented. Section 3 provides the application of the SOSM-DTC scheme to the DFIG. In section 4 the novel SOSM-DTC strategy using on fuzzy logic algorithm is applied to the DFIG control. Section 5 discusses the simulation results to demonstrate the effectiveness of the proposed control strategy.

II. MODEL OF THE DFIG-BASED WTS

A. The WTS model

Equation (1) gives the expression of the power captured by a WTS:

$$P_t = \frac{1}{2} C_P(\lambda, \beta) R^2 \rho v^3 \tag{1}$$

Where, R, ρ, v, C_P, λ and β are respectively: radius of the turbine (m), air density (kg/m^3), wind speed (m/s), the power coefficient, the tip speed ratio and blade pitch angle (deg).

The power coefficient C_p is given as follows [26]:

$$C_P = (0.5 - 0.167)(\beta - 2)\sin\left[\frac{\pi(\lambda + 0.1)}{18.5 - 0.3(\beta - 2)}\right] - 0.0018(\lambda - 3)(\beta - 2) \tag{2}$$

With:

$$\lambda = \frac{\Omega_t R}{v} \tag{3}$$

Where, Ω_t is the wind turbine speed.

B. Model of the DFIG

The DFIG model in Park reference frame is given by [27,28]:

$$\begin{cases} V_{ds} = R_s I_{ds} + \frac{d}{dt}\psi_{ds} - \omega_s \psi_{qs} \\ V_{qs} = R_s I_{qs} + \frac{d}{dt}\psi_{qs} + \omega_s \psi_{ds} \\ V_{dr} = R_r I_{dr} + \frac{d}{dt}\psi_{dr} - \omega_r \psi_{qr} \\ V_{qr} = R_r I_{qr} + \frac{d}{dt}\psi_{qr} + \omega_r \psi_{dr} \end{cases}, \quad \begin{cases} \psi_{ds} = L_s I_{ds} + M I_{dr} \\ \psi_{qs} = L_s I_{qs} + M I_{qr} \\ \psi_{dr} = L_r I_{dr} + M I_{ds} \\ \psi_{qr} = L_r I_{qr} + M I_{qs} \end{cases} \tag{4}$$

Where (V_{ds}, V_{qs}, V_{dr}, V_{qr}), (I_{ds}, I_{qs}, I_{dr}, I_{qr}), (ψ_{ds}, ψ_{qs}, ψ_{dr}, ψ_{qr}) are respectively the stator and rotor voltages, currents and fluxes, R_s and R_r are the resistances of the rotor and stator respectively, L_s, L_r and M are the inductance own stator, rotor, and the mutual inductance between two coils respectively.

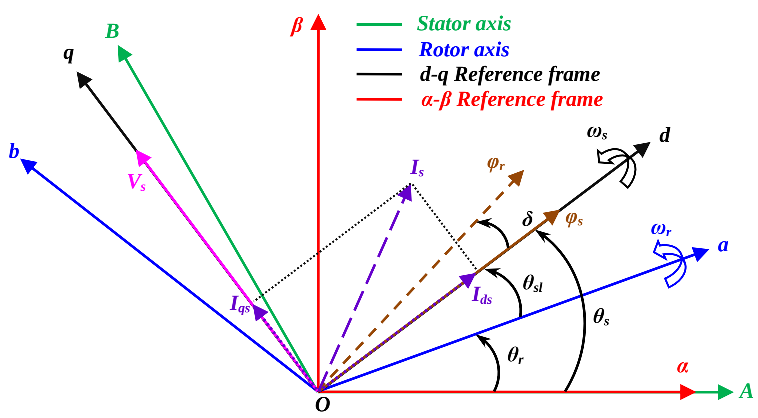

Fig. 1. Field oriented control technique

The stator and rotor pulsations and rotor speed are interconnected by the following equation: $\omega_s = \omega + \omega_r$.

Where ω_s and ω_r are respectively the stator and rotor electrical pulsations, while ω is the mechanical one.

The mechanical equation of the DFIG is:

$$C_{em} = C_r + J \cdot \frac{d\Omega}{dt} + F_r \cdot \Omega \tag{5}$$

Where we can express the electromagnetic torque C_{em} as follows:

$$C_{em} = \frac{3}{2} n_p \frac{M}{L_s}(\psi_{qs} I_{dr} - \psi_{ds} I_{qr}) \tag{6}$$

Where C_r, Ω, J, F_r and n_p are respectively: the load torque (Nm), mechanical rotor speed (rad/s), the inertia (kg.m^2), the viscous friction (Nm/s) and the number of pole pairs.

The stator powers of the DFIG are defined as:

$$\begin{cases} P_s = \frac{3}{2}(V_{ds} I_{ds} + V_{qs} I_{qs}) \\ Q_s = \frac{3}{2}(V_{qs} I_{ds} - V_{ds} I_{qs}) \end{cases} \tag{7}$$

To obtain a decoupled control between the stator active and reactive powers, we use a dq reference frame linked to the stator flux as shown in figure 1. Basing on equation (4) and supposing that the stator resistance can be neglected we can write:

$$\psi_{ds} = \psi_s \quad \text{and} \quad \psi_{qs} = 0 \tag{8}$$

$$\begin{cases} V_{ds} = 0 \\ V_{qs} = \omega_s \psi_s \end{cases} \tag{9}$$

$$\begin{cases} I_{ds} = -\frac{M}{L_s} I_{dr} + \frac{\psi_s}{L_s} \\ I_{qs} = -\frac{M}{L_s} I_{qr} \end{cases} \tag{10}$$

By using (9) and (10), equations (6) and (7) can be written as follows:

$$\begin{cases} P_s = -\dfrac{3}{2}\dfrac{\omega_s \psi_s M}{L_s} I_{qr} \\ Q_s = -\dfrac{3}{2}\left(\dfrac{\omega_s \psi_s M}{L_s} I_{dr} - \dfrac{\omega_s {\psi_s}^2}{L_s}\right) \end{cases} \quad (11)$$

$$C_{em} = -\frac{3}{2} n_p \frac{M}{L_s} I_{qr} \psi_{ds} \quad (12)$$

III. SOSM-DTC of DFIG

The main objective of using SOSM-DTC is to develop a robust control of torque and rotor flux of the DFIG. In our system, the electromagnetic torque and flux are respectively controlled by V_{dr} and V_{qr}.

Chattering effect which is a serious problem that exists in the conventional SMC can be very hurtful for the DFIG because it can create some undesirable phenomenon such as torque pulsation, current harmonics and acoustic noise, etc [29]. To relieve the influence of this problem, various solutions have been proposed [30, 31]. HOSM is one of the solutions proposed recently to eliminate the effect of this problem. This control method can ensure eradication of this undesirable phenomenon because it can acts on the sliding surface and its 1st derivative ($S = \dot{S} = 0$) [17, 32]. On the other hand, to retain the main advantages of the usual method, they debate the chattering phenomenon and offer advanced precision in practice. In the last decade many research works have applied this type of control [22, 23].

The big problem that accompanies the HOSM control executions is the increased required information. Indeed, it's necessary to know the derivatives of the surface $\dot{S}, \ddot{S}, \dots, S^{(n-1)}$ for performing an nth-order controller. Amid all algorithms used recently for the HOSM control, the super-twisting one is an exclusion. Indeed, this kind of algorithms needs just the information about S [24]. Therefore, the super twisting algorithm has been employed in this paper. As presented in [25], for all SOSM controllers stability can be easily verified with this algorithm.

The bloc diagram of the DFIG control using SOSM-DTC is shown in figure 2.

The SOSM controllers of rotor flux and electromagnetic torque are used to act successively on the two rotor voltage components as in (13) and (14) [20,33].

$$\begin{aligned} V_{dr} &= K_1 |S_{\varphi r}|^r \operatorname{sign}(S_{\varphi r}) + V_{dr1} \\ \dot{V}_{dr1} &= K_1 \operatorname{sign}(S_{\varphi r}) \end{aligned} \quad (13)$$

$$\begin{aligned} V_{qr} &= K_1 |S_{Cem}|^r \operatorname{sign}(S_{Cem}) + V_{qr1} \\ \dot{V}_{qr1} &= K_2 \operatorname{sign}(S_{Cem}) \end{aligned} \quad (14)$$

Where the sliding mode variables are the flux magnitude error $S_{\varphi r} = \varphi_r^* - \varphi_r$ and the torque error $S_{Cem} = C_{em}^* - C_{em}$, and the control gains K_1 and K_2 should verify the terms of stability.

A. Controller synthesis

Suppose a dynamic system defined as follows:

$$\frac{dx}{dt} = a(x,t) + b(x,t)u, \quad y = c(x,t) \quad (15)$$

where u is the input, x is the variable state and y is the output.

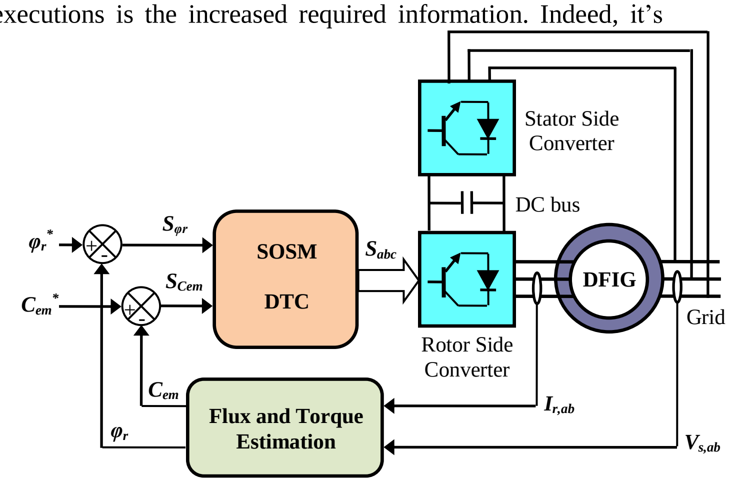

Fig. 2. Bloc diagram of the DFIG with SOSM-DTC

The main object of the control is to find an expression of the input $u = f(y, \dot{y})$ that be able to forces the trajectories of the system toward the beginning dot of the phase plane represented by $y = \dot{y} = 0$, if feasible in restricted period of time. Input u is supposed a new state variable, where the switching control is appended to its derived $\dot{u}$. Output y is regulated by a SOSM controller.

$$\begin{aligned} u &= K_1 |S|^r \operatorname{sign}(S) + u_1 \\ \dot{u}_1 &= K_2 \operatorname{sign}(S) \end{aligned} \quad (16)$$

Where $S = y^* - y$ is the sliding surface.

As indicated by expressions (16), the appropriate stipulation for convergence to S that can verify stability is for the gains to be large sufficient [20].

$$K_1 > \frac{A_M}{B_m},\ K_2 \geq \frac{4A_M}{B_m{}^2} \cdot \frac{B_M(K_1 + A_M)}{B_m(K_1 - A_M)} \qquad (17)$$

Where $A_M \geq |A|$ and $B_M \geq B \geq B_m$ are the bigger and lower limits of *A* and *B* in the 2nd derivative of the output *y*.

$$\frac{d^2y}{dt^2} = A(x,t) + B(x,t)\frac{du}{dt} \qquad (18)$$

IV. Fuzzy Second Order Sliding Mode Direct Torque Control (FSOSM-DTC)

SOSM control has proven in several studies and research applications its effectiveness in minimizing chattering effect which is mainly caused by the presence of a discontinuous control term containing the *sign* function [13-15]. To ameliorate the SOSM-DTC of the DFIG and more and more decrease the adverse effect caused by the *sign* function, in this work we suggest to employ a hybrid approach of second order sliding mode and fuzzy logic by replacing this function by an inference fuzzy system.

For the proposed FSOSM-DTC, the universes of discourses are first divided into the seven linguistic variables NB, NM, NS, EZ, PS, PM, PB, triangular and trapezoidal membership functions are chosen to represent the linguistic variables for the inputs and outputs of the controllers.

The fuzzy labels used in this study are negative big (NB), negative medium (NM), negative small (NS), equal zero (EZ), positive small (PS), positive medium (PM) and positive big (PB).

Figure 3 describes these choices.

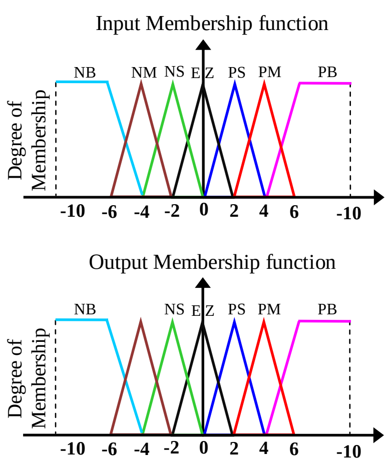

Fig. 3. Fuzzy sets and its memberships functions

V. Simulation Results

In order to evaluate the proposed DTC strategy of the DFIG, simulation tests using MATLAB Software have been realized and discussed in this section. The DFIG parameters used in simulations are as follows: nominal stator power P_{sn} = 1.5 MW, n_p = 2, R_s = 0.012 Ω, R_r = 0.021 Ω, L_s = 0.0137 H, L_r = 0.0136 H, M = 0.0135 H, F_r = 0.0024 Nm/s, J = 1000 kg.m^2. C-DTC, SOSM-DTC and FSOSMC are evaluated by simulations regarding tracking performances, total harmonic distortion (THD) of stator current and robustness versus variation of machine parameters.

A. Tracking performances

This test has the goal to analyze and compare the behavior of the three used DTC control methods regarding tracking performances. The obtained simulation results are shown by figures 4-7. As it's shown by figures 4-6, electromagnetic torque and rotor flux curves for the three used DTC methods follows excellently their references. Furthermore, we observe that the FSOSM-DTC and SOSM-DTC strategies guarantee the decoupling between the *d* and *q* axes contrary to the C-DTC where the coupling trace between them is somewhat clear. Otherwise, figure 7 illustrates the harmonic spectrums of the stator current for the three DTC control methods. Through this figure, it can be noticed that the total harmonic distortion (THD) is minimized for the SOSM-DTC method (THD = 1.31%) when compared to the C-DTC one (THD = 2.22%) and the THD is more and more reduced by using fuzzy logic (THD = 1.15%). Based on the results above, it can be said that the FSOSM-DTC has proven its efficiency in reducing chattering phenomenon in addiction to keeping the same advantages of the SOSM-DTC scheme.

B. Test of Robustness

In order to examine the performances of the three DTC control methods regarding robustness against variation of machine parameters, these last have been deliberately modified as follows: the values of R_s and R_r are multiplied by 2 while the values of L_s, L_r and M are divided by 2. The DFIG speed was kept equal to its face value. Figures 8-10 illustrate the obtained simulation results. These results show clearly that parametric variations test augment somewhat the time-response of the results obtained with C-DTC method. In addition, these results demonstrate that the parametric variations generate a visible influence on electromagnetic torque and rotor flux curves and that the influence seems more significant for the C-DTC compared to the other DTC schemes. Therefore, it can be concluded that the new proposed FSOSM-DTC scheme and in addition to its efficiency in reducing chattering phenomenon has kept the most important advantage of the SMC approach which is the robustness.

VI. Conclusion

In this paper, a new DTC scheme of a doubly fed induction generator attached to the electric network through the stator part and fed by a back to back inverter by the rotor part has been discussed. Firstly, a modeling of a DFIG-based wind turbine has been presented. Frequently used in the WTSs, this generator presents several benefits such as variable speed function and the ability to work in the four quadrants. Secondly, a new DTC scheme using SOSM and fuzzy logic is synthesized and compared to both C-DTC and SOSM-DTC. In term of tracking performances electromagnetic torque and rotor flux curves for the three used DTC methods follows excellently their references, however a problem of coupling is emerged in the C-DTC curves that is removed with the other SOSM-DTC methods. Furthermore, the obtained results have approved that the FSOSM-DTC works with a lesser chattering effect. A test of robustness has also been elaborated in this paper where the machine parameters have been deliberately changed. After these variations, a few ripples have been induced on the curves of electromagnetic torque and rotor flux but with a significant influence with the C-DTC strategy compared to the other DTC methods. In light of the obtained results, one can conclude that the proposed FSOSM-DTC scheme represents an important tool for systems using DFIG such as WTSs.

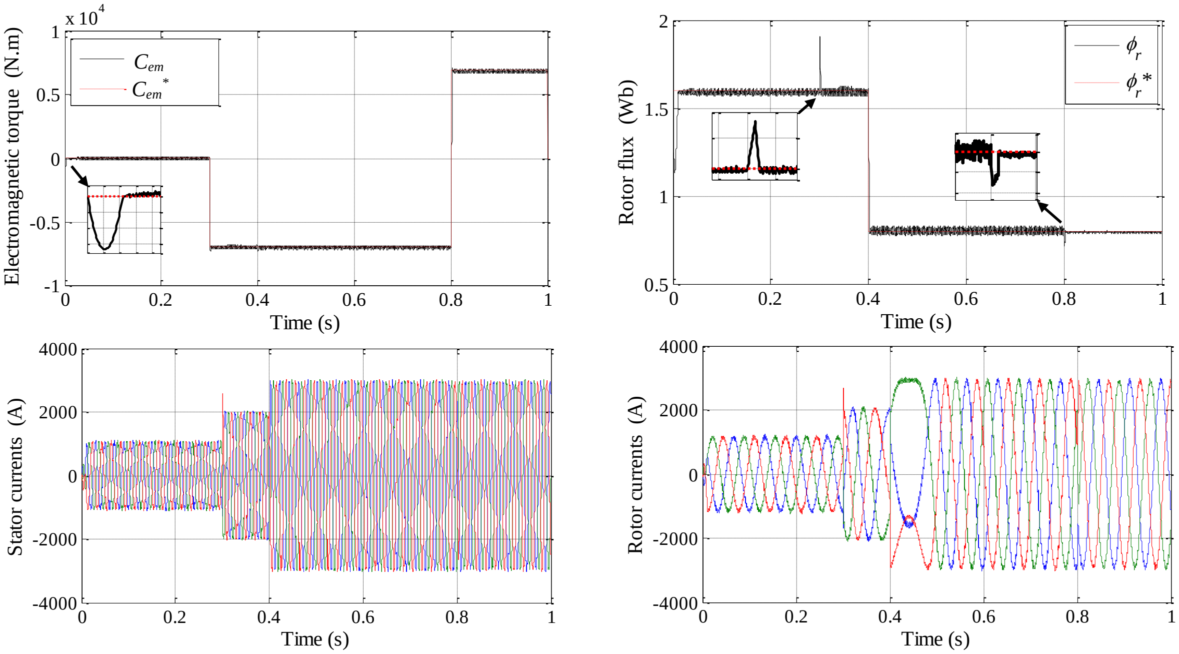

Fig. 4. C-DTC strategy responses (reference tracking test)

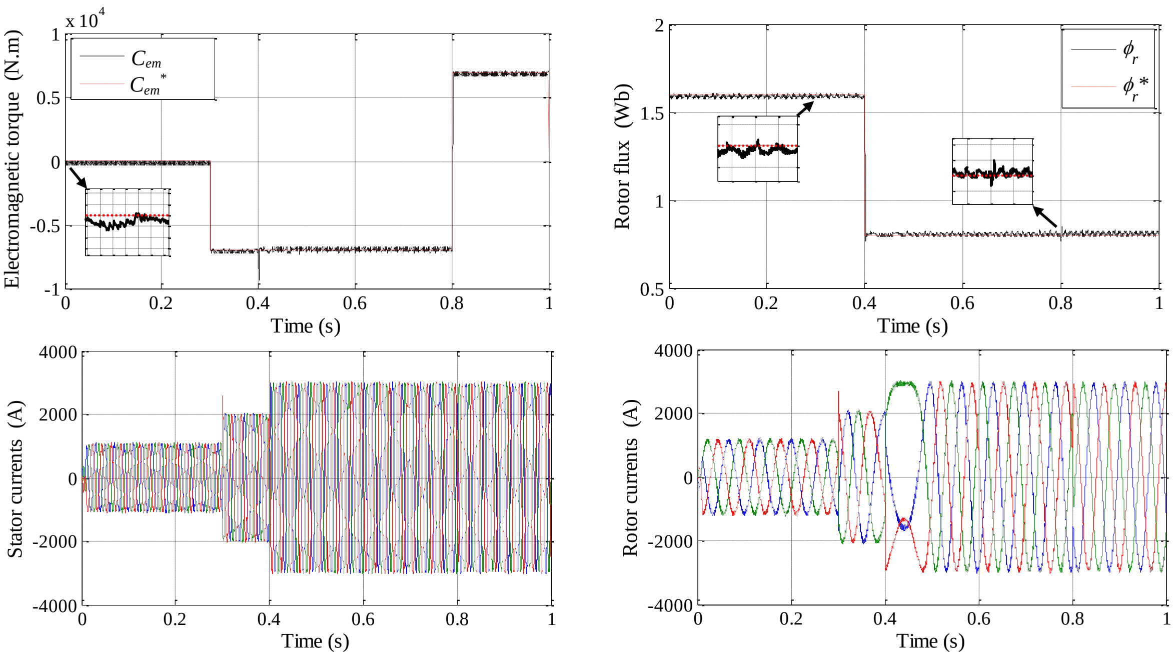

Fig. 5. SOSM-DTC strategy responses (reference tracking test)

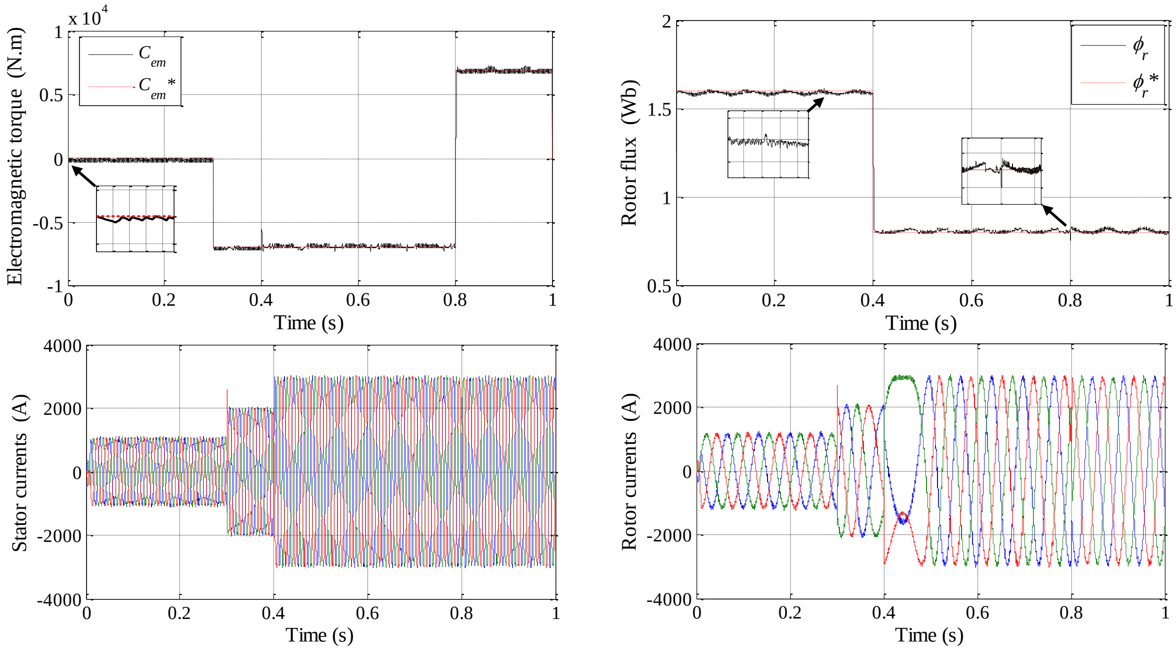

Fig. 6. FSOSM-DTC strategy responses (reference tracking test)

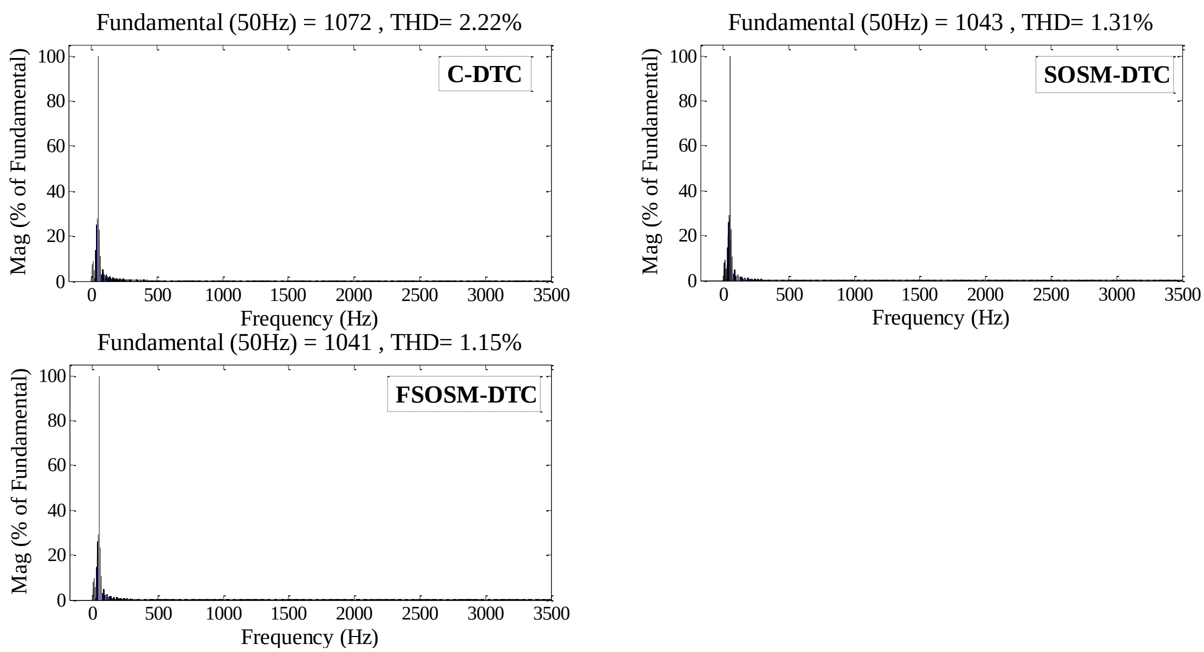

Fig. 7. THD of one phase stator current for a DFIG

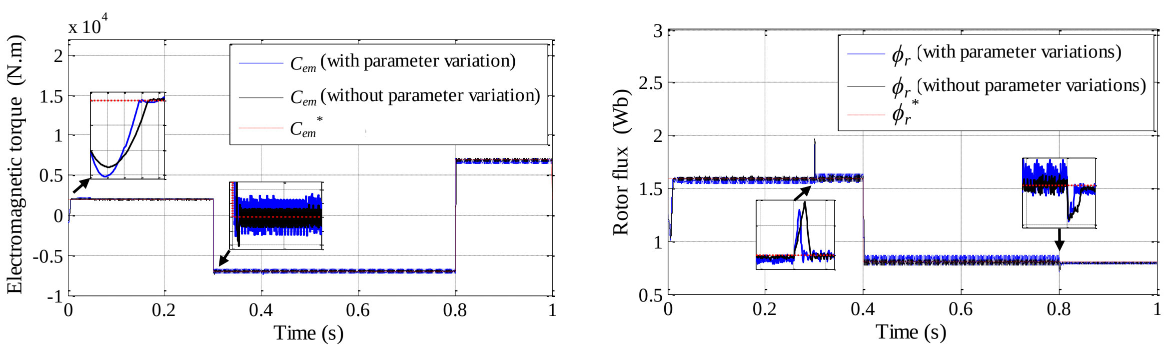

Fig. 8. C-DTC strategy responses (robustness test)

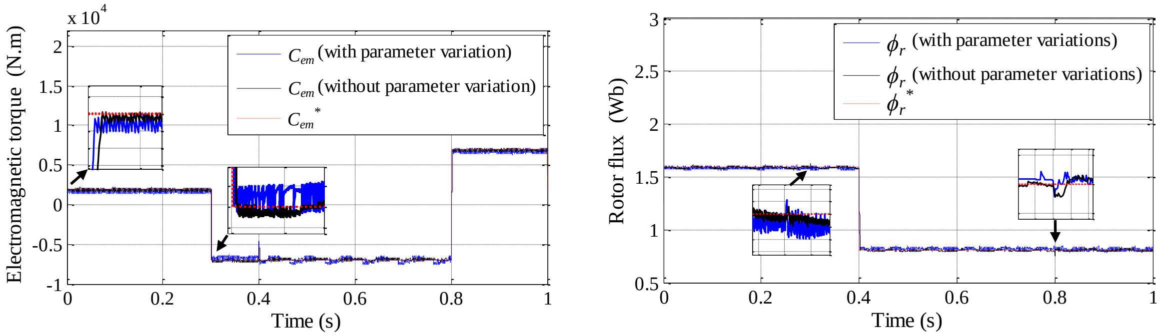

Fig. 9. SOSM-DTC strategy responses (robustness test)

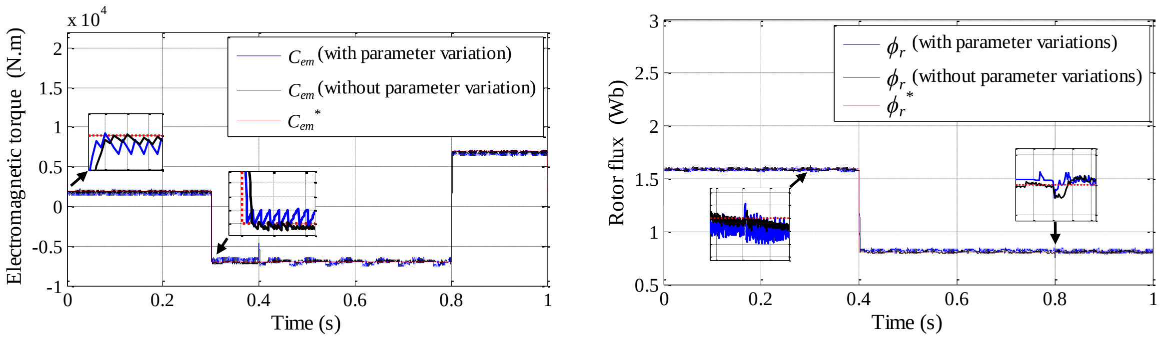

Fig. 10. FSOSM-DTC strategy responses (robustness test)

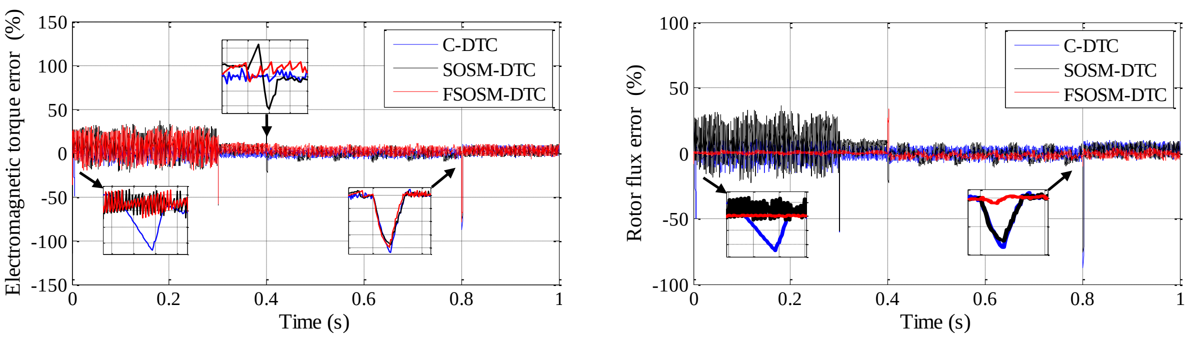

Fig. 11. Error curves (robustness test)

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