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Fuzzy super twisting algorithm dual direct torque control of doubly fed induction machine

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ABSTRACT

This paper proposes the fundamental aspects of hybrid nonlinear control which is composed of the super twisting algorithm (STA) based second order sliding mode control applying fuzzy logic method (FSOSMC), with pertinent simulation results for a doubly fed induction machine (DFIM) drive. To minimize chattering effect phenomenon due to Signum function employed in sliding mode algorithm, a new method is proposed. This technique consists in replacing the signum function by fuzzy switching function in the SOSMC to minimize flux and torque ripples. This FSOSMC is associated to the double direct torque control DDTC of the doubly fed induction machine (DFIM) by combining the advantages of fuzzy logic (FL) and the advantages of super-twisting sliding mode. The FSOSMC-DDTC strategy is compared with a PI-DDTC and SOSMC-DDTC. Simulation results demonstrate good efficiency and excellent robustness of the hybrid nonlinear controller.

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NOMENCLATURE

$V_{s(\alpha,\beta)}, V_{r(\alpha,\beta)}$	Stator, rotor voltage vectors in α,β reference
$I_{s(\alpha,\beta)}, I_{r(\alpha,\beta)}$	Stator, rotor current vectors in α,β reference
$\varphi_{s(\alpha,\beta)}, \varphi_{r(\alpha,\beta)}$	Stator, rotor flux linkage vectors in α,β reference
Ω	Mechanical speed
R_s, R_r	Stator and rotor resistances
L_s, L_r	Stator and rotor self Inductances
$\rho_{s,r}$	Stator and rotor flux angular positions
σ	leakage coefficient
J	Moment of inertia
ω_s, ω_r	Stator and rotor pulsations
$\mu_\Omega\, \delta_\Omega$	Constant positive
T_e	Electromagnetic torque

1. INTRODUCTION

Since the middle of the eighties, the development of the efficiency of induction machines has not been stalled, several previous studies allowed toapplying diverse control technique, and the most common of them, the direct torque control (DTC) [1], [2], because of its many advantages, like fasterdynamic response and less complexity. In [3], Ourici the author proposed to introduce the dual-FOC used inthe rotor and stator of the DFIM simultaneously. Bonnet [4], and Boumaraf [5] use the flux model of DFIM with second switching table in the rotorto improve the DDTC. The DDTC suffers from disadvantages ofvariation in the switching frequency, flux and torque ripples. Recently methods have been proposed to resolve this drawbacks; some papers focus on control optimization of a DFIM [6], some paper focus on low-speed sensorless double DTC for DFIM [7], and other papers propose the introducingof fuzzy logic technique [8], [9], while [10] propose the artificial neural network in DDTC of DFIM. Nevertheless, there are a few difficulties that limit the use of these kinds of controllers, such as a variable switching frequency, torque and flux ripple. In many research papers, these effects are minimized by using space-vector modulation (SVM) method [11], algorithm genetic strategy [12] and feedback linearization [13], but until now, the realization of these algorithms in practice remains more complicated and more expensive than conventional DTC.

Recently, sliding mode control (SMC) was integrated largely in the command of nonlinear systems. [14], [15] have been focused out the remarkable dynamic performances who own SMC in term of improving DTC against the parametric variation. However, this strategy law represents the chattering phenomenon caused by using the sign function. For that, further research is required to eliminate these disadvantages, some authors [16]-[22] proposed the SOSMC, other researchers have been proposed associate the SMC with other techniques like SMC-SVM [23], [24], SMC-feedback control [25], SVM-PID [26] and FL-SMC [27]-[30]. However, this paper presents the DDTC for DFIM using a novel hybridization between FL and SOSMC technique. The main contributions of this work are:

- The new control technique is introduced by embedding a FL strategy into the SOSMC.
- The switching frequency is limited and also the ripples inthe torque, stator and rotor flux are reduced.
- The performance of the DFIM controlled by FSOSMC is comparedto that of the DFIM controlled by PI and SOSMC so as to prove the improvements made.

The rest paper part is structured is being as: The DFIM model is described in section 2. Section 3 gives a basic idea of the DDTC. In section 4, the STAisexplained,while theFSOSMC is discussed in section 5. Section 6 presents the simulation results using the MATLAB/Simulink. Finally, conclusion is drawn in section 7.

2. MATHEMATICAL MODEL OF DFIM

The traditional model of DFIM in the laboratory frame (α,β) is written is being as in (1) [6]. The parameters of DFIM shows in the appendix.

$$\begin{cases} V_{s\alpha} = R_s I_{s\alpha} + \dfrac{d}{dt}\varphi_{s\alpha} \\ V_{s\beta} = R_s I_{s\beta} + \dfrac{d}{dt}\varphi_{s\beta} \\ V_{r\alpha} = R_r I_{r\alpha} + \dfrac{d}{dt}\varphi_{r\alpha} + \omega_r \varphi_{r\beta} \\ V_{r\beta} = R_r I_{r\beta} + \dfrac{d}{dt}\varphi_{r\beta} - \omega_r \varphi_{r\alpha} \end{cases} \qquad \begin{cases} \varphi_{s\alpha} = L_s I_{s\alpha} + \mu I_{r\alpha} \\ \varphi_{s\beta} = L_s I_{s\beta} + \mu I_{r\beta} \\ \varphi_{r\alpha} = L_r I_{r\alpha} + \mu I_{s\alpha} \\ \varphi_{r\beta} = L_r I_{r\beta} + \mu I_{s\beta} \end{cases} \tag{1}$$

The expression of electromagnetic torque for the DFIM is defined as in (2) [7]:

$$\left\|\vec{T}_e\right\| = K \left\|\vec{\varphi}_s\right\| . \left\|\vec{\varphi}_r\right\| sin(\gamma) \tag{2}$$

3. DDTC STRATEGY

The DDTC strategy involves the separate control of $\vec{\varphi}_s$ and $\vec{\varphi}_r$ through the selection of optimums inverters switching modes. To decrease or increase the flux amplitudes $\varphi_{s,r}$ and the angular position $\rho_{s,r}$ in each sector, two adjacent voltage vectors can be used. The voltage vectors control of $\varphi_{s,r}$ planes are shown in Figure 1 [6].

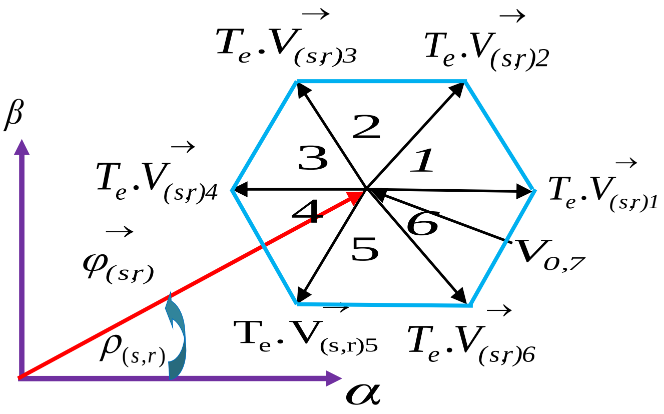

Figure 1. $\vec{\varphi}_{s,r}$ control in six angular sectors

4. SUPER-TWISTING DUAL DIRECT CONTROL OF DFIM

The STA is an exceptional case of SOSMC, where this method is specially developed to control the non linear systems with relative degree 1, respecting the sliding surface [17]. Two parts compose the STA; a discontinuous and continuous part. The sliding surface is defined [18]:

$$s_\Omega = \Omega_{ref} - \Omega \tag{3}$$

$$\frac{d\Omega}{dt} = \frac{T_e - T_r - f\ \Omega}{\mathrm{J}} \tag{4}$$

By replacing (4) into (3) we obtain:

$$\dot{S}_\Omega = \dot{\Omega}_{ref} - \frac{1}{J}(T_e - f\ \Omega - T_r) \tag{5}$$

Wedefine:

$$A_\Omega = \dot{\Omega}_{ref} - \frac{1}{J}(f\ \Omega - T_r) \tag{6}$$

Then the (5) became:

$$\ddot{S}_\Omega = \dot{A} - \frac{1}{J}\dot{T}_e \tag{7}$$

The SOSMC contain two parts [18]:

$$U = U_1 + U_2 \tag{8}$$

$$\dot{U}_1 = \begin{cases} -U & if\ |U| \succ U_M \\ -\delta_\Omega\ sign(S_\Omega) & if\ not \end{cases} \tag{9}$$

$$\dot{U}_2 = \begin{cases} -\mu_\Omega |S_\Omega|^{1/2}\ \ \mathrm{sign}(\mathrm{S}_\Omega) & \mathrm{if}\ |\mathrm{U}| \succ \mathrm{S}_\Omega \\ -\delta_\Omega |S_\Omega|^{1/2}\ sign(S_\Omega) & \mathrm{if\ not} \end{cases} \tag{10}$$

if $S_0 = \infty$ we can simplify the algorithm [23]:

$$\begin{cases} u = -\mu_{\Omega} \left| s_{\Omega} \right|^{1/2} \operatorname{sign}(s_{\Omega}) + \mathrm{u}_1 \\ \dot{u}_1 = -\delta_{\Omega} sign(s_{\Omega}) \end{cases} \tag{11}$$

The closed loop diagram of STA is presented in Figure 2 [18].

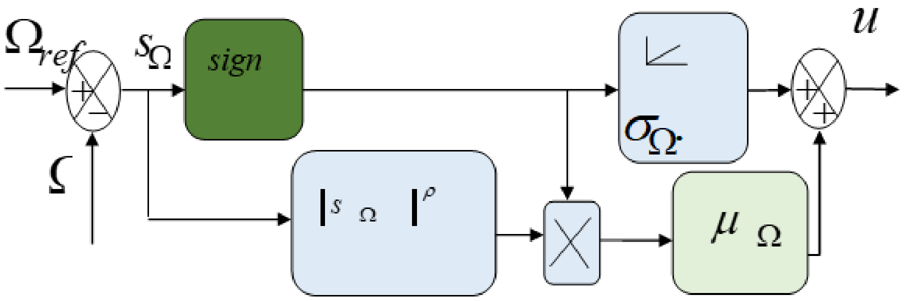

Figure 2. SMC diagram

5. RELATED WORK

5.1. Fuzzy logic-SOSMC

The FSOSMC have been adopted to solve the problem of chattering, where the sign function has been replaced by an inference fuzzy system. The shapes of all membership functions are defined in Figure 3. In FSOSMC, in (11) becomes (12):

$$\begin{cases} u = -\mu_{\Omega} \left| s_{\Omega} \right|^{1/2} \mathrm{fuzzy}(s_{\Omega}) + \mathrm{u}_1 \\ \dot{u}_1 = -\delta_{\Omega}\ \mathrm{fuzzy}(s_{\Omega}) \end{cases} \tag{12}$$

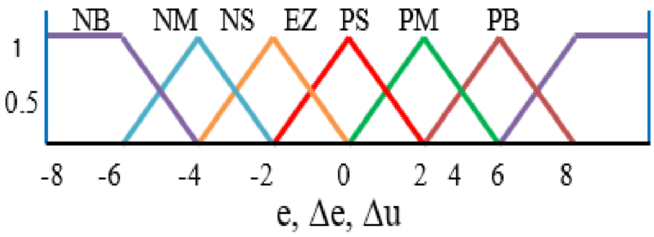

Figure 3. Membership functions (e, Δe, Δu)

5.2. Stability analysis

The analysis and the proof of stability will be exposed to guarantee the system stability. The Lyapuno derivative candidacy is defined by (13):

$$S_{\Omega}.\dot{S}_{\Omega} \prec 0 \tag{13}$$

We replace this in (5) we get:

$$\dot{S}_{\Omega} = -\frac{1}{j}(\mu_{\Omega}|S_{\Omega}|^{\frac{1}{2}} sign(S_{\Omega}) + \int \sigma_{\Omega} sign(S_{\Omega})dt \qquad \text{(14}$$

And the stability condition according to Lyapunov will be [18]:

$$\Rightarrow S_{\Omega}.\dot{S_{\Omega}} = -\frac{\mu_{\Omega}}{j}\left|S_{\Omega}\right|^{\frac{3}{2}} sign(S_{\Omega}) - S_{\Omega}\frac{\sigma_{\Omega}}{j}\int sign(S_{\Omega})dt \qquad (15)$$

The Lyapunov condition $S_{\Omega}.\dot{S}_{\Omega} < 0$ is assured only with coefficients (μ_{Ω} , δ_{Ω}) positives.

6. SIMULATION

We have simulated the proposed FSOSMC on the MATLAB/Simulink as shown in Figure 4, where the FSOSMC consists in replacing the classical regulator PI by the FSOSMC controller, and a series of tests were done to prove the effaiciency of this new technique of control. Therefore, a comparative results between FSOSMC-DDTC and both PI-DDTC and SOSMC-DDTC techniques have been presented.

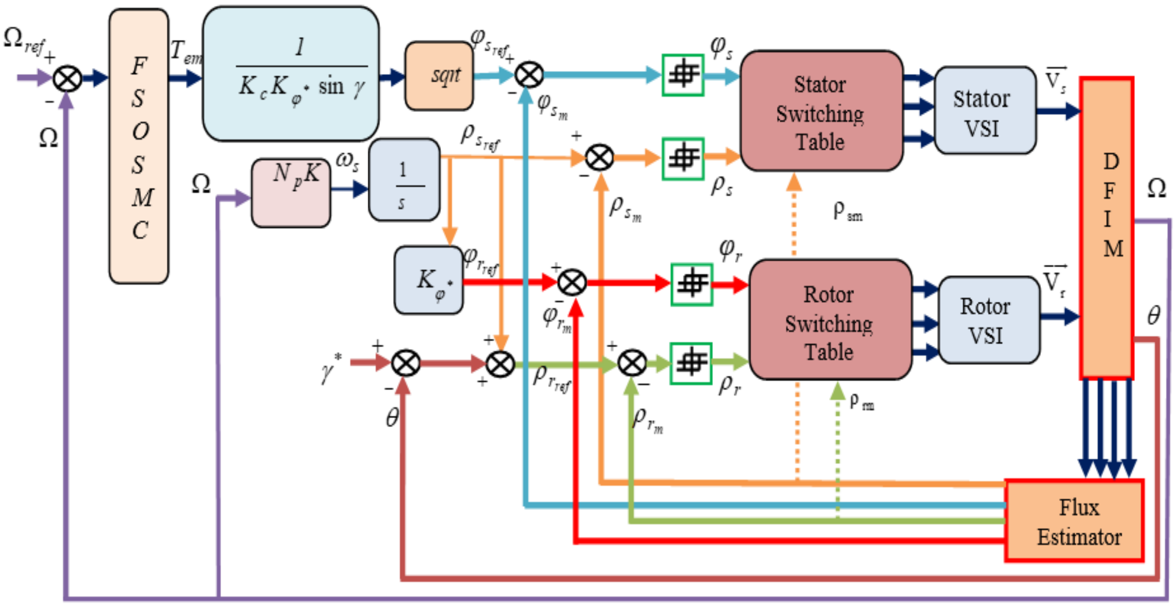

Figure 4. Block diagram of FSOSMC-DDTC scheme for DFIM

6.1. First test (speed reversal)

This test consists on varying the speed reference cycle startingfrom the zero value to 180 rad/s, and changingaccording to the time variation to t=[1 2 3 4] s with respectively Ω_{ref}=[-180 50 -50 157]. Also, anintroduction of load torque at t=2.5 s value to 25 Nm is presented. The comparative curves between PI, SOSMC and our approach are presented in Figures 5 and 6. It can be noticed that the speed variation cycle produces an important effect on electromagnetic torque, rotor and stator flux curves. While the use of the FSOSMC controller give a good performance: Allows the speed to judiciously follow its different reference values with better transient response time. The improvement of the FSOSMC in terms of overshoot, settling time, this result is indicated in Table 1, the rejects of the load disturbance is very rapid with a negligible steady state error, and FSOSMC minimize the chattering effect in the flux and torque ripple compared to the results obtained in [6]-[10].

6.2. Second test (variation of the load torque)

The imposed profile of the load torque changes from 0 Nm value to 25 Nm, this variation is done respectively is being as for a time value t=[1 2 3 4] s and a torque value T_e=[10 25 30 15] Nm. Figures 7 and 8 show that the FSOSMC control law is robust to the variations and the presence of disturbances. Moreover the results obtained in Figure 5, Figures 7, 8, 9 and 10 show that the toque has less ripple of 2 Nm and 1.3 N.m compared to PI, SOSMC, and to the results obtained in [8]-[10]. The rotor and stator flux ripples are also considerably reduced.

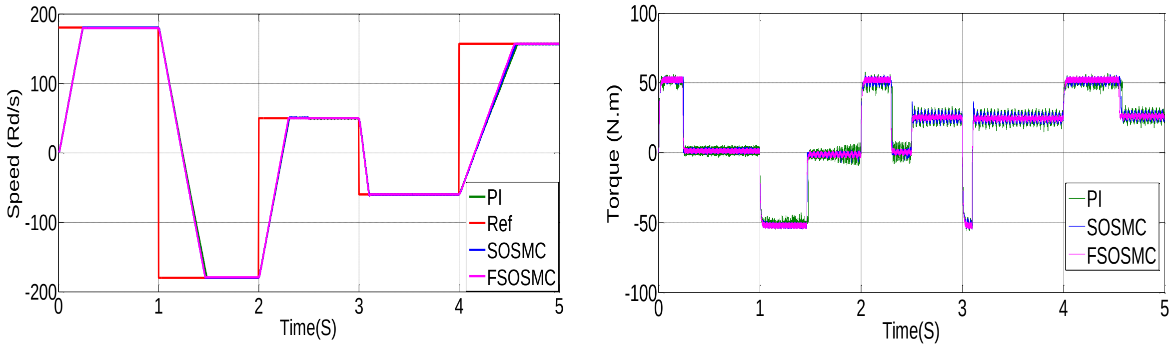

Figure 5. FSOSMC, SOSMC and PI strategy responses (under speed variation)

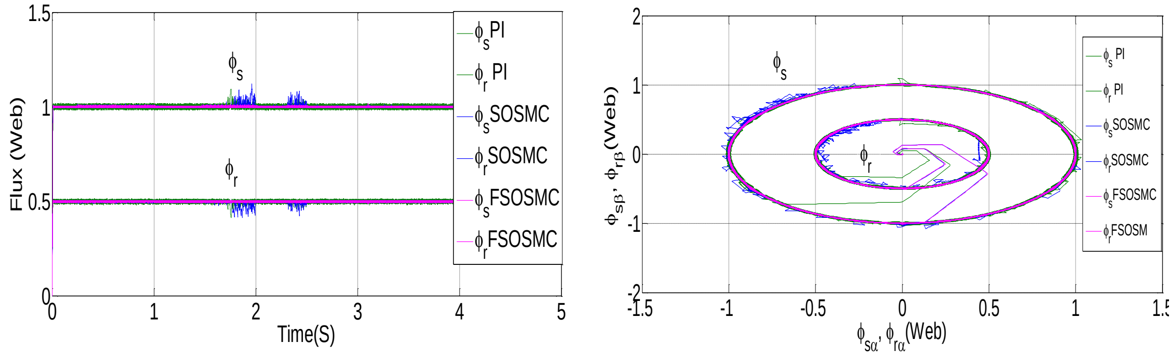

Figure 6. FSOSMC, SOSMC and PI strategy responses (under speed variation)

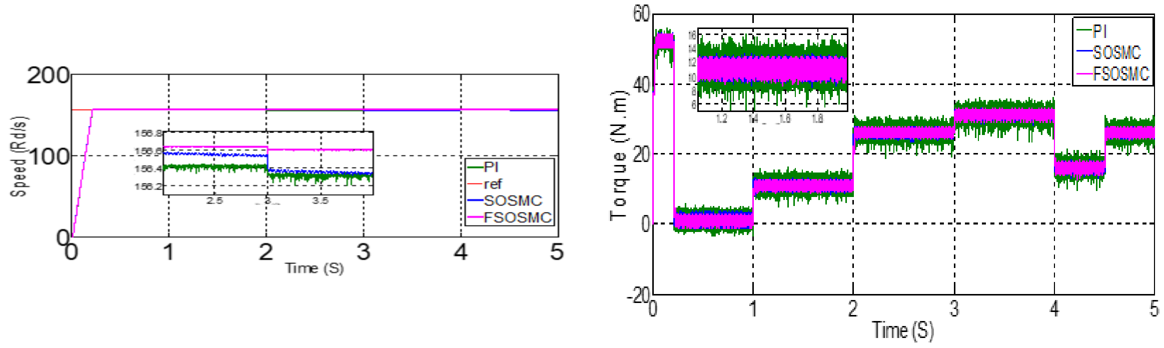

Figure 7. FSOSMC, SOSMC and PI strategy responses (under load torque variation)

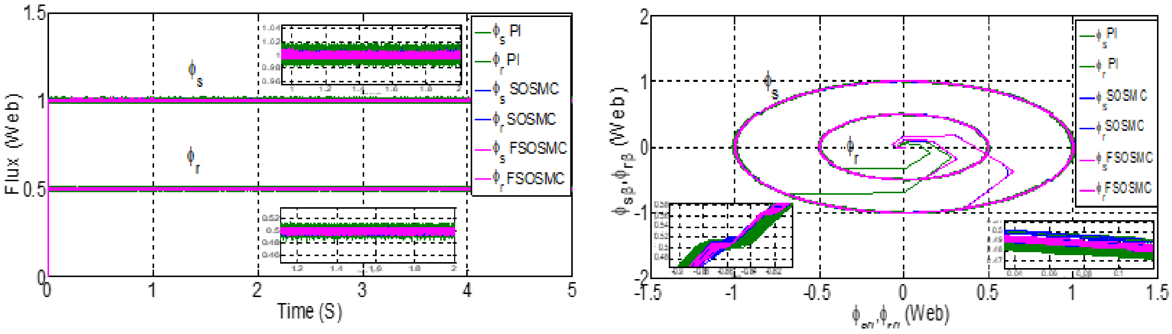

Figure 8. FSOSMC, SOSMC and PI strategy responses (under load torque variation)

6.3. Third test (robustness test)

For testing the performances of the new FSOSMC in our strategy, R_r, R_s have been reduced to 50% of their real valuesinthe intervals of time t=1 s to t=1.5 s and from t=2.9 s to t=3.5 s respectively, then we increased their value to the double at time fixedto t=2 s to 2.5 s for the stator resistance, and between 3.9 and 4.5 s for the rotor resistance as shown in Figure 9. Figures 10 and 11 shows a comparison between different techniques of control under parametric variation. We observe the effect of these variations on the torque and also on both stator and rotor flux. This comparison proves clearly that the performance of the proposed algorithm under parametric variations is better than both the PI and SOSMC controller. Table 1 summarizes the comparison between different techniques.

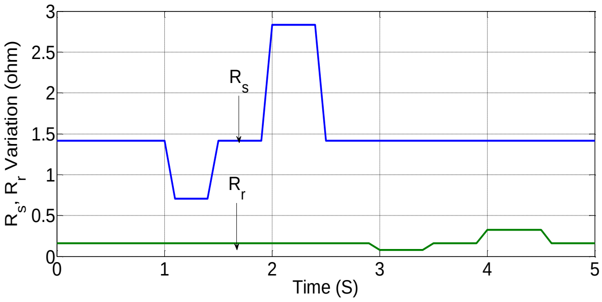

Figure 9. R_s and R_r resistance variations

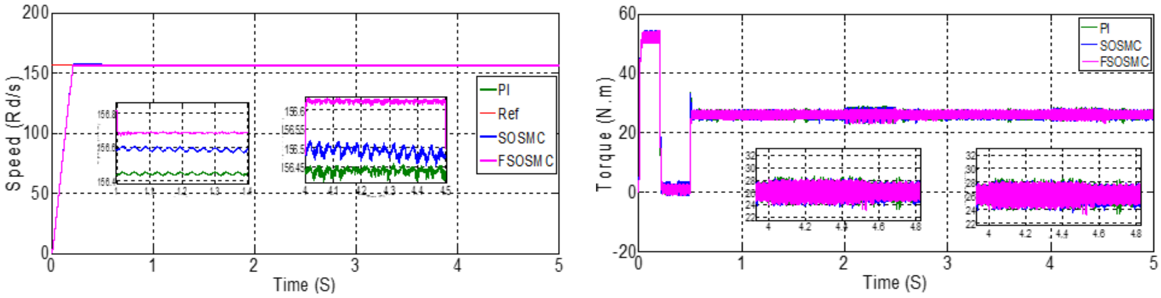

Figure 10. FSOSMC, SOSMC and PI strategy responses (under parameter variations)

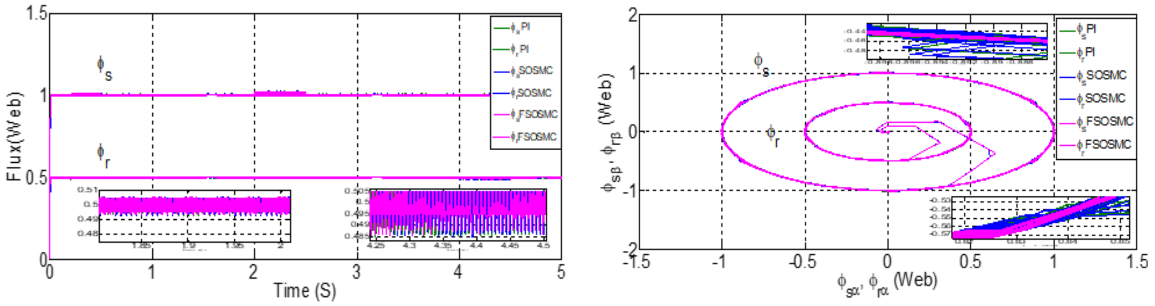

Figure 11. FSOSMC, SOSMC and PI strategy responses (under parameter variations)

Table 1. Performances comparison of the three approachs

Approach	PI-DDTC	SOSMC-DDTC	FSOSMC-DDTC	Improvement compared to PI (%)	Improvement compared to SOSMC (%)
Torqueripple (N.m)	4.5	3.8	2.5	44.44	34.21
Stator flux ripple (Wb)	1.02	0.5	0.3	70.58	40
Rotor flux ripple (Wb)	0.48	0.35	0.25	47.92	28.57
Rising time of the speed	0.218	0.215	0.213	2.3	0.9

7. CONCLUSION

In this paper, FSOSMC-DDTC for DFIM has been presented to improve the DDTC of DFIM performance. The suggested control has been compared to the PI-DDTC and SOSMC-DDTC. The simulation results demonstrate that the DDTC using FSOSMC worked well especially with regard to torque and flux ripples minimization, less performance degradation due to machine parameter variations, robustness to load changes andsystem disturbances, which demonstrate the feasibility of the FSOSMC method. The superiority of the suggested FSOSMC-DDTC isemphasized by the following points: (1) FSOSMC is developed to efficiently control a DFIM. Compared with existing control techniques such as previous studies, the rate of effectiveness presents interesting attributes, such as, high tracking performances and low chattering; (2) The practical realization of the suggested methods will wish be conducted in the future.

APPENDIX

A. DFIM parameters

Symbol	Value
P_n	4 KW
L_s	0.163 H
L_r	0.021 H
R_s	1.417 Ω
R_r	0.163 Ω
μ	0.055 H
P	2
J	0.066 Kg m2

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