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Comparison study between SVPWM and FSVPWM strategy in fuzzy second order sliding mode control of a DFIG-based wind turbine

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Abstract— **In this work, we present a new fuzzy second-order sliding mode controller (FSOSMC) for wind power transformation system based on a doubly-fed induction generator (DFIG) using intelligent space vector pulse width modulation (SVPWM). The proposed command strategy combines a fuzzy logic and a second order sliding mode control (SOSMC) for the DFIG command. This strategy presents attractive features such as chattering-free, compared to the conventional first and second order sliding mode techniques. The use of this method provides very satisfactory performance for the DFIG command. The effectiveness of this command strategy is proven through the simulation results.**

Keywords—FSOSMC, DFIG, SVPWM, SOSMC.

I. INTRODUCTION

Wind power is one of the major components of renewable energy generation. There are two concepts of wind turbine system (WTS) : horizontal axis WT and vertical axis WT. While vertical axis WT has much lower efficiency than horizontal-axis, their use in multi-megawat wind power industry is very limited. Therefore, only horizontal-axis WT are considered in the presented study. Currently, variable speed WTS employing DFIG is the most popular technology in presently installed WT [1]. The DFIG has many advantages are presented in [2]. On the other hand vector command (VC) is the most popular technique scheme used to command reactive and active powers of the DFIG based WTs [3]. Like an every command technique has some disadvantages and advantages, VC command method has too. Some of the advantages is presented in [4]. The basic disadvantage of VC strategy is the dependence on the machine parameters variation due to the decoupling terms [5]. A decoupled command of the instantaneous stator reactive and stator active powers has been achieved by controlling the decomposed rotor currents using classical PI regulators [6]. To solve the disadvantages of VC command of DFIG machine, various techniques have been proposed. Intelligent command method [7, 8]. Robust command scheme [9-11]. DTC (Direct torque control) command of a DFIG [12, 13]. DPC (Direct power control) command of a DFIG [14-16].

For high performance and robust VC command, a sliding mode control (SMC) was studied in the literature [17-22]. However, the SMC technique was proposed by Utkin in 1977 [23]. This technique has many advantages such as good performance against unmodeled dynamics, insensitivity to parameters variation, and external disturbance rejection and fast dynamic response. On the other hand, the disadvantages of SMC controllers is that the chattering phenomenon. However, many papers proposed to eliminate the chattering phenomenon. In [24, 25] SMC and fuzzy logic are combined to the command of a DFIG speed in WTs. In [26] second order sliding mode controller was designed to command stator active and reactive powers of a DFIG. However, the total harmonic distortion (DTC) of the stator current in [26] and [25] is 2.62% and 2.85% respectively. In order to improve the THD value of stator current and minimize the powers ripples, we propose to use the fuzzy second order sliding mode control (FSOSMC).

Since fuzzy logic (FL) is known as the universal approximators and have several applications in command design and identification [27]. This technique is able to use human reasoning not in terms of discrete symbols and numbers, but in terms of fuzzy sets. These terms are quite flexible with respect to the definition and values [28]. To obtain high-performance DFIG machine a robust and simple second order sliding mode controller based on the FL controller is designed to command and regulate the reactive and active power. On the other hand, fuzzy second order sliding mode control (FSOSMC) have many advantages, reducing the chattering phenomenon, simple rule base, nonlinearities and robustness against disturbances.

On the other hand, the stator winding is directly connected to the grid when the rotor winding is connected to the grid via a bidirectionnels space vector pulse width modulation (SVPWM) power converter. However, SVPWM technique is normally developed as vector approach to pulse width modulation (PWM) for three-phase converter. The disadvantage of the SVPWM is presented in [29]. In this article, a new SVPWM inverter based on intelligent techniques is presented. The intelligent SVPWM method which ensures the back to back converter operation with constant frequency modulation. The proposed SVPWM technique is easy to implement, simple modulation scheme and gives minimum THD value. In this work, we apply the FSOSMC technique to the wind energy transformation systems of DFIG using the new modulation technique known as fuzzy SVPWM technique (FSVPWM) and compared to the traditional SVPWM technique.

II. Fuzzy space vector pulse width modulation

The SVPWM technique is the preferred method over the former one due to the advantages introduced such as maximized output voltage range, minimum harmonic distortion, and even reduced switching losses [30]. However, this technique based on the principles of space-vectors and need to calculated of sector and angle [31, 32]. The details about this technique inverter can be found in [33-36].

In this section, we proposed SVPWM scheme simple of two- level based on calculation of minimum and maximum of voltages. The advantages of proposed SVPWM method is not needed to calculate the sector and angle, easy to implement and it presents a strong performance for the real-time feedback command. The proposed SVPWM technique, which is designed to command the two-level inverter is shown in Fig. 1.

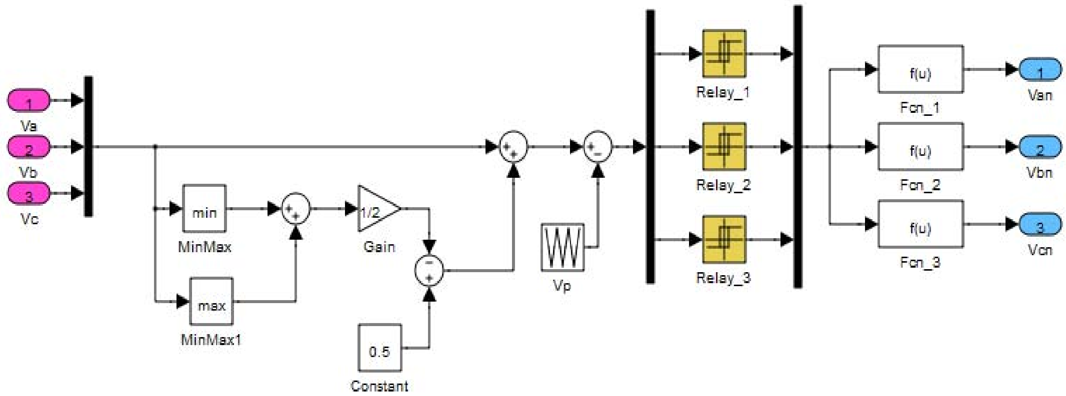

Fig. 1 Simulation block of proposed SVPWM technique.

In order to improve the two-level SVPWM, a complimentary use of fuzzy regulator is proposed. The FL regulator has been used in many application and the fuzzy theory was introduced by Zadeh [37]. This technique based on observation and engineering experience. In FL method, does not need a mathematical model [38].

For the proposed fuzzy space vector modulation (FSVPWM) in Fig. 2, the universes of discourses are first partitioned into the seven linguistic changes NB, NM, NS, EZ, PS, PM, PB. The FL controller contains three blocks: fuzzification, fuzzy rule base and defuzzification.

The block diagram of FL controllers based hysteresis comparators is shown in Fig. 3. The membership function definition for the input changes “Error ” and “Change in Error ” is given by Fig. 4.

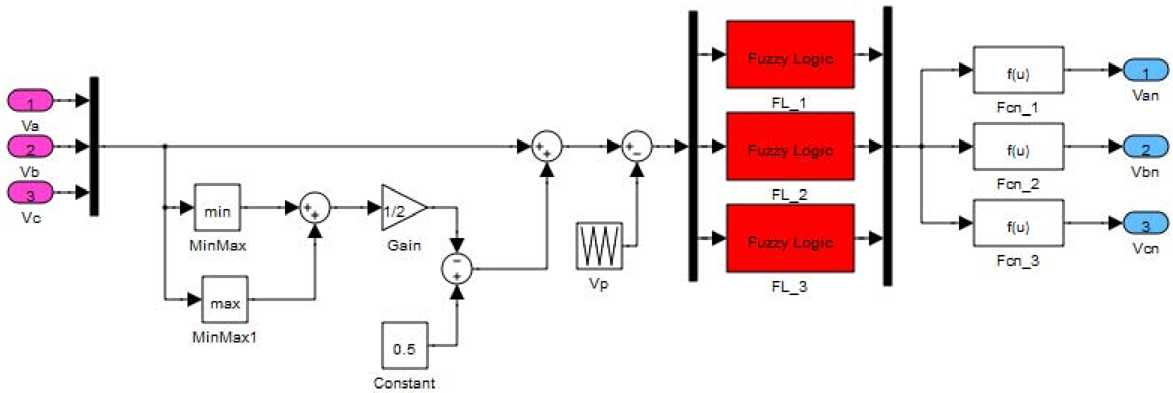

Fig. 2 SVPWM method with FL controllers.

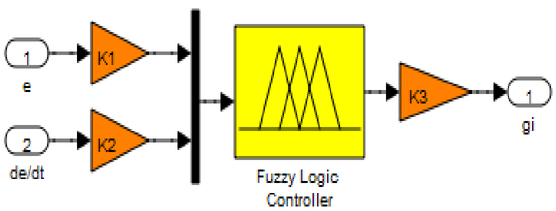

Fig. 3 Fuzzy command of hysteresis comparators.

On the other hand, the FL rules are developed using linguistic changes that are formulated in the form of « IF THEN » rules. The Table 1 show this rules [39, 40].We use the following designations for membership functions :

NB : Negative Big NM : Negative Middle
NS : Negative Small PS: Positive Small
PB: Positive Big EZ : Equal Zero
PM : Positive Middle.

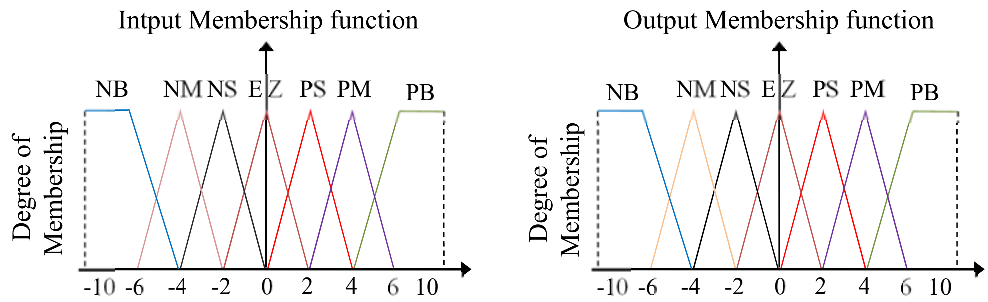

Fig. 4 Fuzzy sets and its memberships functions.

Table 1 Matrix of Inference

e / Δe	NB	NM	NS	EZ	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	EZ
NM	NB	NB	NB	NM	NS	EZ	PS
NS	NB	NB	NM	NS	EZ	PS	PM
EZ	NB	NM	NS	EZ	PS	PM	PB
PS	NM	NS	EZ	PS	PM	PB	PB
PM	NS	EZ	PS	PM	PB	PB	PB
PB	EZ	PS	PM	PB	PB	PB	PB

The Table 2 shows the parameters of FL controller.

Table 2 Parameters of FL controller

Fis type	Mamdani
And method	Min
Or method	Max

III. Model of DFIG

The traditional electrical equations of the doubly fed induction generator in the Park frame are written as follows [41- 43]:

$$\begin{cases} V_{ds} = R_s I_{ds} + \frac{d}{dt}\psi_{ds} - \omega_s \psi_{qs} \\ V_{qs} = R_s I_{qs} + \frac{d}{dt}\psi_{qs} + \omega_s \psi_{ds} \\ V_{dr} = R_r I_{dr} + \frac{d}{dt}\psi_{dr} - \omega_r \psi_{qr} \\ V_{qr} = R_r I_{qr} + \frac{d}{dt}\psi_{qr} + \omega_r \psi_{dr} \end{cases} \tag{1}$$

The rotor and stator flux can be expressed as:

$$\begin{cases} \psi_{ds} = L_s I_{ds} + M I_{dr} \\ \psi_{qs} = L_s I_{qs} + M I_{qr} \\ \psi_{dr} = L_r I_{dr} + M I_{ds} \\ \psi_{qr} = L_r I_{qr} + M I_{qs} \end{cases} \tag{2}$$

The reactive and active powers at the stator can be expressed as:

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

The electromagnetic torque is expressed as:

$$T_e = pM\,(I_{dr}.I_{qs} - I_{qr}.I_{ds}) \tag{4}$$

$$T_e = T_r + J \cdot \frac{d\Omega}{dt} + f \cdot \Omega \tag{5}$$

IV. Control of Active and Reactive Power of DFIG

In this section, we choose a *dq* reference frame coordinated with the stator flux (See Fig.5) [44]. By setting the stator flux linkage vector aligned with d-axis, and neglecting Rs we can write [45-47]:

$$\psi_{qs} = 0, \psi_{ds} = \psi_s \tag{5}$$

$$\begin{cases} \psi_s = L_s.I_{ds} + M.I_{dr} \\ 0 = L_s.I_{qs} + M.I_{qr} \end{cases} \tag{6}$$

The energies controlled between the grid and the DFIG are based on VC strategy with indirect vector command (IVC). This command technique is detaid in [48-51]. The important grandeurs of this system like: the reactive power, the torque and active power are expressed in the Park frame as follows:

$$P_s = -V_s \cdot \frac{M}{L_s} \cdot I_{qr} \tag{7}$$

$$Q_s = V_s \cdot \frac{V_s^2}{L_s} \frac{M}{L_s} \cdot I_{dr} \tag{8}$$

$$T_e = p \frac{M}{L_s} I_{qr} \psi_{ds} \tag{9}$$

The command reactive and active powers of the DFIG directly connected through the stator windings to the grid, is shown in Fig.6.

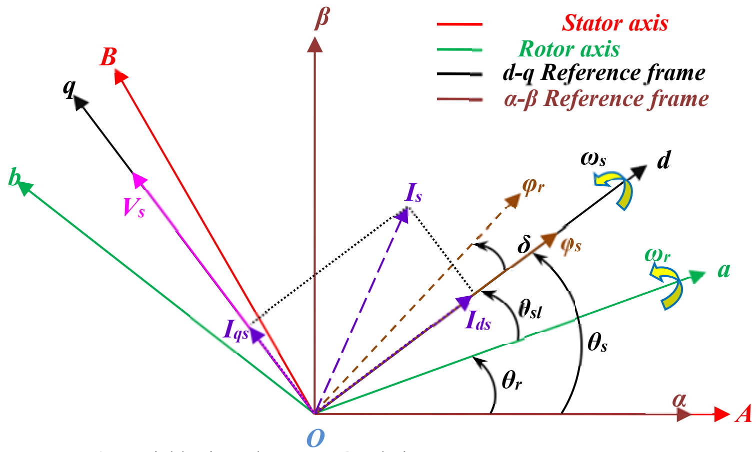

Fig. 5 Field oriented command technique.

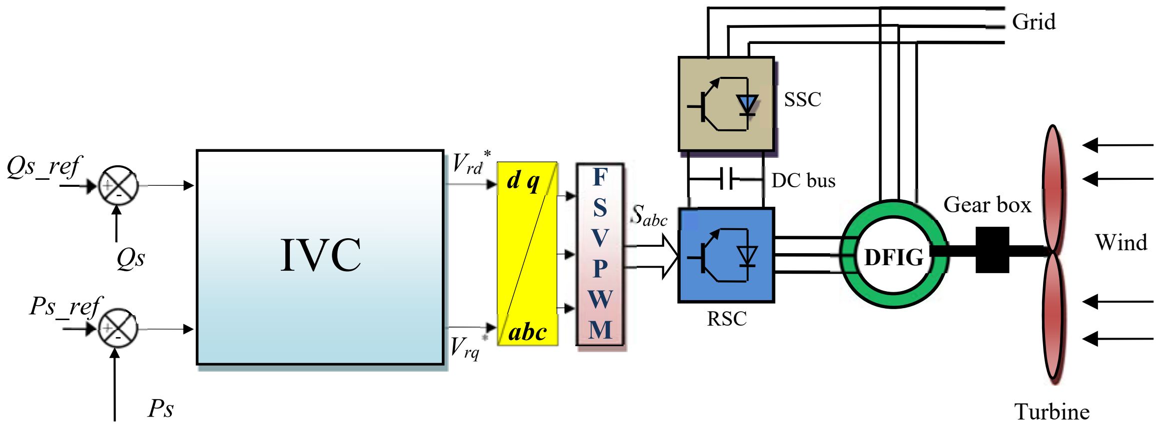

Fig. 6 IVC method block with FSVPWM inverter.

The internal structure of IVC strategy is shown in Fig. 7.

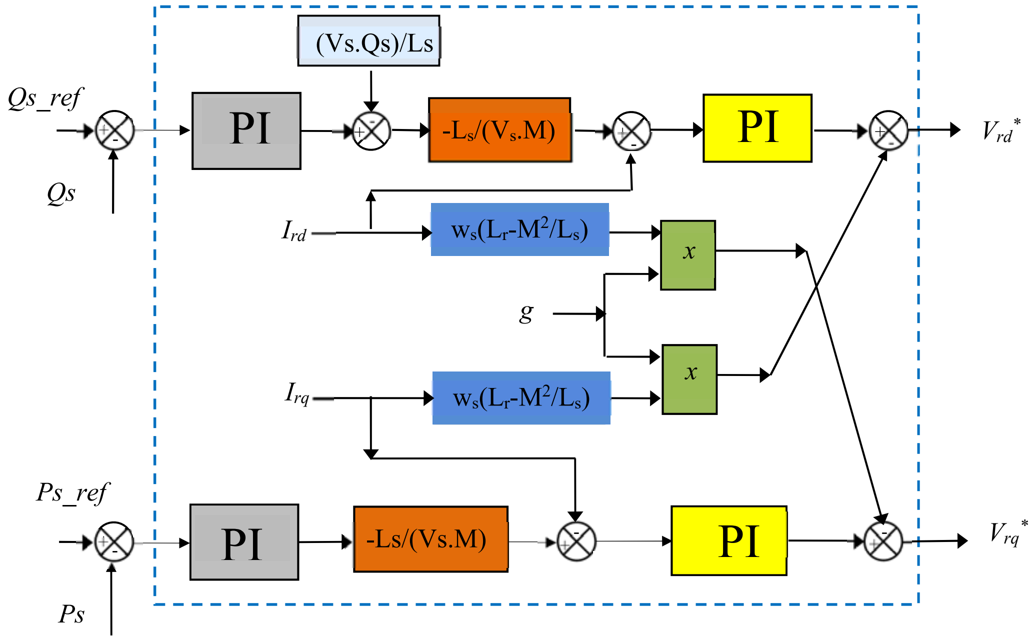

Fig. 7 Structure of IVC strategy.

V. FUZZY SECOND ORDER SLIDING MODE CONTROL

A. Second Order Sliding Mode Control

Variable structure control (VSC) is an effective and high-frequency switching command for nonlinear systems with uncertainties [52]. However, the SMC technique is a particular of systems with VSC. The SMC method has been widely used for nonlinear systems and robust command [53, 54]. The principle of SMC method is detailed in [55-57]. In this section, we propose second order sliding mode control to command the stator reactive power, the active power, and the rotor currents of a DFIG machine. However, the surfaces are chosen between the reference stator energies and measured energies. So we can write the following expression :

$$\begin{bmatrix} S_p \\ S_q \end{bmatrix} = \begin{bmatrix} P_{s\,ref} - P_s \\ Q_{s\,ref} - Q_s \end{bmatrix} \quad (10)$$

With: Sp, Sq is the errors of the active power and reactive power respectively.

We derived the above errors, we obtain

$$\begin{bmatrix} \dot{S}_p \\ \dot{S}_q \end{bmatrix} = \begin{bmatrix} \dot{P}_{s\,ref} - P_s \\ \dot{Q}_{s\,ref} - Q_s \end{bmatrix} \quad (11)$$

Then we will have

$$\begin{bmatrix} \dot{S}_p \\ \dot{S}_q \end{bmatrix} = \begin{bmatrix} \dot{P}_{s\,ref} - \dfrac{\alpha}{\sigma L_r}\left[V_{qr} - R_r.I_{qr} - g.w_s.\sigma.L_r.I_{dr} - g\dfrac{M.V_s}{L_s}\right] \\ \dot{Q}_{s\,ref} - \dfrac{\alpha}{\sigma L_r}\left[V_{dr} - R_r.I_{dr} + g.w_s.\sigma.L_r.I_{qr}\right] \end{bmatrix} \quad (12)$$

Where : α=-Vs.M/Ls

If we define the $A1$ and $A2$ functions as follows.

$$\begin{bmatrix} A_1 \\ A_2 \end{bmatrix} = \begin{bmatrix} \dot{P}_{s\,ref} - \dfrac{\alpha}{\sigma L_r}\left[-R_r.I_{qr} - g.w_s.\sigma L_r.I_{dr} - g\dfrac{M.V_s}{L_s}\right] \\ \dot{Q}_{s\,ref} - \dfrac{\alpha}{\sigma L_r}\left[-R_r.I_{dr} - g.w_s.\sigma.L_r.I_{qr}\right] \end{bmatrix} \quad (13)$$

Thus we have

$$\begin{bmatrix} \dot{S}_p \\ \dot{S}_q \end{bmatrix} = \begin{bmatrix} \dfrac{\alpha}{\sigma.L_r} V_{qr} + A_1 \\ \dfrac{\alpha}{\sigma.L_r} V_{dr} + A_2 \end{bmatrix} \quad (14)$$

On driving the relationship of equation (14) yields :

$$\begin{bmatrix} \ddot{S}_p \\ \ddot{S}_q \end{bmatrix} = \begin{bmatrix} \dfrac{\alpha}{\sigma.L_r} \dot{V}_{qr} + \dot{A}_1 \\ \dfrac{\alpha}{\sigma.L_r} \dot{V}_{dr} + \dot{A}_2 \end{bmatrix} \quad (15)$$

The SOSMC proposed based on the super twisting algorithm known (ST) which is introduced by levant.

$$V_{dr} = u_1 + u_2 \quad (16)$$

Then it follows that :

$$\begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = \begin{bmatrix} -\lambda_1 sign(S_q) \\ -\delta_1 \left|S_q\right|^{0.5} sign(S_q) \end{bmatrix} \quad (17)$$

And :

$$V_{qr} = w_1 + w_2 \quad (18)$$

Including :

$$\begin{bmatrix} w_1 \\ w_2 \end{bmatrix} = \begin{bmatrix} -\lambda_2 sign(S_p) \\ -\delta_2 \left|S_p\right|^{0.5} sign(S_p) \end{bmatrix} \quad (19)$$

To ensure the convergence of regulators in the infinity of time constants and are chosen to satisfy the following inequality :

$$\begin{cases} \lambda_i \le \dfrac{\mu_i}{\sigma.L_r} \\ \delta_i \ge \dfrac{4\mu_i(\lambda_i + \mu_i)}{(\lambda_i - \mu_i)(L_r\sigma)^2} \\ \left|\dot{A}_i\right| \prec \mu_i; i=1,2 \end{cases} \quad (20)$$

B. Fuzzy Second Order Sliding Mode Control

FSOSMC is a hybrid development of second order sliding mode control and fuzzy command, where the sign function has been replaced by an inference fuzzy rules. However, the membership function in a triangular shape is shown in Fig. 3. And the rule base of the FSOSMC is shown in the Table. 1. On the other hand, the parameters of FL controllers are shown in the Table. 2. Fig. 8 represents the FSOSMC command scheme of doubly fed induction generator driven by a FSVM technique. On the other hand, the internal structure of FSOSMC strategy is shown in Fig. 9.

VI. SIMULATION RESULTS

In this part, simulation tests are realised with a 1.5 MW doubly fed induction generator connected to a 398V/50Hz grid. The doubly fed induction generator parameters are given in the Table. 3. Simulation of the doubly fed induction generator controlled by FSOSMC technique has been realised using Matlab/Simulink. The both command strategies FSOSMC-SVPWM and FSOSMC-FSVPWM are simulated and compared in terms of reference tracking, stator current harmonics distortion, powers ripples and robustness against DFIG parameter variations.

The DFIG used in this case study is a 1.5MW, 380/696V, two poles, 50Hz; with the following parameters: Rs = 0.012Ω, Rr = 0.021Ω, Ls = 0.0137H, Lr = 0.0136H and Lm = 0.0135H, J = 1000 kg.m2, fr = 0.0024 Nm/s.

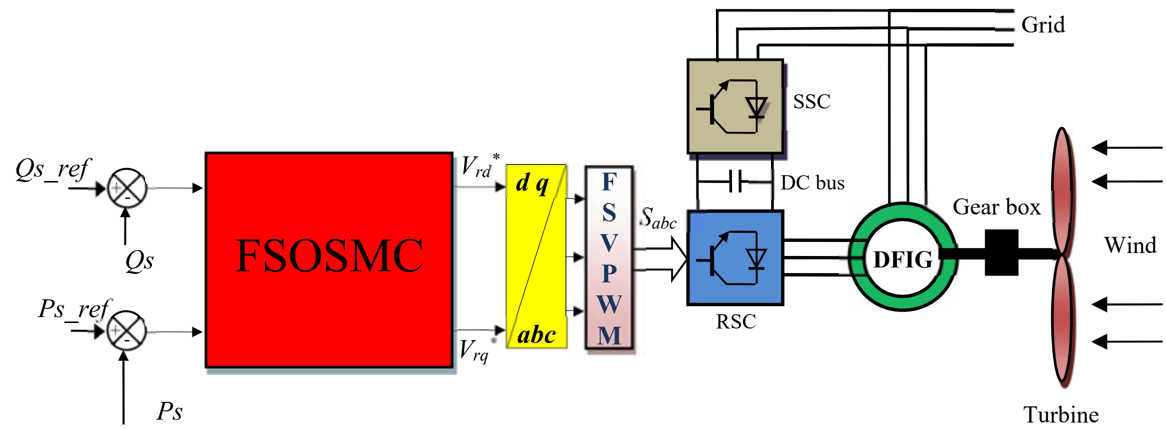

Fig. 8 FSOSMC block with FSVPWM inverter.

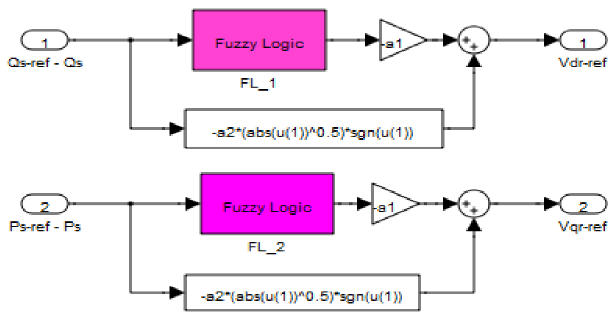

Fig.9 Structure of FSOSMC scheme.

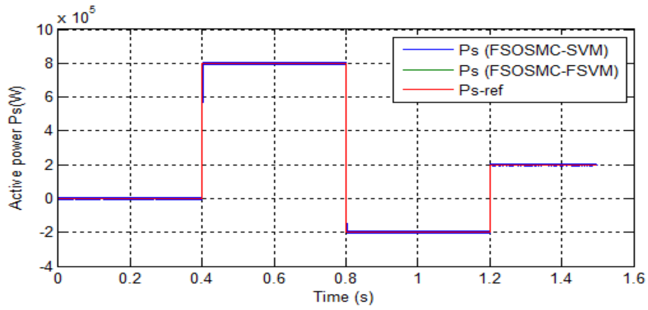

Fig. 10 Active power (RTT).

A. *Reference tracking test (RTT)*

Figs 10-14 shows the obtained simulation results for tracking test of doubly fed induction generator. As it's shown by Figs. 10-11, for the two proposed commands, the stator reactive and active powers tracks almost perfectly their references values, but with better transient response time in the case of the FSOSMC-FSVPWM strategy.

On the other hand, Figs. 13-14 shows the harmonic spectrums of stator current of the doubly fed induction generator obtained using FFT (Fast Fourier Transform) method for both proposed command schemes. It can be clear observed that the total harmonic distortion is reduced for FSOSMC-FSVPWM command. Table 4 shows the comparative analysis of the THD value of stator current for proposed command schemes.

Table 4 Comparative analysis of THD value

	THD (%)	
	FSOSMC-SVM	**FSOSMC-FSVM**
Stator current	0.42	**0.06**

Figs. 15-17 shows the zoom in the active, reactive powers and stator current of the FSOSMC-FSVPWM and FSOSMC-SVPWM command scheme. This figure shows that the ripple of reactive, active powers, and stator current in the FSOSMC-FSVPWM command has been zero.

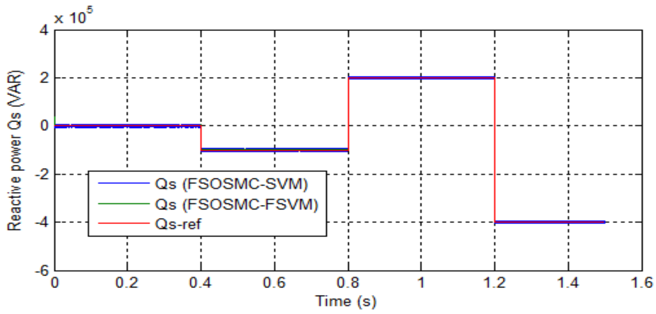

Fig. 11 Reactive power (RTT).

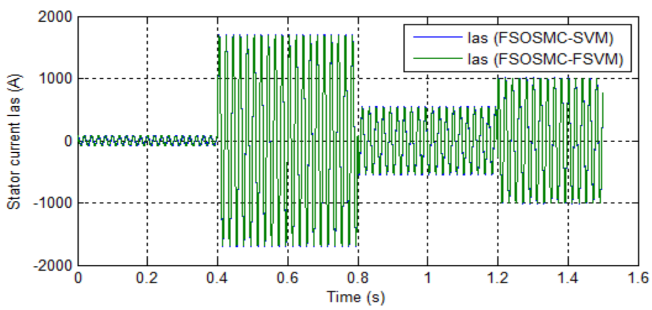

Fig. 12 Stator current (RTT).

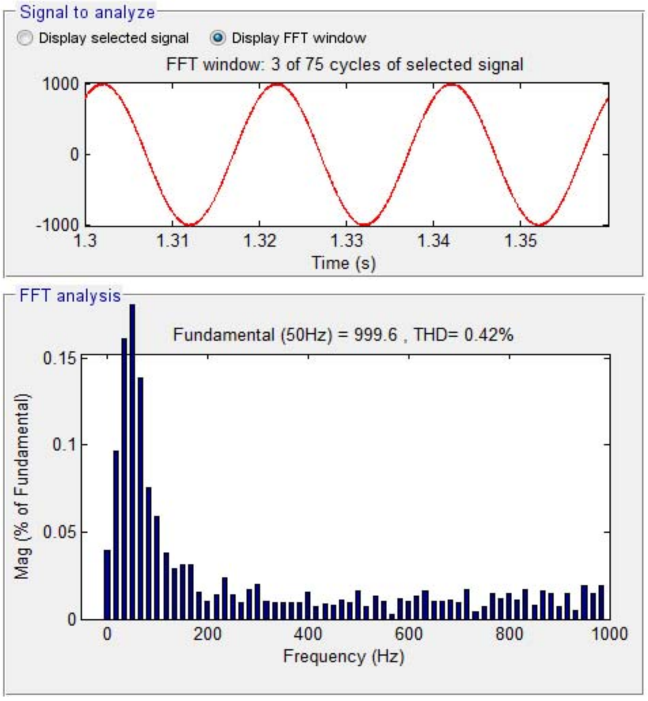

Fig. 13 Spectrum harmonic of stator current (FSOSMC-SVPWM).

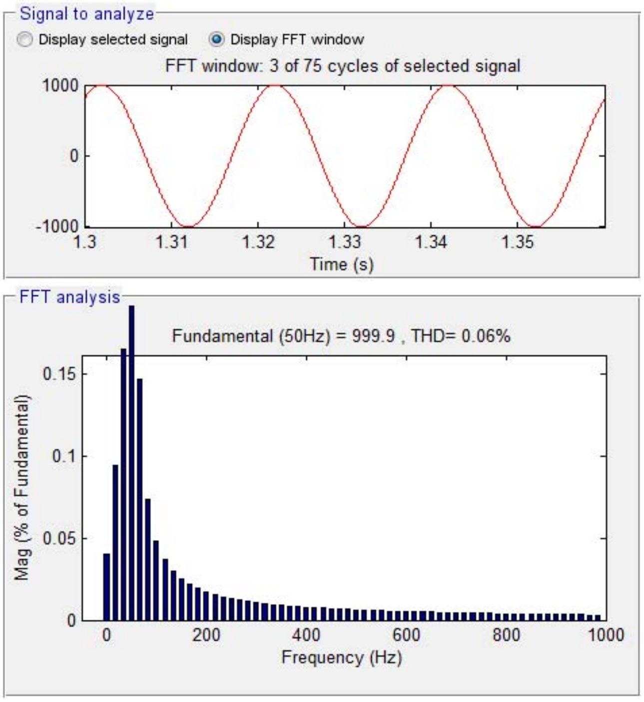

Fig. 14 Spectrum harmonic of stator current (FSOSMC-FSVPWM).

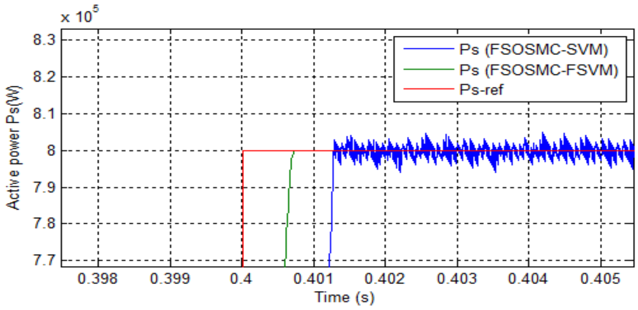

Fig. 15 Zoom in the active stator power (RTT).

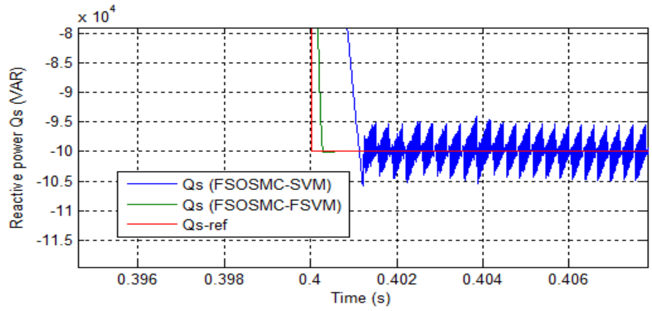

Fig. 16 Zoom in the reactive stator power (RTT).

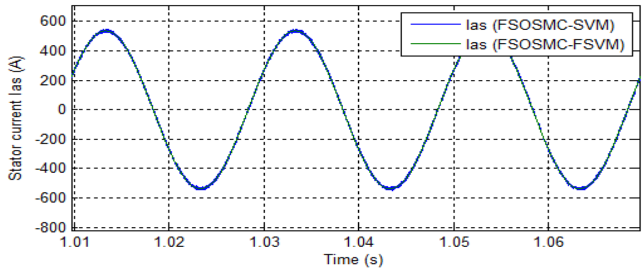

Fig. 17 Zoom in the stator current (RTT).

B. *Robustness test (RT)*

In this section, the nominal value of the R_r and R_s is multiplied by 2, the values of inductances L_s, M, and L_r are multiplied by 0.5. Simulation results are presented in Figs 18-22. As its shown by these Figures, these variations present a clear effect on the active, reactive powers, and stator current curves and that the effect appears more important for the FSOSMC-SVPWM command (See Figs. 23-25). On the other hand, this results show that the THD value of stator current in the FSOSMC-FSVPWM command scheme has been reduced significantly (See Figs. 21-22). Table 5 shows the comparative analysis of THD value. Thus it can be concluded that the proposed FSOSMC-FSVPWM command is more robust than the FSOSMC-SVPWM one.

Table 5 Comparative analysis of THD value

	THD (%)	
	FSOSMC-SVM	**FSOSMC-FSVM**
Stator current	0.83	**0.07**

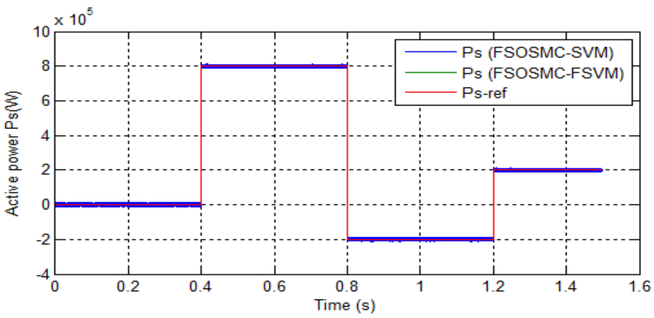

Fig. 18 Active power (RT).

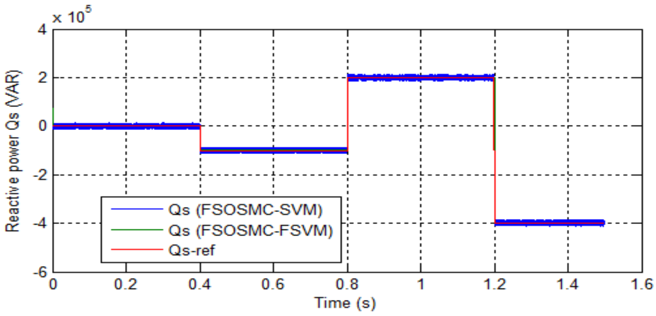

Fig. 19 Reactive power (RT).

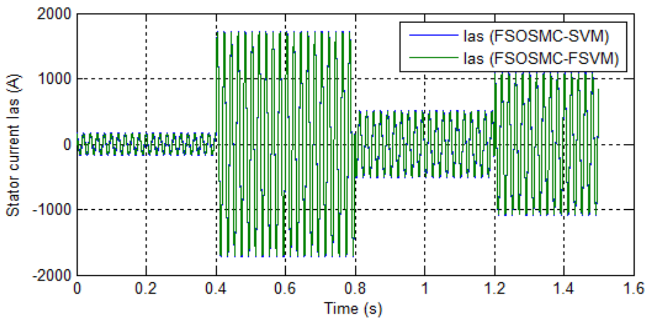

Fig. 20 Stator current power (RT).

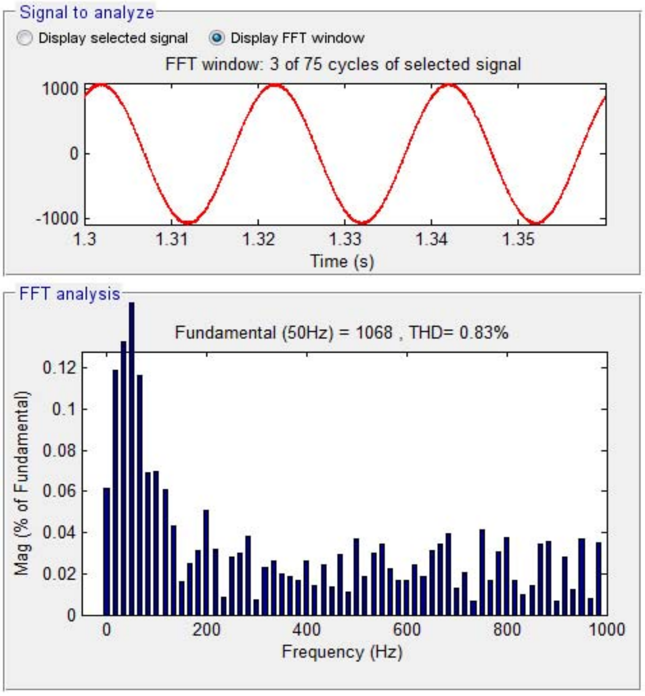

Fig. 21 Spectrum harmonic of stator current (FSOSMC-SVPWM).

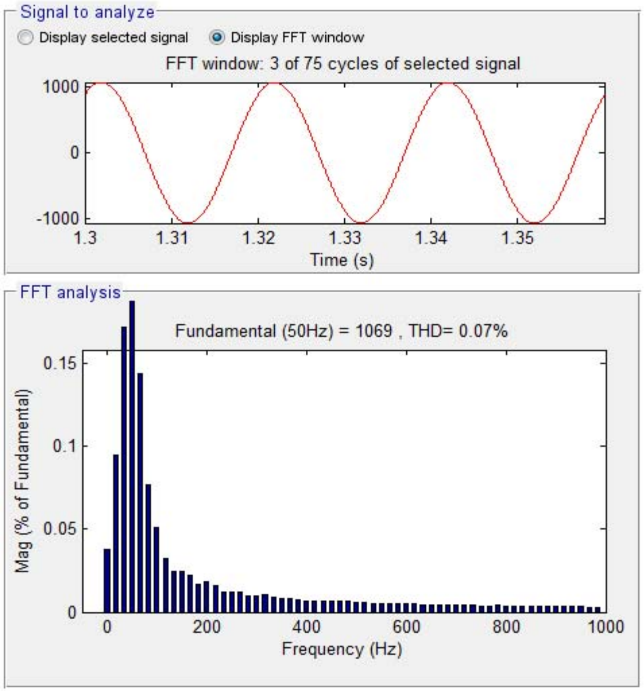

Fig. 22 Spectrum harmonic of stator current (FSOSMC-FSVPWM).

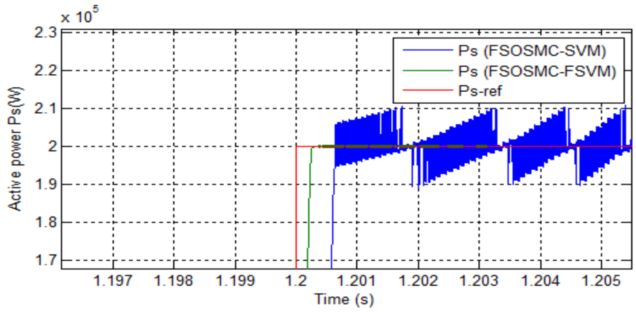

Fig. 23 Zoom in the active power (RT).

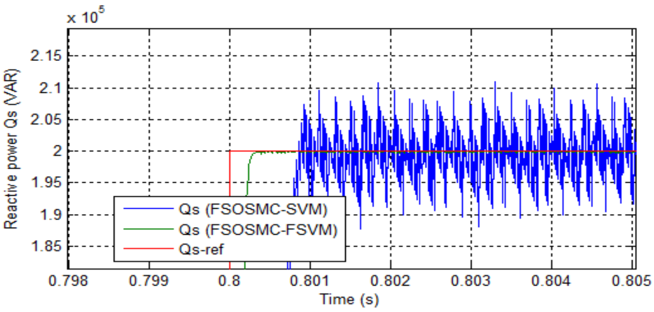

Fig. 24 Zoom in the reactive power (RT).

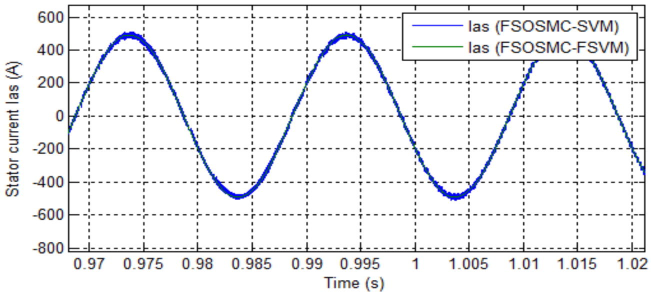

Fig. 25 Zoom in the stator current (RT).

VII. Conclusion

In this article, two command schemes of a doubly fed induction generator connected to the electric network through the stator part and fed by a back to back inverter by the rotor part have been proposed and simulated using Matlab/Simulink. An FSOSMC with fuzzy space vector pulse width modulation inverter is synthesized and compared to FSOSMC using traditional space vector pulse width modulation technique. In terms of tracking performances reactive and active powers references, and THD of stator current. Furthermore, the obtained results have approved that the FSOSMC using fuzzy space vector pulse width modulation inverter minimize the THD value of stator current, and powers ripple more and more than the FSOSMC using traditional SVPWM strategy.

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