Comparative Study Between Direct Vector Control and Fuzzy Sliding Mode Controller in Three-Level Space Vector Modulation Inverter of Reactive and Active Power Command of DFIG-Based Wind Turbine Systems

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Abstract- This article deals with the dynamic simulation of a directly driven wind turbine (WT) with a full-scale converter as the interface to the grid. Using the doubly fed induction Generator (DFIG), the system is controlled by two command strategies. I the first step, we have considered the direct vector control (DVC) strategy with three-level space vector modulation (SVM) and in the second one, we have applied the fuzzy sliding mode control (FSMC) strategy with three-level SVM inverter. Simulation results investigated good performances of both proposed non-linear approaches.

Keywords Doubly fed induction generator, wind turbine, direct vector control, fuzzy sliding mode control, and three-level space vector modulation.

1. Introduction

Traditionally, wind turbine systems (WTSs) based on the doubly fed induction generator (DFIG) dominated the wind energy generations due to the outstanding advantages, including small converters rating around 30% of the generator rating, lower converter cost. However, the DFIG-based WTS are mainly installed in remote and rural areas [1]. Various command schemes have been proposed for studying the behaviour of DFIG based WTSs during normal operation. Most existing structures widely used a traditional vector command (VC) based on stator flux orientation or a stator voltage orientation. In [2] VC commands is the most popular technique used in the doubly fed induction generator-based WTSs. On the other hand, the VC command is a simple command scheme and easy implement. The VC command needs accurate values of DFIG parameters and rotor speed. This command gives more total harmonic distortion (THD) of rotor current, powers ripples, stator flux and electromagnetic torque.

The conventional command strategy of doubly fed induction generator-based WTS is the indirect vector control (IVC) and direct vector control (DVC), where the reactive and active powers of doubly fed induction generator are controlled using current controller blocks [3]. In this article, we propose to command stator active and reactive powers of a DFIG by using a DVC command. This command is a simple command scheme and easy to implement. However, this command gives more rotor current ripple, stator flux ripple and electromagnetic torque ripple.

For robust and high-performance DVC, a sliding mode controller (SMC) was proposed to command stator active power and stator reactive power of a doubly fed induction generator [4, 5]. This strategy was proposed by Utkin in 1974 [6]. This technique is one of the nonlinear strategies. It is a particular operation mode of variable structure command systems [7]. Since the robustness is the best advantage of the SMC technique. However, the SMC strategy has a major inconvenience which the chattering effect is created by the discontinuous part of the command. In order to resolve this problem, various adjustments to the usual command law have been discussed. The approach based on the boundary layer is applied in almost all cases. Another efficiency solution consists to substitute the discontinuous command signal by fuzzy logic (FL) one has also been used recently in some research works [8-9]. FL controller and SMC technique are combined to command DFIG [10].

Since the space vector modulation (SVM) technique is widely used in command AC machine. This strategy is based on the representation of the voltage vector in a rotating complex frame [11]. However, this strategy is detailed in [12-14]. In addition, this strategy is difficult to implement. To overcome this disadvantages an SVM technique is proposed based on calculating of maximum and minimum of three-phase voltages. The proposed SVM technique is a simple scheme and easy to implement. In this paper, we propose a new SVM technique for three-level inverter based on calculating the min and max of three-phase voltages.

In our paper, two different command schemes will be compared with each other. These schemes are DVC command using three-level SVM strategy and FSMC using three-level SVM inverter. The proposed commands schemes are described clearly and simulation results are reported to demonstrate its effectiveness. The used command schemes are implemented in Matlab software.

2. Three-level space vector modulation

The SVM strategy is a kind of a modulation scheme with a superior performance compared to classical pulse width modulation (PWM) and third harmonic injection PWM (THIPWM) for the inverter-command applications. In the traditional SVM technique, it is always necessary to perform many trigonometric operations and coordinate matrix transformations to determine the sector position of the equivalent voltage space vector [15]. For simple and high-performance SVM, a new SVM technique was studied in the literature [16, 17]. This proposed SVM is a simple scheme, easy to implement and give more THD value of stator current of a DFIG-based WTSs.

In this article, we proposed a new space vector modulation for the three-level inverter. These proposed modulations based on calculating of maximum (max) and minimum (min) of three voltages. The advantages of the proposed SVM strategy is not needed to calculate the sector and angle, easy to implement and gives a strong performance for the real-time feedback command compared with classical SVM strategy. Fig. 1 shows the principle of the SVM technique of three-level inverter.

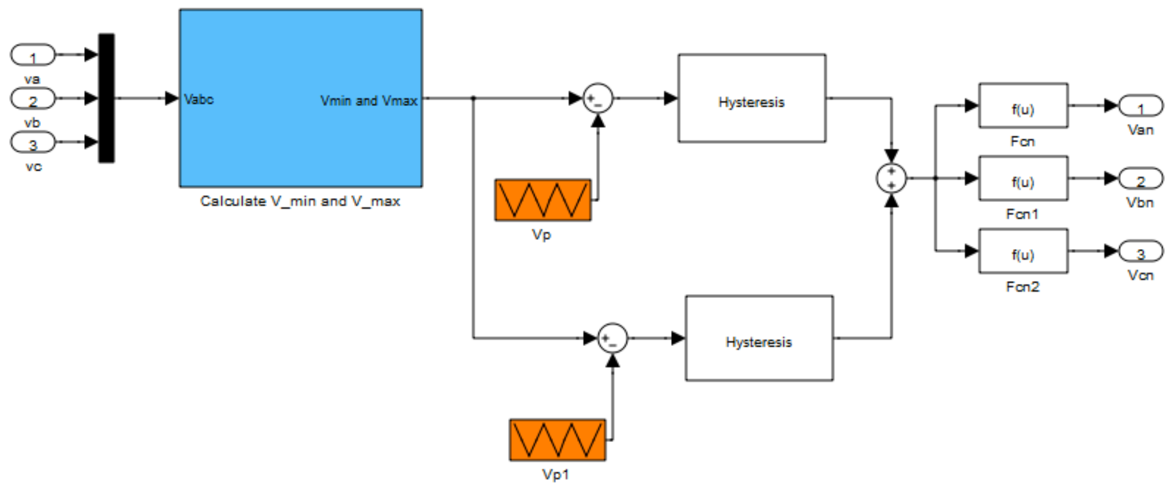

Fig. 1. Three-level SVM strategy.

Fig. 2 represents the block diagram of the hysteresis comparators for five-level inverter.

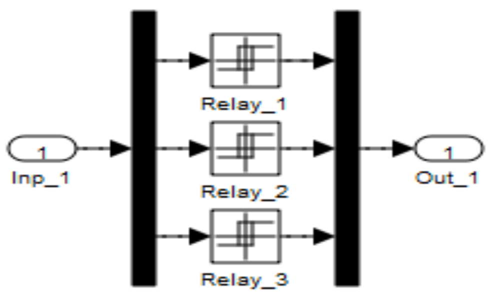

Fig. 2. Block diagram of the hysteresis comparators.

3. The DFIG model

The traditional electrical equations of the doubly fed induction generator in the Park frame are written as follows [18, 19]:

$$\begin{cases} \psi_{ds} = L_s I_{ds} + M I_{dr} \\ \psi_{qs} = L_s I_{qs} + M I_{qr} \\ \psi_{dr} = L_r I_{dr} + M I_{ds} \\ \psi_{qr} = L_r I_{qr} + M I_{qs} \end{cases} \quad (1)$$

$$\begin{cases} V_{ds} = R_s I_{ds} + \frac{d}{dt}\psi_{ds} - \omega_s \psi_{qs} \\ V_{qs} = R_s I_{qs} + \frac{d}{dt}\psi_{qs} + \omega_s \psi_{ds} \\ V_{dr} = R_r I_{dr} + \frac{d}{dt}\psi_{dr} - \omega_r \psi_{qr} \\ V_{qr} = R_r I_{qr} + \frac{d}{dt}\psi_{qr} + \omega_r \psi_{dr} \end{cases} \tag{2}$$

$$\begin{cases} \psi_{ds} = L_s I_{ds} + M I_{dr} \\ \psi_{qs} = L_s I_{qs} + M I_{qr} \\ \psi_{dr} = L_r I_{dr} + M I_{ds} \\ \psi_{qr} = L_r I_{qr} + M I_{qs} \end{cases} \tag{3}$$

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

$$\begin{cases} P_s = \frac{3}{2}(V_{ds} I_{ds} + V_{qs} I_{qs}) \\ Q_s = \frac{3}{2}(V_{qs} I_{ds} - V_{ds} I_{qs}) \end{cases} \tag{4}$$

The torque is expressed as:

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

V_{dr}, V_{qr}, V_{qs} and V_{ds}, are the two-phase rotor and stator voltages, I_{dr}, I_{qr}, I_{ds} and I_{qs}, are the two-phase rotor and stator currents, ψ_{dr}, ψ_{qr}, ψ_{ds} and ψ_{qs}, are the two-phase rotor and stator fluxes, L_r, L_s and M are respectively the inductance own rotor, stator, and the mutual inductance between two coils, R_r and R_s are respectively the resistances of the rotor and stator windings.
T_r is the load torque, T_e is the electromagnetic torque, Ω is the mechanical rotor speed, J is the inertia, f is the viscous friction coefficient and p is the number of pole pairs.
P_s is the active power, Q_s is the stator reactive power.

4. Command techniques of the DFIG

In this part, comparison of doubly fed induction generator performances using different command schemes: direct vector control (DVC) with three-level SVM (3L-SVM) and fuzzy sliding mode controller (FSMC) with 3L-SVM.

4.1 Direct vector control (DVC)

The principle of DVC command is detailed in [20, 21]. This command is a simple scheme and easy to implement. However, the major disadvantage of the DVC command is the ripple powers and harmonic distortion of stator current. To eliminate these drawbacks, a DVC-SVM is proposed in this article. The structure of DVC-SVM of a doubly fed induction generator is shown in Fig. 3. However, the internal structure of DVC is shown in Fig. 4.

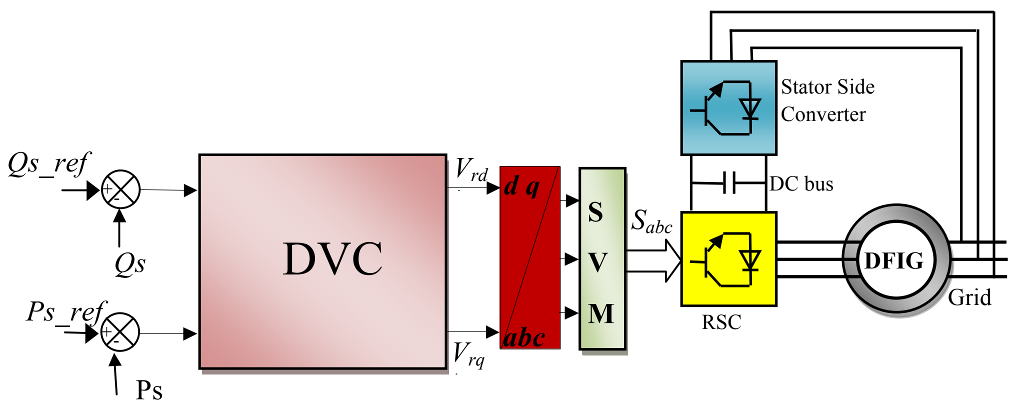

Fig. 3. DVC command with SVM inverter.

4.2 Fuzzy sliding mode controller (FSMC)

In command systems, fuzzy sliding mode control (FSMC) is a modification of an SMC strategy. This strategy minimizes more and more the chattering phenomenon.

On the other hand, this strategy reduces the powers ripples and the THD value of rotor current for DFIG-based WTSs. In this strategy the switching controller term sat (S(x)), has been replaced by a fuzzy command input as given below.

$$V_{dq}^{com} = V_{dq}^{eq} + V_{dq}^{Fuzzy} \quad (4)$$

The proposed FSMC command, which is designed to command the stator reactive and active powers of the doubly fed induction generator, is shown in Fig. 5.

For the two proposed FSMC in Fig. 5, the universes of discourses are first partitioned into the 7 linguistic variables NB, NM, NS, EZ, PS, PM, PB, triangular membership functions are chosen to represent the linguistic variables and fuzzy singletons for the outputs are used. The fuzzy rules that produce these command actions are reported in Table 1.

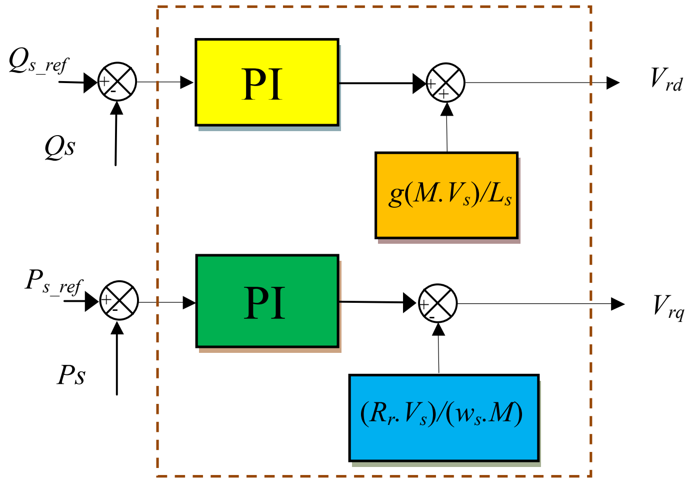

Fig. 4. Structure of DVC command scheme.

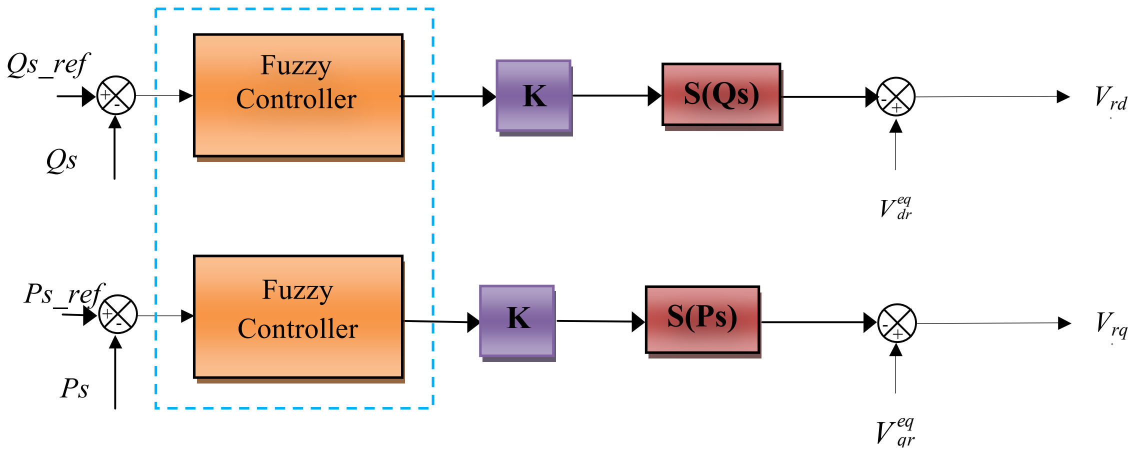

Fig. 5. Bloc diagram of the DFIG command with FSMC.

Table 1. The fuzzy logic rules of hysteresis comparators.

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

Table 2 shows the parameters of fuzzy controllers.

Table 2. Parameters of fuzzy controller

Fis type	Mamdani
And method	Min
Or method	Max
Implication	Min
Aggregation	Max
Defuzzification	Centroid

The membership function definition for the input variables and output membership is given by Fig. 6.

The structure of DVC-SVM of a doubly fed induction generator is shown in Fig. 7.

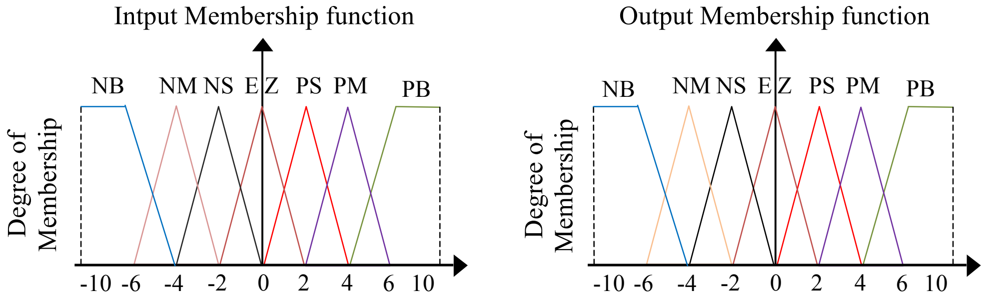

Fig. 6. Fuzzy sets and its memberships functions.

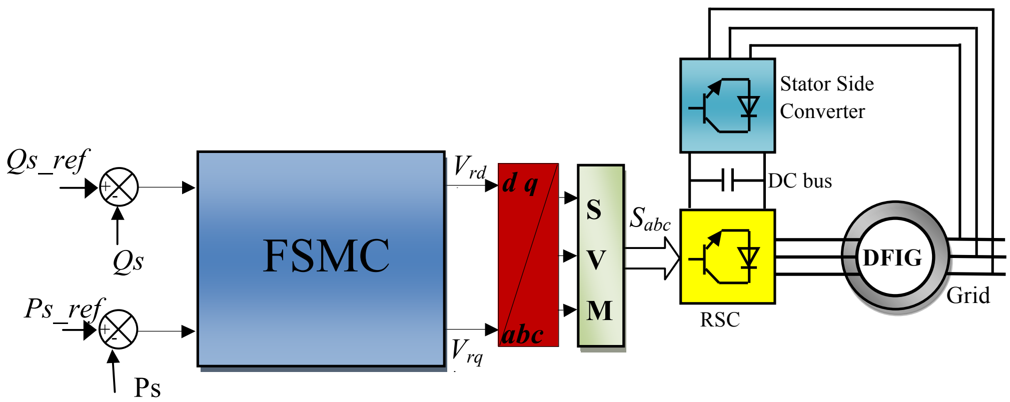

Fig. 7. FSMC command with SVM strategy.

5. Simulation results

In this part, simulations are carried out with a 1.5MW doubly fed induction generator attached to a 398V/50Hz grid, using the Matlab/Simulink. Two command schemes, DVC-3L-SVM and FSMC-3L-SVM, are simulated and compared regarding powers ripples, reference tracking, rotor current harmonics distortion, 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.

The system has the following mechanical parameters: J = 1000 kg.m2, fr = 0.0024 Nm.s/rad.

5.1 Reference tracking test (RTT)

Figs. 14-15 show the harmonic spectrums of one phase rotor current of the 1.5MW DFIG for DVC-3L-SVM and FSMC-3L-SVM one respectively. Table 3 shows the comparative analysis of THD value. It can be clearly observed that the THD is minimized for FSMC-3L-SVM command (THD = 0.37%) when compared to DVC-3L-SVM (THD = 3.04%).

Figs. 8-10 show the obtained simulation results. For the two command schemes, the stator active and stator reactive power tracks almost perfectly their references values. Moreover, the FSMC-3L-SVM command minimized the powers ripples and torque ripple compared to the DVC-3L-SVM command (See Figs. 11-113).

Table 3. Comparative analysis of THD value (RTT)

	THD (%)	
	DVC-3L-SVM	**FSMC-3L-SVM**
Rotor current	3.04	**0.37**

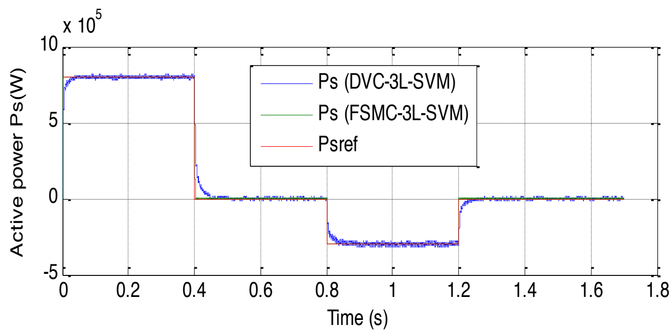

Fig. 8. Active power (RTT).

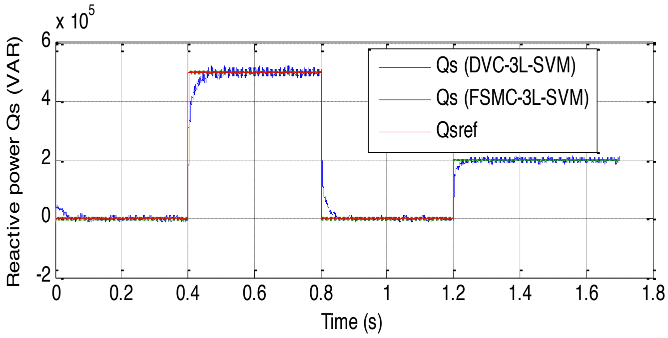

Fig. 9. Reactive power (RTT).

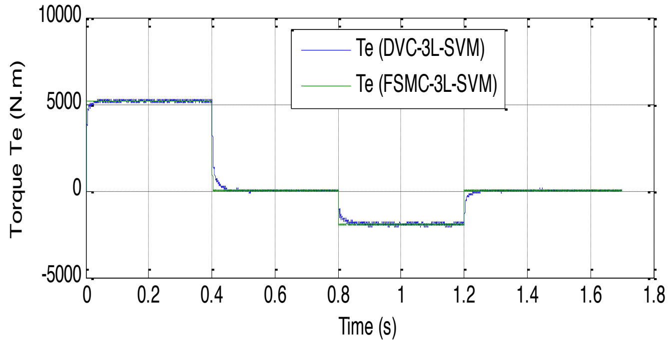

Fig. 10. Torque (RTT).

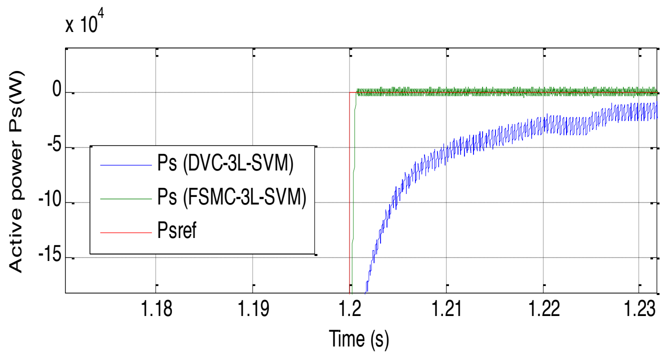

Fig. 11. Zoom in the active power (RTT).

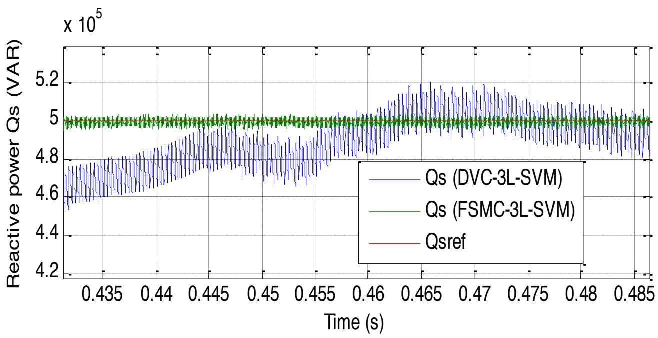

Fig. 12. Zoom in the reactive power (RTT).

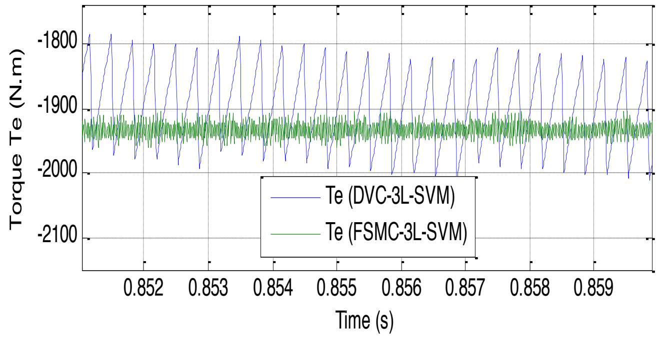

Fig. 13. Zoom in the torque (RTT).

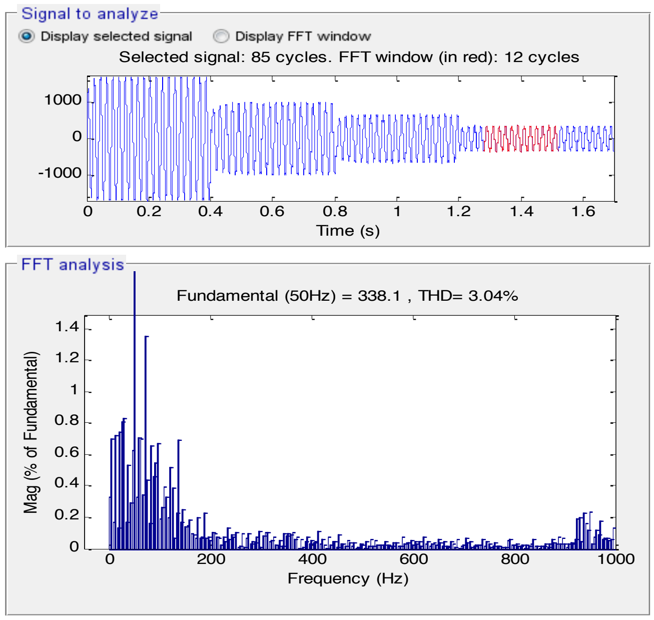

Fig. 14. THD of one phase rotor current for DVC-3L-SVM control (RTT).

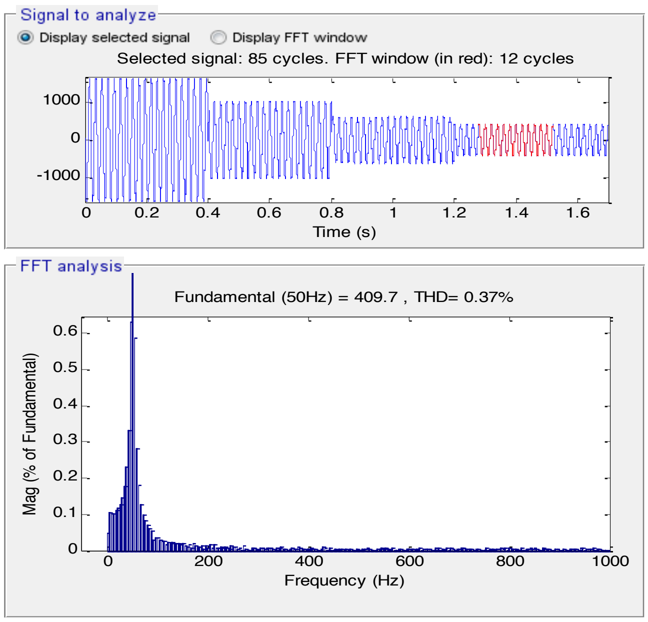

Fig. 15. THD of one phase rotor current for FSMC-3L-SVM control (RTT).

5.2 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. 16-23. As it's shown by these Figures, these variations present a clear effect on the active power, stator reactive power, and electromagnetic torque curves and that the effect appears more important for the DVC-3L-SVM command compared to FSMC-3L-SVM command (See Figs. 19-21). On the other hand, the THD value of rotor current in the FSMC-3L-SVM has been minimized significantly (See Figs 22-23). Thus it can be concluded that the FSMC-3L-SVM command is more robust than the DVC-3L-SVM command.

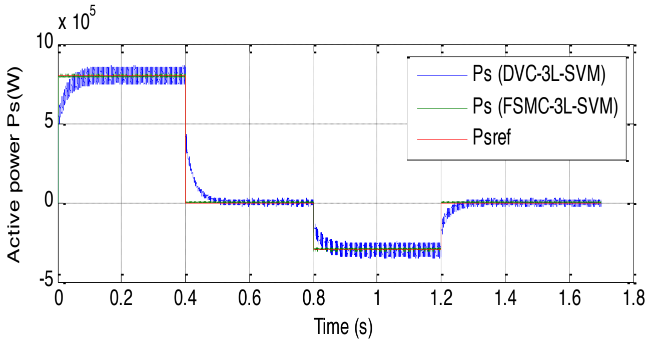

Fig. 16. Active power (RT).

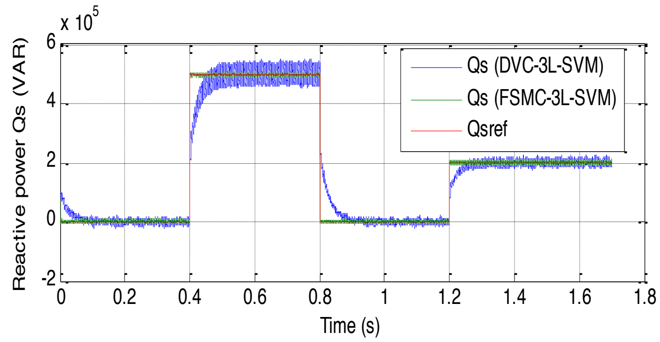

Fig. 17. Reactive power (RT).

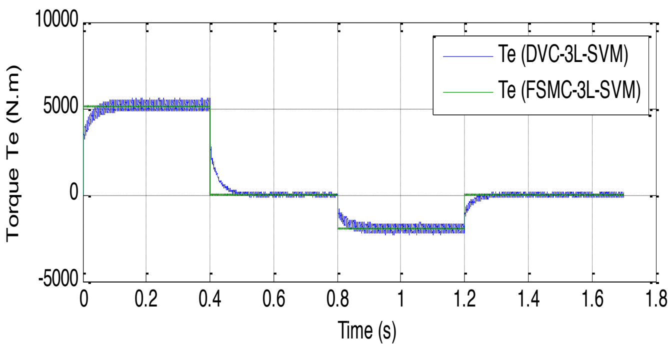

Fig. 18. Torque (RT).

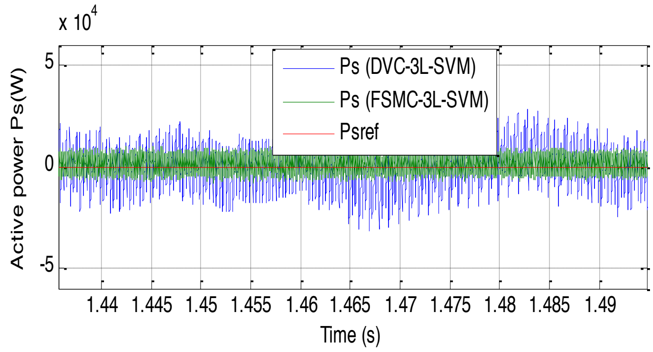

Fig. 19. Zoom in the active power (RT).

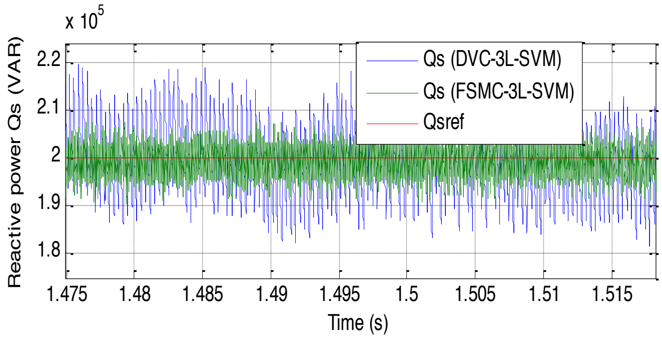

Fig. 20. Zoom in the reactive power (RT).

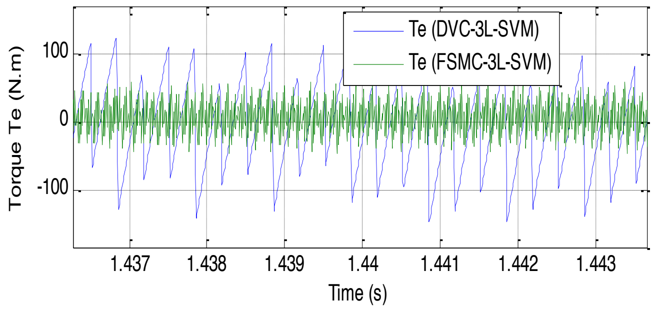

Fig. 21. Zoom in the torque (RT).

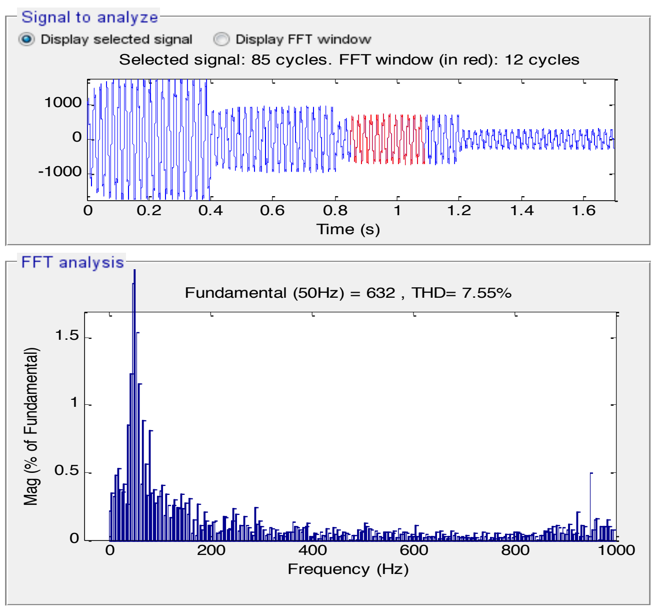

Fig. 22. THD of one phase rotor current for DVC-3L-SVM control (RT).

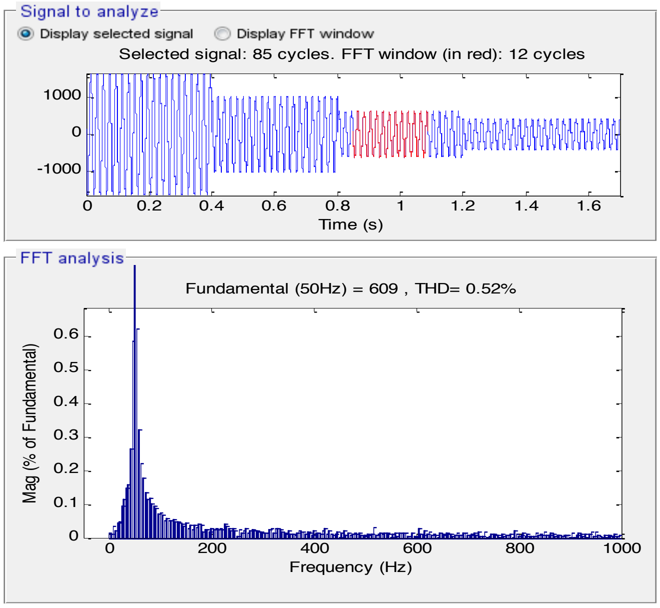

Fig. 23. THD of one phase rotor current for FSMC-3L-SVM control (RT).

6. Conclusion

This work presents simulation results of direct vector control and the fuzzy sliding mode control for reactive and stator active power command of a doubly fed induction generator, using the new modulation technique of space vector modulation inverter. With results obtained from the simulation, it was clear that for the similar operation conditions, the doubly fed induction generator reactive and active power command with FSMC command using three-level SVM strategy had better performance than the DVC command with three-level and that is clear in the harmonic distortion of phase rotor current which the use of the FSMC with three-level SVM, it is minimizes of harmonics more and more than DVC with three-level SVM strategy.

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