Indirect Vector Control of a DFIG Supplied by a Two-Level FSVM Inverter for Wind Turbine System

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ABSTRACT:
Doubly fed induction generator (DFIG) is one of the most popular generators recently used in wind turbine systems (WTSs). This machine has some interesting advantages especially in variables speed applications. In the DFIG-based WTS, the rotor side of the machine is normally fed by a two-level power inverter controlled by the usual pulse width modulation (PWM) technique which has a principal disadvantage; the high level of harmonic distortion. In this paper, a novel technique based on space vector modulation (SVM) and fuzzy logic is proposed to perform the power, provided by the DFIG, to the grid. Simulation results show the efficiency of the proposed technique especially on the quality of the provided power comparatively to the usual PWM.

KEYWORDS: Doubly Fed Induction Generator, Wind Turbine, PWM, SVM, Fuzzy Logic, THD.

1. INTRODUCTION

Currently, the variable speed WTS based on DFIG is frequently used in onshore wind farms [1]. The major advantage of this machine is that the rotor side inverter is only sized for 30% of rated power compared to other generators applied in WTSs. Therefore, the inverter price becomes lesser [2].

The rotor side of the DFIG in WTS applications is habitually controlled by the PWM technique, especially for vector control scheme where the rotor voltage and frequency can be controlled with minimum online computational requirement [3]. In addition, this technique is simple to realize. Nevertheless, this algorithm has some drawbacks. This technique is unable to fully utilize the available DC bus supply voltage to the VSI. This technique gives more total harmonic distortion (THD), this algorithm does not smooth the progress of future development of vector control implementation of AC drive [3].

These disadvantages lead to develop of a new algorithm based on SVM technique and fuzzy logic which can be named briefly FSVM. This algorithm gives 80 % more voltage output compare to the sinusoidal PWM algorithm, thereby increasing the DC bus utilization. Furthermore, it minimizes the THD as well as loss due to minimize number of commutations in the inverter [4].

The paper is arranged as follows: the WTS model is presented in section 2. The model of the DFIG machine is presented in section 3. The vector control of the DFIG is discussed in section 4. Section 5 provides the application of the FSVM technique for the rotor side of the DFIG. The effectiveness of the proposed strategy is verified through simulation results in section 6.

2. WTS MODEL

The maximum power that can be collected by the blades [5, 6]:

$$P_{\max} = 0.5\rho\pi R^2 V_{vent}^3 \quad (1)$$

The mechanical power is given by [7]:

$$P_m = 0.5.C_p(\lambda).\rho\pi R^2 V_{vent}^3 \quad (2)$$

$$\lambda = \frac{R.\Omega_1}{V_1} \quad (3)$$

$$C_p(\beta,\lambda) = C_1.(\frac{C_2}{\lambda_i} - C_3.\beta - C_4).\exp(\frac{-C_5}{\lambda_i}) + C_6.\lambda \quad (4)$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08.\beta} - \frac{0.035}{\beta^3+1} \quad (5)$$

The torque produced by the turbine is expressed in the following way:

$$T_t = \frac{P_t}{\Omega_t} = 0.5\rho.\pi.R^3.v^2.C_t \quad (6)$$

C_t is the torque coefficient expressed by:

$$C_t = \frac{C_p}{\lambda} \quad (7)$$

The mechanical torque is expressed in the following way:

$$T_{mec} = \frac{T_{turbine}}{G} \quad (8)$$

The mechanical angular speed of the generator is given by:

$$\Omega_{mec} = G.\Omega_{turbine} \quad (9)$$

The fundamental equation of dynamics can be written:

$$T_{turbine} = J \cdot \frac{d\Omega_{mec}}{dt} + f \cdot \Omega_{mec} \quad (10)$$

The total torque of the wind turbine is expressed by:

$$T_{turbine} = T_{mec} + T_{em} \quad (11)$$

Where, C_1=0.5176, C_2=116, C_3=0.4, C_4=5, C_5=21, C_6=0.0068.
ρ: is air density.
S: Surface swept by the propeller (m^3).
V_{vent}: Wind speed (m/s).
P_{max}: Maximum power in (watts).
R: Radius of the turbine in (m).
C_p: The aerodynamic coefficient of power.
λ : The tip speed ratio.
β: The blade pitch angle in a pitch-controlled wind turbine.
T_t: The turbine torque (N.m).
Ω_{mec}: The mechanical angular speed of the generator (rad/sec).
C_{mec}: The mechanical torque (N.m).
G: Value of the multiplier.
Tem: Electromagnetic torque generator.
f: Viscous friction coefficient (N.m.s/rad).
J: Inertia (Kgm2).

3. THE DFIG MODEL

The model of the DFIG machine used in this article is presented here using the dq synchronous reference frame. The equations for the rotor and stator windings can be written as [8, 9]:

$$\begin{cases} V_{ds} = R_s I_{ds} + \frac{d}{dt}\psi_{ds} - \omega_s \psi_{qs} \\ V_{qs} = R_s I_{qs} + \frac{d}{dt}\psi_{qs} + \omega_s \psi_{ds} \\ V_{dr} = R_r I_{dr} + \frac{d}{dt}\psi_{dr} - \omega_r \psi_{qr} \\ V_{qr} = R_r I_{qr} + \frac{d}{dt}\psi_{qr} + \omega_r \psi_{dr} \end{cases} \quad (12)$$

The dq synchronous reference frame equations of the rotor flux and stator may be written also as [10]:

$$\begin{cases} \psi_{ds} = L_s I_{ds} + M I_{dr} \\ \psi_{qs} = L_s I_{qs} + M I_{qr} \\ \psi_{dr} = L_r I_{dr} + M I_{ds} \\ \psi_{qr} = L_r I_{qr} + M I_{qs} \end{cases} \quad (13)$$

The torque is expressed as:

$$T_e = pM(I_{dr}.I_{qs} - I_{qr}.I_{ds}) \quad (14)$$

$$T_e = T_r + J \cdot \frac{d\Omega}{dt} + f \cdot \Omega \quad (15)$$

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

$$\begin{cases} P_s = \frac{3}{2}(V_{ds} I_{ds} + V_{qs} I_{qs}) \\ Q_s = \frac{3}{2}(V_{qs} I_{ds} - V_{ds} I_{qs}) \end{cases} \quad (16)$$

4. VECTOR CONTROL OF THE DFIG

In this section, we proposed a vector control low for DFIG machine based on the orientation of the stator flux. We use a Park reference frame linked to the stator flux [11, 12]. By supposing that the d-axis is oriented along the stator flux position and based on equations (12 and 13), By neglecting Rs we can write:

$$\psi_{qs} = 0, \psi_{ds} = \psi_s \quad (17)$$

$$\begin{cases} V_{qs} = 0 \\ V_{ds} = \omega_s \psi_s \end{cases} \quad (18)$$

$$\begin{cases} I_{ds} = -\frac{M}{L_s} I_{dr} + \frac{\psi_s}{L_s} \\ I_{qs} = -\frac{M}{L_s} I_{qr} \end{cases} \quad (19)$$

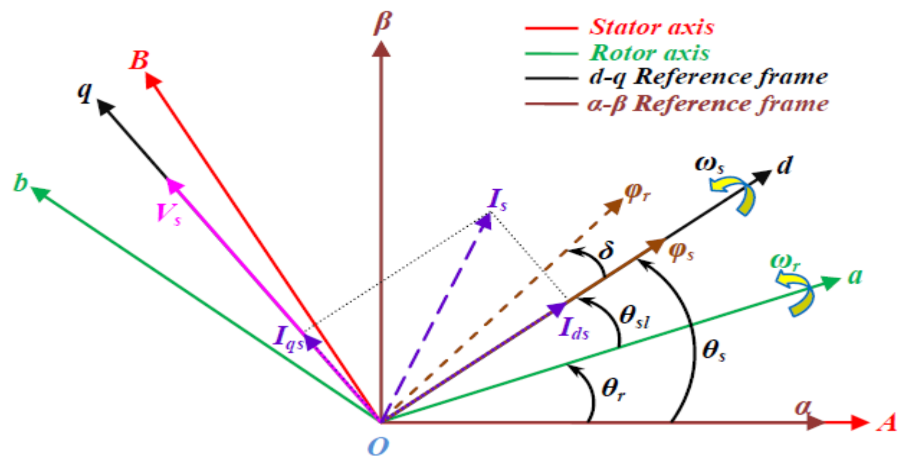
By using equations (17), (18) and (19), equation (16) can be written as follows [13]:

$$\begin{cases} P_s = -\frac{3}{2}\frac{\omega_s \psi_s M}{L_s} I_{qr} \\ Q_s = -\frac{3}{2}\left(\frac{\omega_s \psi_s M}{L_s} I_{dr} - \frac{\omega_s \psi_s{}^2}{L_s}\right) \end{cases} \quad (20)$$

The expression of the electromagnetic torque becomes:

$$T_e = -\frac{3}{2} p \frac{M}{L_s} I_{qr} \psi_{ds} \quad (21)$$

The expression of the rotor flux becomes:



F.ig. 1. Field oriented control method.

$$\begin{cases} \Psi_{dr} = (L_r - \frac{M^2}{L_s}) I_{dr} + \frac{M.V_s}{L_s \cdot w_s} \\ \Psi_{qr} = (L_r - \frac{M^2}{L_s}) I_{qr} \end{cases} \quad (22)$$

From these equations, one can deduce the expressions of rotor voltages:

$$\begin{cases} V_{dr} = R_r . I_{dr} - w_r .(L_r - \frac{M^2}{L_s}). I_{qr} \\ V_{qr} = R_r . I_{qr} + w_r .(L_r - \frac{M^2}{L_s}). I_{dr} + g. \frac{M.V_s}{L_s} \end{cases} \quad (23)$$

5. INDIRECT VECTOR CONTROL BASED ON THE FSVM INVERTER

In this section, the indirect vector control based on the fuzzy space vector modulation (FSVM) to control stator active power and stator reactive power of the DFIG. However, the proposed FSVM technique can decrease the active power ripple, reactive power ripple, and gives more minimum harmonic distortion of stator current. A block diagram control structure of IVC with FSVM is shown as in Fig. 3.

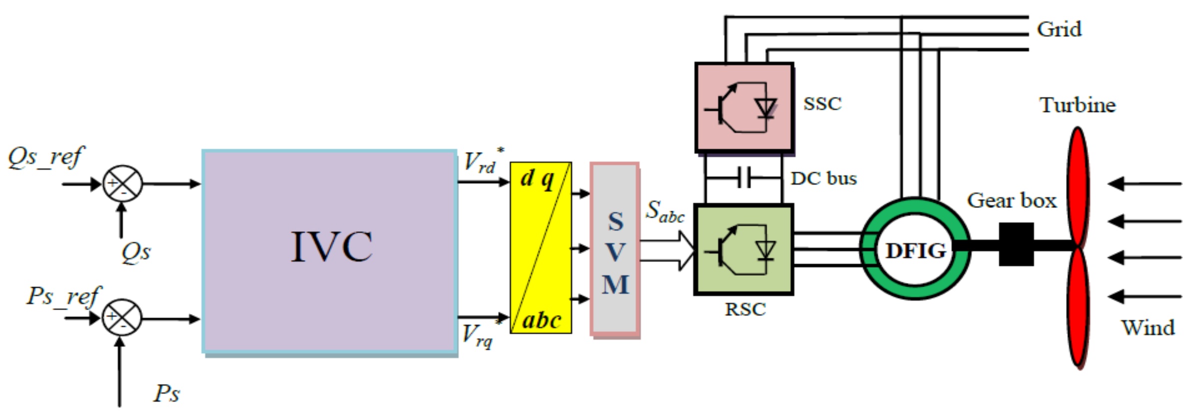


Fig. 2. Indirect vector control method block with SVM inverter.

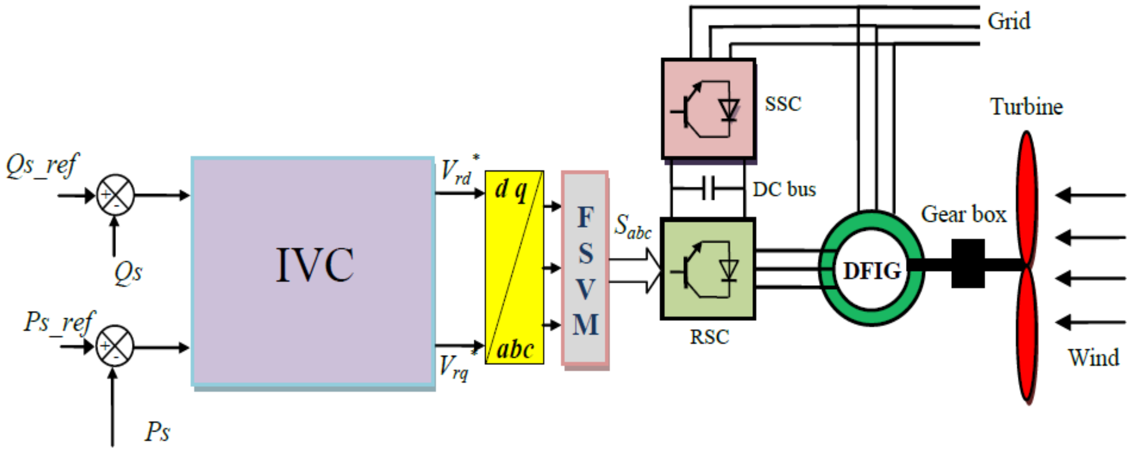


Fig. 3. Indirect vector control method block with FSVM inverter.

Various modulation techniques have been proposed.: Pulse width modulation technique (PWM) [15]. Space vector modulation (SVM) method [16, 17]. Discontinuous pulse width modulation (DPWM) control method [18].

The SVM technique, one of the most popular types of modulation for inverter, is selected in this research; this technique is based on principles of space vectors and the angle and sector parameters need to be calculated [24, 25].

This method has described and justified in previous studies [26-29]. In this paper, we proposed a new SVM technique of two-level inverter based on calculation of maximum and minimum of three-phase voltages (Va, Vb, Vc). On the other hand, in the proposed SVM scheme the sector and angle calculations are not needed; system has simple control scheme and is easy to implement. The proposed SVM technique which is designed to control the two-level inverter is shown in Fig. 4.

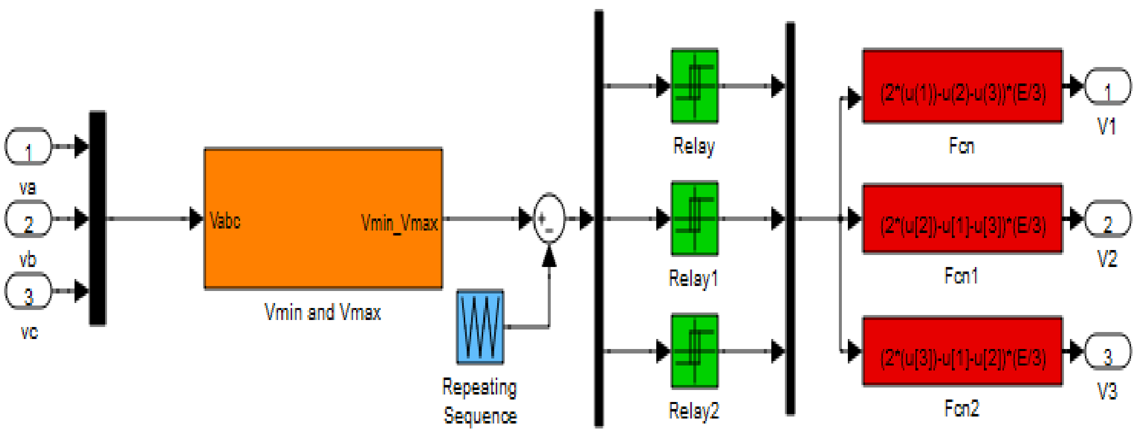


Fig. 4. Simulation block of proposed SVM inverter.

Third harmonic injection PWM is used in [19], and selective harmonic elimination strategy (SHEPWM) is used in [20, 21]. In [22], the SHEPWM technique was designed to control multi-level inverter. Inverted since carrier pulse width modulation (ISCPWM) technique is used in [23].

The fuzzy logic (FL) controller has used in many applications. This technique was introduced by Zadeh [30]. FL strategy, does not need a mathematical model [31].

In this article, we proposed SVM technique based on FL controller (FSVM). This modulation technique has simple control scheme; it is easy to implement and gives minimum harmonic distortion of stator current.

The principle of FSVM technique is similar to conventional SVM method. The difference is using a fuzzy controller to replace the hysteresis loop controllers. As shown in Fig. 5.

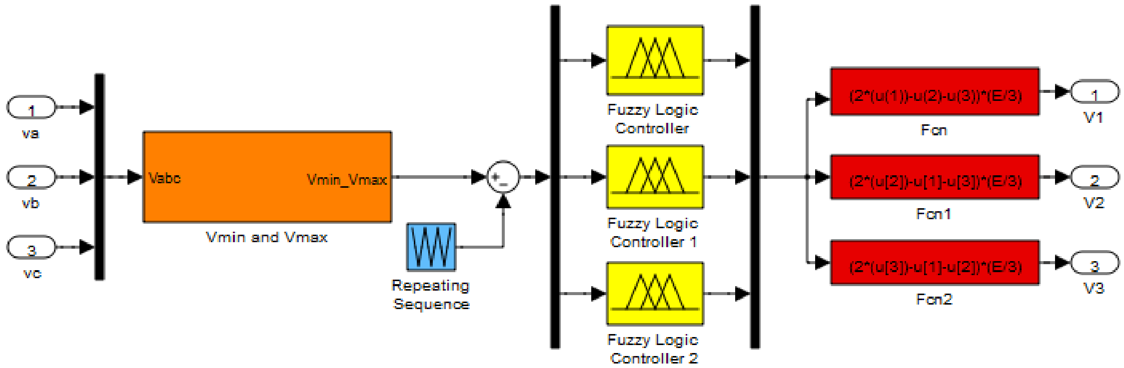


Fig. 5. Simulation block of proposed SVM inverter.

The block diagram of the FL controller, based on hysteresis controllers, is shown in Fig. 6. The membership function definition for the input changes "Error in hysteresis comparators" and "Change in Error of hysteresis comparators" is given by Fig. 7.

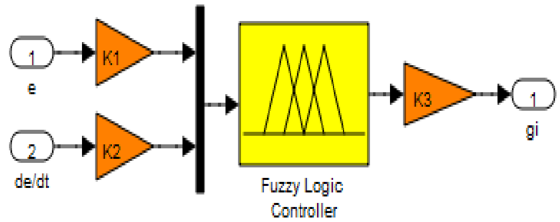


Fig. 6. Fuzzy control of hysteresis comparators.

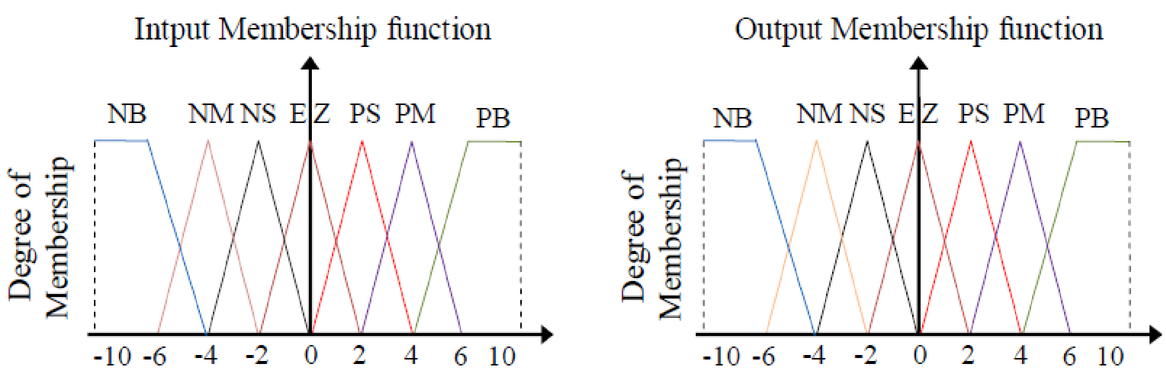


Fig. 7. Fuzzy sets and its memberships functions.

On one hand, the structure of a complete FL control system is composed from the following blocs [32]:

- Fuzzification
- Knowledge base
- Inference engine
- Defuzzification

On the other hand, the FL rules are developed using linguistic changes that are formulated in the form of « IF THEN » rules. These rules are described in table 1 [33, 34]. 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.

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

Table 2 shows the parameters of FL controller.

Table 2. Parameters of fuzzy controller

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

6. SIMULATION RESULTS

Simulation of the proposed control strategies for a DFIG machine are conducted by using the Matlab/Simulink package. The DFIG is connected to a 398V/50Hz grid. On the other hand, the DFIG is rated at 1.5MW, and its parameters are listed in the Table. 3. The both control strategies IVC-SVM and IVC-FSVM are simulated and compared in terms of reference tracking, stator current harmonics distortion, powers ripples and robustness against DFIG parameter variations.

Table 3. The DFIG parameters.

Parameters	Rated Value	Unity
Nominal power	1.5	MW
Stator voltage	398	V
Stator frequency	50	Hz
Number of pairs poles	2	
Stator resistance	0.012	Ω
Rotor resistance	0.021	Ω
Stator inductance	0.0137	H
Rotor inductance	0.0136	H
Mutual inductance	0.0135	H
Inertia	1000	Kg m^2
Viscous friction	0.0024	Nm/s

6.1. Reference Tracking Test

Figures 8 to 12 show the obtained simulation results for tracking test of the DFIG machine. As it's shown by Figs. 8-10, for the two proposed controls, the reactive and active powers track almost perfectly their references values.

On the other hand, Figs. 11-12 show the harmonic spectrums of stator current of the DFIG obtained using Fast Fourier Transform (FFT) method for both proposed control schemes. It can be clear observed that the THD is more and more reduced for IVC-FPSVM control scheme. Table 4 shows the comparative analysis of the THD value of stator current for proposed controls scheme.

Table 4. Comparative analysis of THD value.

	THD (%)	
	IVC-PWM	**IVC-FPWM**
Stator current	0.89	**0.09**

Figs. 13-14 show the zoom in the stator active power, stator reactive power, and torque of the IVC-SVM and IVC-FSVM controls schemes. These figures show that the ripple of stator reactive power, stator active power, and electromagnetic torque in the IVC-FSVM control scheme has been zero compared with the IVC-SVM control.

It is clear from the results that the FSVM inverter has performed satisfactorily.

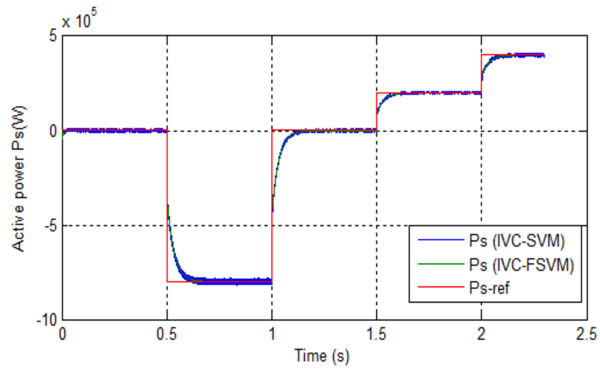


Fig. 8. Stator active power response.

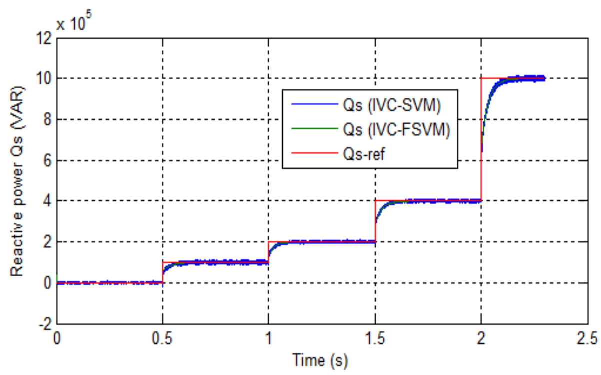


Fig. 9. Stator reactive power response.

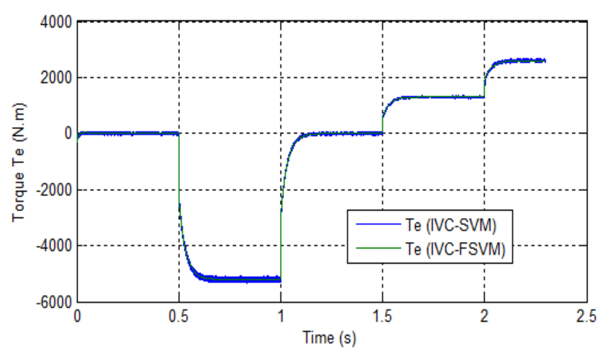


Fig. 10. Electromagnetic torque response.

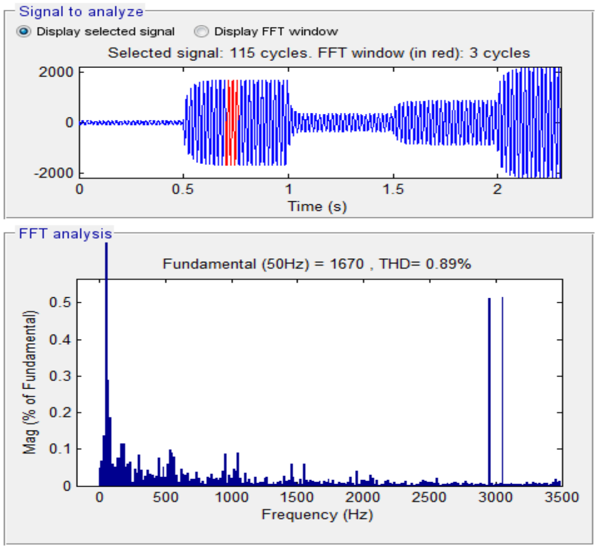


Fig. 11. THD of one phase stator current for a DFIG (IVC-SVM).

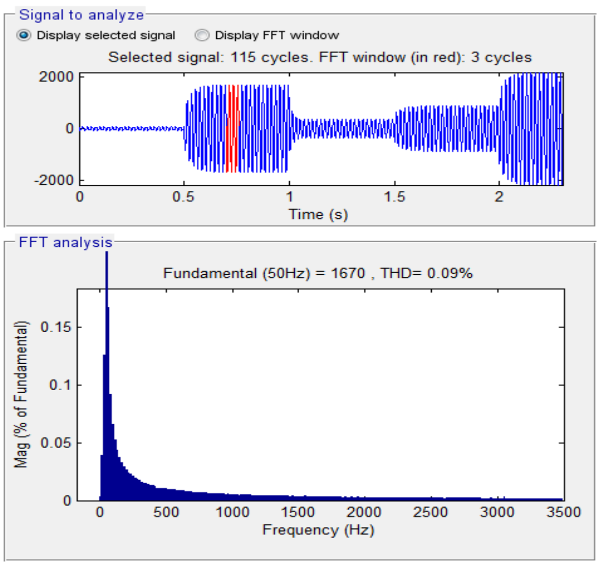


Fig. 12. THD of one phase stator current for a DFIG (IVC-FSVM).

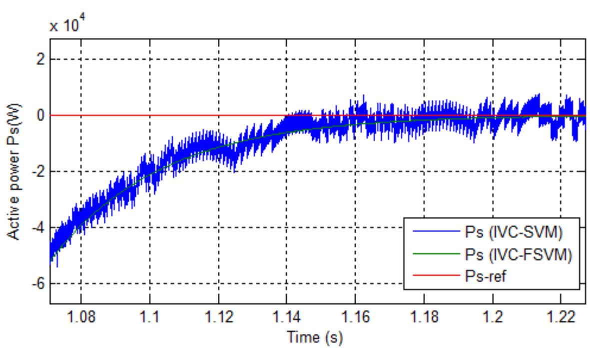


Fig. 13. Zoom in the stator active power (reference tracking test).

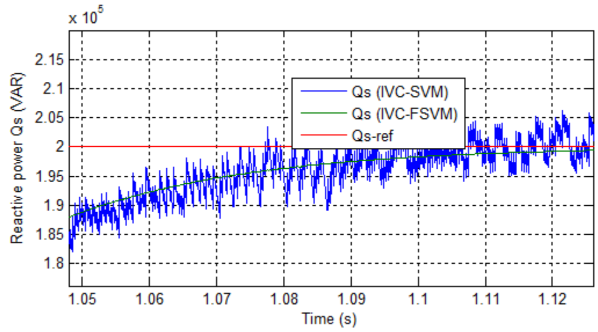


Fig. 14. Zoom in the stator reactive power (reference tracking test).

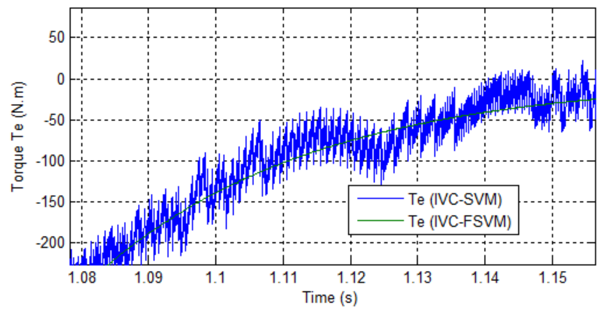


Fig. 15. Zoom in the torque (reference tracking test).

6.2. Robustness Test

In order to investigate the robustness of the proposed controls schemes of the DFIG machine, 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 16-20. As its shown by these Figures, these variations present a clear effect on the stator active power, stator reactive power, and electromagnetic torque curves and that the effect appears more and more important for the IVC-SVM control scheme. On the other hand, this results show that the THD value of stator current in the IVC-FSVM control scheme has been reduced significantly. Table 5 shows the comparative analysis of THD value. Thus it can be concluded that the proposed IVC using FSVM control scheme is more and more robust than the IVC using SVM one.

Table 5. Comparative analysis of THD value (robustness test).

	THD (%)	
	IVC-SVM	**IVC-FSVM**
Stator current	2.64	**0.09**

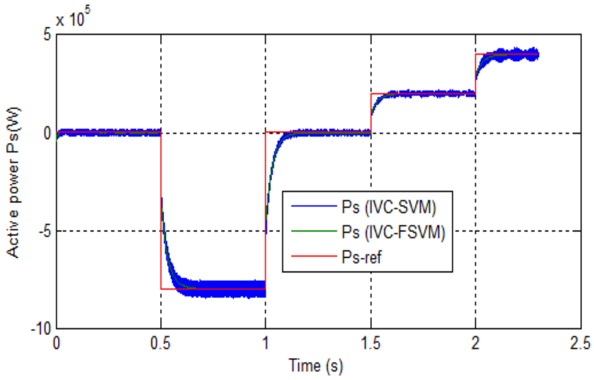


Fig. 16. Stator active power response.

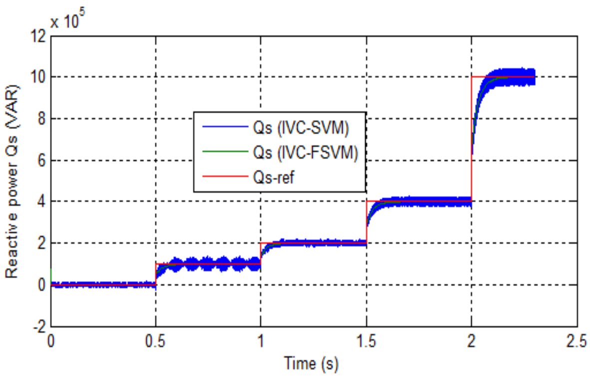


Fig. 17. Stator reactive power response.

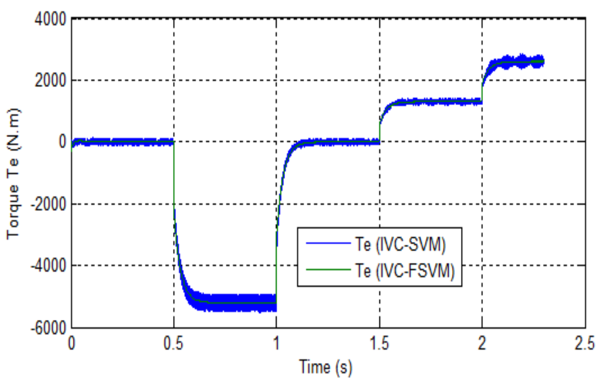


Fig. 18. Electromagnetic torque response.

Figs. 21-23 show the zoom in the active power, active power, and electromagnetic torque of the IVC-SVM and IVC-FSVM controls schemes. These figures show that the IVC with FSVM illustrate a more and more robust compared to the IVC with SVM technique.

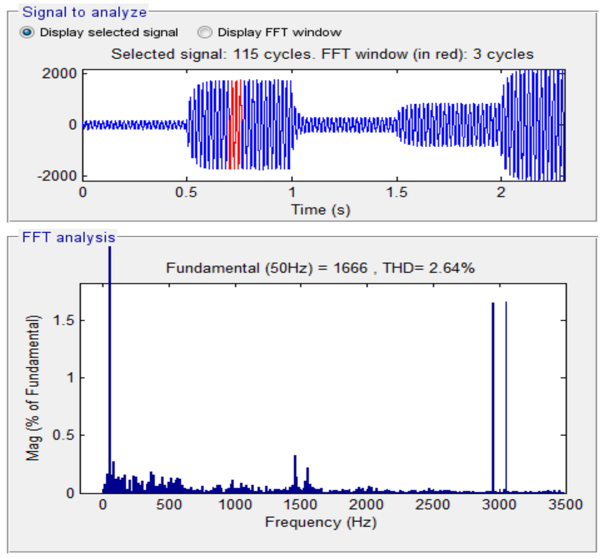


Fig. 19. THD of one phase stator current for a DFIG (IVC-SVM).

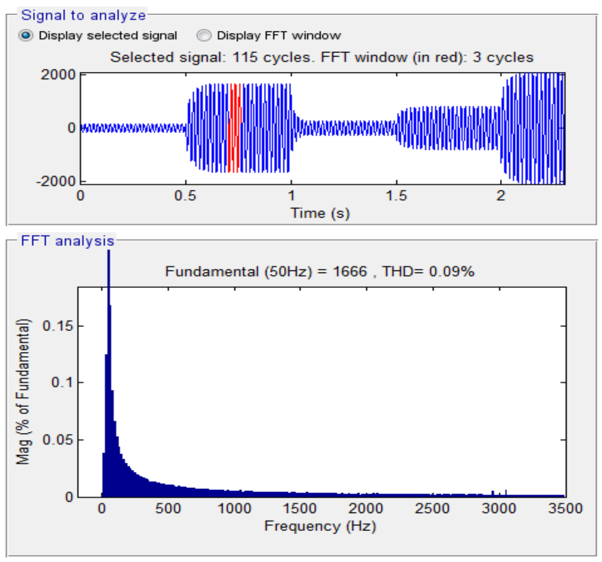


Fig. 20. THD of one phase stator current for a DFIG (IVC-FSVM).

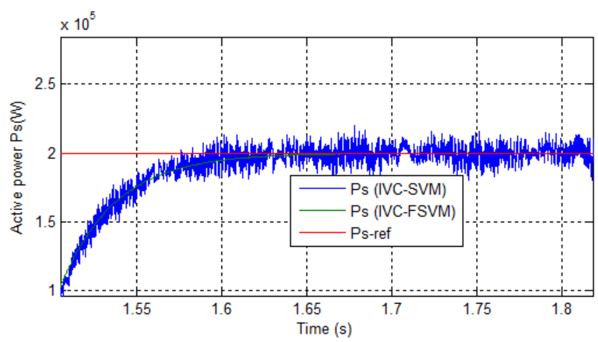


Fig. 21. Zoom in the stator active power (robustness test).

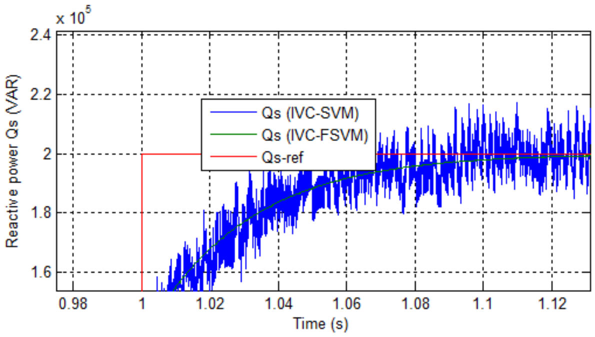


Fig. 22. Zoom in the stator reactive power (robustness test).

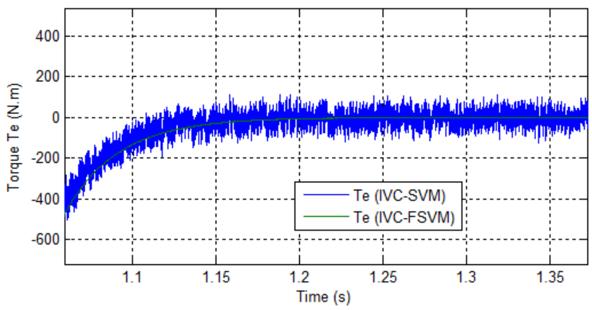


Fig. 23. Zoom in the torque (robustness test).

7. CONCLUSION

In this paper, a novel SVM technique based on the fuzzy logic controller (FSVM) is proposed to control active and reactive powers. On the other hand, the vector control with FSVM inverter for a doubly fed induction generator is presented. The simulation results obtained for the vector control with FSVM technique illustrate a considerable reduction in stator reactive power ripple, stator active power ripple, electromagnetic torque ripple and THD value of stator current compared to the vector control with conventional SVM technique.

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