DFIG-Based WT System Using FPWM Inverter

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Abstract- In this work, we present a comparative study between fuzzy pulse width modulation (FPWM) and classical PWM technique in indirect vector command (IVC) of stator reactive power and stator active energy command of a doubly fed induction generator (DFIG) based wind turbine system (WTS). The obtained results showed that, the IVC using FPWM technique have current with low total harmonic distortion (THD) and more minimum electromagnetic torque ripple, stator reactive and stator active powers ripples then conventional PWM strategy.

Keywords DFIG, pulse width modulation, fuzzy pulse width modulation, indirect vector command, stator reactive power, stator active power.

1. Introduction

Traditionally the PWM strategy is generally used in changeable speed drive of AC machine [1]. This technique is easy to realize and simple modulation scheme. On the other hand, the PWM technique gives more total harmonic distortion (THD). To solve the disadvantages of PWM method of AC machine, various modulation techniques have been proposed. Space vector modulation method (SVM) [2, 3]. Selective harmonic elimination strategy (SHEPWM) [4, 5]. Third harmonic injection PWM [6, 7]. Discontinuous pulse width modulation (DPWM) commands scheme [8]. Inverted sine carrier pulse width modulation (ISCPWM) method [9]. These modulation strategies are used in order to improve the performance of the power electronic circuit, minimize the size, lower cost and increase reliability [9]. In this article, we propose new PWM technique based on the fuzzy logic regulator (FPWM). This proposed modulation is simple modulation scheme, easy to realize and give more and more minimum THD of current compared with the classical PWM strategy.

Since DFIG that are one of the largely accepted types of WTS [10]. The rotor of the DFIG is related to AC-DC-AC converter and the stator is coupled to the power grid. However, various command strategies have been proposed for studying the behaviour of DFIG based WTS during normal operation [11]. In [12], a direct torque command (DTC) was proposed to regulate the rotor flux and torque. In [13], a direct power command method based on hybrid artificial intelligent command with SVM strategy. In [14], a field oriented command for grid-associated DFIG. In [15], a sliding mode command (SMC) was proposed to command stator reactive and stator active energy of a doubly fed induction generator. In [16], backstepping command was designed to command stator reactive and active powers. In [13] vector command is the largely accepted method used to command the stator active and stator reactive powers of a DFIG machine based wind energy conversion system.

In this work, we apply the indirect vector command (IVC) to the WTS of a 1.5MW DFIG with the modulation scheme identified as FPWM method and compared with the classical PWM scheme.

2. FPWM Inverter

The PWM inverter has been accepted in the area of power electronics and drive systems. The main objective of the PWM technique is to command the inverter output voltage and to reduce the harmonic in the output voltage. Fig. 1 shows the principle of the PWM technique of the two-level inverter.

Since fuzzy logic (FL) is known as the universal approximators and have several applications in command design and identification [17]. Zadeh first introduced the fuzzy set theory in 1965 [18]. However, 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 [19]. To obtain high-performance DFIG machine a robust and simple indirect vector command based on the fuzzy pulse width modulation (FPWM) technique is designed to command and regulate the stator reactive power and stator active power. On the other hand, indirect vector command with FPWM inverter (IVC-FPWM) have many advantages, reducing the powers ripples, gives more and more minimum THD value of stator current, simple rule base, simple command and robustness against disturbances.

For the proposed FSVM 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 regulator based hysteresis comparator is shown in Fig. 3. The membership function definition for the input changes “Error in comparators hysteresis” and “Change in Error of comparators hysteresis” is given by Fig. 4.

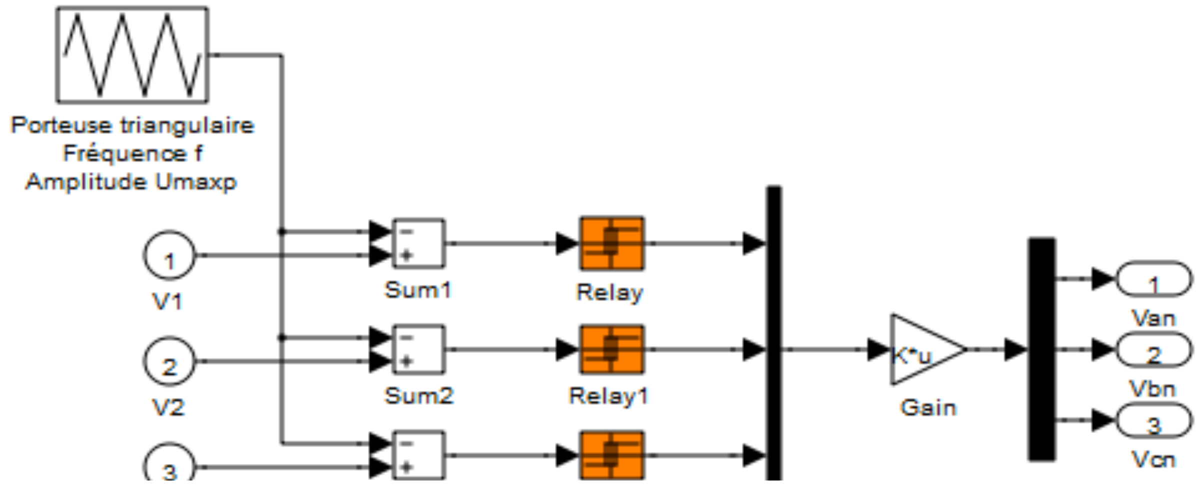

Fig. 1 PWM inverter.

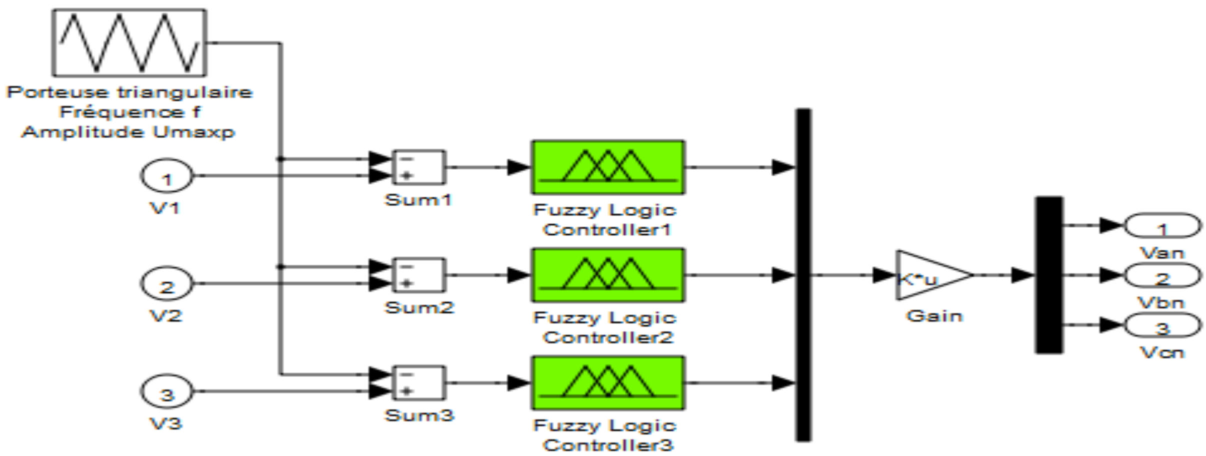

Fig. 2 FPWM inverter.

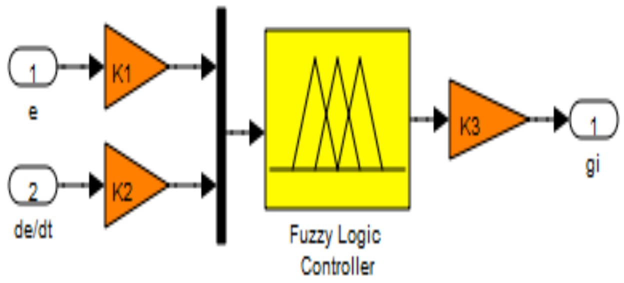

Fig. 3 Fuzzy command of PWM inverter.

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 shows this rules [20, 21].We use the following designations for membership functions:

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

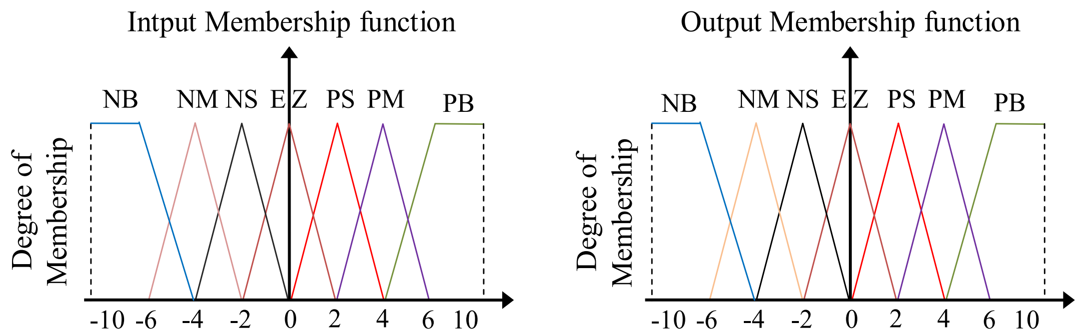

Fig. 4 Fuzzy sets and its memberships functions.

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 for PWM inverter.

Table 2. Parameters of fuzzy regulator

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

3. The DFIG Model

Dynamic model equations of the DFIG in d-q reference frame are as follows [22, 23]:

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

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

The electromagnetic torque is expressed as:

$$T_e = pM(I_{dr}.I_{qs} - I_{qr}.I_{ds}) \quad (3)$$

$$T_e = T_r + J \cdot \frac{d\Omega}{dt} + f \cdot \Omega \quad (4)$$

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

$$\begin{cases} P_s = \frac{3}{2}(V_{ds}I_{ds} + V_{qs}I_{qs}) \\ Q_s = \frac{3}{2}(V_{qs}I_{ds} - V_{ds}I_{qs}) \end{cases} \quad (5)$$

4. Indirect Vector Control

The indirect vector command (IVC) goal is to command the reactive power and active power of the doubly fed induction generator. In the IVC, reactive power is controlled by means of the direct axis voltage V_{dr}, while the active power is controlled by means of the quadrature axis voltage V_{qr}. On the other hand, the principle of IVC method is presented in [24-26]. The proposed IVC with FPWM (IVC-FPWM), which is designed to command stator reactive and stator active of the doubly fed induction generator, is exposed in Fig. 5. The proposed IVC-FPWM command scheme is easy to implement, simple scheme, reduce powers ripples, robust command and gives minimum total harmonic distortion. The internal structure of IVC command is exposed in Fig. 6.

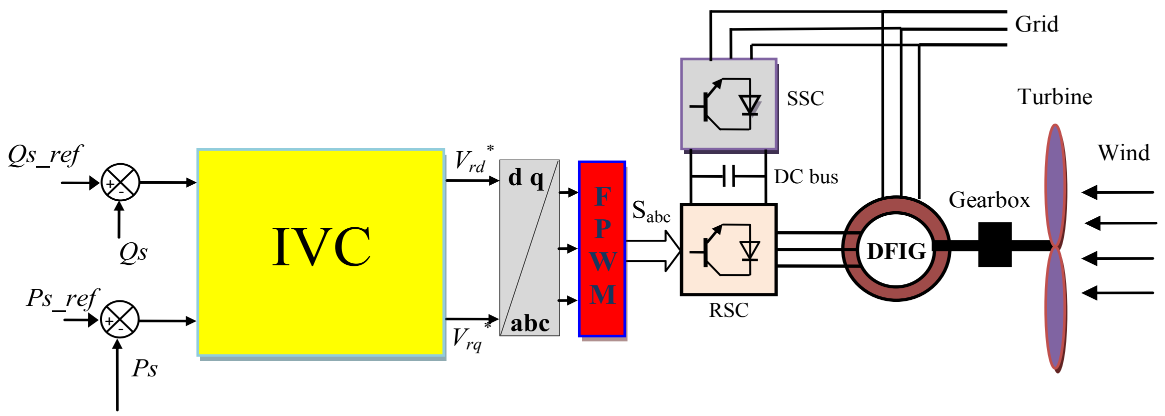

Fig. 5 Structure of IVC-FPWM command.

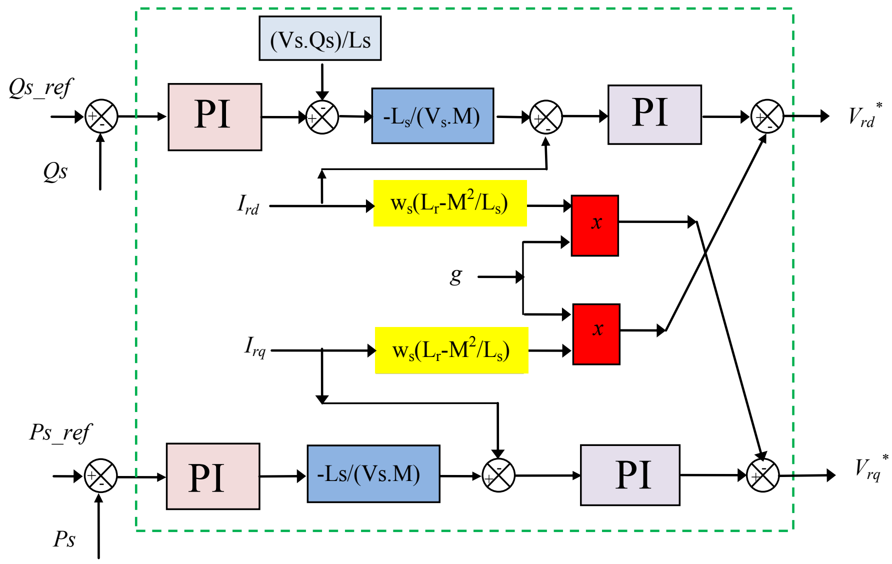

Fig. 6 Structure of IVC scheme.

5. Simulation Results

Simulation of the proposed command techniques for a doubly fed induction generator is conducted by using the Matlab/Simulink package. The doubly fed induction generator is connected to a 398V/50Hz grid. On the other hand, the doubly fed induction generator is rated at 1.5MW, and its parameters are listed in Table 3. The both command strategies IVC-PWM and IVC-FPWM are simulated and compared in terms of current harmonics distortion, reference tracking, 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	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

5.1 Reference Tracking Test

Figs. 7-11 show the obtained simulation results for tracking test of the DFIG machine. As it's shown by Figs. 7-9, for the two proposed commands, the reactive and active powers tracks almost perfectly their references values, but with better transient response time in the case of the IVC-FPWM command scheme. On the other hand, Figs. 10-11 show the harmonic spectrums of current of the doubly fed induction generator obtained using Fast Fourier Transform (FFT) method for both proposed command schemes. It can be clearly observed that the THD is reduced for IVC-FPWM command scheme. Table 4 shows the comparative analysis of the THD value of stator current for proposed commands scheme.

Table 4. Comparative analysis of THD value

	THD (%)	
	IVC-PWM	**IVC-FPWM**
Stator current	0.83	**0.08**

Figs. 12-14 show the zoom in the reactive power, active power, and torque of the IVC-PWM and IVC-FPWM controls schemes. This figure shows that the ripple of reactive, active powers and torque in the IVC-PWM command scheme has been zero compared with the IVC-PWM command. It is clear from the results that the FPWM inverter has satisfied performance.

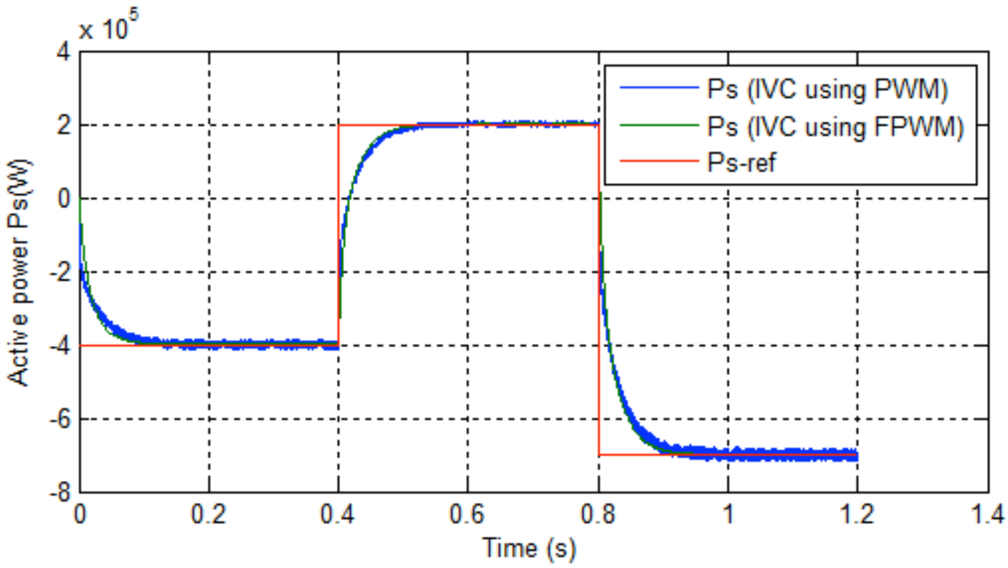

Fig. 7 Stator active energy.

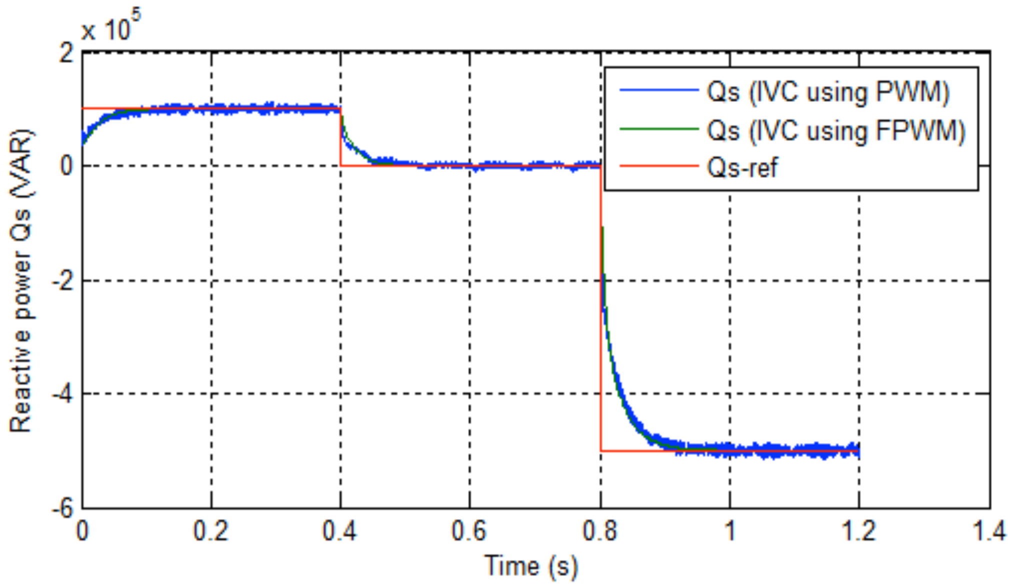

Fig. 8 Stator reactive energy.

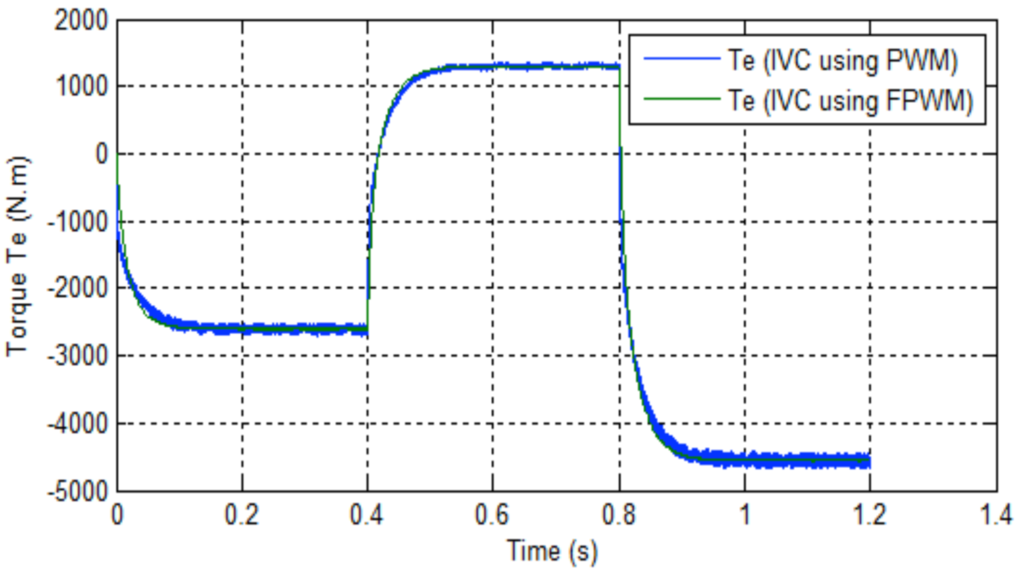

Fig. 9 Electromagnetic torque.

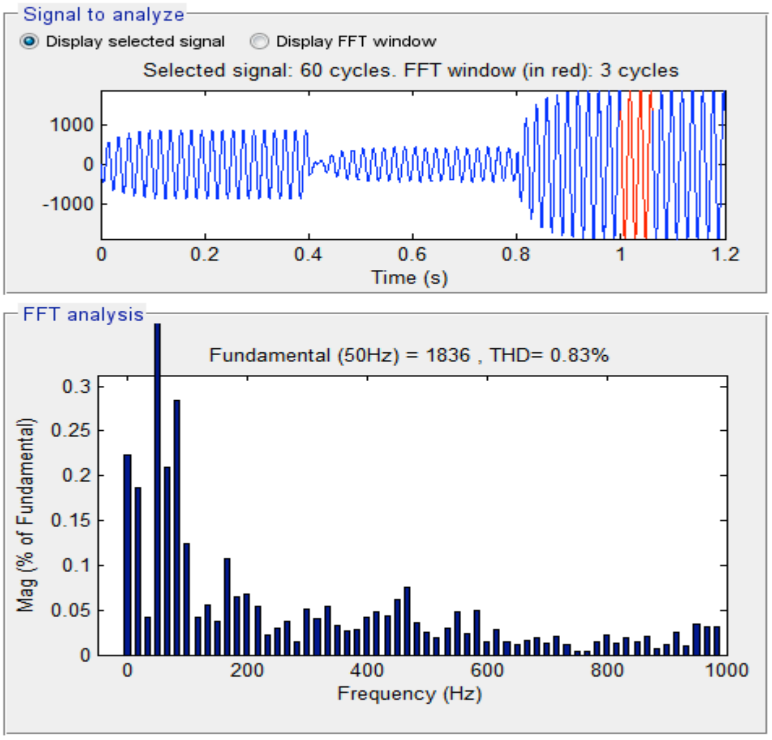

Fig. 10 THD of one phase current for a doubly fed induction generator (IVC-PWM).

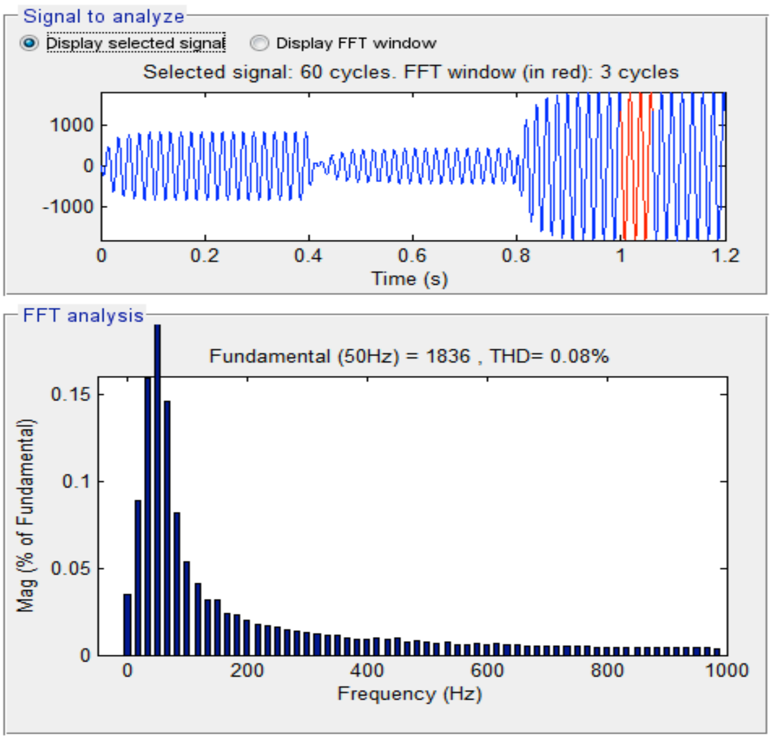

Fig. 11 THD of one phase current for a doubly fed induction generator (IVC-FPWM).

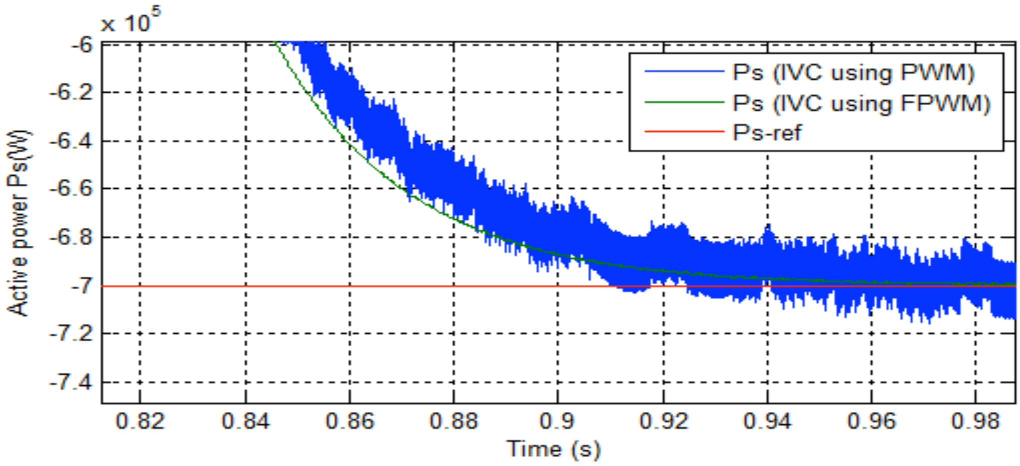

Fig. 12 Zoom in the active power (reference tracking test).

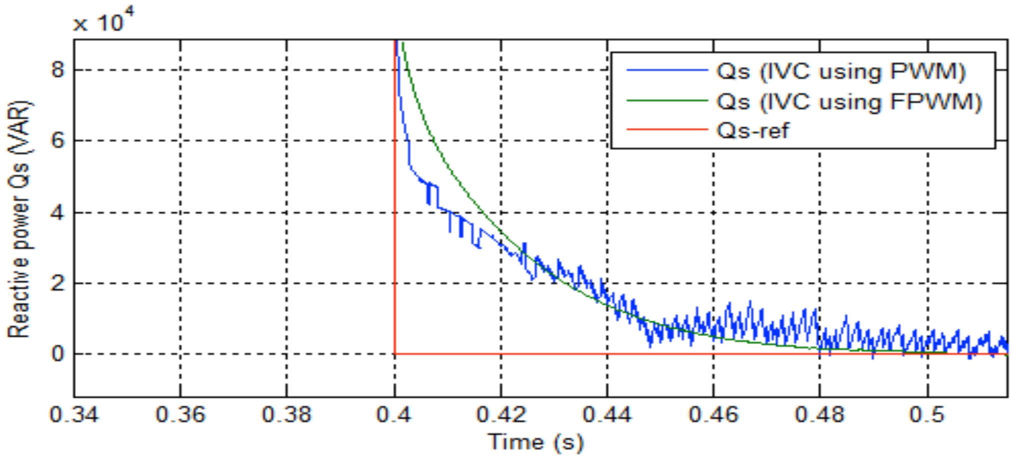

Fig. 13 Zoom in the stator reactive power (reference tracking test).

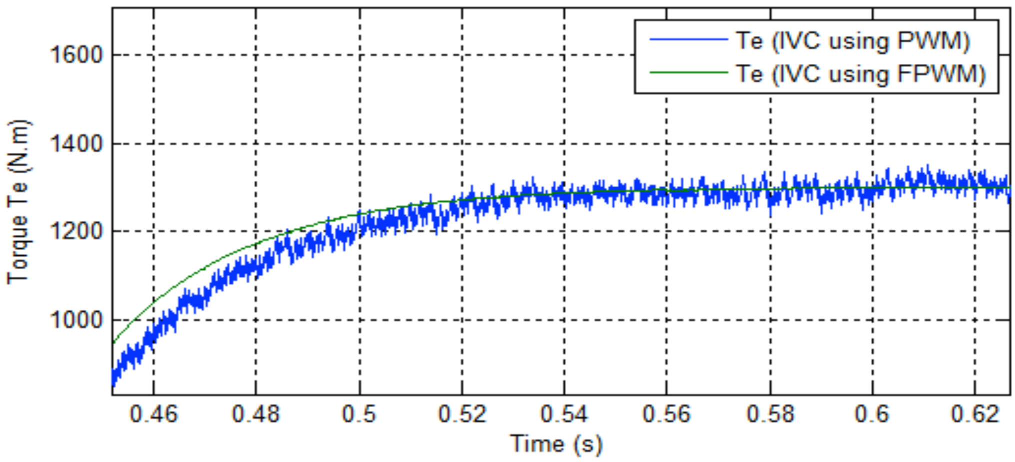

Fig. 14 Zoom in the torque (reference tracking test).

5.2 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 15-17. As it's shown by these Figures, these variations present a clear effect on the stator active, stator reactive power, and torque curves and that the effect appears more and more important for the IVC-PWM command scheme. On the other hand, these results show that the THD value of stator current in the IVC-FPWM command scheme has been reduced significantly. Table 5 shows the comparative analysis of THD value. Thus it can be concluded that the proposed IVC using FPWM command scheme is more and more robust than the IVC using PWM one.

Table 5. Comparative analysis of THD value

	THD (%)	
	IVC-PWM	**IVC-FPWM**
Stator current	2.46	**0.10**

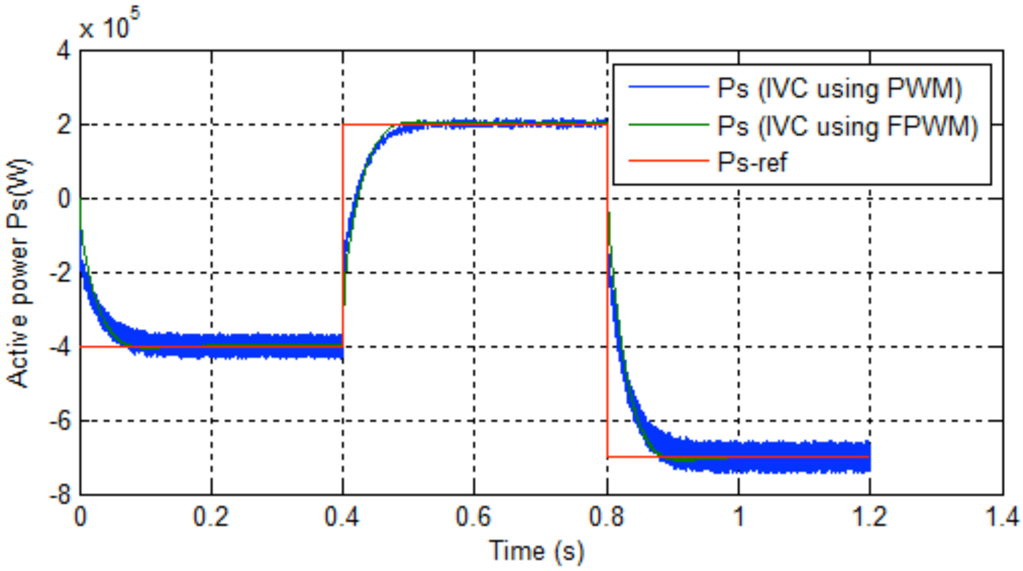

Fig. 15 Stator active power.

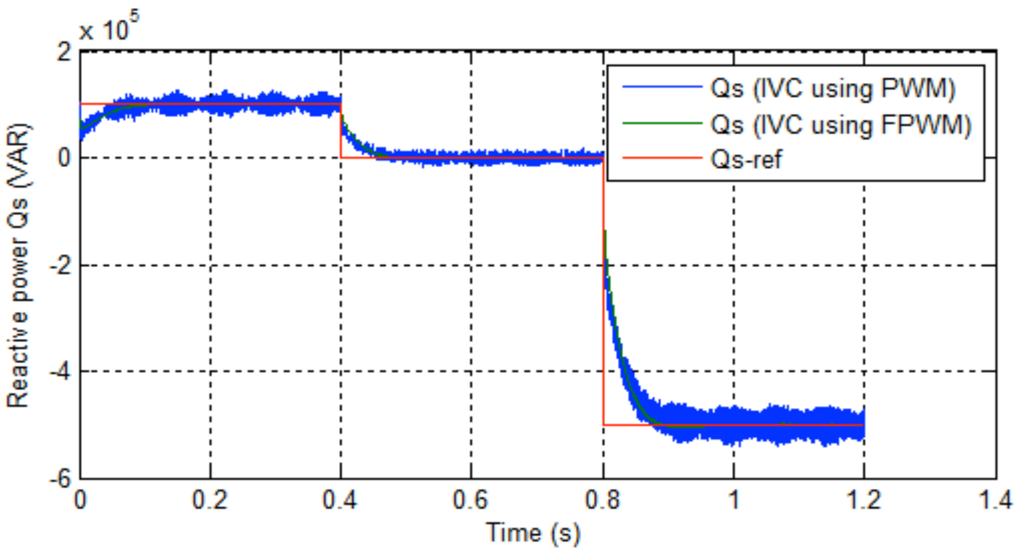

Fig. 16 Stator reactive power.

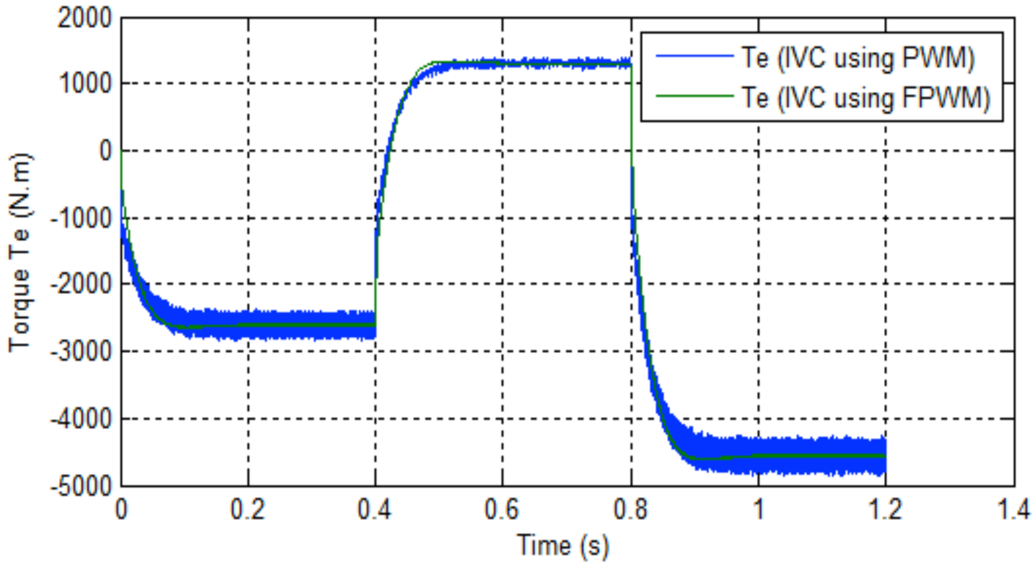

Fig. 17 Electromagnetic torque.

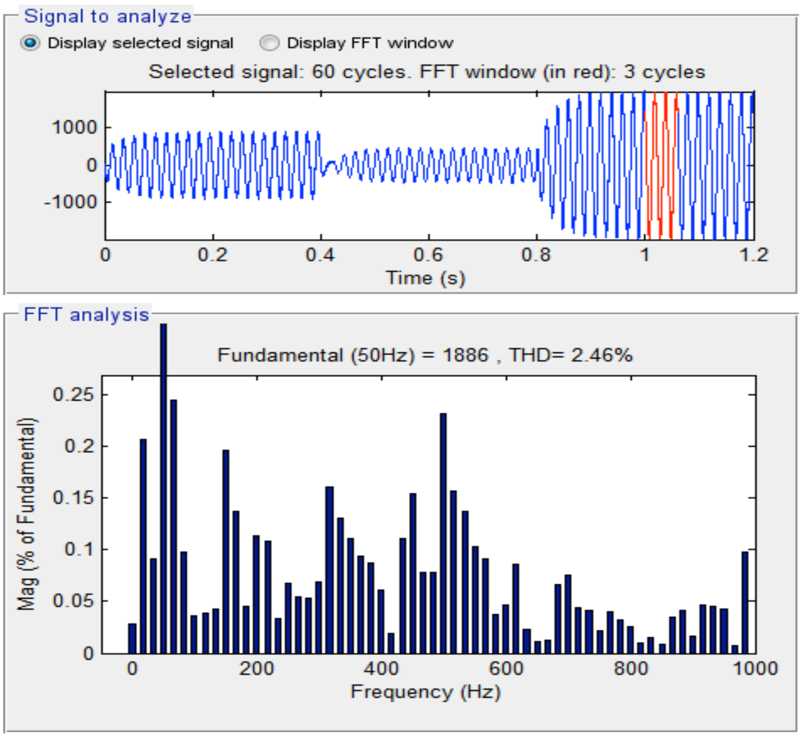

Fig. 18 THD of one phase current for a doubly fed induction generator (IVC-PWM).

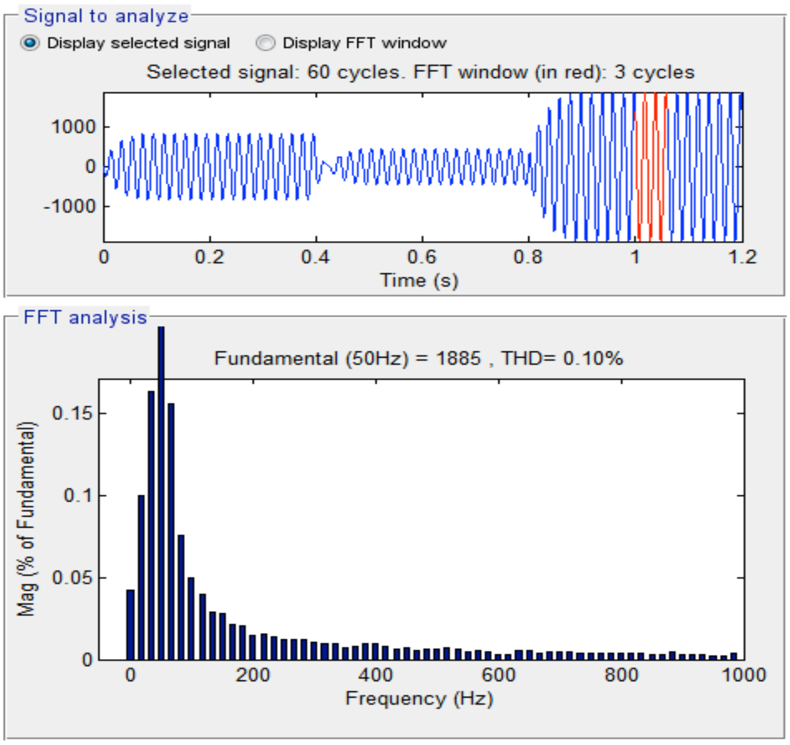

Fig. 19 THD of one phase current for a doubly fed induction generator (IVC-FPWM).

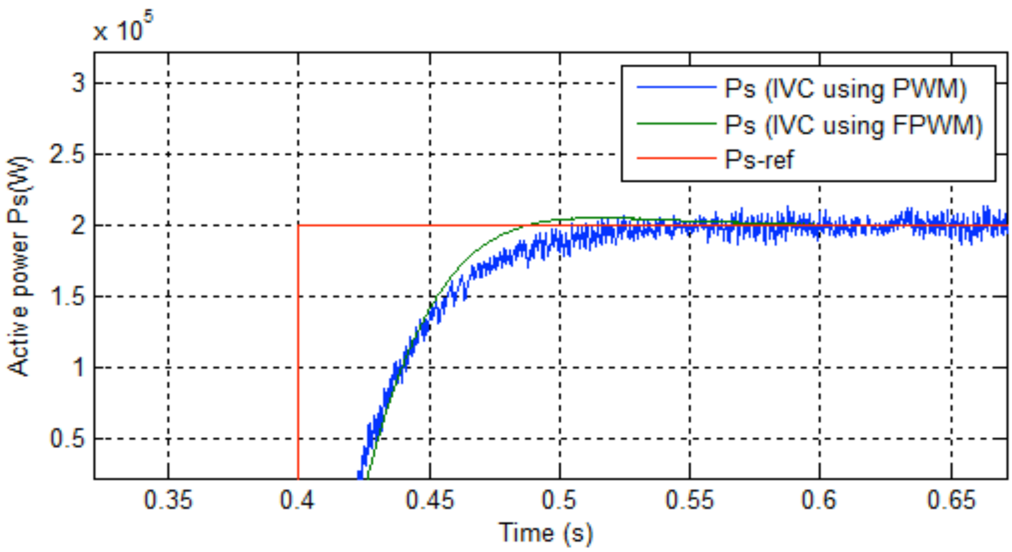

Fig. 20 Zoom in the stator active power (robustness test).

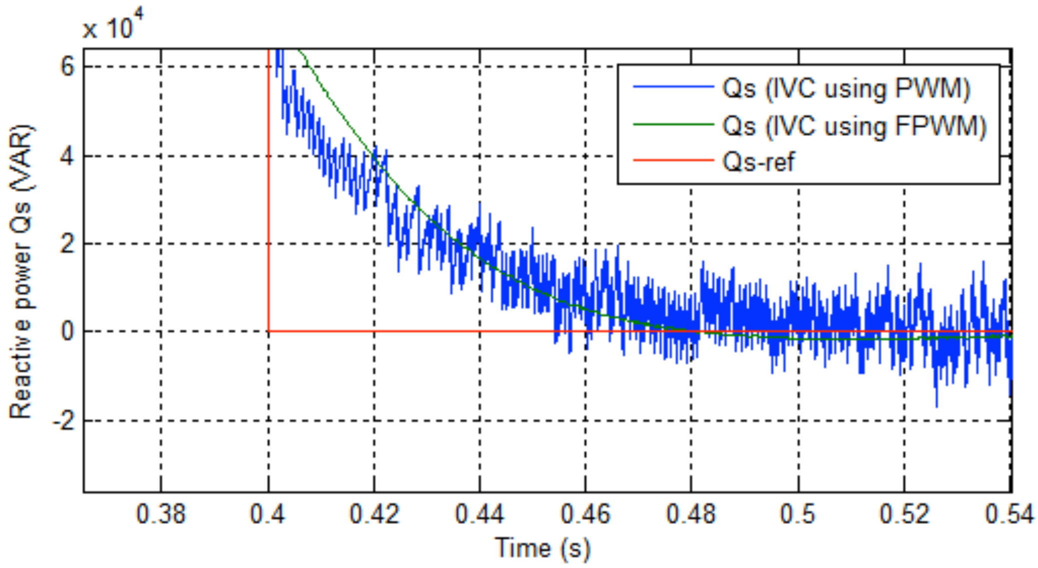

Fig. 21 Zoom in the stator reactive power (robustness test).

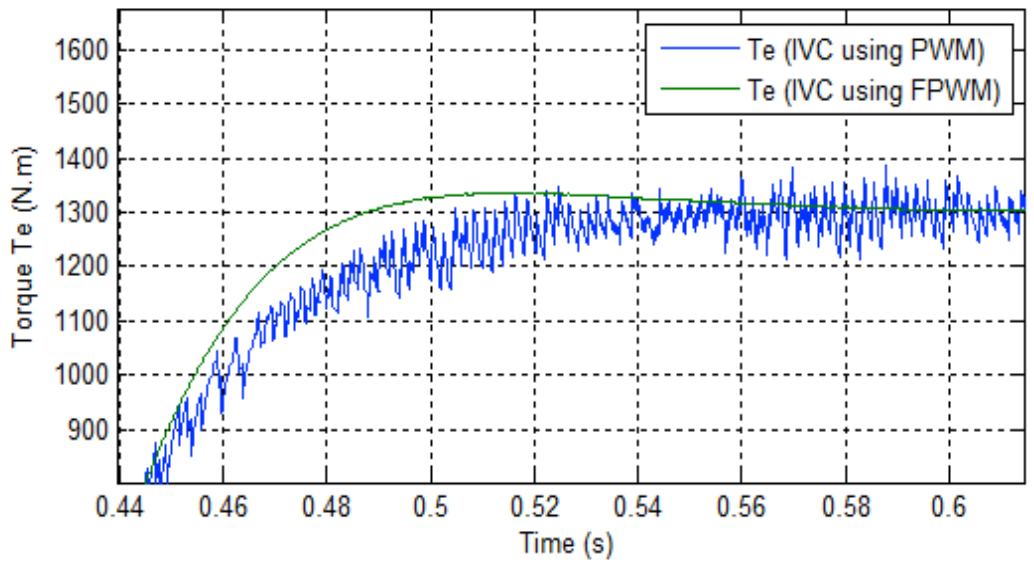

Fig. 22 Zoom in the torque (robustness test).

6. Conclusion

This work presents simulation results of indirect vector command for stator reactive power and active power command of the doubly fed induction generator, using the modulation technique of the FPWM and classical PWM strategy. With results obtained from simulation, it is clear that for the same operation condition, the doubly fed induction generator reactive power and stator active power command with IVC using FPWM inverter had better performance than the conventional PWM strategy and that is clear in the spectrum of one phase current harmonics which the use of the FPWM strategy, it is reduced of THD more and more than conventional pulse width modulation strategy.

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