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Enhanced Finite-State Predictive Torque Control of Induction Motor Using Space Vector Modulation

***Abstract**. This paper proposes a different strategy of predictive torque control applied to induction motor drive. The classical Direct Torque Control or DTC is wildly widespread in the industry, because of its known advantage like robustness, simplicity and the important one is the minimal torque response time. But, it shows its limitations in terms of torque undulation and variable switching frequency. To improve this classical type of control, two techniques have been introduced. Firstly application of Finite Set Model Predictive Control (FCS-MPTC) which has the advantage of being easy to implement and has a quick dynamic but its switching frequency is inconsistent. Secondly technique it’s based on space vector modulation showed that the PTC-SVM has superior performance especially the constancy of the switching frequency which will decrease the oscillation of electromagnetic torque and stator current and finally improve the THD.*

Streszczenie.** W artykule zaproponowano inną strategię predykcyjnej kontroli momentu obrotowego stosowaną w napędzie silnika indukcyjnego. Klasyczna bezpośrednia kontrola momentu obrotowego lub DTC jest szeroko rozpowszechniona ze względu na jej znane zalety, takie jak solidność, prostota, a najważniejszą z nich jest minimalny czas reakcji na moment obrotowy. Ale pokazuje swoje ograniczenia pod względem falowania momentu obrotowego i zmiennej częstotliwości przełączania. Aby ulepszyć ten klasyczny rodzaj sterowania, wprowadzono dwie techniki. Po pierwsze zastosowanie skończonego sterowania predykcyjnego modelu zbioru skończonego (FCS-MPTC), które ma tę zaletę, że jest łatwe do wdrożenia i ma szybką dynamikę, ale jego częstotliwość przełączania jest niespójna. Po drugie, technika oparta na modulacji wektora przestrzennego wykazała, że PTC-SVM odznacza się doskonałą wydajnością, zwłaszcza stałą częstotliwością przełączania, która zmniejszy oscylacje momentu elektromagnetycznego i prądu stojana, a ostatecznie poprawi THD. **(Ulepszona kontrola momentu obrotowego przewidywania stanu skończonego silnika indukcyjnego przy użyciu Modulacja Wektora Przestrzeni)

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Keywords: induction motor, predictive control, pulse width modulation, torque control.
Słowa kluczowe: silnik indukcyjny, sterowanie predykcyjne, modulacja szerokości impulsu, kontrola momentu obrotowego.

Introduction

Induction machine (IM) is widely used in industry, because of its advantages: simplicity of construction, robustness, low cost and ease of maintain however its main disadvantage is the coupling between flux and torque. So, in order to improve the dynamic performance of IM, much research has been developed in order to find simpler control schemes of induction motors that meet the requirements like low torque ripple, low harmonic distortion and quick response. Various strategies of control have been suggested to enhance the performance of IM, among which the field-oriented control (FOC) and direct torque control (DTC).

The aim of field-oriented control is to control independently and effectively the electromagnetic torque and stator flux.

Classical direct torque control method often called ‘’CDTC ‘’was proposed by DEPENBROCK and TAKAHASHI for the control of induction motor [1]. DTC is recognized to create a robust and a fast response in AC motors. But, through steady state, notable torque and current ripples occur [2]. The CDTC topology has a purpose of regulation of the electromagnetic torque and stator flux, without having measures of speed, flux or torque. The only measures are the stator voltage and current. So, we have a directly control of stator flux and electromagnetic torque separately and keep them inside hysteresis band [3]. The CDTC is a new control technique based on the direction of the stator flux by a direct action on the positions of the inverter (two-level) [4].The classical direct Torque Control (CDTC) founded on a switching table of the voltage vector and also on hysteresis regulators (two level for flux control and three level for electromagnetic torque control) which are the principal sources of the ripple appearing at the stator current, stator flux and the electromagnetic torque hence due to their variable switching frequency.

Predictive torque control ‘PTC’ is an important branch of Finite Control Set Model Predictive Control (FCS-MPC). PTC reduces the torque ripples, while keeping the merits of DTC: simple algorithm and fast dynamic. Moreover, PTC can handle well with over-current protections [5]. The predictive-DTC provides an improvement in the behavior of the drive compared to that obtained by the classical DTC due to his easy of processing. In PTC topology three steps are used estimation, prediction and cost function determination. Moreover, the PTC control it’s also suffers from the variation of the switching frequency.

To upgrade the performance of the classical DTC and the PTC method in terms of ripples and variation in the switching frequency, the PTC based on the space vector modulation technique (PTC-SVM) was a solution [4]; By the SVM technique each reference vector can be expressed as a combination of two adjacent active voltage vectors and zero state voltage vectors, this new technique has a constant switching frequency, so the combination of this technique with the predictive torque control (PTC-SVM) will make it possible to reduce the ripple of the stator current and torque, thus improved the quality of the signal and therefore the ‘THD’ obtained by the PTC based on the SVM technique is the best one compared to the other studied strategies CDTC and PTC control.

Induction motor model

Basing on a set of assumptions and considering the model of induction motor, in a fixed reference frame (α, β) linked to the stator, can be presented by the following equations [6,7]:

Electrical Equation

(1) $$\bar{V}_s = R_s\,\bar{i}_s + \frac{d\bar{\psi}_s}{dt}$$

(2) $$0 = R_r\,\bar{i}_r + \frac{d\bar{\psi}_r}{dt} - j\omega_e\bar{\psi}_r$$

Magnetic Equation

(3) $$\bar{\psi}_s = L_s\,\bar{i}_s + L_m\bar{i}_r$$

(4) $$\bar{\psi}_r = L_r\,\bar{i}_r + L_m\bar{i}_s$$

Mechanical Equation

(5) $$j\frac{d\Omega}{dt} = T - T_L - F_r.\Omega$$

The electromagnetic torque is defined by:

(6) $$T = 1.5\ p\Im m\left\{\overline{\psi}_s^*.\bar{i}_s\right\}$$

The state model of an induction machine is given below [1], [8]:

(7) $$[\dot{X}] = [A][X] + [B][U]$$

With:

(8) $$X = \lfloor i_{s\alpha} \quad i_{s\beta} \quad \psi_{s\alpha} \quad \psi_{s\beta} \rfloor ; V_s = \lfloor v_{s\alpha} \quad v_{s\beta} \rfloor$$

Inverter Model

Three-phase inverter is a DC-AC static converter that allows having three balanced voltages of adjustable amplitude and frequency. For modelling, the converter used, is considered as two-level voltage source inverter VSI-2L.

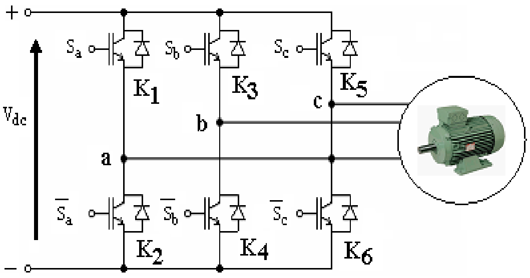


Fig. 1. Voltage Source Inverter (VSI-2L)

The mathematical model of a two-level voltage inverter is presented by:

(9) $$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \frac{E}{3}\begin{vmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{vmatrix}\begin{vmatrix} S_a \\ S_b \\ S_c \end{vmatrix}$$

Classical DTC applied to IM

As its name suggests, its purpose is to regulate the electromagnetic torque and stator flux, without having measures of speed, flux or torque. This regulation is based on the direct determination of the control sequence to be applied to a voltage inverter [23].

The choice of the appropriate sequence is based on the use of hysteresis controllers whose function is to control the stator flux and the electromagnetic torque [4].

DTC requires the estimation of flux and torque from measurements of voltages and stator currents. The stator flux of induction motor is obtained from the following equation [8-9]:

(10) $$\overline{\psi}_s = \int_0^t \left(\overline{V}_s - R_s.\bar{i}_s\right)dt$$

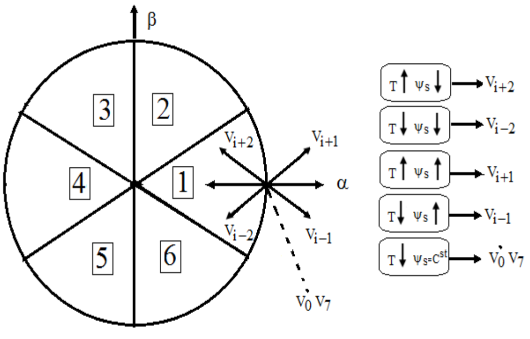


Fig. 2. Voltage Vector Selection

During a sampling time, if stator resistance is neglected and the voltage vector applied to the IM is considered constant. So we can write:

(11) $$\Delta\overline{\psi}_s = \overline{V}_s T_s$$

The flux modulus and phase are obtained by calculation as:

(12) $$\begin{cases} \overline{\psi}_s = \sqrt{\psi_{s\alpha}^2 + \psi_{s\beta}^2} \\ \angle\overline{\psi}_s = actg\left(\dfrac{\psi_{s\beta}}{\psi_{s\alpha}}\right) \end{cases}$$

The electromagnetic torque can be estimated as follow [4], [10]:

(13) $$T_s = 1.5p\left(\psi_{s\alpha}.i_{s\beta} - \psi_{s\beta}.i_{s\alpha}\right)$$

The synoptic control of DTC is given as follow: [4], [11]

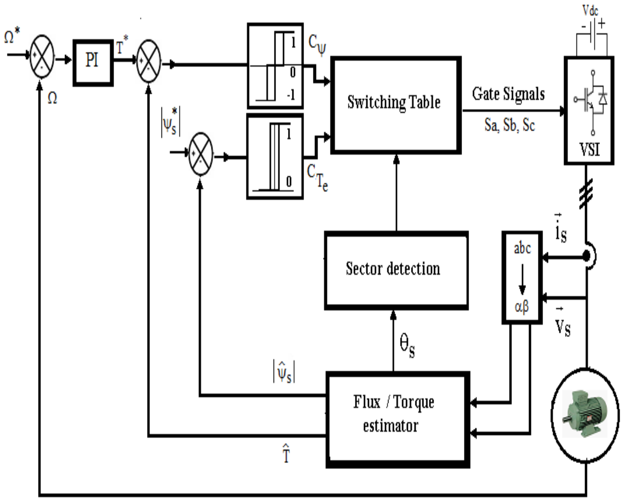


Fig. 3. Block diagram of conventional DTC

The two variables stator flux and electromagnetic torque are controlled by hysteresis controllers [23].

For stator flux a two level hysteresis comparator is chosen, on the other part, the torque needs a three level comparator. The selection of the voltage vector is based on stator flux sector and hysteresis controller's outputs, as depicted in Table I.

Table. I. Switching table for classical DTC

Stator Flux error	Torque error	Sector					
		1	2	3	4	5	6
C_φ=1	C_{Te}=1	V2	V3	V4	V5	V6	V1
	C_{Te}=0	V7	V0	V7	V0	V7	V0
	C_{Te}=-1	V6	V1	V2	V3	V4	V5
C_φ=0	C_{Te}=1	V3	V4	V5	V6	V1	V2
	C_{Te}=0	V0	V7	V0	V7	V0	V7
	C_{Te}=-1	V5	V6	V1	V2	V3	V4

where: - Ve Voltage vector, - C_{Te} Torque comparator, - C_φ Flux comparator.

Predictive Torque Control Model

The FCS-MPTC is based on three steps: estimation, prediction and cost function determination [5]. The synoptic control of PTC is detailed as Fig.4 [22], [12].

The predictive torque control (PTC) is based on the prediction of the future measurements of stator flux and electromagnetic torque [13], [22].

The predictions are computed for the eight possible cases of the voltage vector Vs and the cost function selects the voltage vector that creates the best flux and torque control.

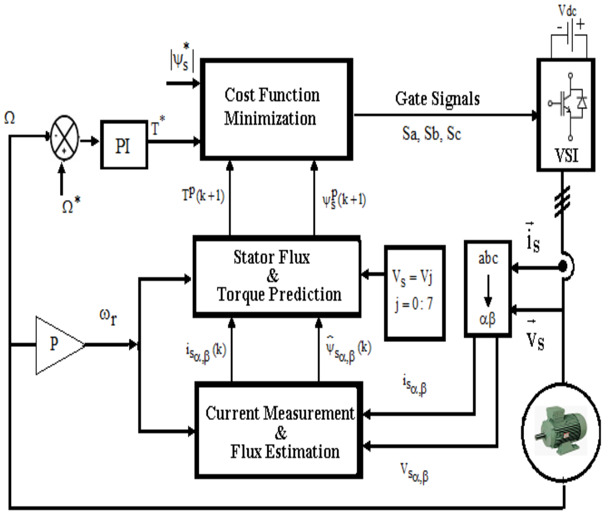


Fig. 4. PTC control diagram

The cost function is defined as [12], [14-15]:

$$F = \left|T_e^* - T_e^p(k+1)\right| + A\left|\psi_s^* - \psi_s^p(k+1)\right| \tag{14}$$

With :

$$A = \left|\frac{T_{enom}}{\psi_{snom}}\right| \tag{15}$$

T_e^*, ψ_s^* : Reference torque and stator flux.

T_e^p, ψ_s^p : Predictive torque and stator flux.

Current, flux and torque predictions are given as [3],[5], [16], [22]:

$$\begin{aligned}\hat{i}_s(k+1) &= \left(\frac{T_s\, R_r}{\sigma\, L_s L_r} - j\frac{T_s\, \omega_r}{\sigma\, L_s}\right)\psi_s(k) + \\ &\left(1 - \frac{T_s\, R_s}{\sigma\, L_s} - \frac{T_s\, R_r}{\sigma\, L_r} + jT_s\,\omega\right)i_s(k) + \frac{T_s}{\sigma\, L_s}V_s\end{aligned} \tag{16}$$

$$\psi_s(k+1) = \psi_s(k) + T_s V_s(k) - T_s R_s i_s(k) \tag{17}$$

$$T_s(k+1) = 1.5\,p\Im m\left\{\psi_s(k+1)\,\hat{i}_s(k+1)\right\} \tag{18}$$

Predictive Torque Control with Space Vector Modulation Space vector modulation is one of popular modulation techniques that allows a several advantages like less harmonic distortion, less switching losses, large modulation ratio and fixed switching frequency [17].

In this technique, each reference vector can be defined as a combination of two adjacent active voltage vectors and zero state voltage vectors [18]. If the reference vector is assumed in n$^{\text{ème}}$ sector [4], [19], [22]:

$$T_s\,\overline{V}_{ref} = T_1\,\overline{V}_n + T_2\,\overline{V}_{n+1} + T_0\,\overline{V}_7 + T_0\,\overline{V}_0 \tag{19}$$

With:

$$T_1 = \frac{\sqrt{3}\,T_s\left|\overline{V}_{ref}\right|}{V_{dc}}\left(\sin(\frac{n}{3}\pi)\,\cos\varphi - \cos(\frac{n}{3}\pi)\,\sin\varphi\right) \tag{20}$$

$$T_2 = \frac{\sqrt{3}\,T_s\left|\overline{V}_{ref}\right|}{V_{dc}}\left(-\sin(\frac{n-1}{3}\pi)\cos\varphi + \cos(\frac{n-1}{3}\pi)\sin\varphi\right) \tag{21}$$

$$T_0 = T_s - T_1 - T_2 \tag{22}$$

T_n: Switching period and n Sector number

The SVM technique used in this work can be called symmetrical SVM. It's seen that this technique is to replace the null vector in each sequence and inverse the sequence after each null vector, all that in each modulation period T_s. However, with this sequence strategy the 3 legs inverter are in commutation which generates 8 switching states in each T_s, as follow [20-21]:

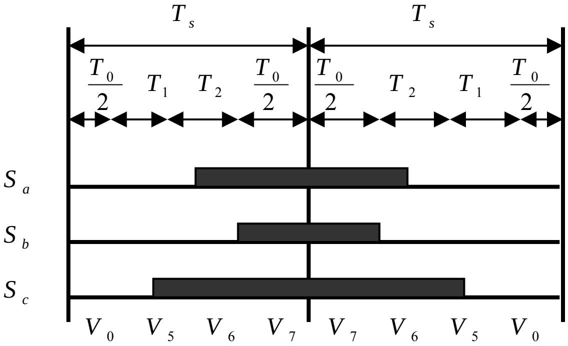


Fig. 5. Time sequences and applications of adjacent vectors in the first sector

The PTC-SVM control works at constant modulation frequency. The block scheme of the PTC based on SVM techniques for a voltage source inverter fed IM is presented in Fig.7.

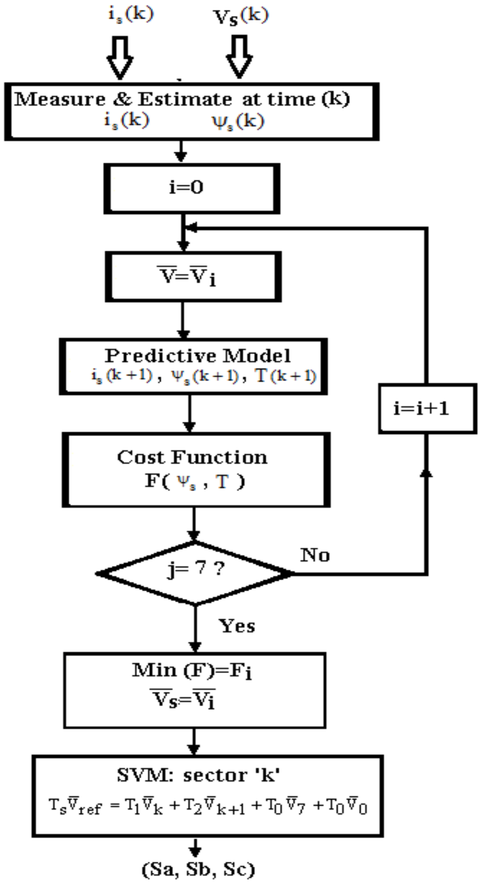


Fig. 6. Flowchart of PTC-SVM

Simulation Results

In order to study the performance of the developed Conventional DTC and predictive torque control, their Simulink model is developed in Matlab environment for 1.5Kw, 1423tr/m, 4pole, 50Hz, 3-phase induction motor.

So, three variants of direct torque control are compared: Classic direct torque control (CDTC), Predictive torque control (PTC), based on the combination of the both conventional DTC and FCS-MPTC schemes and Predictive Torque Control with Space Vector Modulation-PTC-SVM.

The simulation results show in Fig. 08, 09, 10, 11, 12 and 13 validate that:

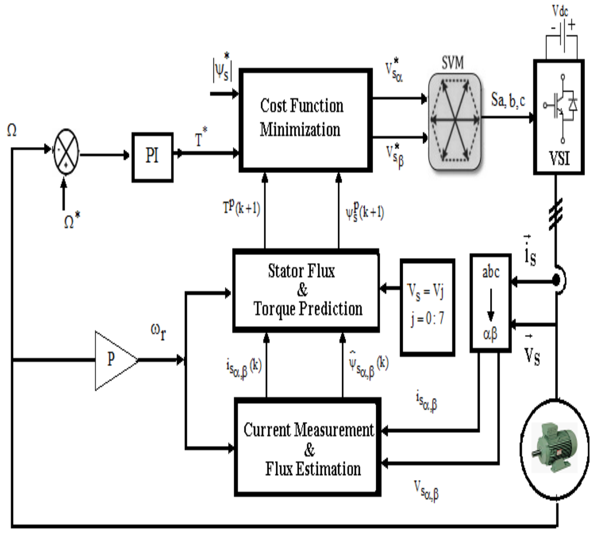


Fig. 7. Block diagram of the PTC-SVM Control

The conventional DTC is used, for its simplicity its fast dynamic response as well (fast response time), but it suffers from a major disadvantage which is the variation of the switching frequency which causes oscillations at the current, torque and flux.

PTC is a very good choice for improving the performance of conventional DTC, In addition, this control strategy has insensitivity to the variations of the rotor parameters, but it has a variable switching frequency generates undesirable harmonic in the signal.

The better solution for the reduction of current and torque ripples and improve the quality of signal is the PTC-SVM method which is able to work with a constant switching frequency. Therefore it is the best improvement of the DTC among the different variants studied.

To confirmed the last result and also to controlled the behavior of each method, a variation of load and a reversal of direction of rotation is assumed, the load is presented by a resistant torque (5N.m) it's applied at the moment:(1sec),than at (1.5 sec) a reversal of direction rotation of the IM is applied. Finally at moment (2sec), the load was cut, during this period the (PTC-SVM) presents its fast dynamics and their remarkable effect on the minimization of the ripples which appears at the level of the electromagnetic torque and the stator current which ensure that it's the best method compared to the other studied variant (DTC and PTC).

THD values present an improvement of the classical DTC control with harmonic percentage reduction for the stator current signal of almost 1% for the use of the predictive torque control and 2% for the new method which is the combination of predictive torque control with the space vector modulation (SVM).

The values of the THD obtained by the deferent methods studied presented as:

Table II. Total harmonic distortion (THD) of stator current

THD		
DTC	PTC	PTC-SVM
4.23%	3.23%	2.28%
Computation time		
53 (μS)	69 (μS)	75 (μS)

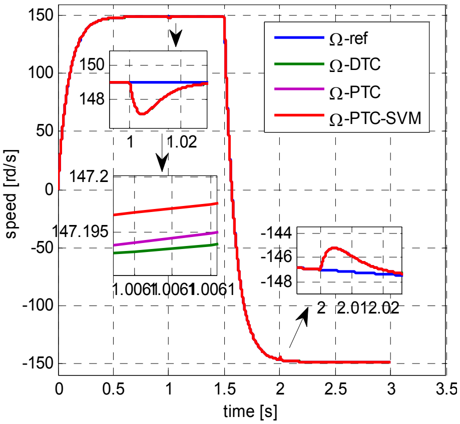


Fig. 8. Dynamic responses of motor speed

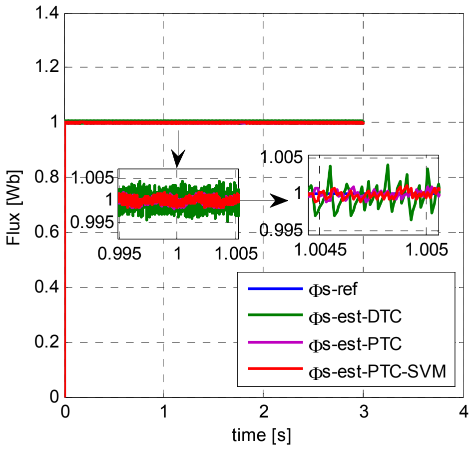


Fig. 9. Flux variation

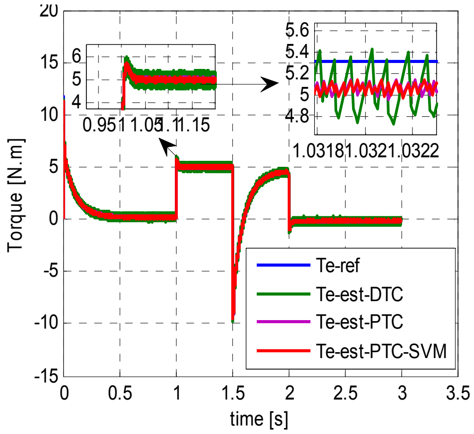


Fig. 10. Dynamic responses of electromagnetic torque

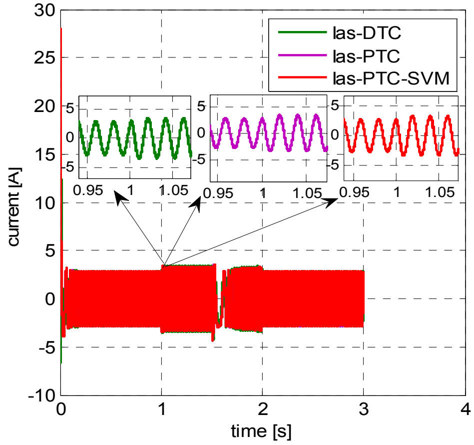
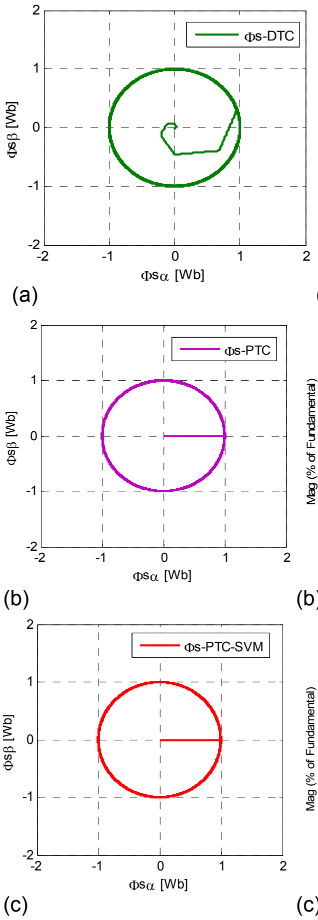


Fig. 11. Dynamic responses of the current



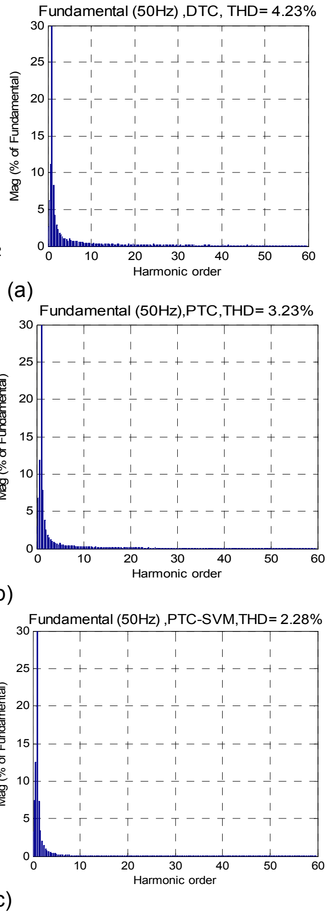


Fig. 12. Trajectory of the stator flux.
(a) DTC, (b) PTC, (c) PTC SVM

Fig. 13. Spectrum of Harmonics.

Experimental results

Fig. 14 illustrates the experimental setup used the motor is fed by a controlled 2L-VSI from SEMKRON. The DTC, PTC and PTC-SVM algorithm is implemented in real time using dSPACE 1104 platform.

Fig.15, 16 and 17 show experimental steady-state results for the dynamic response of electromagnetic torque, stator flux and current at the rated speed and with a value of the load torque equal of 7Nm, for all methods (DTC, PTC, PTC-SVM).

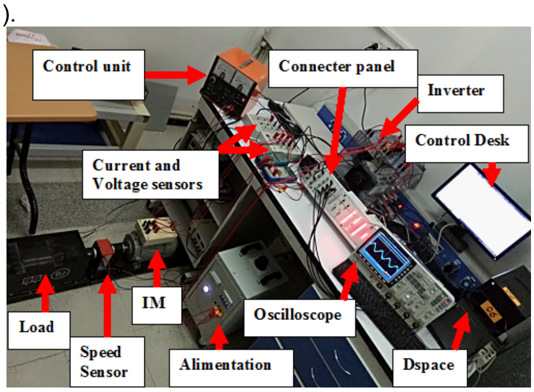
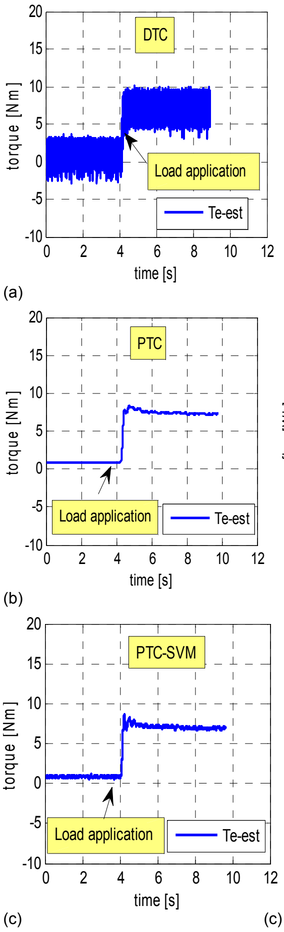


Fig. 14. Experimental setup for: DTC, PTC and PTC-SVM

It can be seen from the analysis of different experimental results shown that:

We observe through the curves of the torque, the stator flux and the currents obtained by the conventional DTC method strong ripples caused by the variation of the switching frequency of the hysteresis controllers.



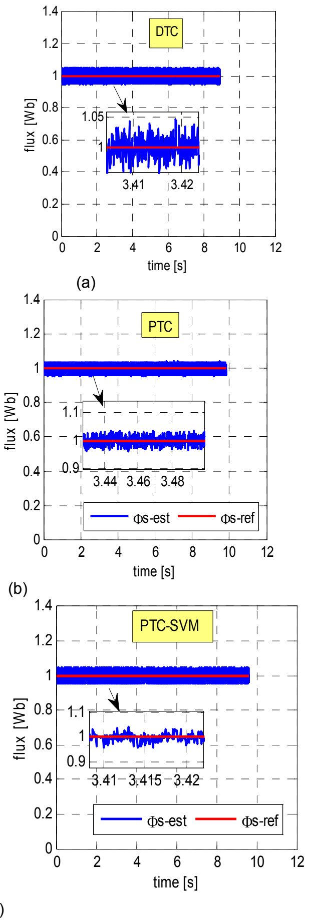
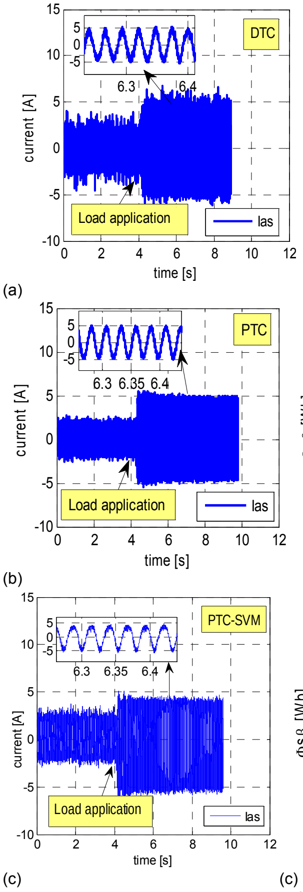


Fig. 15. Dynamic responses of electromagnetic torque, (a) DTC, (b) PTC, (c) PTC SVM

Fig. 16. Flux variation



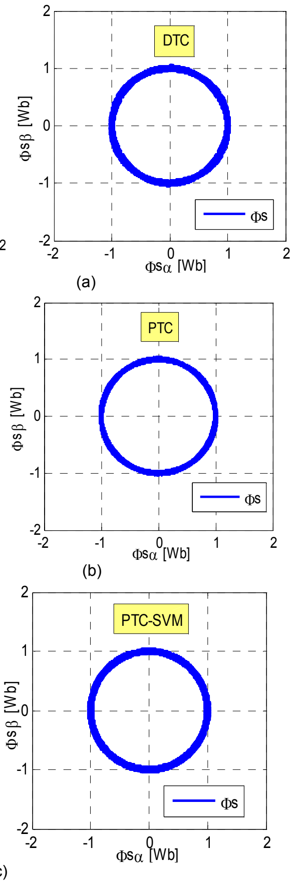


Fig. 17. Dynamic responses of the Current

Fig. 18. Trajectory of the stator flux, DTC, (b) PTC, (c) PTC SVM

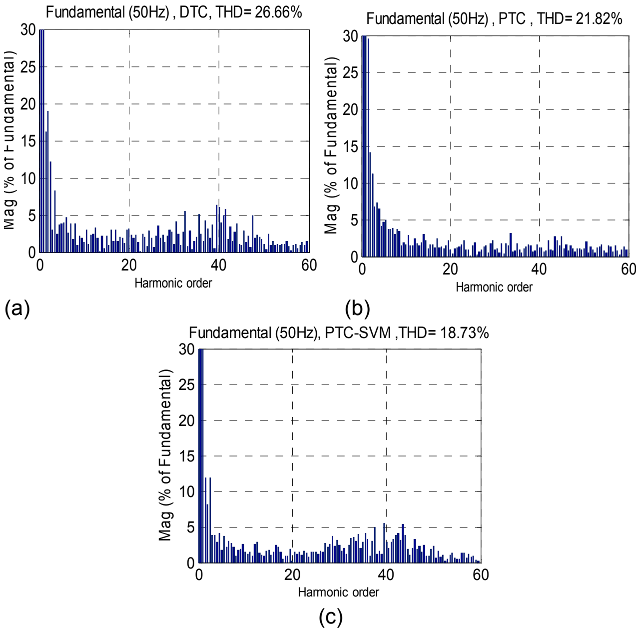


Fig. 19. Spectrum of Harmonics. DTC, (b) PTC, (c) PTC SVM

The stator flux and torque ripples for the proposed control strategy PTC-SVM are well reduced compared to the conventional method.

Fig. 18 shows the trajectory of the amplitude of the stator flux vector in the plane (α, β). We can observe that the thickness of the circle which corresponds to the method, PTC-SVM has fewer ripples than the other methods; this is due to the reduction in the band ripples of the stator flux.

The experimental values of the THD obtained by the deferent methods studied presented as:

Table III. Total harmonic distortion (THD) of stator current

THD		
DTC	PTC	PTC-SVM
26.66%	21.82%	18.73%

THD values present an improvement of the classical DTC control with harmonic percentage reduction for the stator current signal of almost 5% for the predictive torque control method and 8% for the new method which is the combination of predictive torque control with the space vector modulation (SVM).

Conclusion

This paper presents an efficient PTC algorithm for IM drives. A comparative study between three variants of direct torque control (DTC) applied to induction motor with load variation and reversal direction of rotation has been proposed in this paper. As results, we can conclude that:

The classical direct torque control (CDTC) is used, for its simplicity and its fast dynamic response however it suffers from a main drawback which is the variation of the switching frequency which causes oscillations at the stator current, electromagnetic torque and stator flux.

The predictive torque control algorithm is a good solution that improves the performance of conventional DTC. In addition to its simplicity of implementation, flexibility in definition of the cost function, the torque, current and flux oscillations can be decreased. However, it has a non-constant switching frequency.

It is interesting to note that the predictive torque control using space vector modulation technique (PTC-SVM) is characterized by a significant attenuation of the torque, current and flux ripples due to its constant switching frequency and less current harmonics than the other methods.

All of methods were confirmed by simulation and experimental results.

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