Proposed Schemes for Improving the Steady State Behaviour of Direct Torque Controlled Induction Motor

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Abstract: - This paper presents two modified Direct Torque Control (DTC) schemes, which were designed to provide a lower torque ripple than that exhibited by the conventional DTC. The effectiveness of the proposed schemes has been evaluated for a set of operating points and numerical results are presented.

Key-Words: - Direct torque control, torque ripple, pulse width modulation, space vector modulation

1 Introduction

Direct Torque Control was introduced by I. Takahashi and T. Noguchi [1] as a new high performance control strategy for induction motor drives fed by Voltage Source Inverters (VSI). It was introduced on the market by ABB [4], which considers it a viable alternative to Vector Flux Oriented Control. The main advantages of DTC are: simple control scheme, a very good torque dynamic response, absence of the inner current loops and rotor speed measurement. However, it has some drawbacks, and one of these is the high torque ripple generated in steady state operation.

In conventional DTC, the voltage vector selection is based on the torque and flux errors, but small and large errors are not differentiated by the hysteresis controllers. The voltage vectors are applied for the entire sample period, even for small errors, resulting large torque overshoots in steady-state regime.

The problem of reducing the torque ripple in conventional DTC has been studied by many researchers, which have proposed solutions for it. One approach is to increase the number of voltage vectors applied in a sampling period, using some sorts of pulsewidth modulation (PWM). Among the possible choices, a simpler one is to use two voltage vectors: a nonzero one, applied for a fraction of the sampling period, and the null vector for the rest. The duty ratio (the ratio of active vector duration to the whole period) must be calculated each sample period, and by varying it between its extreme values, it is possible to apply more voltage levels to the motor, according to the desired torque variation. In [12], an analytical online algorithm calculates the optimum duty ratio each sampling period, by using a torque ripple minimization condition, wich is based on ripple equations. However, this algorithm requires high computational effort and additional motor parameters to be known. În [13] the duty ratio value is provided by a new fuzzy logic module, whose inputs are the stator flux position, the electromagnetic torque and an input defining the motor operating point, given by the speed and the torque values. This algorithm involves expert knowledge and needs the rotor speed.

To overcome this problem, the authors proposed two modified DTC schemes, which are based on the idea of increasing the number of voltage vectors applied in a sample period. This makes it possible to obtain more voltage levels at the inverter output, in accordance to the desired torque and flux variations.

The proposed schemes were tested by numerical simulations for a set of motor operating points. Their effectiveness was evaluated by calculating the root mean square (RMS) deviation of the instant torque values from the load torque, in steady state regime.

2 Direct Torque Control principle

The basic model of the classical DTC induction motor scheme is shown in figure 1. It consists of torque and stator flux estimators, torque and flux hysteresis comparators, a switching table and a VSI. The basic idea of DTC is to choose the optimum inverter voltage vector in order to control both stator flux and electromagnetic torque of machine simultaneously [1].

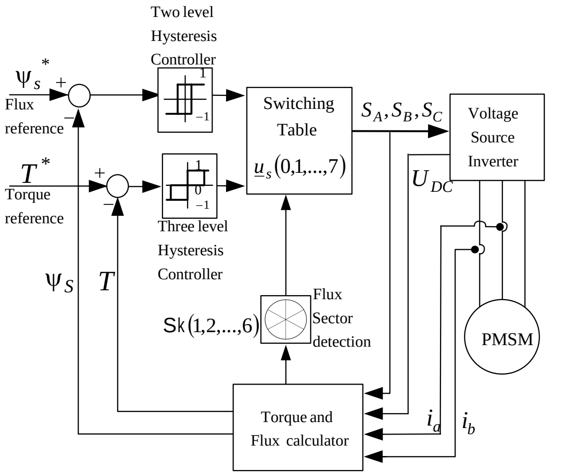


Fig. 1. Block diagram of the conventional DTC

The stator flux space vector, $\underline{\psi}_s$, is calculated in the stationary reference frame ($\alpha - \beta$) using the stator voltage equations [5]. The circular trajectory of stator flux is divided into six symmetrical sectors referred to inverter voltage vectors. The $\alpha - \beta$ components of the stator flux are used to determine the sector in which the flux vector are located. The calculated magnitude of stator flux and electromagnetic torque are compared with their reference values in their corresponding hysteresis comparators. Finally, the outputs of the comparators and the number of sector at which the stator flux space vector is located are fed to a switching table to select an appropriate inverter voltage vector [5].

2.1 The proposed DTC schemes

In conventional DTC, a single stator voltage vector of the inverter standard topology is selected during every control sampling period, and it is maintained constant for the whole period. By this switching technique, based on hysteresis, large and small torque and flux errors are not differentiated, which causes an extra torque ripple in motor steady state operation.

2.1.1 DTC with the variable amplitude of the inverter basic space phasors

The proposed method for torque ripple reduction, presented in this paper, consists in the modulation of the nonzero voltage vector duration over a sampling period, according to the torque and stator flux errors, using simmetric PWM. The nonzero voltage vectors are selected using a switching table, like in classical DTC. The null vectors are automatically inserted by using PWM, so they are no more needed in the switching table. Consequently, in the proposed control scheme, shown in figure 2Fig. , simple comparators, with no hysteresis, are used. A duty ratio calculator and a PWM block have been added to the classical scheme.

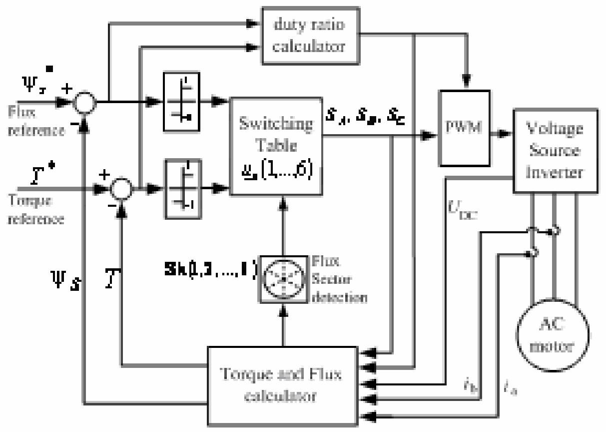


Fig. 2: Block diagram of the proposed control

Every sample time, one of the six nonzero voltage vectors are selected from the switching table, and it is applied to the inverter using simmetric PWM switching strategy. The PWM period is considerred equal to the control sample period.

To apply to the inverter the selected voltage vector (denoting the corresponding inverter switching states S_i, $i = A, B, C$), with a given duty ratio, it was adopted the following method: for $S_i = 0$, the pulse duty ratio of the corresponding inverter leg takes zero value, otherwise it takes the calculated value.

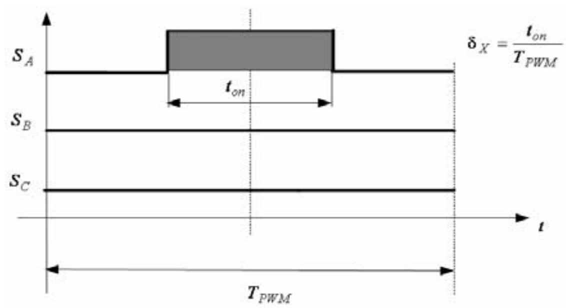


Fig. 3 Example: voltage vector (100) with reduced amplitude, accordin to calculated duty ratio

The calculation procedure of the duty ratio is presented below.

In order to preserve the very good dynamic response of the classical DTC, the voltage duty ratio is modified only when the actual torque value is located in a ”proximity” zone, arround the reference value, otherwise it is kept at 100%. This zone, whose width is denoted by Z_T, is similar to the torque hysteresis band of the classical DTC torque comparator.

The duty ratio, as a function of the torque and flux error, is calculated as in (1), so that to be a fractionar value.

$$\delta = \left|\frac{\varepsilon_T}{Z_T}\right| + \left|\frac{\varepsilon_F}{Z_F}\right|\left(1-\left|\frac{\varepsilon_T}{Z_T}\right|\right) \le 1 \qquad (1)$$

where: ε_T and ε_F are the torque error and respectively the flux error;

Z_T and Z_F are the corresponding base values used for normalization. [8]

The second term in (1) was introduced in order to avoid the flux decrease at low frequencies, due to the stator ohmic drops, which can occure when the torque error becomes too small. This term takes into account the flux error, which is normalized in the same manner as the torque error.

The duty ratio δ is limitted to a minimum value, $\delta_{\min}$, in order to consider the maximum inverter switching frequency.

Considering the voltage duty ratio, the line voltage at the inverter output is given by (2).

$$U_l = \delta \cdot U_{DC} \qquad (2)$$

where: U_l is the line voltage at the inverter output,

U_{DC} is the DC link voltage.

At current sample time, the $\alpha-\beta$ components of the stator voltage are calculated using (3) and (4).

$$u_{s\alpha} = \frac{2}{3}\delta U_{DC}\left(S_A - \frac{S_B - S_C}{2}\right) \qquad (3)$$

$$u_{s\beta} = \frac{2}{3}\delta U_{DC}\frac{S_B - S_C}{\sqrt{3}} \qquad (4)$$

where δ is the duty ratio calculated at previous sample time.

2.1.2 DTC using Space Vector Modulation

In this scheme, a reference stator voltage space vector is calculated, in terms of magnitude and phase, using the instant values of torque and stator flux errors, and the flux position.

A normalized value of the reference voltage magnitude was calculated using equation (5). The right side of the equation is the same as that utilised for the duty ratio calculation in the previous scheme.

$$m = \left|\frac{\varepsilon_T}{Z_T}\right| + \left|\frac{\varepsilon_F}{Z_F}\right|\left(1-\left|\frac{\varepsilon_T}{Z_T}\right|\right) \le 1 \qquad (5)$$

For torque and flux errors situated in these zones, m is calculated using the expression (5), otherwise m equals 1 [9].

As regarding the voltage vector phase, its calculation is based on the conventional DTC principle. As presented in Section 2, the main idea of DTC is to choose the optimum voltage vector in order to achieve a simultaneous and decoupled control of the stator flux and electromagnetic torque. Every control sample time, one of the inverter voltage vector is selected according to the torque and flux errors and the sector in which the actual flux vector is situated. The phase difference, $\Delta\theta$, between the selected voltage vector and the middle of the flux sector, is $k \cdot \pi/3$, where $k \in \{-2,-1,1,2\}$.

It can be prooved that for a given voltage vector and a flux sector, the torque slope depends on the flux vector phase angle. This determines a irregular torque ripple in steady state operation, especially when the sector changes.

In order to obtain a uniform torque ripple, the above mentioned dependency can be eliminated by considerring a voltage vector which is phase shifted with $\Delta\theta$ relatively to the flux vector phase angle (θ), instead of the middle of the sector like in the conventional DTC. For simplicity, there were preserved the phase difference quantities. The phase of the reference voltage vector were calculated by adding to the flux phase angle the phase difference $\Delta\theta$, whose value is simply derived from the sign of the torque and flux errors, like in equation (6).

$$\Delta\theta = sign(\varepsilon_T)\cdot\frac{\pi}{6}\left(3 - sign(\varepsilon_F)\right) \qquad (6)$$

$$\alpha = \theta + \Delta\theta \qquad (7)$$

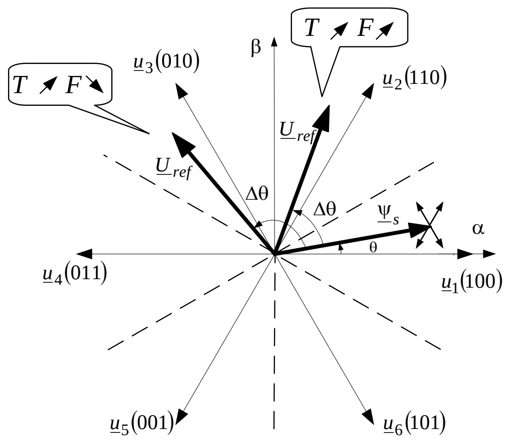


Fig. 4 The voltage space vector angle for two cases of torque and flux commands

The reference voltage vector, with the calculated magnitude, m, and phase θ, is applied to the inverter using Space Vector Modulation [6]. In the linear region, the voltage vector at the inverter output is:

$$\underline{U}_{ref} = m \cdot \frac{\sqrt{3}}{2} \left| \underline{u}_i \right| \cdot e^{j\alpha} \quad (13)$$

where: $\left| \underline{u}_i \right|$ is the modulus of the inverter basic space vectors.

$m = \frac{\left| \underline{U} \right|_{ref}}{\left| \underline{U} \right|_{max}}$ is the normalized value of the reference voltage vector magnitude; $\left| \underline{U} \right|_{ref}$ is the magnitude of the reference voltage.

In figure 5 is presented the block diagram of the proposed DTC-SVM scheme.

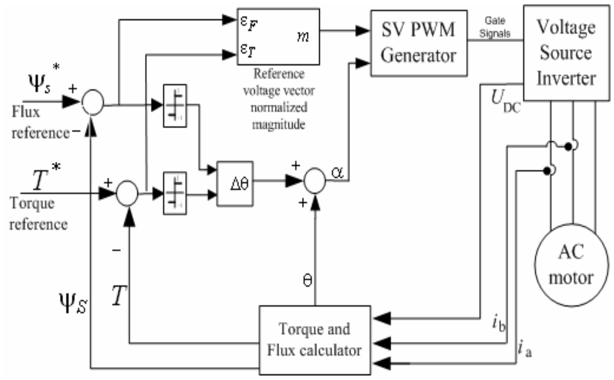


Fig. 5 Simulink block diagram of the proposed DTC-SVM scheme

The blocks within the dotted frame illustrate the algorithm for the reference voltage calculation.

Figure 6 illustrates the reference voltage space vector generation [6]. The values t_1 and t_2 represent the durations of the two inverter voltage vectors which are adjacent to the reference voltage vector, and are calculated using equations (14).

$$t_1 = m \cdot \cos\left(\alpha_1 + \frac{\pi}{6} \right)$$
$$t_2 = m \cdot \sin \alpha_1 \quad (14)$$
$$t_0 = 1 - t_1 - t_2$$

where: t_0 is the duration of the null vector.

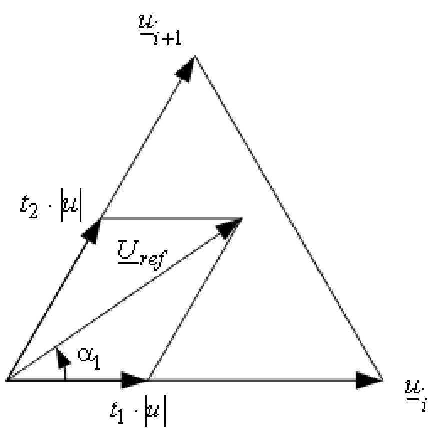


Fig. 6 The reference voltage space vector generation

From t_1, t_2 and t_0 there are derived the switching moments (comp1, comp2, comp3), corresponding to each inverter leg (K_1, K_2, K_3), as shown in figure 7.

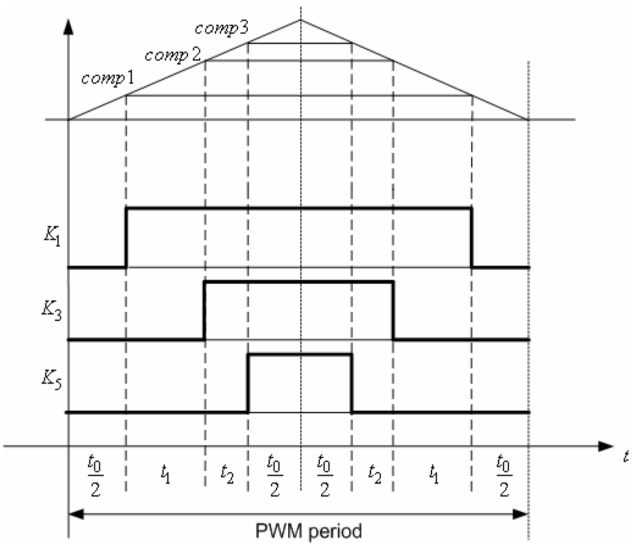
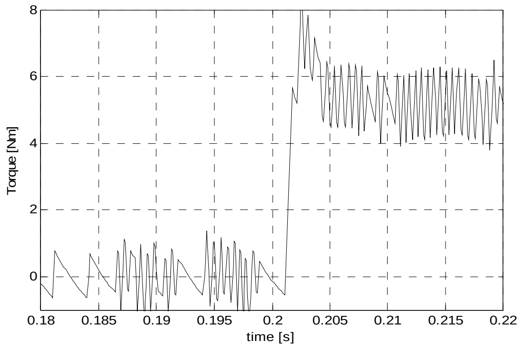


Fig. 7 SVM switching pattern

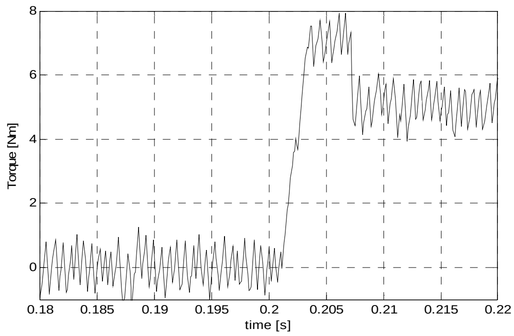
3 Results

The numerical simulations were made in Matlab-Simulink environment for a 0.75 kW induction motor drive.

In figures 8, 9 and 10 is represented the electromagnetic torque produced by the motor in the conventional DTC scheme and the two proposed schemes, respectively.

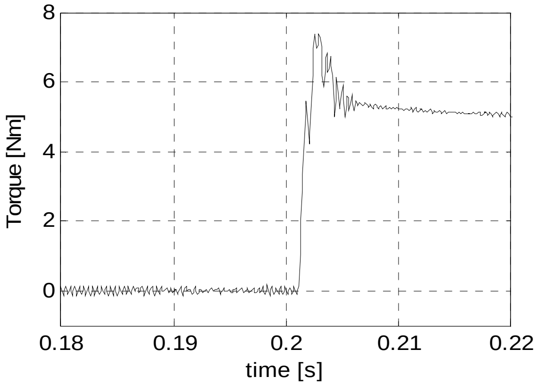


(a)



(b)

Fig. 8 Conventional DTC



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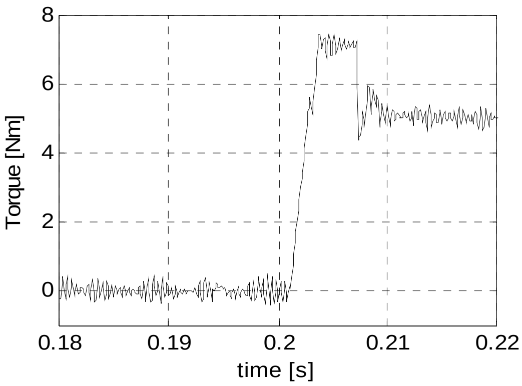
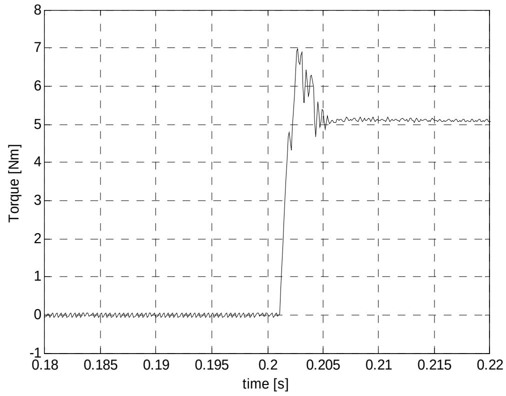
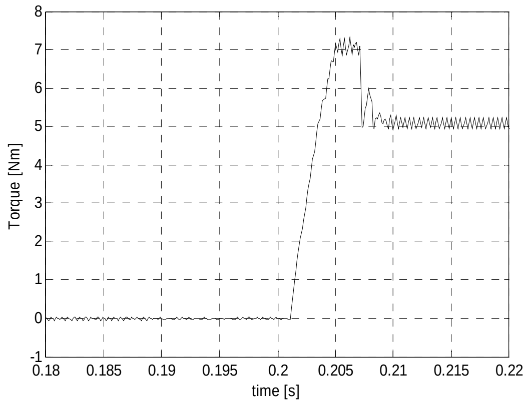


(b)

Fig. 9 The proposed method using variable duty ratio



(a)



(b)

Fig. 10 The proposed method using SVM

Motor parameters:

$P_n = 750\ (W);\ n_n = 1390\ (rpm);\ M_n = 5{,}15\ (Nm)$

$p = 2;\ I_n = 2{,}1(A);\ R_s = 10(\Omega);\ R_r = 6{,}3(\Omega)$

The control sampling period was set to 0.1 *ms* for all three control schemes, and in both proposed control schemes the PWM period was set to 10 kHz.

Graphical results of electromagnetic torque are presented for few operating points, showing the motor no load operation, followed by the operation with rated torque. The motor was subjected to a step load equal to the rated torque at 0.2 s.

As it can be observed, a torque ripple reduction was obtained using the proposed methods, for both low and high speed operation.

For a quantitative evaluation of the proposed methods, in table I it is presented the root mean square (RMS) deviation of the developed torque. This are calculated for a set of operating points in steady state regime.

TABLE I
ROOT MEAN SQUARE (RMS) DEVIATION OF THE INSTANT TORQUE VALUES FROM THE LOAD TORQUE

		RMS of the torque deviation in percent of T_N		
speed [%]	torque [%]	Conventional DTC	DTC with variable duty ratio	DTC using SVM
10	10	10.1	1.27	0.84
	50	11.3	1.46	0.35
	100	11.8	1.58	0.68
50	10	10. 4	3.60	1.11
	50	9.7	2.99	1.33
	100	9.4	3.09	1.87
100	10	9.6	3.30	1.31
	50	9.9	3.75	1.15
	100	11.2	3.13	1.31

4 Conclusion

The paper presented two modified DTC schemes, which were designed to provide a lower torque ripple than the classical DTC. They utilize two different Pulse Width Modulation techniques to control the inverter output voltage.

The first proposed scheme has the advantage of preserving the structural simplicity of the conventional DTC, while adding very little computation effort.

In the last scheme the torque ripple is reduced in a significant larger amount than in the first one, but in the expense of an increased complexity which is inherently added by the Space Vector Modulation. However, SVM offers a better utilization of the inverter switching capability.

The specific algorithms proposed for the calculation of the duty ratio and, respectively, the reference voltage vector, are simple and also allow an easy tuning.

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