Direct Torque Control of Permanent Magnet Synchronous Motor (PMSM) – an approach by using Space Vector Modulation (SVM)

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Abstract: - This paper proposes a method of applying the Space Vector Modulation technique for Direct Torque Control (DTC) of a permanent magnet synchronous motor (PMSM) drive. By this method it is preserved the principle of the conventional DTC regarding the decoupled torque and flux control, while providing more flexibility for the inverter voltage utilization, in order to compensate the torque and flux errors in a smoother way than conventional DTC. For this purpose, a reference voltage space vector is calculated every sample time, using a simple algorithm, based on the torque error and the stator flux angle. Numerical simulations have been made to test the proposed method and results are presented.

Key-Words: - Direct Torque Control, permanent magnet synchronous motor, Space Vector Modulation

1 Introduction

Direct Torque Control was introduced by I. Takahashi and T. Noguchi [1] as a new performant control strategy for induction motor drives fed by Voltage Source Inverters (VSI).

It was introduced on the market by ABB [4], which consider it a viable alternative to Vector Flux Oriented Control.

The main advantages of DTC are the simple control scheme, a very good torque dynamic response, as well as the fact that it does not need the rotor speed or position to realize the torque and flux control (for this reason DTC is considerred a ”sensorless” control strategy).

These advantages can be fully exploited in those electric drives where not the speed, but only the torque is to be controlled. For this kind of applications, DTC can be a very attractive option, because it is able to provide high dynamic performance at convenient costs.

However, the classical DTC has some drawbacks, and one of these is the significant torque and current ripple generated in steady state operation.

Taking into account the large slopes of the resulted torque and the fact that only a single voltage vector is applied to the inverter in a control sampling period, the classical DTC needs high sampling frequencies (above 40 kHz [2]) to obtain a good steady state behavior. This requires high performance controllers, like the DSP, which rises the overall cost of the drive.

An effective modality for reducing the torque ripple without using a high sampling frequency is to calculate a proper reference voltage vector that can produce the desired torque and flux values, and then applied to the inverter using SVM. This approach is known in the literature as DTC-SVM [3], [4].

In this paper is proposed a simple method for the calculation of the reference voltage vector, which preserves the conventional DTC principle regarding the decoupled torque and flux control.

Excepting that inherent complexity is added to the classical DTC scheme due to the utilisation of SVM, the proposed method for calculating the reference voltage space vector requires little computation effort.

Numerical simulations have been made for both classical DTC and the proposed DTC-SVM scheme. The results are presented for several motor operating points, to show the improved steady state operation as compared to conventional DTC.

2 Direct Torque Control principle

The basic model of the classical DTC PMSM 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 voltage source inverter (VSI).

The configuration is much simpler than that of the FOC system where frame transformation, rotor position or speed sensors are required. The basic idea of DTC is to choose the best voltage vector in

order to control both stator flux and electromagnetic torque of machine simultaneously [1].
At each sample time, the two stator currents i_{SA} and i_{SB} and DC-bus voltage U_{DC} are sampled.

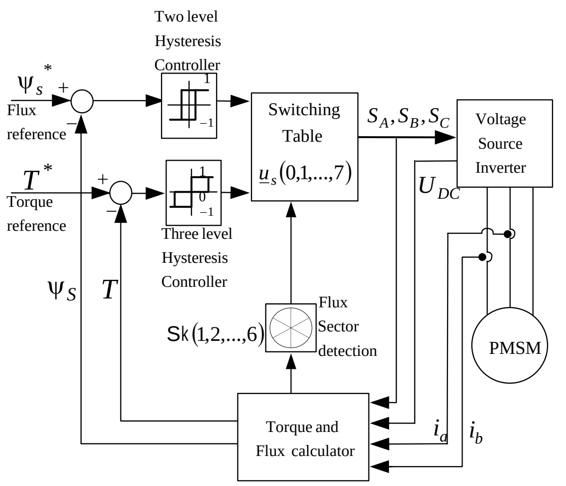

Fig. 1 Block diagram of the conventional DTC

The $\alpha-\beta$ components of the stator voltage space vector in the stationary reference frame are calculated as shown in (1) and (2) [5].

$$u_{s\alpha} = \frac{2}{3}U_{DC}\left(S_A - \frac{S_B - S_C}{2}\right) \tag{1}$$

$$u_{s\beta} = \frac{2}{3}U_{DC}\frac{S_B - S_C}{\sqrt{3}} \tag{2}$$

where: S_A, S_B, S_C denote the inverter switching states, in which $S_i = 1$ $(i = A, B, C)$, if the upper leg switch is on and $S_i = 0$, if the upper leg switch is off.
The $\alpha-\beta$ components of the stator current space vector are calculated using equations (3) and (4), supposing the motor has the star connection.

$$i_{s\alpha} = i_{sA} \tag{3}$$

$$i_{s\beta} = \frac{i_{sA} + 2i_{sB}}{\sqrt{3}} \tag{4}$$

Using the equations (1)–(4) and the stator resistance, the $\alpha-\beta$ components of the stator flux are calculated in (5) and (6):

$$\psi_{s\alpha} = \int (u_{s\alpha} - R_s i_{s\alpha})dt \tag{5}$$

$$\psi_{s\beta} = \int (u_{s\beta} - R_s i_{s\beta})dt \tag{6}$$

The circular trajectory of stator flux is divided into six symmetrical sections (S_1 – S_6) referred to inverter voltage vectors, as shown in figure 2.
The $\alpha-\beta$ components of the stator flux are used to determine the sector in which the flux vector are located.

Then using equations (3) – (6), the magnitude of the stator flux and electromagnetic torque are calculated in (7) and (8).

$$|\psi_s| = \sqrt{\psi^2{}_{s\alpha} + \psi^2{}_{s\beta}} \tag{7}$$

$$T_e = \frac{3}{2}P\left(\psi_{s\alpha}i_{s\beta} - \psi_{s\beta}i_{s\alpha}\right) \tag{8}$$

where: P is the number of pole pairs
Rs is the Stator resistance

The calculated magnitude of stator flux and electric torque are compared with their reference values in their corresponding hysteresis comparators as are shown in figure 1.
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].
As shown in figure 2, eight switching combinations can be selected in a two-level voltage source inverter, two of which determine zero voltage vectors and the others generate six equally spaced voltage vectors having the same amplitude.

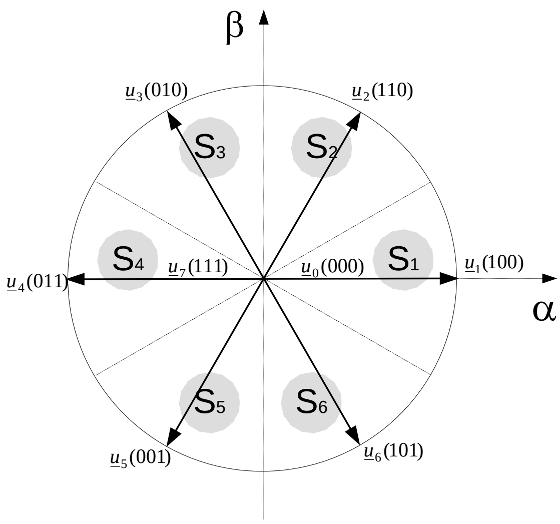

Fig. 2 The inverter voltage vectors and the stator flux sectors

The selected voltage vector will be applied to the AC motor at the end of the sample time.

3 Principle of the proposed method

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 are not differentiated, which

causes an extra torque ripple in motor steady state operation.

In the proposed control scheme, a reference stator voltage space vector is calculated, in terms of magnitude and phase, using the instant value of torque, and the flux angle.

To determine the normalized magnitude of the reference voltage, it was introduced the expression (9).

$$m = \left|\frac{\varepsilon_T}{Z_T}\right| \le 1 \tag{9}$$

where: $\left|\frac{\varepsilon_T}{Z_T}\right|$ is the normalized value of the torque error ;

ε_T is the torque error;

Z_T is the corresponding base value used for normalization;

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

$|\underline{U}|_{ref}$ is the magnitude of the reference voltage.

The base value Z_T represents a proximity zone arround the torque reference value (analog to the hysteresis band in the conventional DTC).

For torque errors situated in this zone, m is calculated using the expression (9), otherwise m equals unity. Expression (9) establishes a linear dependency between the voltage vector normalized magnitude and the torque error, as shown in figure 3.

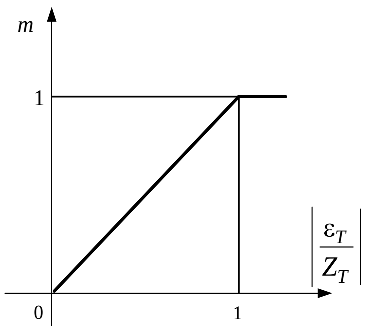

Fig. 3 The characteristic of the normalized voltage magnitude (m) with respect to the normalized torque error

The modality adopted for the calculation of the voltage vector phase is based on the conventional DTC principle. As presented in Section 1, 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:

$$k\frac{\pi}{3}\text{, where } k \in \{-2,-1,1,2\} \tag{10}$$

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 an 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 (11).

$$\Delta\theta = sign(\varepsilon_T)\cdot\frac{\pi}{6}\left(3 - sign(\varepsilon_F)\right) \tag{11}$$

$$\alpha = \theta + \Delta\theta \tag{12}$$

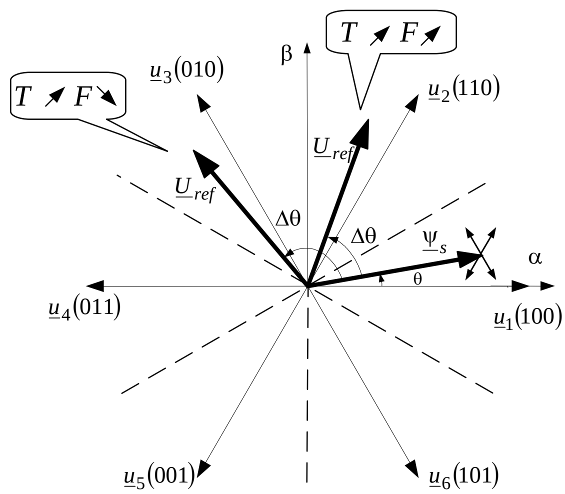

Fig. 4 The voltage space vector angle for two cases of torque and flux commands

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

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

where $\left| \underline{u}_i \right|$ is the modulus of the inverter basic space vectors.
In figure 5 is presented the Simulink block diagram of the proposed DTC-SVM scheme.

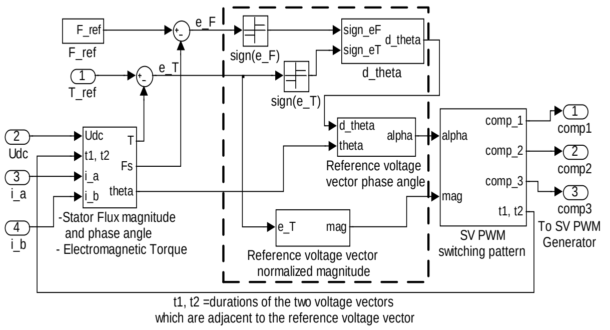

Fig. 5 Simulink block diagram of the proposed DTC-SVM scheme

The blocks within the dashed 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 (per unit) of the two inverter voltage vectors which are adjacent to the reference voltage vector, and are calculated using equations (14).

$$\begin{aligned} t_1 &= m \cdot \cos\left(\alpha_1 + \frac{\pi}{6}\right) \quad [pu] \\ t_2 &= m \cdot \sin \alpha_1 \quad [pu] \\ t_0 &= 1 - t_1 - t_2 \quad [pu] \end{aligned} \tag{14}$$

where: t_0 is the duration of the null vector.

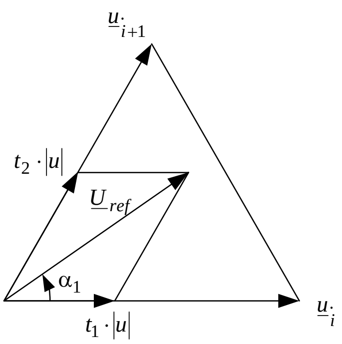

Fig. 6 The reference voltage space vector generation

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

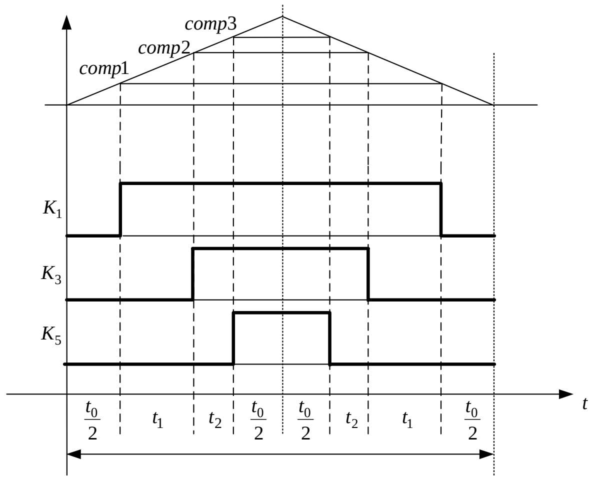

Fig. 7 SVM switching pattern

3 Results

Graphical results are presented for few operating points, showing the motor no load operation, followed by the operation with rated torque.
The simulations were made in Matlab-Simulink® environment, for a nonsalient-poles PMSM, with the following parameters:

- Rated torque: $T_n = 3\,Nm$;
- Number of pole pairs: $P = 2$
- Stator resistance: $R_s = 2.875\,\Omega$
- q and d axis inductances: $L_d = L_q = 8.5\,mH$
- Flux induced by magnets: $\Psi_m = 0.175\,Wb$

In order to adequately illustrate the comparison between the conventional DTC and DTC with proposed improvement scheme, the torque and flux hysteresis bands widths were set (by trial and error) so that the torque to be as low as possible in conventional DTC:

$$HB_T = 0.11 \cdot T_n$$

where: HB_T is the torque hysteresis band width
T_n is the motor rated torque,

$$HB_F = 0.04 \cdot F_n$$

where: HB_F is the flux hysteresis band width
F_n is the rated flux.

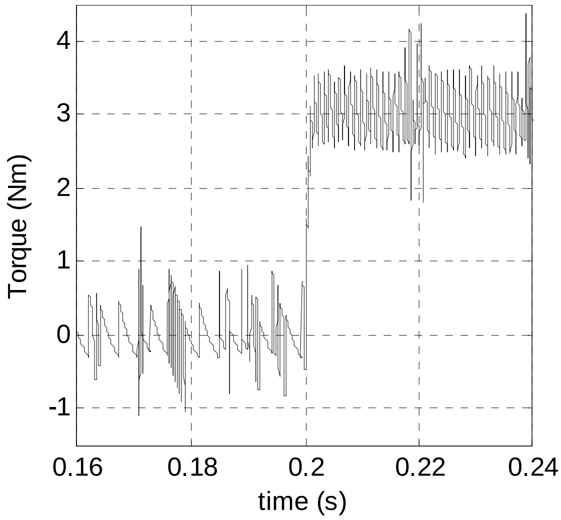

Fig. 8 Classic DTC, at 100 rpm

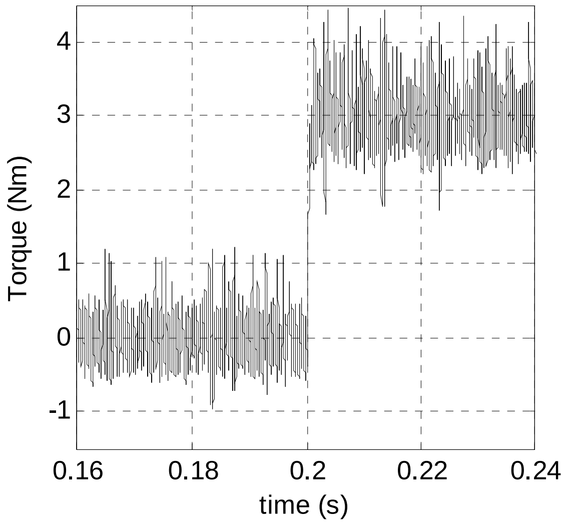

Fig. 9 Classic DTC, at 1000 rpm

The motor was subjected to a step load equal to the rated torque at 0.2 s.

The control sampling period was set to 100 μs. The PWM period, when used SVM, is equal to the control sample period.

The zone width Z_T introduced by the proposed method, was set to $0.1 \cdot T_n$.

The results obtained by conventional DTC are represented in figure 8 and 9, for low and respectively high frequency.

In Figure 10 and 11 are shown the results obtained by using the proposed DTC-SVM scheme, also for low and respectively high frequency. There can be seen the diminished torque ripple as compared to conventional DTC.

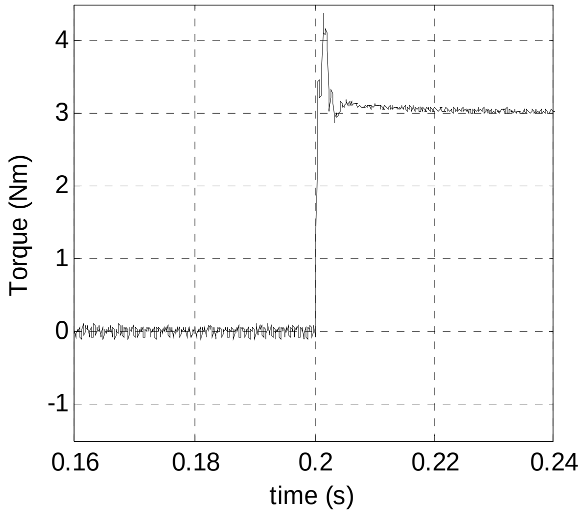

Fig. 10 DTC with voltage control using the proposed method, at 100 rpm

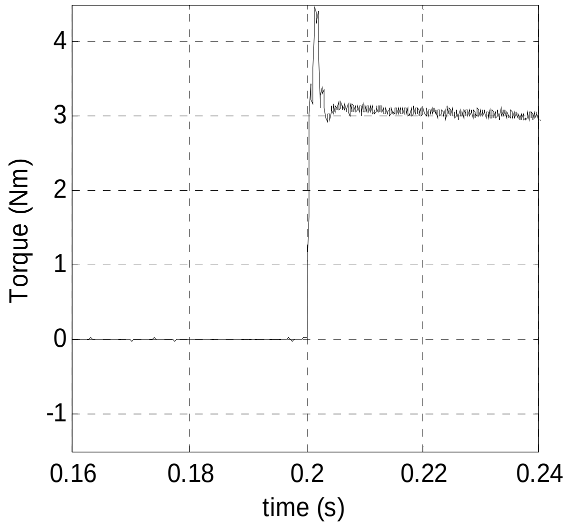

Fig. 11 DTC with voltage control using the proposed method, at 1000 rpm

4 Conclusion

In this paper it was presented a method of utilisation of Space Vector Modulation for the Direct Torque Control of a PMSM. For this purpose, at every control sample time a reference voltage vector is calculated and applied to the inverter using SVM. To determine the reference voltage, a simple algorithm was proposed, based on the torque error and the flux phase angle.

The results show that a smooth steady state operation was obtained when using the proposed method. Moreover, a constant inverter switching frequency is ensured by using SVM.

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