APPLICATION OF SPACE VECTOR MODULATION IN DIRECT TORQUE CONTROL OF PMSM

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Summary The paper deals with an improvement of direct torque control method for permanent magnet synchronous motor drives. Electrical torque distortion of the machine under original direct torque control is relatively high and if proper measures are taken it can be substantially decreased. The proposed solution here is to combine direct torque control with the space vector modulation technique. Such approach can eliminate torque distortion while preserving the simplicity of the original method.

1. INTRODUCTION

Direct torque control (DTC) as the control method for electric drives of small and medium range was developed more than twenty years ago in Japan [1]. Since then many attempts to improve DTC properties have been made due to its known drawbacks. One of the first improvements was proposed by the author of the method Isao Takahashi himself. To smooth the torque of the machine he suggested implementation of double three-phase inverter [2]. This type of inverter offers higher number of switching vectors with subsequent decrease of torque deviation. The high cost of such inverter was the reason why this method was not generally accepted (*especially in general industry applications*).

Another proposed improvement of DTC solved the problem related to non-zero sampling period interval in the case of digital implementation [3]. In classical DTC there are delays due to the non-zero sampling time and in the worst case subsequent increasing or decreasing vector is applied later than is sampling interval duration. Such way the drive with small electrical time constant shows very fast rise of the torque and therefore also high torque distortion. The main idea of the proposed approach was to calculate time interval for torque increasing and decreasing vector. The main drawback, which disqualifies this method, is excessive computation. There are also some works which try to combine DTC with algorithms based on artificial intelligence [4] but with the same drawbacks as were mentioned above.

This paper proposes the elimination of DTC drawbacks by exploitation of space vector modulation. Some works with this approach were already published but they were related to induction machine mainly. Further DTC of permanent magnet synchronous motor (PMSM) with modulator based on space vectors is described.

2. PMSM MATHEMATICAL DESCRIPTION

PMSM is widely used in servo-drive applications because of its advantages such as high efficiency, high power density and torque/inertia ratio and maintenance free. For investigation of the system properties the mathematical model of PMSM is in rotor fixed d_q frame is as follows:

$$\bar{u}_s = R_s \bar{i}_s + \frac{d}{dt}\bar{\Psi}_s \tag{1}$$

Components of magnetic flux vector in this reference frame are defined as:

$$\Psi_{sd} = L_{sd} i_{sd} + \Psi_{PM} \tag{2}$$

$$\Psi_{sq} = L_{sq} i_{sq} \tag{3}$$

An interaction between motor and load is described by the electro-mechanical differential equation:

$$\frac{d\omega_s}{dt} = \frac{1}{J}\left(T_e - T_L\right) \tag{4}$$

$$T_e = \frac{3}{2} p\left(\Psi_{PM} i_{qs} - \left(L_{sd} - L_{sq}\right) i_{sq} i_{sd}\right) \tag{5}$$

3. DIRECT TORQUE CONTROL OF PMSM

The principle of DTC is based on the selection of a suitable stator voltage vector according to the differences between the reference and actual values of the stator flux and according to the electromagnetic torque demand.

If proper voltage vector is selected then the stator flux is forced to rotate and produces the desired torque. During this rotation, the magnitude of the stator flux is maintained in a defined hysteresis range as it is shown in *fig.1*. Here in the second sector (θ_2) the third and fourth voltage vector will keep the vector of magnetic flux in defined hysteresis range. The proper instantaneous voltage vector is chosen according to the output signals from hysteresis controller as it is described the switching table.

s_T s_Ψ, θ		θ_1	θ_2	θ_3	θ_4	θ_5	θ_6
$s_\Psi = 1$	$s_T = 1$	u_2	u_3	u_4	u_5	u_6	u_1
	$s_T = -1$	u_6	u_1	u_2	u_3	u_4	u_5
	$s_T = 0$	u_0	u_7	u_0	u_7	u_0	u_7
$s_\Psi = 0$	$s_T = 1$	u_3	u_4	u_5	u_6	u_1	u_2
	$s_T = -1$	u_5	u_6	u_1	u_2	u_3	u_4
	$s_T = 0$	u_7	u_0	u_7	u_0	u_7	u_0

Described control principle brings a lot of advantages such as fast torque response, absence of PI controllers, absence of decoupling circuit and the most important overall simplicity of the method. In opposite the drawbacks of the method are torque and current distortion, variation of the switching frequency, high sampling frequency, selection of the same voltage vector to eliminate small and high torque (flux) differences etc.

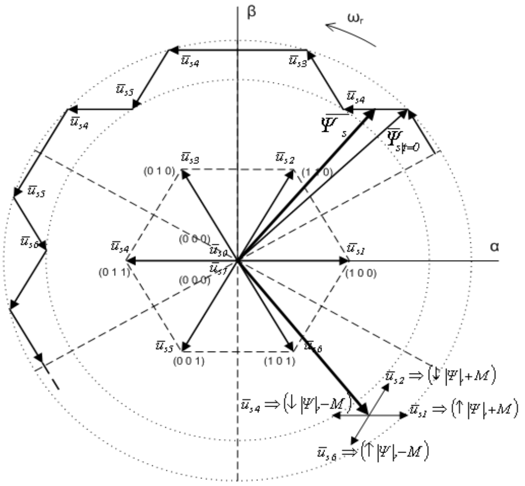

Fig.1. Switching of voltage vector in the sector 2 and 6

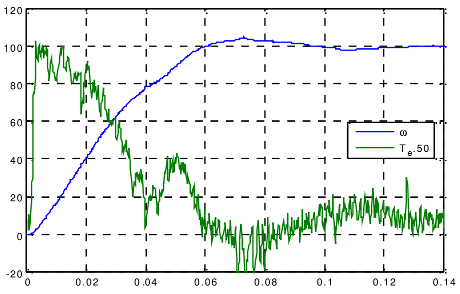

Fig.2. Typical torque response of the classical DTC

Fig. 2 shows behavior of PMSM with DTC during transient, which is step change of the demanded velocity (*experimental results*). From *fig. 2* the significant torque distortion is evident.
Changes in switching frequency are shown in *fig.3.*

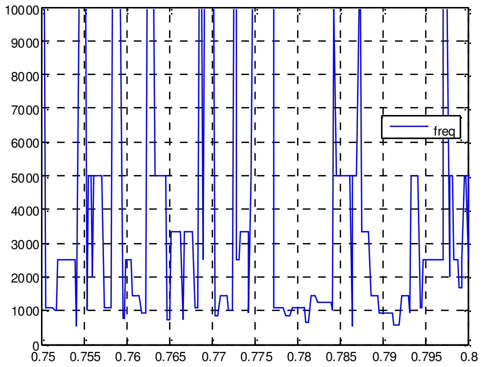

Fig.3. Detail of switching frequency

4. SPACE VECTOR MODULATION

Space vector modulation (SVM) was published two years earlier than DTC [5]. The principle of SVM is based on approximation of the reference voltage space vector by the discrete voltage space vector, which should minimize switching frequency and reduce current harmonics. SVM it achieves by switching of two voltage vectors which bounds actual sector in which the demanded voltage space vector is located.

If the magnitude and position (sector) of the reference voltage space vector are known there is possibility to calculate the proper switching time for switch on of the mentioned space vectors. The sum of them has to copy the reference in the best possible way. Only non-zero space vectors mentioned above are exploited this way. But there are also zero vectors, which has influence on amplitude level (*zero switching time of the zero vector results at the highest amplitude level*).

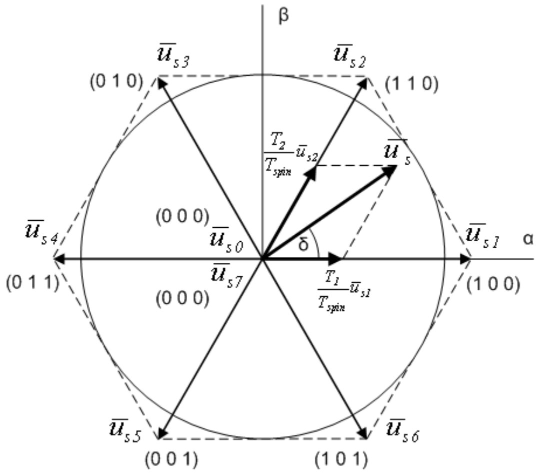

Fig.4. Space vector voltages

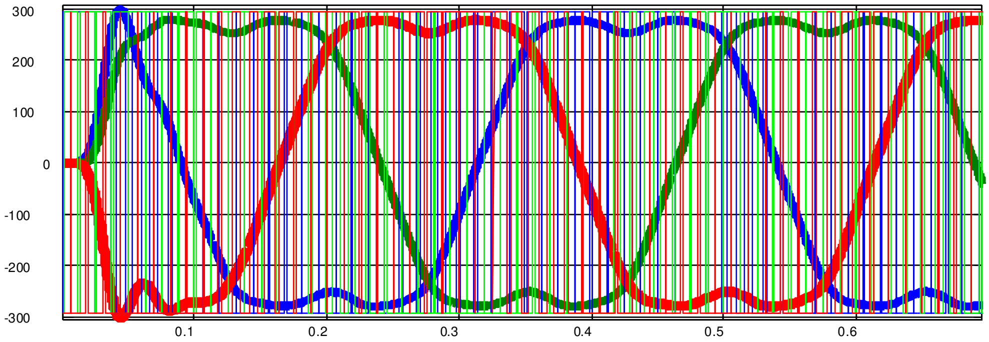

Fig.5. Phase voltages before and after filtration

Fig. 5 shows output (*modulated*) voltage and its filtered version where the influence of third harmonic is visible. This content helps to dislocate voltage neutral point, which results in better utilization of DC bus voltage.

5. DTC WITH SVM

The simplicity is one of the most significant DTC advantage. Every modification usually results in reduction of it. Therefore, the aim of proposed modification is to find improved version while maintaining the simplicity. Consequence of SVM will be an increase in complexity but moderate way only because nowadays space vector modulator is the standard part of DSP drive control boards of every producer. The only one problem which needs to be solved is how to obtain the references for modulator?

The answer might be simple. Every switched voltage space vector can be expressed in stator reference frame as α, β components. These components can be computed as (6):

$$\bar{u}_s = \left| s_T \right| \frac{2}{3} U_{DC} e^{j\left(\theta_{ss} + \frac{2\pi s_T}{3} = \frac{\pi s_T s_\Psi}{3} \right)} \qquad (6)$$

which represent analytical expression of the switching table (*tab.1*). Here θ_{ss} is the angle defining the middle of the sector ($\theta_{ss}=\pi(sector-1)/3$). Unfortunately this simple approach cannot be used due to the unacceptable references variances.

Another possibility to obtain the demanded voltage space vector in the stator reference frame is implementation of PI controllers. Such approach with two PI controllers for torque and flux control was already presented, [6]. But such arrangement reduces simplicity and can have negative influence on the drive dynamics. Compromise is achieved with utilization of the one PI controller as shown below.

In this modification the torque hysteresis comparators are replaced by PI controller. Its output represents the demanded motor load angle θ_L, which is proportional to the demanded torque change. In the next step, according to equations (2), (3) the components of magnetic flux vector are calculated. For transformation from d_q (rotor) to α_β (stator) coordinates general transformation functions are used. Exploiting the equation (1), the demanded α_β components of space voltage vector are obtained. Overall control structure for SVM of PMSM DTC is shown in *fig.4*.

Performance of the original and modified version of DTC are compared in *fig. 7*. As can be seen from this figure the difference between them is significant.

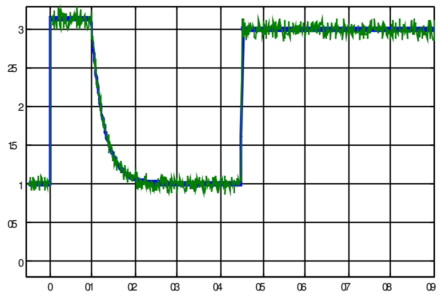

Fig. 7. Torque behavior, classical and modified version

Fig. 8 shows comparison of the step torque change in detail. As it was expected the settling time is shorter for the classical DTC but the torque distortion is smaller in the modified version.

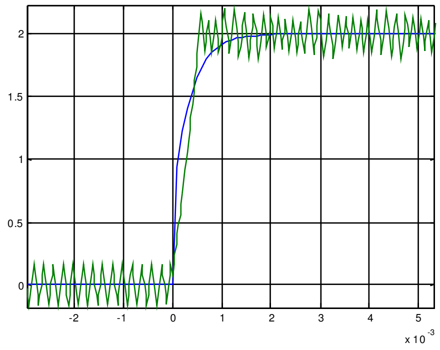

Fig. 8. Detailed view of torque step change

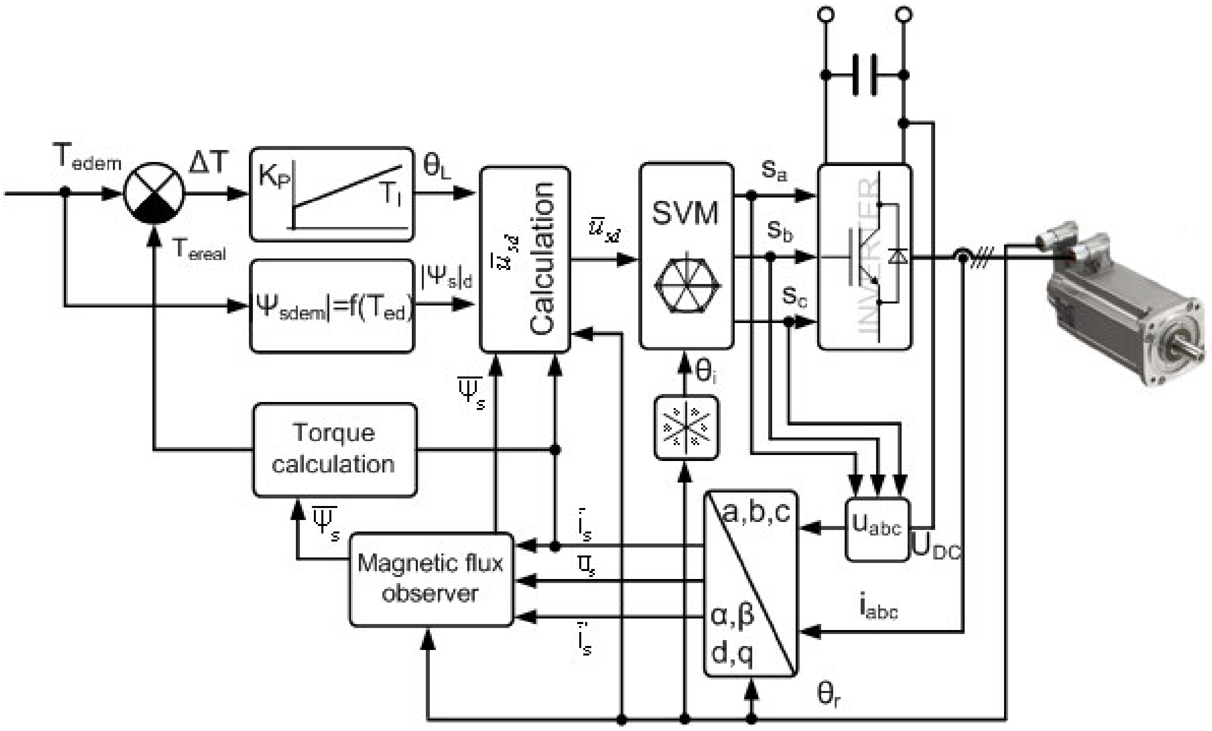

Fig. 9. Overall control structure of proposed DTC modification (without velocity loop)

6. CONCLUSION

A comparison of classical and modified version of DTC was presented. The aim of modification was the elimination of some drawbacks of the classical DTC version (*such as torque and current distortion or variable switching frequency*). Simulation results confirm the intention of modification. Motor torque and flux are smoother due to the change of modulation technique. The feedback based modulation technique was replaced by carrier based space vector modulation at the expense of simplicity lost and partially worse dynamics.

Acknowledgement

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REFERENCES

[1] Takahashi, I. and Noguchi, T.: *A New Quick Response and High Efficiency Strategy of Induction Motor*, IEEE IAS Meeting, 1985 , p. 496-502

[2] Takahashi, I. and Ohmori, Y.: *High performance direct torque control of an induction motor,* In *Ind. Applicat. Soc. Annu. Meet. Rec., 1987*, volume 1, pages 163–169.

[3] Flach, E, Hoffmann, R. and Mutschler, P.: *Direct Mean Torque Control Of Induction Motor,* Proc. European Power Electronics and Applications, 1997, Trondheim, Norway

[4] Arials, A., Romeral, J. L., Aldabas, E. and Jayne, M. G.: *Fuzzy logic Direct Torque Control*, ISIE `00, IEEE International Symposium on Industrial Electronics, dec.2000, Puebla, Mexico

[5] Pfaff, G.: *Steuerverfahren und Steuereinrichtung für einen Pulsewechselrichter,* Patent, German patent office, Nr. DE 31 31 344 C2, 1983.

[6] Kaźmierkowski M. P., Żelechowski M. and Świerczyński D.: *DTC-SVM an Efficient Method for Control Both Induction and PM Synchronous Motor*, In Proc. of the EPE-PEMC, 2004, Conf. 2-4 September, Riga, Latvia