Experimental Analysis of Direct Torque Control Methods for Electric Drive Application

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Abstract **– In this paper different direct torque and flux control of induction motor schemes (DTC) are presented. A control techniques, analysed in this paper, related to voltage inverters and their solutions are essential diverse. Classical DTC method, its modifications for torque and flux ripple reduction, as well as modified DTC method with PI controllers (PI-DTC) based on space vector modulation (SVPWM), are considered. For each of methods, theoretical principles and experimental results, at laboratory condition using dSPACE development tool realised, are presented.**

Keywords **– induction motor drive, space vector modulation, direct torque and flux control.**

I. INTRODUCTION

Direct Torque Control (DTC) was proposed by Takahashi and Depenbrock [1-2]. This method presents the advantage of a very simple control scheme of stator flux and torque by two hysteresis controllers, which give the input voltage of the motor by selecting the appropriate voltage vectors of the inverter through a look-up-table in order to keep stator flux and torque within the limits of two hysteresis bands. Different voltage vector selection criteria can be employed to control the torque according to whether the flux has to be reduced or increased, leading to different switching tables. Very high dynamic performance can be achieved by DTC, however, the presence of hysteresis controllers leads to a variable inverter switching frequency operation. In addition, the time discretization, due to digital implementation, plus the limited number of available voltage vectors is source of large current and torque ripple, causing the deterioration of the steady performance especially in low speed range. In order to improve the steady performance, different DTC strategies have been proposed to perform constant switching frequency operation and to decrease the torque ripple.

This paper presents the theoretical principles of conventional DTC method, its modification in order to reduce the torque and stator flux pulsations, and constant switching frequency DTC method with PI controllers (PI-DTC), which solved some of the above-mentioned shortcomings [3-4]. Each of the considered method was implemented and experimentally verified in the dSPACE development system in the laboratory.

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II. PRINCIPLES OF DIRECT TORQUE CONTROL

A. DTC with Classical Switching Technique (c_DTC)

A uniform rotating stator flux is desirable, and it occupies one of the sectors at any time, Fig. 1. The stator flux vector has a magnitude of ψ_s with instantaneous angle $\theta_{\psi s}$.

If the stator flux vector is in sector 2, Fig. 1, the left influencing voltage vector has to be either $\mathbf{U}_1$ or $\mathbf{U}_6$. As seen from vector diagram, in case of applying voltage vector $\mathbf{U}_1$, the flux vector increases in magnitude. In case of vector $\mathbf{U}_6$, it decreases. This implies that the closer voltage vector applying increase the flux and the farther voltage vector decreases the flux and both of them change the flux vector magnitude and orientation. Similarly for all other sectors, the switching logic can be developed. A flux error (ψ_s^*-ψ_s), thus determines which voltage vector has to be called, is converted to the error state signal S_ψ using hysteresis flux controller with $\Delta\psi_s$ hysteresis band. The digitized output signals of the two level flux controller are given in Table I.

Torque error is processed through hysteresis controller to produce error state signal, S_m as shown in Table II. Interpretation is as follows: S_m=1 requires increasing the voltage angle, 0 means to keep it at zero, and S_m= -1 requires decreasing the voltage angle.

Combining the flux error output S_ψ, the torque error output S_m, and the sector number of the flux vector, a switching table can be realized to obtain the switching states of the inverter.

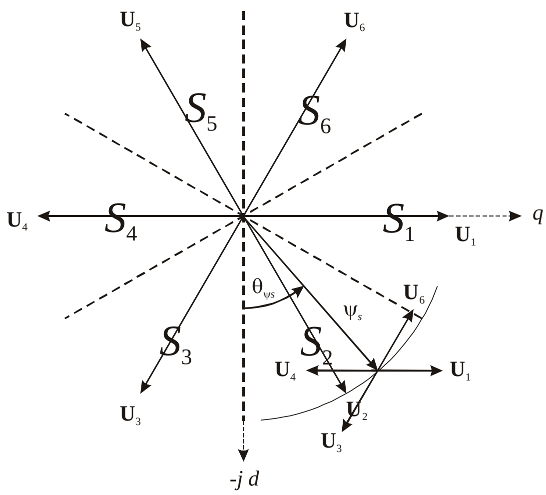

Fig. 1. Classical DTC and its sectors

In the classical DTC, there are several drawbacks [5-6]. Some of them can be summarized as follows:

- large and small errors in flux and torque are not distinguished. In other words, the same vectors are used during start up and step changes and during steady state;
- high torque pulsation especially at low speed.

TABLE I SWITCHING LOGIC FOR FLUX ERROR

State	S_ψ
$\psi_s^* - \psi_s > \Delta\psi_s/2$	1
$\psi_s^* - \psi_s < -\Delta\psi_s/2$	-1

TABLE II SWITCHING LOGIC FOR TORQUE ERROR

State	S_m
$m_e^* - m_e > \Delta m_e/2$	1
$-\Delta m_e/2 \le m_e^* - m_e \le \Delta m_e/2$	0
$m_e^* - m_e < -\Delta m_e/2$	-1

B. DTC with Modified DTC Technique (m_DTC)

In order to overcome the mentioned drawbacks, there are different solutions. One of the possible methods to improve the DTC performance is sector modification. Similar to the classical DTC six sectors is used including change in their orientation. Hence, instead of a first sector from 60º up to 120º, it will be from 30º up to 90º. The new sector division is shown in Fig. 2.

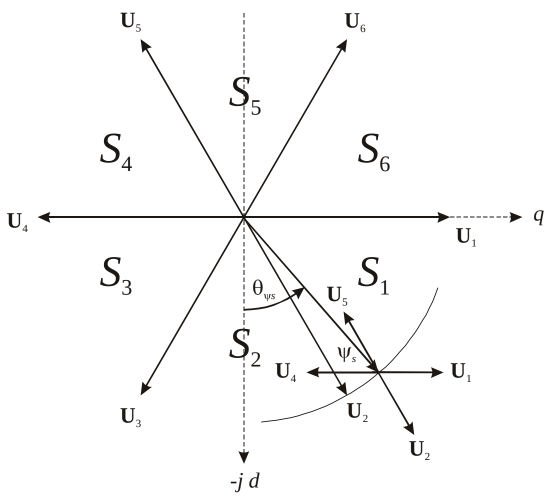

Fig. 2. Modified DTC and its sectors

Control of the flux and torque can be done by the similar procedure as for the classical DTC method. It can be observed that the states $\mathbf{U}_k$ and $\mathbf{U}_{k+3}$ are not used in the classical DTC (c_DTC) because they can increase or decrease the torque at the same sector depending on if the position is in its first 30 degrees or in its second ones. In the modified DTC (m_DTC), $\mathbf{U}_{k+2}$ and $\mathbf{U}_{k+5}$ are the states not used. However, now the reason is the ambiguity in flux instead of torque, as it was in the c_DTC. This is considered to be an advantage in favour of the m_DTC as long as the main point is to control the torque. Therefore, it is better to loose the usage of two states for flux ambiguity that for torque one [7-8].

C. DTC with Twelve sector Switching technique (12_DTC)

In classical DTC there are two states per sector that present a torque ambiguity. Therefore, they are never used. In a similar way, in the modified DTC there are two states per sector that introduce flux ambiguity, so they are never used either. It seems a good idea that if the stator flux locus is divided into twelve sectors instead of just six, all six active states will be used per sector. Consequently, it is arisen the idea of the twelve sector modified DTC (12_DTC). This novel stator flux locus is introduced in Fig. 3. Notice how all six voltage vectors can be used in all twelve sectors. However, it has to be introduced the idea of small torque increase instead of torque increase, mainly due to the fact that the tangential voltage vector component is very small and consequently its torque variation will be small as well.

As it has been mentioned, it is necessary to define small and large torque variations (S_m=1 - torque small increase, S_m=2 - torque large increase, S_m=-1 - torque small decrease, S_m=-2 - torque large decrease). Therefore, the torque hysteresis block should have four hysteresis levels and eight levels of flux and torque variation, Table III. It is obvious that $\mathbf{U}_2$ will produce a large increase in flux and a small decrease in torque in sector 2. On the contrary, $\mathbf{U}_3$ will decrease the torque in large proportion and the flux in a small one.

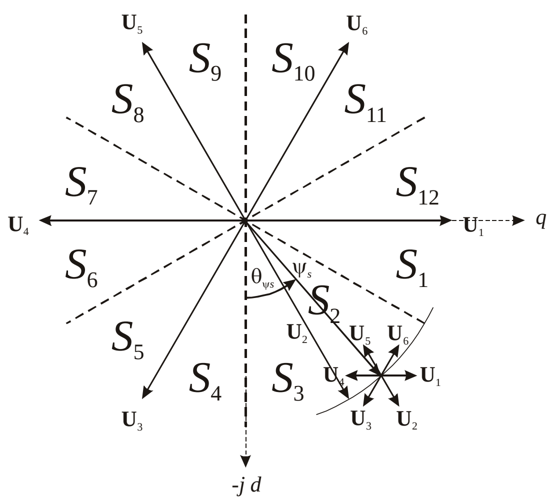

Fig. 3. Twelve sectors DTC

TABLE III LOGIC FOR TORQUE ERROR (12_DTC)

State	S_m
$m_e^* - m_e > \Delta m_e/2$	2
$\Delta m_e/2 \ge m_e^* - m_e \ge 0$	1
$0 > m_e^* - m_e \ge -\Delta m_e/2$	-1
$m_e^* - m_e < -\Delta m_e/2$	-2

D. DTC with PI Controllers (PI_DTC)

In subsections *A* to *C* the classical DTC method and its modifications are described, where regulation is in discrete values of output voltage inverter, with 8 discrete state (6 non-zero and 2 zero state).

The application of space vector modulation, SVPWM, enables to select the inverter output voltage of any phase position and amplitude in the domain of possible values. This approach allows the development of new DTC algorithm to improve the performance of existing ones. Fig. 4 shows the stator flux vector $\boldsymbol{\psi}_s$, which, in relation to the $-jd$ stationary reference system has a phase position $\theta_{\psi s}$. If we adopt the q-axis of synchronous reference system, q^e, coincides with stator flux vector, it is clear that the q component of inverter output voltage in synchronous reference system $\mathbf{U}_{qs}^e$, affects only to the amplitude of stator flux vector. Also, the d component of inverter output voltage in synchronous reference system, $\mathbf{U}_{ds}^e$, affects only to the phase position of the stator flux vector and consequently to the torque response.

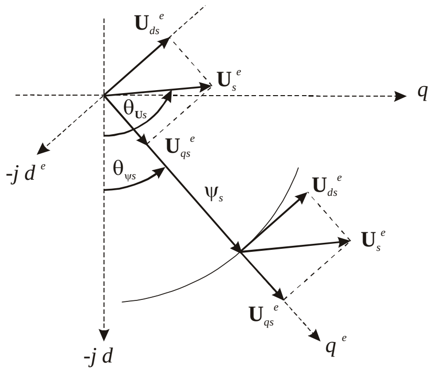

Fig. 4. Stator flux vector in synchronous reference frame

The above statements represent the basis for a modified DTC method with PI controllers (PI_DTC method). PI_DTC method uses PI controllers for calculation *qd* components of inverter output voltage in synchronous reference system. Trigonometric functions, necessary for the transformation from synchronous to stationary reference system, can be avoided by using the appropriate equations [8]. The need for adjusting the parameters of PI controller makes the method more complex than the traditional DTC methods described in subsections *A* to *C*. However, with well-designed PI controllers, we should expect much better performances in stationary conditions and slightly slower in the transient responses.

III. Experimental Results

In order to verify described DTC algorithms an experimental model of induction motor is formed. Its flow chart is presented on Fig. 5.

Control algorithm model of different DTC methods is formed in MATLAB/Simulink software. Measurement of motor currents is performed using LEM current probe and acquired with two analog inputs with sampling frequency 10 kHz. Speed measurement is realised using incremental encoder interfaced to dSPACE quadrature decoder with sampling frequency 1 kHz. In DTC methods described in subsections *A* to *C* (c_DTC, m_DTC and 12_DTC), inverter switching elements controled by three digital outputs with maximum switching frequency equal to 10 kHz. In DTC method described in subsection *D* (PI_DTC), control of inverter switching elements is performed by SVPWM with 5 kHz switching frequency. Discretization time in all experiments is 100 μs. Control of experiments, visualization, parameters variation and data acquisition are realised by dSPACE software *ControlDesk Developer.*

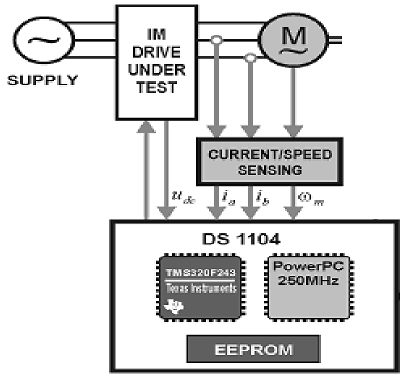

Fig. 5. Block diagram of experimental model

For DTC methods from subsections *A* to *C*, parameters: stator flux hysteresis band, $\Delta\psi_s$ and torque hysteresis width are adjusted on values 2% and 20%, respectively, in regard corresponding rated values. In this section experimental results of induction motor operation with DTC in torque control mode are presented. Reference stator flux is set to rated value, $\psi_s^*=\psi_{sn}$. Reference torque has square waveform, $m_e^*=\pm 3$ Nm, with the period 0.25 s. Motor is unloaded.

On Figs. 6 to 9 stator flux and estimated torque during the operation of described drive for previously explained DTC methods are presented. Also, torque is zoomed at the moment of its passing through zero for better insight. On the basis of the figures it can be concluded that the waveforms of stator flux and torque correspond to the conclusions given in section II. As was expected, PI_DTC method yields incomparable lower ripple waveform. Considering this criteria, presented control algorithm is equally good as vector control. Torque response during the change of reference is very fast and for DTC methods described in subsections *A* to *C* is about 0.0003 s. As expected, the PI_DTC method has a slower torque response and in the given case is 0.0012 s.

IV. Conclusion

In this paper, the theoretical principles of conventional DTC method, its modification in order to reduce the torque and stator flux pulsations, and constant switching frequency DTC method with PI controllers (PI-DTC), is presented. Each of the considered methods was implemented and experimentally verified in the dSPACE development system in the laboratory. Also, their advantages and limitations have been examined.

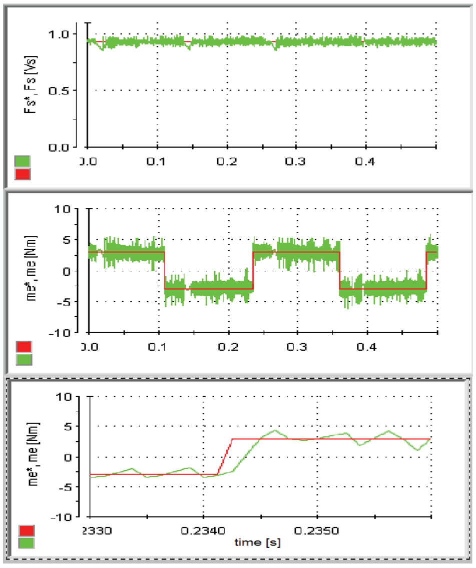

Fig. 6. Classical DTC method

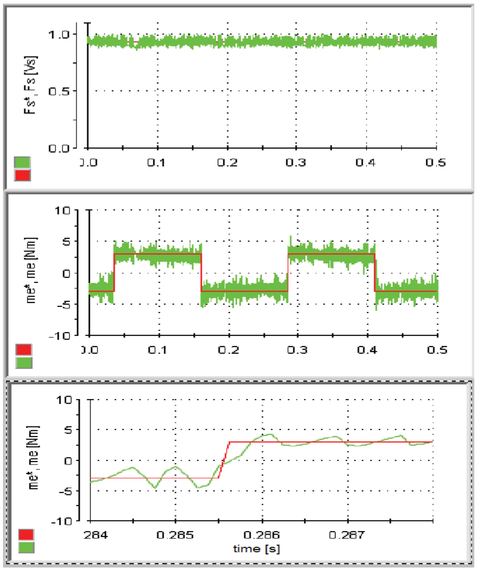

Fig. 7. Modified DTC method

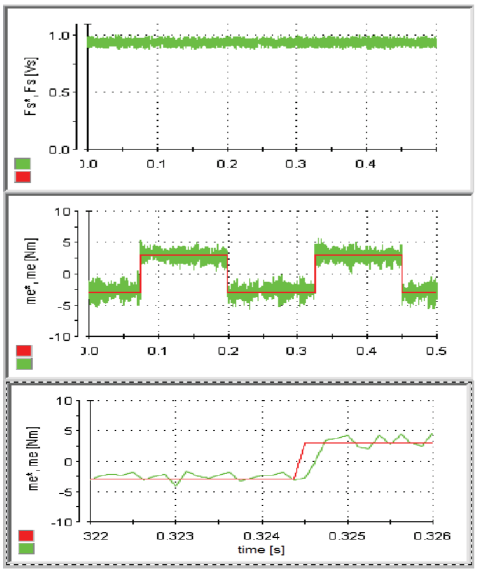

Fig. 8. DTC with twelve sector switching technique

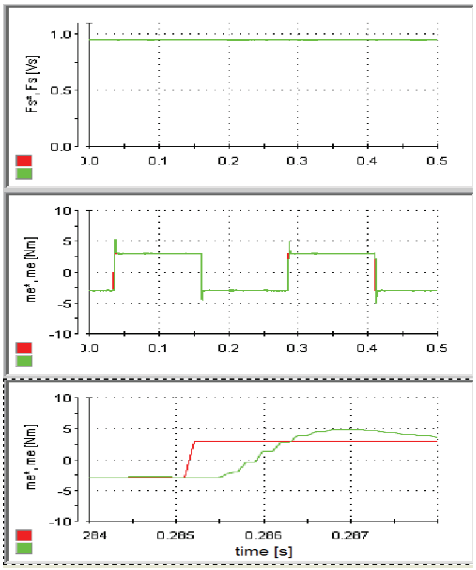

Fig. 9. DTC with PI controllers

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