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EXPERIMENTAL VERIFICATION 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. The control techniques, analysed in this paper, related to voltage inverters and their solutions are essentially 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 method, theoretical principles and experimental results, at laboratory condition using dSPACE development tool realised, are presented.*

Key words: *induction motor drive, space vector, direct torque control*

1. INTRODUCTION

Direct Torque Control (DTC) was proposed by M. Depenbrock and Takahashi [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 as shown in Fig.1. The application of this principle allows a decoupled control of flux and torque without the need of coordinate transformations, PWM pulse generators and current regulators. 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 the 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. In general, they require more complex control schemes in comparison to the basic DTC ones.

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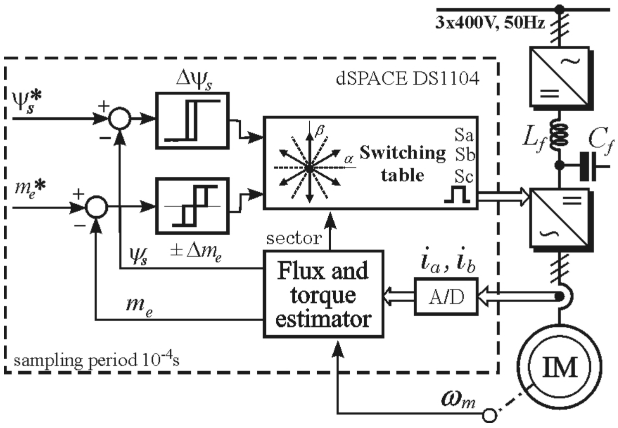


Fig. 1 Basic Direct Torque Control scheme for ac motor drives

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 [3-5]. Each of the considered method was implemented and experimentally verified in the dSPACE development system in the laboratory..

2. PRINCIPLES OF DIRECT TORQUE CONTROL

The implementation of the DTC scheme requires flux linkages and torque computations and generation of switching states through a feedback control of the torque and flux directly without inner current loops. For implementing the control loop, the actual stator flux (amplitude and orientation) and electromagnetic torque are calculated by an estimator from the stator voltages and currents

The stator q and d axis flux linkages are an integral of the stator EMF:

$$\psi_{qs} = \int (u_{qs} - r_s i_{qs}) dt \tag{1}$$

$$\psi_{ds} = \int (u_{ds} - r_s i_{ds}) dt \tag{2}$$

where r_s is stator resistance and u_{qs}, u_{ds}, i_{qs}, i_{ds} are voltage and current qd components.

Thus, flux magnitude strongly depends on the stator voltage. As the stator voltage changes, stator flux follows rapidly whereas the rotor flux (rotor current) changes are slower and less pronounced than that of the stator flux. This effect modifies the angle between stator and rotor fluxes and consequently the torque increases or decreases. Thus, stator flux and developed torque can be directly controlled by proper selection of the stator voltage, that is selection of consecutive inverter states without coordinate transformations.

The developed torque is obtained by the product of stator current and flux as:

$$m_e = \frac{3}{2}\frac{P}{2}(i_{qs}\psi_{ds} - i_{ds}\psi_{qs}) \tag{3}$$

where P is pole number.

Consider the inverter shown in Fig. 2. The terminal voltage u_a, with respect to negative of the *dc* supply, is determined by switching state S_a as shown in Table 1. The switching states S_b and S_c for line *b* and *c* can be similarly derived. The total number of switching states S_a, S_b, and S_c is eight and they are shown in Fig. 3. The stator *qd* voltages for each state are given by:

$$u_{qs} = u_{as} \tag{4}$$

$$u_{ds} = \frac{1}{\sqrt{3}}\left(u_{cs} - u_{\mathrm{bs}}\right) = \frac{1}{\sqrt{3}}u_{cb}\,. \tag{5}$$

The limited states of the inverter create discrete movement of the stator voltage vector $\mathbf{U}_s$, derived from components u_{qs} and u_{ds}.

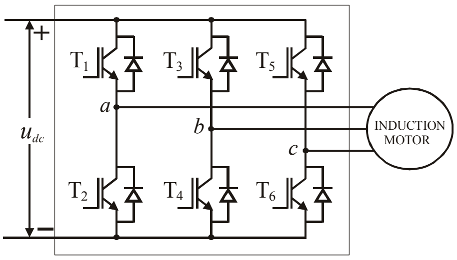


Fig. 2 Power circuit configuration of induction motor drive

Table 1 Switching state of inverter phase leg *a*

T_1	T_2	S_a	u_a
On	Off	1	u_{dc}
Off	On	0	0

3. 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. 4. 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. 4, the left influencing voltage vector has to be either $\mathbf{U}_1$ or $\mathbf{U}_6$. As seen from the 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 2.

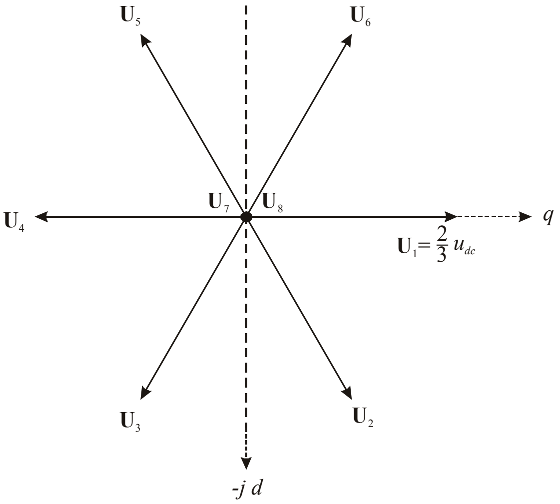


Fig. 3 Inverter output voltages

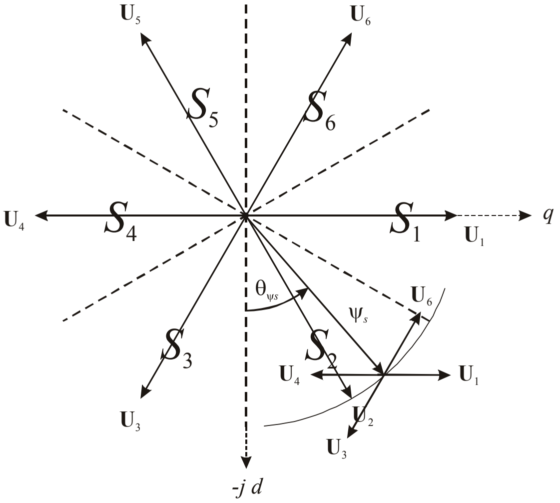


Fig. 4 Division of sectors for stator flux identification (c_DTC)

Table 2 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

Torque error is processed through hysteresis controller to produce error state signal, S_m as shown in Table 3. 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.

Table 3 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

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. The sectors of the stator flux vector are denoted from S_1 to S_6. Stator flux error after the hysteresis block can take only two values. Torque error after the hysteresis block can take three different values. The zero voltage vectors $\mathbf{U}_7$ and $\mathbf{U}_8$ are selected when the torque error is within the given hysteresis band, and must remain unchanged. Finally, the classical DTC (c_DTC) look up table is shown in Table 4.

In the classical DTC, there are several drawbacks [6-8]. 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 4 Switching states for c_DTC

S_ψ	S_m	S_1	S_2	S_3	S_4	S_5	S_6
1	**1**	$\mathbf{U}_6$	$\mathbf{U}_1$	$\mathbf{U}_2$	$\mathbf{U}_3$	$\mathbf{U}_4$	$\mathbf{U}_5$
1	**0**	$\mathbf{U}_8$	$\mathbf{U}_7$	$\mathbf{U}_8$	$\mathbf{U}_7$	$\mathbf{U}_8$	$\mathbf{U}_7$
1	-1	$\mathbf{U}_2$	$\mathbf{U}_3$	$\mathbf{U}_4$	$\mathbf{U}_5$	$\mathbf{U}_6$	$\mathbf{U}_1$
-1	1	$\mathbf{U}_5$	$\mathbf{U}_6$	$\mathbf{U}_1$	$\mathbf{U}_2$	$\mathbf{U}_3$	$\mathbf{U}_4$
-1	0	$\mathbf{U}_7$	$\mathbf{U}_8$	$\mathbf{U}_7$	$\mathbf{U}_8$	$\mathbf{U}_7$	$\mathbf{U}_8$
-1	-1	$\mathbf{U}_3$	$\mathbf{U}_4$	$\mathbf{U}_5$	$\mathbf{U}_6$	$\mathbf{U}_1$	$\mathbf{U}_2$

4. DTC WITH MODIFIED DTC TECHNIQUE (M_DTC)

In order to overcome the mentioned drawbacks, there are different solutions. One of the possible methods for improving the DTC performance is table 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. It can be observed that in this case, the states $\mathbf{U}_3$ and $\mathbf{U}_6$ are not used in the first sector, instead of $\mathbf{U}_1$ and $\mathbf{U}_4$ in c_DTC. The new sector division is shown in Fig. 5.

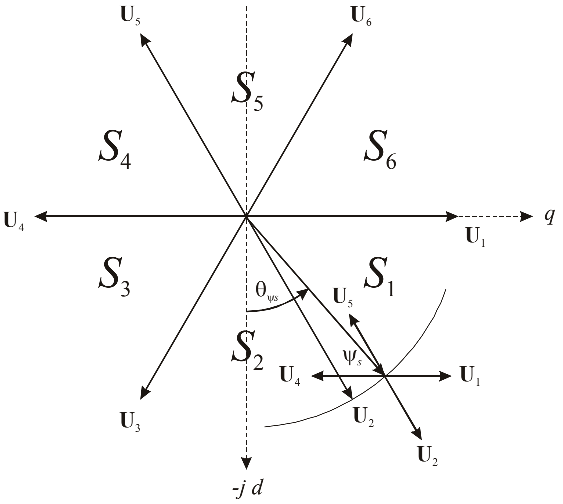


Fig. 5 Modified DTC and its sectors

Control of the flux and torque can be done by similar procedure as for the classical DTC method.

Table 5 shows the m_DTC look up table for all its six sectors. It can be seen 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 than for torque one [9].

Table 5 Switching states for m_DTC

S_ψ	S_m	S_1	S_2	S_3	S_4	S_5	S_6
1	**1**	$\mathbf{U}_1$	$\mathbf{U}_2$	$\mathbf{U}_3$	$\mathbf{U}_4$	$\mathbf{U}_5$	$\mathbf{U}_6$
1	**0**	$\mathbf{U}_7$	$\mathbf{U}_8$	$\mathbf{U}_7$	$\mathbf{U}_8$	$\mathbf{U}_7$	$\mathbf{U}_8$
1	-1	$\mathbf{U}_2$	$\mathbf{U}_3$	$\mathbf{U}_4$	$\mathbf{U}_5$	$\mathbf{U}_6$	$\mathbf{U}_1$
-1	1	$\mathbf{U}_5$	$\mathbf{U}_6$	$\mathbf{U}_1$	$\mathbf{U}_2$	$\mathbf{U}_3$	$\mathbf{U}_4$
-1	0	$\mathbf{U}_8$	$\mathbf{U}_7$	$\mathbf{U}_8$	$\mathbf{U}_7$	$\mathbf{U}_8$	$\mathbf{U}_7$
-1	-1	$\mathbf{U}_4$	$\mathbf{U}_5$	$\mathbf{U}_6$	$\mathbf{U}_1$	$\mathbf{U}_2$	$\mathbf{U}_3$

5. 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, the idea of the twelve sector modified DTC (12_DTC) arises. This novel stator flux locus is introduced in Fig. 6. Notice how all six voltage vectors can be used in all twelve sectors. However, the idea of small torque increase instead of torque increase has to be introduced, 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 6. It is obvious that $\mathbf{U}_2$ will produce a large increase in flux and a small decrease in torque in sector S_2. On the contrary, $\mathbf{U}_3$ will decrease the torque in large proportion and the flux in a small one. Finally, the look up table is presented in Table 7.

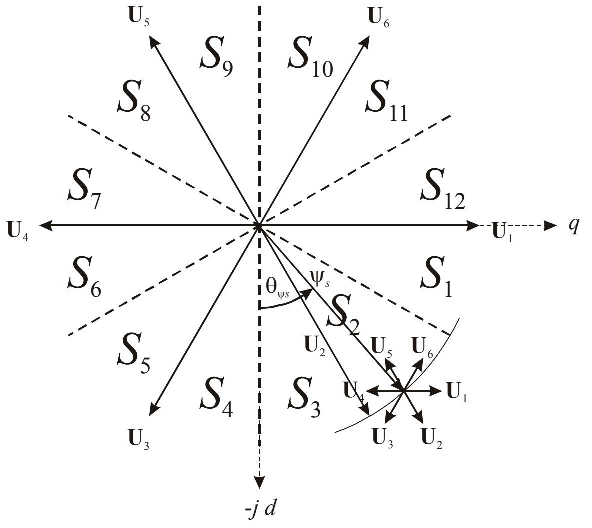


Fig. 6 Twelve sectors DTC

Table 6 Switching logic for torque error (12_DTC)

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

Table 7 Switching states for 12_DTC

S_ψ	S_m	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	S_{10}	S_{11}	S_{12}
1	2	U_6	U_1	U_1	U_2	U_2	U_3	U_3	U_4	U_4	U_5	U_5	U_6
1	1	U_1	U_1	U_2	U_2	U_3	U_3	U_4	U_4	U_5	U_5	U_6	U_6
1	-1	U_2	U_2	U_3	U_3	U_4	U_4	U_5	U_5	U_6	U_6	U_1	U_1
1	-2	U_2	U_3	U_3	U_4	U_4	U_5	U_5	U_6	U_6	U_1	U_1	U_2
-1	2	U_5	U_6	U_6	U_1	U_1	U_2	U_2	U_3	U_3	U_4	U_4	U_5
-1	1	U_5	U_5	U_6	U_6	U_1	U_1	U_2	U_2	U_3	U_3	U_4	U_4
-1	-1	$\mathbf{U}_4$	$\mathbf{U}_7$	$\mathbf{U}_5$	$\mathbf{U}_8$	$\mathbf{U}_6$	$\mathbf{U}_7$	$\mathbf{U}_1$	$\mathbf{U}_8$	$\mathbf{U}_2$	$\mathbf{U}_7$	$\mathbf{U}_3$	$\mathbf{U}_8$
-1	-2	U_3	U_4	U_4	U_5	U_5	U_6	U_6	U_1	U_1	U_2	U_2	U_3

6. DTC WITH PI CONTROLLERS (PI_DTC)

In Chapters 3 to 5 the classic 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 the selection of 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. 7 shows the stator flux vector $\mathbf{\Psi}_S$, 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.

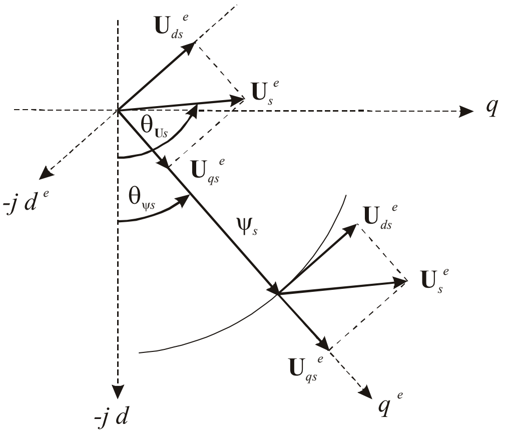


Fig. 7 Stator flux vector in synchronous reference frame

The above statements represent the basis for a modified DTC method with PI controllers (PI_DTC method) and principal block diagram is shown in Fig. 8.

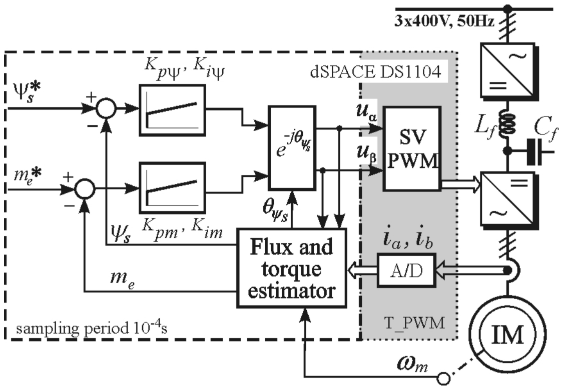


Fig. 8 PI_DTC principle block diagram

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 following equation:

$$\sin(\theta_{\psi s}) = \psi_{qs}/|\psi_s| \tag{6}$$

$$\cos(\theta_{\psi s}) = \psi_{ds}/|\psi_s| \tag{7}$$

The need for adjusting the parameters of PI controller makes the method more complex than the traditional DTC methods described in Chapters 3 to 5. However, with well-designed PI controllers, we should expect much better performances in stationary conditions and slightly slower in the transient responses.

7. EXPERIMENTAL RESULTS

In order to verify described DTC algorithms an experimental model of induction motor is formed. Its flow chart is presented in Fig. 9. The experimental setup consist of a 2.2 kW three phase induction motor, IGBT based PWM voltage-source inverter, incremental encoder, two current sensor, dSPACE ACE-Kit 1104 with DS1104 R&D Controller Board and PC. DS1104 R&D Controller Board is based on Texas Instruments' DSP TMS320F240. The board is equipped with 8 MB boot flash for applications, 32 MB global DRAM, eight analog-to-digital converters (four 16-bit and four 12-bit), eight digital-to-analog channels (16-bit), three-phase PWM outputs plus four single PWM outputs, twenty bits of digital I/O, incremental encoder interface and serial interface. PC is used for software development and results visualization.

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 sections 3 to 5 (c_DTC, m_DTC and 12_DTC), inverter switching elements controlled by three digital outputs with maximum switching frequency equal to 10 kHz. In DTC method described in section 6 (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.*

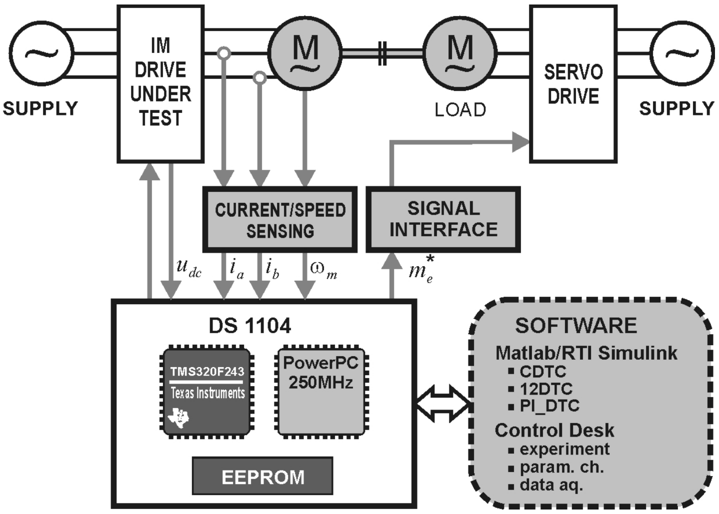
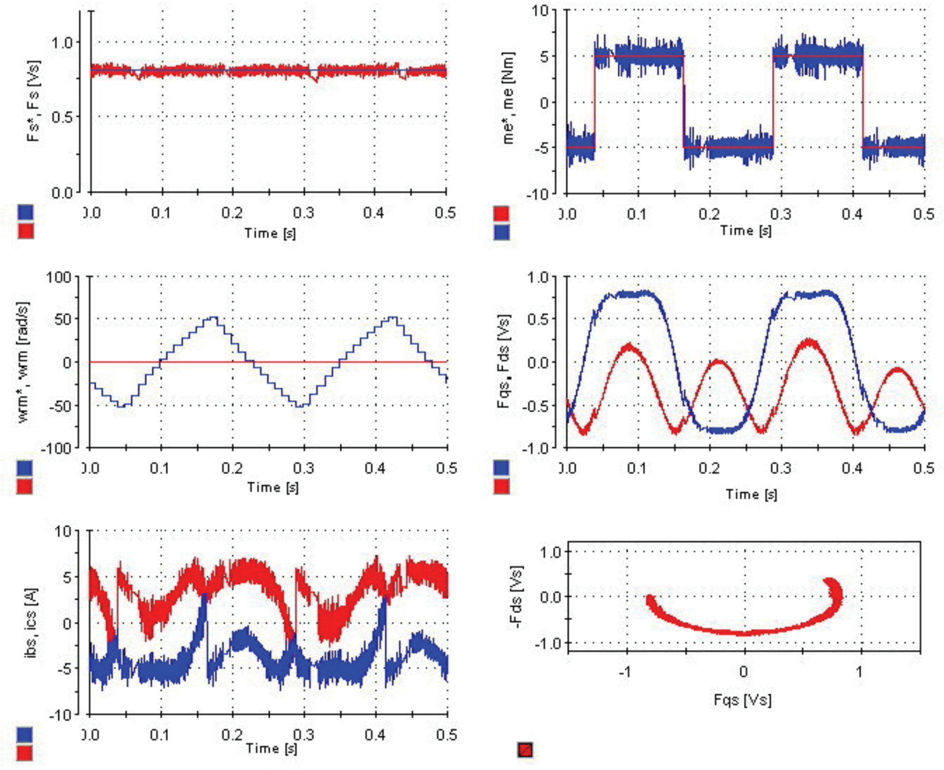


Fig. 9 Block diagram of experimental model

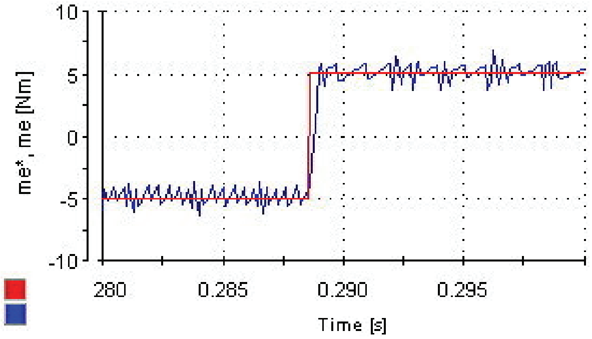
For DTC methods from sections 3 to 5, parameters: stator flux hysteresis band, $\Delta\psi_s$ and torque hysteresis width are adjusted on values 2% and 20%, respectively, in regard corresponding rated values. In this section experimental results of induction motor operation with DTC in torque control mode are presented. Reference stator flux is set to rated value, $\Psi_s^*=\Psi_{sn}$. Reference torque has square waveform, $m_e^*=\pm 5$ Nm, with the period 0.25 s. Motor is unloaded.

In Figs. 10a) to 13a) stator flux (F_s) and flux components (F_{qs},F_{ds}), estimated torque (m_e), actual speed (ω_{rm}), stator line currents (i_{bs}, i_{cs}) 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, Fig.10b)-13b).

On the basis of the figures it can be concluded that the waveforms of stator flux and torque correspond to the conclusions given in sections 3 to 6. 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 sections 3 to 5 is about 0.0003 s. As expected, the PI_DTC method has a slower torque response and in the given case it is 0.0012 s.

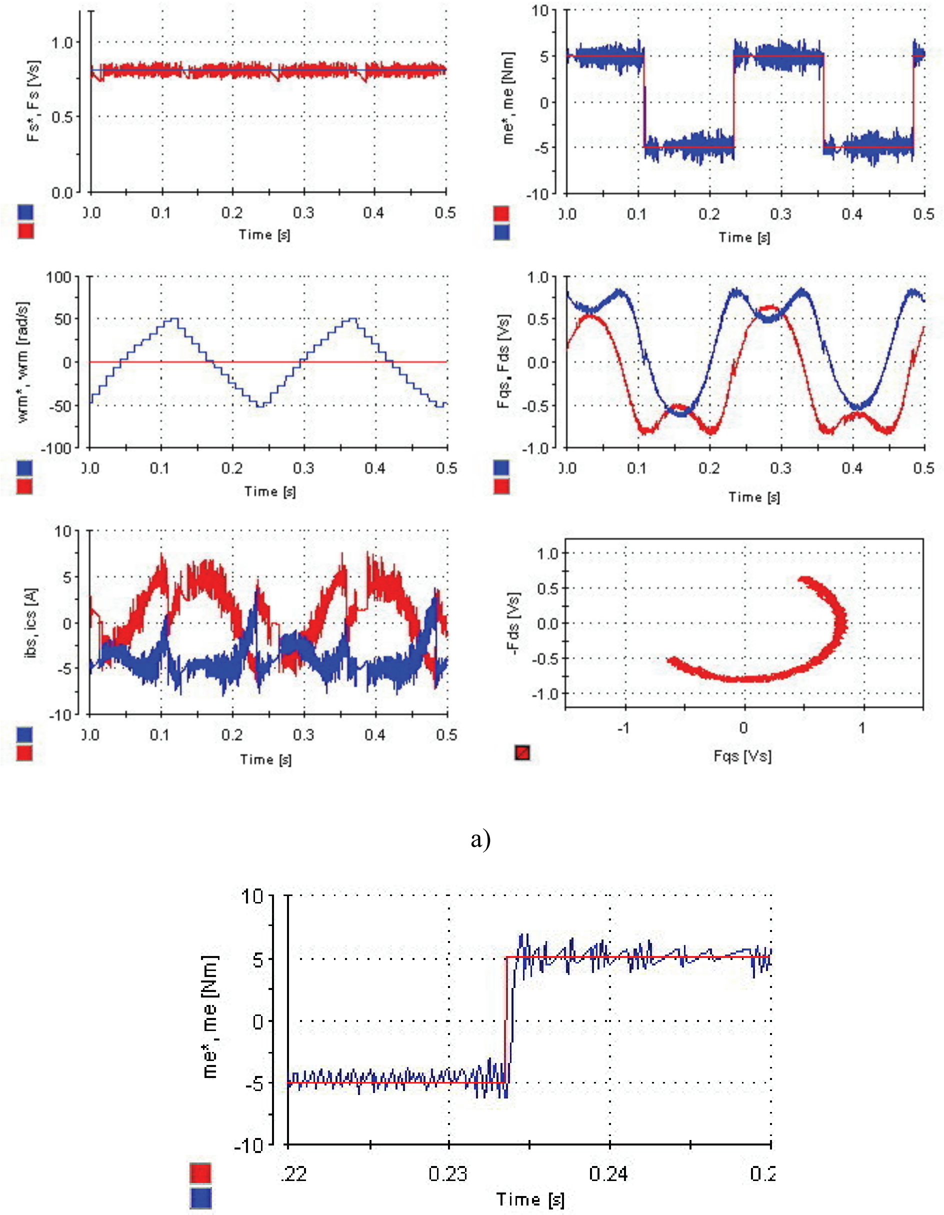


a)



b)

Fig. 10 Classical DTC method



a)

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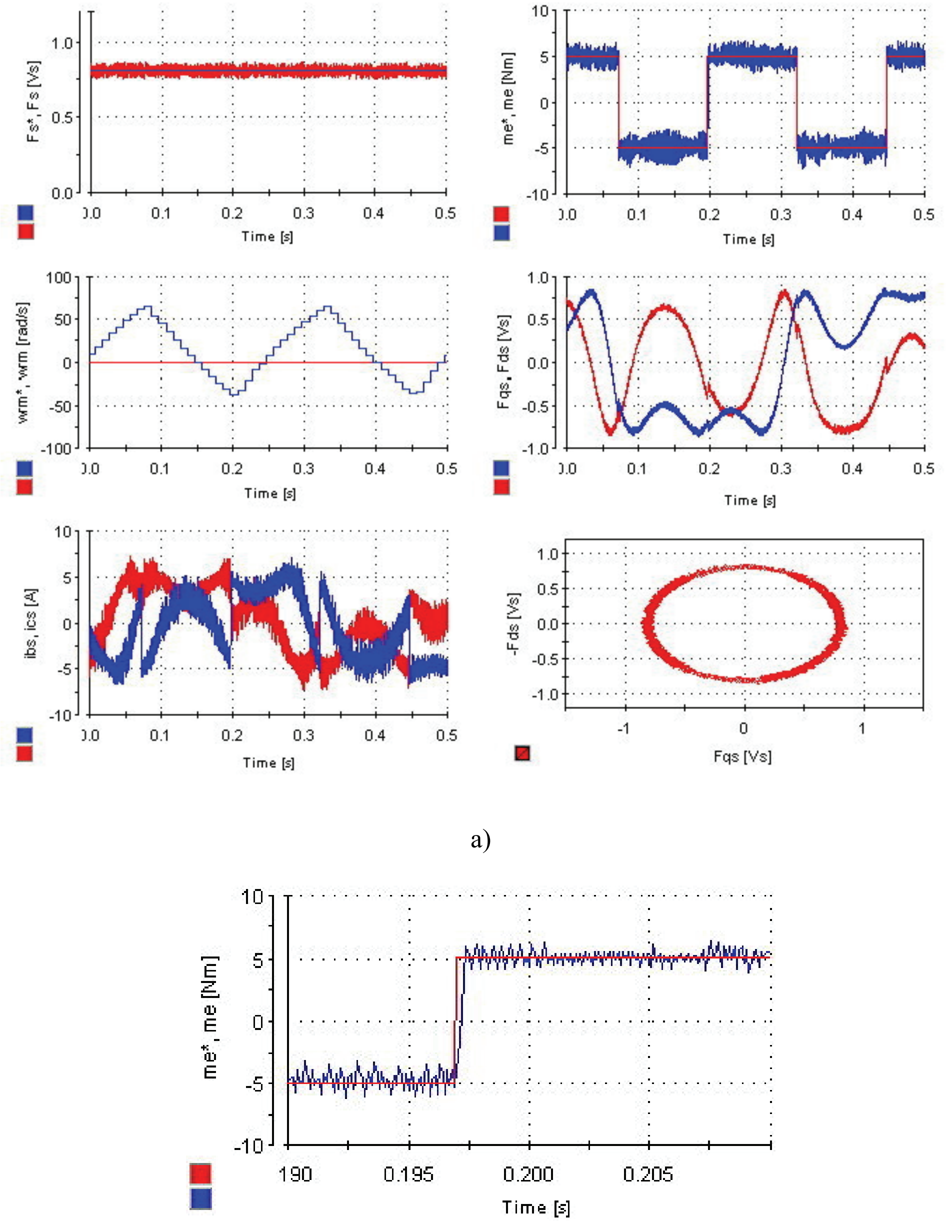
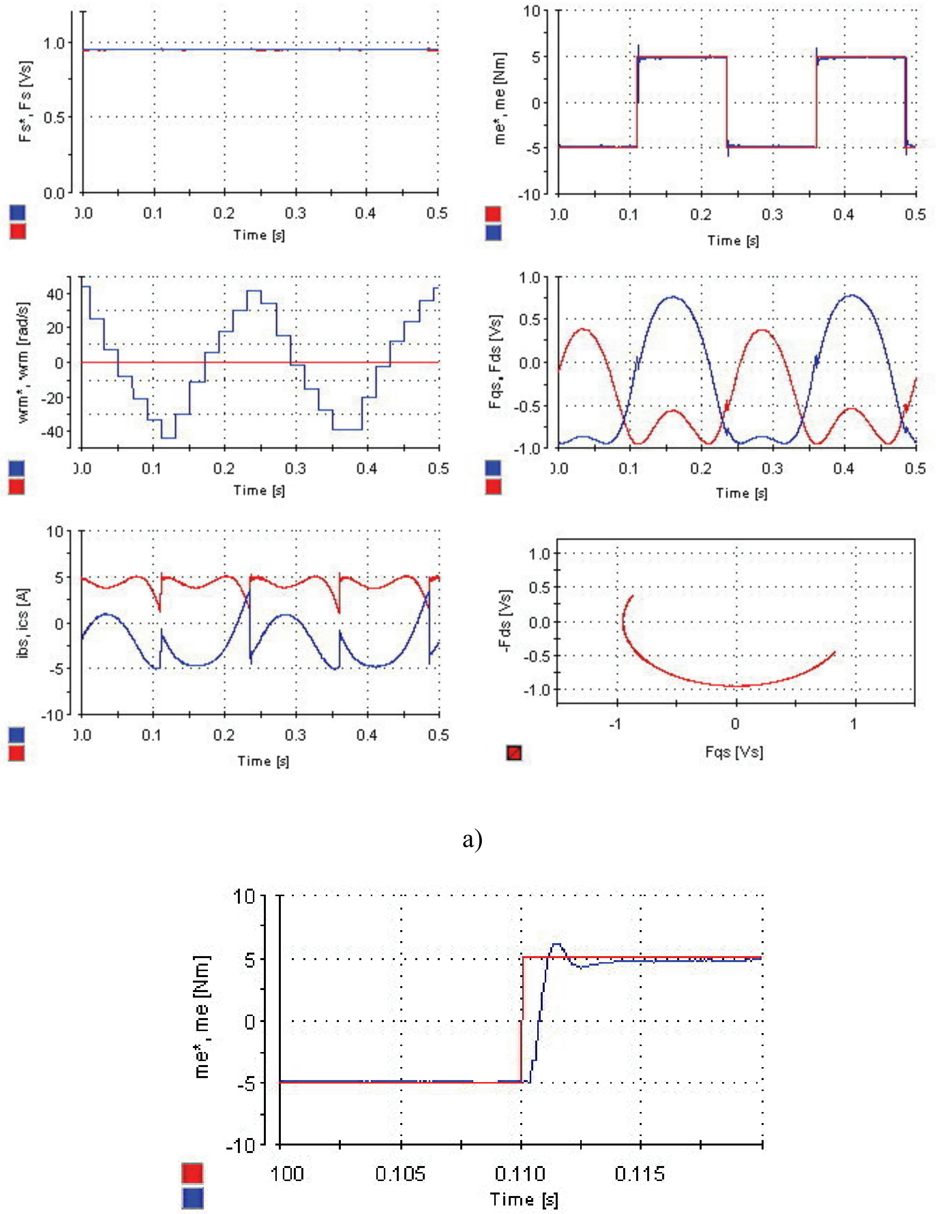
Fig. 11 Modified DTC method



a)

b)

Fig. 12 DTC with twelve sector switching technique



a)

b)

Fig. 13 DTC with PI controllers

8. CONCLUSION

This paper has reviewed Direct Torque Control strategies for PWM inverter-fed AC motor drives. The DTC represents a viable alternative to Field Oriented Control (FOC) being also a general philosophy for controlling the AC drives. The main features of DTC can be summarized as follows:

- According to adopted definition, DTC operates with closed torque and flux loops but without current controllers,
- DTC needs stator flux and torque estimation and, therefore, is not sensitive to rotor parameters,
- DTC has fast dynamic response,
- DTC has simple and robust control structure; however, the performance of DTC strongly depends on estimation accuracy of the stator flux and motor torque.

DTC strategies have been divided into two groups: hysteresis-based switching table DTC, and constant switching frequency schemes operating with space vector modulators (PI_DTC). The basic principles and the latest developments of these strategies have been systematically presented. Their advantages and limitations have been briefly examined.

Constant switching frequency PI_DTC schemes improve considerably the drive performance in terms of reduced torque and flux pulsations, reliable start up and low speed operation, well-defined harmonic spectrum as well as radiated noise. Therefore, PI_DTC is an excellent solution for general purpose IM drives in a very wide power range. Short sampling time required by the switching table DTC schemes makes them suited to very fast torque and flux controlled drives in spite of the simplicity of the control algorithm. In conclusion, it is believed that the DTC principle will continue to play a strategic role in the development of high performance drives.

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EKSPERIMENTALNA VERIFIKACIJA METODA ZA DIREKTNO UPRAVLJANJE MOMENTOM U ELEKTROMOTORNIM POGONIMA

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U ovom radu prikazani su različiti algoritmi za direktno upravljanje momentom i fluksom asinhronog motora (DTC upravljanje). Tehnike upravljanja, analizirane u ovom radu, odnose se na naponske invertore i po svom rešenju se konceptualno razlikuju. Razmatrane su: klasična DTC metoda, njene modifikacije za smanjenje talasnosti elektromagnetnog momenta i fluksa statora, kao i modifikovana DTC metoda sa PI regulatorima (PI-DTC), koja se bazira na primeni modulacije prostornog vektora (SVPWM). Za svaku od metoda izložena je teorijska osnova i prikazani su eksperimentalni rezultati, realizovani u laboratorijskim uslovima primenom dSPACE razvojnog sistema.

Ključne reči: *Asinhroni motor, prostorni vektor, direktno upravljanje momentom.*