Comparison by Simulation of Torque Control Schemes for Electric Drive Application

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Abstract – **This paper presents results of an investigation into the suitable torque control schemes for high performance induction motor drive application. Three different control schemes for direct torque control (DTC) are considered: classical, modified and twelve sector DTC. A brief overview of the operation of each scheme is presented followed by simulation results**

Keywords – **induction motor drive, direct torque control**

I. Introduction

The method of Direct Torque Control use feedback control of torque and stator flux, which are computed from the measured stator voltages and currents of induction motor [1,2]. As the method does not use position or speed sensor to control the machine and use its output currents and terminal voltages, this is also called as direct vector control scheme. The scheme uses stator flux-linkages control which is directly proportional to the induces emf. The method uses a stator reference model of the induction motor for its implementation, avoiding the trigonometric operations in the coordinate transformations of the synchronous reference frames.

II. 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.

The stator q and d axis flux linkages are

$$\lambda_{qs} = \int (V_{qs} - R_s i_{qs})dt \tag{1}$$

$$\lambda_{ds} = \int (V_{ds} - R_s i_{ds})dt \; , \tag{2}$$

where R_s – stator resistance, V_{qs}, V_{ds}, i_{qs}, i_{ds} – qd voltage and current components.

Consider the inverter shown in Fig. 1. The terminal voltage (V_a) with respect to negative of the dc supply is determined by a set of switches, Sa, consisting switchig device T1 and T4 as shown in Table 1. The switching of Sb and Sc sets for line b and c can be similarly derived. The total number of switching states possible with Sa, Sb, and Sc is eight and they are shown in Fig. 2. The stator q and voltages for each state are given by

$$V_{qs} = V_{as} \tag{3}$$

$$V_{ds} = \frac{1}{\sqrt{3}}\left(V_{cs} - V_{bs}\right) = \frac{1}{\sqrt{3}} V_{cb} \; . \tag{4}$$

The limited states of the inverter create discrete movement of the stator voltage phasor V_s, consisting of the resultant of V_{qs} and V_{ds}.

For control of voltage phasor both in its magnitude and phase, the requested voltage vector's phase and magnitude are sampled, say once every switching period. The phase of requested voltage vector identifies the neariest two nonzero voltage vectors.

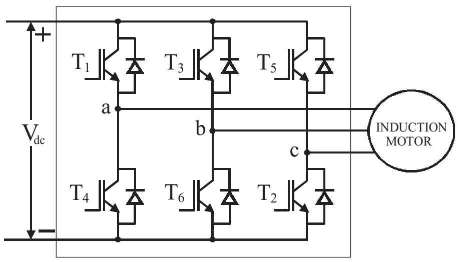

Fig. 1. Power circuit configuration of induction motor drive

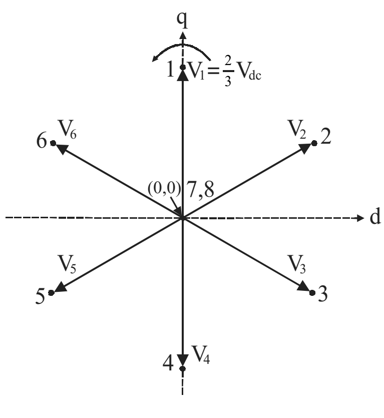

Fig. 2. Inverter output voltages

Table 1. Switching state of inverter phase leg a

T_1	T_4	Sa	V_a
On	Off	1	V_{dc}
Off	On	0	0

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III. Classical DTC Model (C-DTC)

A uniform rotating stator flux is desirable, and it occupies one of the sectors at any time, Fig. 3. The stator flux phasor has a magnitude of λ_s with instantaneous position θ_{fs}.

If the stator flux phasor is in sector 2, Fig. 3, the left influencing voltage phasor has to be either V6 or V1. As seen from phasor diagram, in case switching voltage phasor V1, the flux phasor increases in magnitude. In case of of phasor V6, it decrease. This implies that the closer voltage phasor set increase the flux and the farther voltage phasor set decreases the flux and both of them change (rise) the flux phasor in position. Similarly for all other sectors, the switching logic can be developed. A flux error $(\lambda_s^* - \lambda_s)$ thus determines which voltage phasor has to be called, and this flux vector is converted to a digital signal S_λ with hysteresys controller with hysteresis band of $\delta\lambda_s$. The switching logic to realize S_λ is given in Table 2.

Table 2. Switching logic for flux error

State	S_λ
$\lambda_s^* - \lambda_s > \delta\lambda_s / 2$	1
$\lambda_s^* - \lambda_s < - \delta\lambda_s / 2$	0

Torque control is exercised by comparison of the command torque to the torque measured from the stator flux linkages and stator currents as

$$T_e = \frac{3}{2}\frac{P}{2}(i_{qs}\lambda_{ds} - i_{ds}\lambda_{qs}) \; , \qquad (5)$$

where P is pole number.

Torque error is processed through hysteresis controller to produce digital outputs, S_T as shown in Table 3. Interpretation of S_T ai as follows: when it is 1 amounts to increasing the voltage phasor, 0 means to keep it at zero, -1 requires retarding the voltage phasor.

Combining the flux error output S_λ, the torque error output S_T, and the sextant of the flux phasor S_θ, a switching table can be realized to obtain the switching states of the inverter. The sectors of the stator flux space vector are denoted from S1 to S6. Stator flux modulus error after the hysteresis block can take just two values. Torque error after the hysteresis block can take three different values. The zero voltage vectors V7 and V8 are selected when the torque error is within the given hysteresis limits, and must remain unchanged. Finally, the DTC classical (c-DTC) look up table is shown in Table 4.

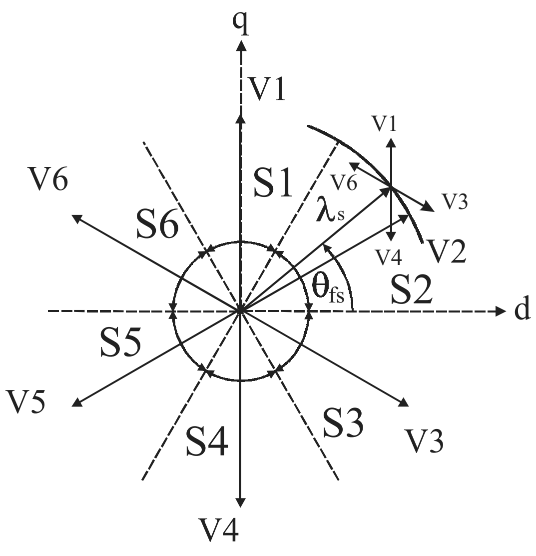

Fig. 3. Division of sectors for stator flux identification (c-DTC)

Table 3. Switching logic for torque error

State	S_T
$T_e^* - T_e > \delta T_e / 2$	1
$-\delta T_e / 2 \le T_e^* - T_e \le \delta T_e / 2$	0
$T_e^* - T_e < -\delta T_e / 2$	-1

In the classical DTC, there are several drawbacks [3,4]. Some of them can be summarized as follows:

- slow response in both start up and changes in either flux or torque,
- 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.

Table 4. Switching states for c-DTC

S_λ	S_T	S1	S2	S3	S4	S5	S6
1	1	V6	V1	V2	V3	V4	V5
1	0	V8	V7	V8	V7	V8	V7
1	-1	V2	V3	V4	V5	V6	V1
0	1	V5	V6	V1	V2	V3	V4
0	0	V7	V8	V7	V8	V7	V8
0	-1	V3	V4	V5	V6	V1	V2

IV. Modified DTC Model (M-DTC)

In order to overcome the mentioned drawbacks, there are different solutions. First idea that comes up, when it is tried to improve the DTC by means of changing the tables, is to use six sectors, as in classical DTC, but changing the zones. Hence, instead of having as a second sector the zone from 0° up to 60°, it will be from 30° up to 90°. It can be observed that in this case, the states not used in the second zone will be V3 and V6 instead of V2 and V5. This novel sector division is shown in Fig. 4.

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

Table 5 shows the m_DTC look up table for all its six sectors. It can be seen that the states V2 and V5, 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), V3 and V6 are the states not used. However, now the reason is the ambiguity in flux instead of

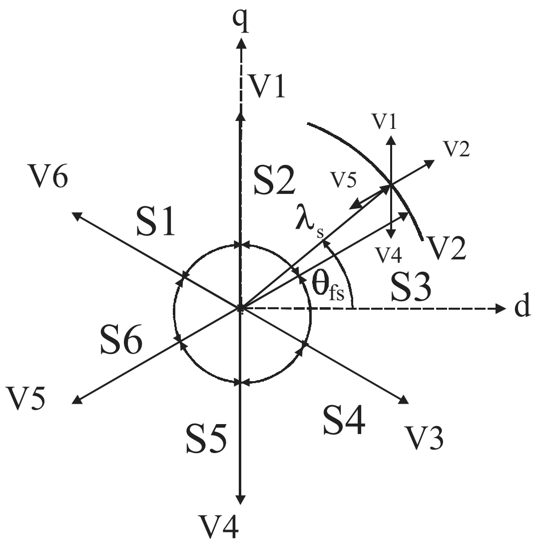

Fig. 4. Modified DTC and its sectors

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 [5].

Table 5. Switching states for m-DTC

S_λ	S_T	S1	S2	S3	S4	S5	S6
1	1	V6	V1	V2	V3	V4	V5
1	0	V8	V7	V8	V7	V8	V7
1	-1	V1	V2	V3	V4	V5	V6
0	1	V4	V5	V6	V1	V2	V3
0	0	V7	V8	V7	V8	V7	V8
0	-1	V3	V4	V5	V6	V1	V2

V. Twelve sector DTC model (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. 5. 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 variations (S_T=1 - torque increase, S_T=2- torque small increase, S_T=3 - torque small decrease, S_T=4 - torque large increase). It is obvious that V2 will produce a large increase in flux and a small increase in torque in sector $S5$. On the contrary, V1 will increase the torque in large proportion and the flux in a small one.

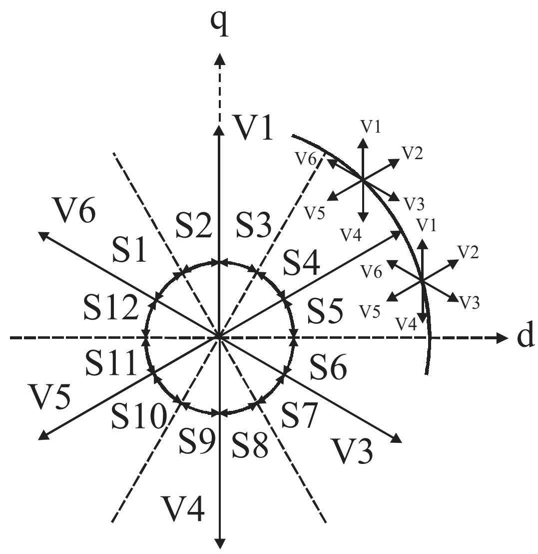

Fig. 5. Twelve sectors DTC

Therefore, the torque hysteresis block should have four hysteresis levels and eight levels of flux and torque variation. Finally, the look up table is presented in Table 6.

Table 6. Switching states for 12-DTC

		Sector number S_θ											
S_λ	S_T	1	2	3	4	5	6	7	8	9	10	11	12
1	1	5	6	6	1	1	2	2	3	3	4	4	5
1	2	6	6	1	1	2	2	3	3	4	4	5	5
1	0	8	8	7	7	8	8	7	7	8	8	7	V7
1	3	1	1	2	2	3	3	4	4	5	5	6	6
1	4	1	2	2	3	3	4	4	5	5	6	6	1
0	1	4	5	5	6	6	1	1	2	2	3	3	4
0	2	4	4	5	5	6	6	1	1	2	2	3	3
0	0	7	7	8	8	7	7	8	8	7	7	8	8
0	3	3	8	4	7	5	8	6	7	1	8	2	7
0	4	2	3	3	4	4	5	5	6	6	1	1	2

VI. Simulation Results

Simulations have been carried out for the comparison of a described schemes. The simulations were conducted using Matlab/Simulink simulation package. The DTC drive for all simulation were run with speed feedback. The control algorithms are taking into account by the appropriate look-up tables. The system is discredited with sample time $T_s = 2 \cdot 10^{-6}$ s.

Simulation parameters are as follows;

Motor rating: 3 phase, 2 pole, 380V, 37 kW,

Parameters: R_s=0.087 Ω, R_r=0.228 Ω, L_s=35.5 mH, L_m=34.7 mH, L_r=35.5 mH.

Fig. 6 shows actual speed, motor torque and stator flux of c-DTC, m-DTC and 12_DTC schemes, speed reference is set

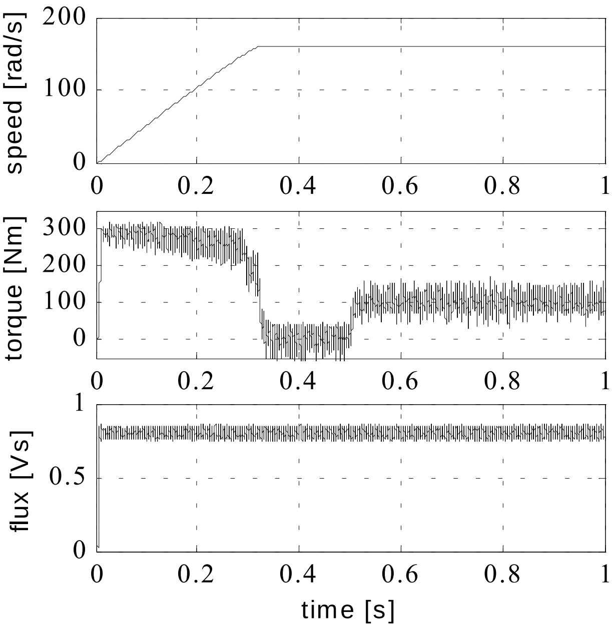

Fig. 6a. Dynamic performance of the drive with c-DTC

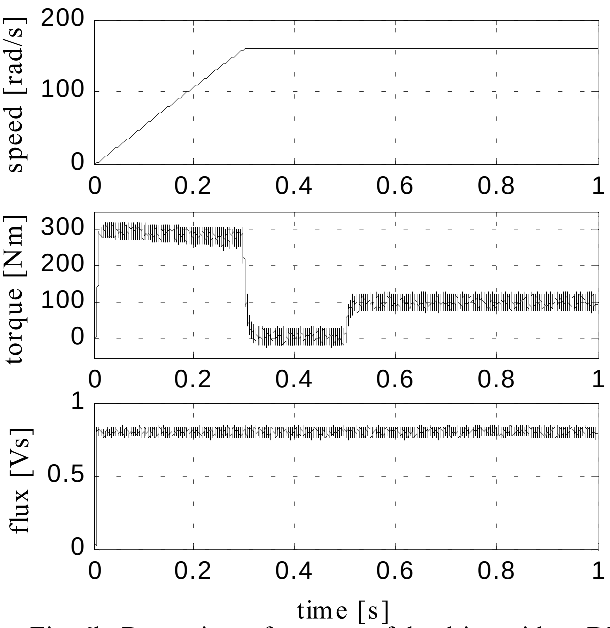

Fig. 6b. Dynamic performance of the drive with m-DTC

to 160 rad/s, torque limit at start-up is $3T_n$. At t=0.5 s load torque is set to 100 Nm.

In all cases it is possible to control directly the stator flux and the torque by selecting the appropriate inverter state. According to the Fig. 6, smaller variation can be seen in the torque and flux with m-DTC and 12_DTC scheme than c-DTC

VII. Conclusion

In this paper, three different schemes for direct torque control for induction motor drives are presented. In all cases it is possible to control directly the stator flux and the torque by

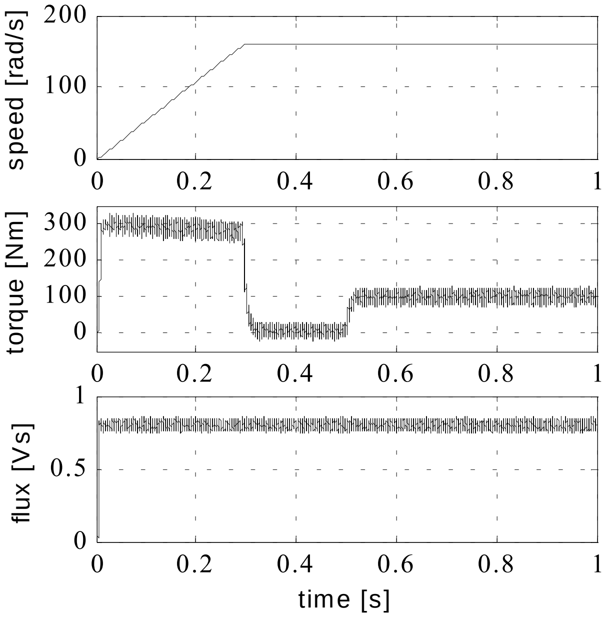

Fig. 6c. Dynamic performance of the drive with 12-DTC

selecting the appropriate inverter state. Its main features are as follows: direct torque control and direct stator flux control, indirect control of stator currents and voltages, approximately sinusoidal stator fluxes and stator currents, high dynamic performance even at locked rotor. Some disadvantages are present: possible problems during starting requirement of torque and flux estimators, implying the consequent parameters identification, inherent torque and flux ripples.

A further publication may show drive behaviour at low speed and dead time influence.

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