FOC and DTC: Two Viable Schemes for Induction Motors Torque Control

Domenico Casadei, *Member, IEEE*, Francesco Profumo, *Senior Member, IEEE*, Giovanni Serra, *Member, IEEE*, and Angelo Tani

***Abstract*—Field-oriented control and direct torque control are becoming the industrial standards for induction motors torque control. This paper is aimed to give a contribution for a detailed comparison between the two control techniques, emphasizing advantages and disadvantages. The performance of the two control schemes is evaluated in terms of torque and current ripple, and transient response to step variations of the torque command. The analysis has been carried out on the basis of the results obtained by numerical simulations, where secondary effects introduced by hardware implementation are not present.**

***Index Terms*—Digital signal processor, direct field oriented control, direct signal processor, direct torque control, discrete space vector modulation, field oriented control, pulse-width modulation.**

I. INTRODUCTION

ALMOST 30 years ago, in 1971 F. Blaschke [1] presented the first paper on field-oriented control (FOC) for induction motors. Since that time, the technique was completely developed and today is mature from the industrial point of view. Today field oriented controlled drives are an industrial reality and are available on the market by several producers and with different solutions and performance [2]–[19].

Thirteen years later, a new technique for the torque control of induction motors was developed and presented by I. Takahashi as direct torque control (DTC) [20]–[22], and by M. Depenbrock as direct self control (DSC) [23]–[25]. Since the beginning, the new technique was characterized by simplicity, good performance and robustness [20]–[31]. Using DTC or DSC it is possible to obtain a good dynamic control of the torque without any mechanical transducers on the machine shaft. Thus, DTC and DSC can be considered as "sensorless type" control techniques. The basic scheme of DSC is preferable in the high power range applications, where a lower inverter switching frequency can justify higher current distortion. In this paper, the attention will be mainly focused on the basic DTC scheme, which is more suitable in the small and medium power range applications.

Several papers have been published on FOC and DTC in the last 30 years, but only few of them was aimed to emphasize differences, advantages and disadvantages.

Manuscript received April 16, 2001; revised October 27, 2001. Recommended by Associate Editor G. K. Dubey. This paper was presented at the EPE-PEMC'00 Conference, Kosice (Slovak Republic).

D. Casadei, G. Serra, and A. Tani are with the Dipartimento di Ingegneria Elettrica, University of Bologna, Bologna 40136, Italy (e-mail: domenico.casadei@mail.ing.unibo.it; giovanni.serra@mail.ing.unibo.it; angelo.tani@mail.ing.unibo.it).

F. Profumo is with the Dip. Ingegneria Elettrica Industriale, Politecnico di Torino, Torino 10129, Italy (e-mail: profumo@polito.it).

Publisher Item Identifier 10.1109/TPEL.2002.802183.

The name direct torque control is derived by the fact that, on the basis of the errors between the reference and the estimated values of torque and flux, it is possible to directly control the inverter states in order to reduce the torque and flux errors within the prefixed band limits.

Unlike FOC, DTC does not require any current regulator, coordinate transformation and PWM signals generator (as a consequence timers are not required). In spite of its simplicity, DTC allows a good torque control in steady-state and transient operating conditions to be obtained. The problem is to quantify how good the torque control is with respect to FOC.

In addition, this controller is very little sensible to the parameters detuning in comparison with FOC.

On the other hand, it is well known that DTC presents some disadvantages that can be summarized in the following points:

1) difficulty to control torque and flux at very low speed;
2) high current and torque ripple;
3) variable switching frequency behavior;
4) high noise level at low speed;
5) lack of direct current control.

Thus, on the basis of the experience of the authors, the aim of this paper is to give a fair comparison between the two techniques (FOC and DTC) in both steady-state and transient operating conditions. The comparison is useful to indicate to the users which one of the two schemes can be efficiently employed in the various applications that today require torque control.

II. FOC AND DTC COMPARISON LINES

In the last five years, many researches have been carried out to try to solve the above mentioned problems of DTC scheme [26]–[44]. In particular the following solutions have been developed:

1) use of improved switching tables [29]–[32];
2) use of comparators with and without hysteresis, at two or three levels [28], [30], [31];
3) implementation of DTC schemes for constant switching frequency operation with PWM or SVM techniques [33]–[39];
4) introduction of fuzzy or neuro-fuzzy techniques [40]–[42];
5) use of sophisticated flux estimators to improve the low speed behavior [43], [44].

All these contributions allow the DTC performance to be improved, but at the same time they lead to more complex schemes. Analyzing these works in details it appears that one of the basic

0885-8993/02$17.00 © 2002 IEEE

features of DTC scheme at least is lost. So, a crucial question is to establish which one of these new schemes might be included in "DTC family."

It is then necessary to propose, first of all, an answer to the last question and to clarify which control scheme can be considered as DTC scheme and which one has to be classified in different way. Because the DTC technique is intrinsically sensorless, the authors feel that it is more suitable for the comparison to consider a direct field oriented control (DFOC) scheme, instead of a general FOC scheme.

Starting from this basis, the DTC scheme is characterized (in comparison with the DFOC) by the absence of:

1) PI regulators;
2) coordinate transformations;
3) current regulators;
4) PWM signals generators (no timers).

So, only the control schemes, which meet all these requirements, should be considered as real DTC schemes. According to these considerations, the analysis is carried out with reference to a basic DTC scheme characterized by the above mentioned features.

Some criteria to evaluate the performance of DFOC and DTC are proposed in this paper. They are used to compare the two control schemes in both steady-state and transient operating conditions.

With reference to steady-state operating conditions, the current and torque ripple evaluated for different values of speed and torque will be analyzed. For this purpose the three-phase rms current ripple, defined by

$$I_{\text{rip,rms}} = \sqrt{\frac{1}{T}\int_0^T \left(i_{\text{ripA}}^2 + i_{\text{ripB}}^2 + i_{\text{ripC}}^2\right) dt}$$

will be calculated in a period of the fundamental current component.

With reference to transient operating conditions, the time response to a step variation of the torque command will be analyzed at different rotor speeds.Furthermore, some comments will be presented with reference to flux level changes and low-speed operation of DTC scheme.

In order to fairly compare the two solutions, the following conditions have been considered as constraints:

1) the same DSP board for implementing DFOC and DTC schemes;
2) the same average switching frequency of the inverter.

Related to this last point, the authors think that the comparison carried out with the same cycle period is not fair enough. This because the same cycle period does not allow a suitable use of the basic characteristics of DTC scheme, which are: easy implementation and reduced calculation time with respect to DFOC.

The same average switching frequency for the two schemes can be obtained varying the amplitude of the hysteresis bands in DTC scheme.

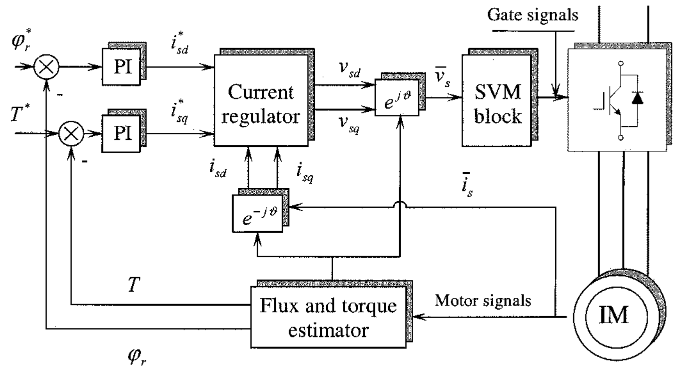


Fig. 1. Basic DFOC scheme.

III. FOC PRINCIPLES

The machine equations in the stator reference frame, written in terms of space vectors, are

$$\bar{v}_s = R_s\bar{i}_s + \frac{d\bar{\varphi}_s}{dt} \tag{1}$$

$$0 = R_r\bar{i}_r + \frac{d\bar{\varphi}_r}{dt} - j\omega_m\bar{\varphi}_r \tag{2}$$

$$\bar{\varphi}_s = L_s\bar{i}_s + M\bar{i}_r \tag{3}$$

$$\bar{\varphi}_r = L_r\bar{i}_r + M\bar{i}_s \tag{4}$$

$$T = p\frac{M}{\sigma L_s L_r}\left(\bar{\varphi}_s \cdot j\bar{\varphi}_r\right) \tag{5}$$

where p is the pole pair number and

$$\sigma = 1 - \frac{M^2}{L_s L_r}.$$

Assuming a rotor flux reference frame, and developing the previous equations with respect to the d axis and q axis components, leads to

$$\frac{d\varphi_{rd}}{dt} + \frac{1}{\tau_r}\varphi_{rd} = \frac{M}{\tau_r}i_{sd} \tag{6}$$

$$T = \frac{3}{2}p\frac{M}{L_r}\varphi_{rd}i_{sq}. \tag{7}$$

These equations represent the basic principle of the FOC: in the rotor flux reference frame, a decoupled control of torque and rotor flux magnitude can be achieved acting on the q and d axis stator current components, respectively. A block diagram of a basic DFOC scheme is presented in Fig. 1.

The rotor flux estimation is carried out by

$$\frac{d\bar{\varphi}_s}{dt} = \bar{v}_s - R_s\bar{i}_s \tag{8}$$

$$\bar{\varphi}_r = \frac{L_r}{M}\left(\bar{\varphi}_s - \sigma L_s\bar{i}_s\right). \tag{9}$$

The flux estimator has been considered to be ideal, being the effects due to parameter variations at low speed out of the major aim of this paper.

The current controller has been implemented in the rotor flux reference frame using PI regulators with back emf compensation.

IV. DTC PRINCIPLES

The basic DTC scheme is shown in Fig. 2.

The error between the estimated torque T and the reference torque T^* is the input of a three level hysteresis comparator,

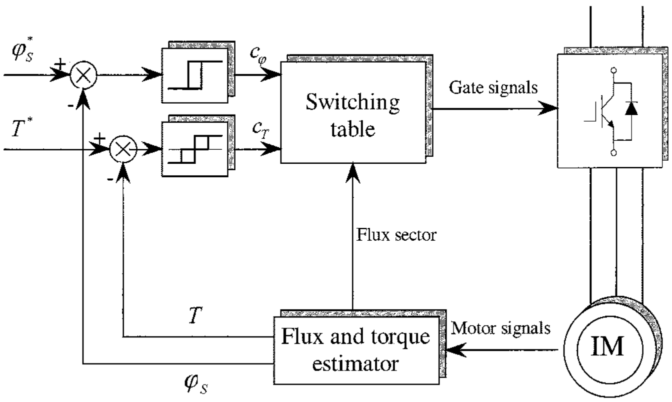


Fig. 2. Basic DTC scheme.

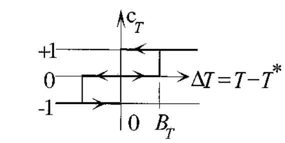


Fig. 3. Torque hysteresis comparator.

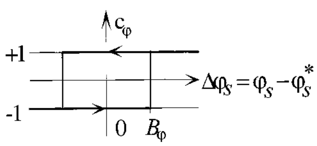


Fig. 4. Flux hysteresis comparator.

whereas the error between the estimated stator flux magnitude φ_S and the reference stator flux magnitude φ_S^* is the input of a two level hysteresis comparator.

Figs. 3 and 4 illustrate the torque and flux comparators, respectively.

The selection of the appropriate voltage vector is based on the switching table given in Table I. The input quantities are the stator flux sector and the outputs of the two hysteresis comparators. Assuming the stator flux vector lying in sector 1 of the d–q plane, the voltage vectors used by DTC technique are shown in Fig. 5.

This simple approach allows a quick torque response to be achieved, but the steady-state performance is characterized by undesired ripple in current, flux and torque. This behavior is mainly due to the absence of information about torque and rotor speed values in the voltage vector selection algorithm.

In order to explain this point, it is useful to derive from (1)–(4) the state-variable form of the induction machine equations with stator and rotor fluxes as state variables. Then, for small values of the cycle period Δt, the stator and rotor fluxes at time t_{k+1} can be expressed as [32]

$$\bar{\varphi}_{s_{k+1}} = \bar{\varphi}_{s_k}\left(1-\frac{1}{\sigma\tau_s}\Delta t\right)+\varphi_{r_k}\frac{M}{\sigma\tau_s L_r}\Delta t + \bar{v}_{s_k}\Delta t \tag{10}$$

$$\bar{\varphi}_{r_{k+1}} = \bar{\varphi}_{r_k}\left[1+\left(j\omega_{m_k}-\frac{1}{\sigma\tau_r}\right)\Delta t\right] + \bar{\varphi}_{s_k}\frac{M}{\sigma L_s\tau_r}\Delta t \tag{11}$$

where $\tau_r = L_r/r_r$ and $\tau_s = L_s/r_s$.

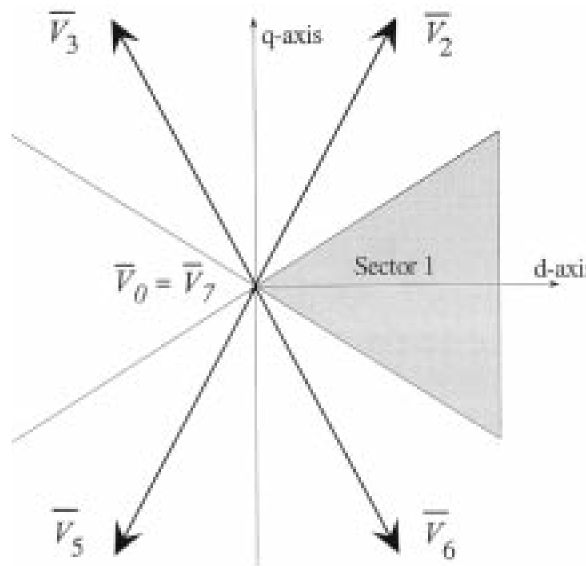


Fig. 5. Voltage vectors utilized in basic DTC scheme when stator flux is in sector 1.

TABLE I
BASIC SWITCHING

Sector		1	2	3	4	5	6
$c_\varphi = -1$	$c_T = -1$	$\overline{V}_2$	$\overline{V}_3$	$\overline{V}_4$	$\overline{V}_5$	$\overline{V}_6$	$\overline{V}_1$
	$c_T = 0$	$\overline{V}_7$	$\overline{V}_0$	$\overline{V}_7$	$\overline{V}_0$	$\overline{V}_7$	$\overline{V}_0$
	$c_T = +1$	$\overline{V}_6$	$\overline{V}_1$	$\overline{V}_2$	$\overline{V}_3$	$\overline{V}_4$	$\overline{V}_5$
$c_\varphi = +1$	$c_T = -1$	$\overline{V}_3$	$\overline{V}_4$	$\overline{V}_5$	$\overline{V}_6$	$\overline{V}_1$	$\overline{V}_2$
	$c_T = 0$	$\overline{V}_0$	$\overline{V}_7$	$\overline{V}_0$	$\overline{V}_7$	$\overline{V}_0$	$\overline{V}_7$
	$c_T = +1$	$\overline{V}_5$	$\overline{V}_6$	$\overline{V}_1$	$\overline{V}_2$	$\overline{V}_3$	$\overline{V}_4$

With reference to the electromagnetic torque, at time t_{k+1}, (5) may be rewritten as

$$T_{k+1} = p\frac{M}{\sigma L_s L_r}\left(\bar{\varphi}_{s_{k+1}}\cdot j\bar{\varphi}_{r_{k+1}}\right). \tag{12}$$

Substituting (10) and (11) in (12) and neglecting terms proportional to the square of Δt, the torque at time t_{k+1} is given by

$$T_{k+1} = T_k + \Delta T_{k_1} + \Delta T_{k_2} \tag{13}$$

where

$$\Delta T_{k_1} = -T_k\left(\frac{1}{\tau_s}+\frac{1}{\tau_r}\right)\frac{\Delta t}{\sigma} \tag{14}$$

$$\Delta T_{k_2} = p\frac{M}{\sigma L_s L_r}\left[(\bar{v}_{s_k}-j\omega_{m_k}\bar{\varphi}_{s_k})\cdot j\bar{\varphi}_{r_k}\right]\Delta t. \tag{15}$$

The first contribution ΔT_{k_1} is due to stator and rotor resistances and acts in order to reduce the absolute value of the torque. This contribution is proportional to the torque value at time t_k and is independent of $\bar{v}_{s_k}$ and ω_{mk}. The second contribution ΔT_{k_2} represents the effect of the applied voltage vector on the torque variation and is dependent on the operating conditions. For a given voltage vector this contribution is mainly affected by the rotor speed through the dynamic emf $\omega_{m_k}\varphi_{s_k}$. A graphical rep-

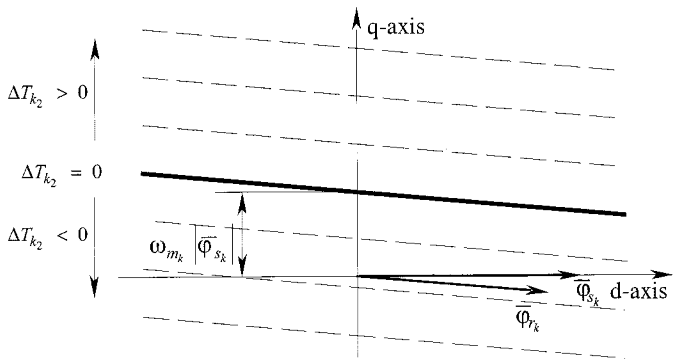


Fig. 6. Graphical representation of the torque variation ΔT_{k_1}.

TABLE II
MOTOR DATA

Standard 3-phase, 4 kW, 4-pole, 220V, 50 Hz induction motor
Rated current 16.6 A, Rated torque 26.5 Nm, Rated speed 1440 rpm

TABLE III
THREE-PHASE RMS CURRENT RIPPLE (DFOC)

Torque \ Speed	1440 rpm	720 rpm	144 rpm
26.5 Nm	0.64 A	0.93 A	0.58 A
13.25 Nm	0.64 A	0.94 A	0.47 A
0 Nm	0.65 A	0.93 A	0.34 A

TABLE IV
THREE-PHASE RMS CURRENT RIPPLE (DTC)

Torque \ Speed	1440 rpm	720 rpm	144 rpm
26.5 Nm	1.10 A	1.57 A	1.46 A
13.25 Nm	1.09 A	1.56 A	1.27 A
0 Nm	1.18 A	1.46 A	1.21 A

resentation of (15), is given in Fig. 6. The bold-faced line represents the locus of the stator voltage vectors which determine a null value of ΔT_{k_2}. This line is parallel to the direction of $\bar{\varphi}_{r_k}$ and its position depends on the rotor speed. Each dashed line represents the locus of the stator voltage vectors determining a constant value of ΔT_{k_2}.

Using Fig. 6 it is possible to verify that a given voltage space vector may determine positive torque variations at low speed, and negative torque variations at high speed. Furthermore, at low speed, two voltage vectors having the same magnitude and opposite direction produce torque variations with nearly the same absolute value. On the contrary, at high speed, the same vectors produce torque variations having quite different absolute values. This behavior determines different torque ripple at low and at high speed as it can be observed in basic DTC schemes.

V. SIMULATION RESULTS

A detailed comparison between the two solutions has been carried out by numerical simulations, where secondary effects which could mask the switching behavior are not present. In this way it is possible to make a significant comparison of the steady-state and transient performance of the two control schemes.

The numerical simulations take the effects of time discretization and delay caused by the sampling of signals into account.

In DFOC scheme, the space vector modulation has been implemented according to the two-phase modulation technique. The cycle period has been assumed equal to 160 μs, which determines, with two-phase modulation, a switching frequency of about 4.1 kHz.

In DTC scheme, the cycle period has been assumed equal to 40 μs, which is much lower than the cycle period of DFOC to represent the different level of complexity. The amplitude of the hysteresis bands has been adjusted in order to achieve a mean

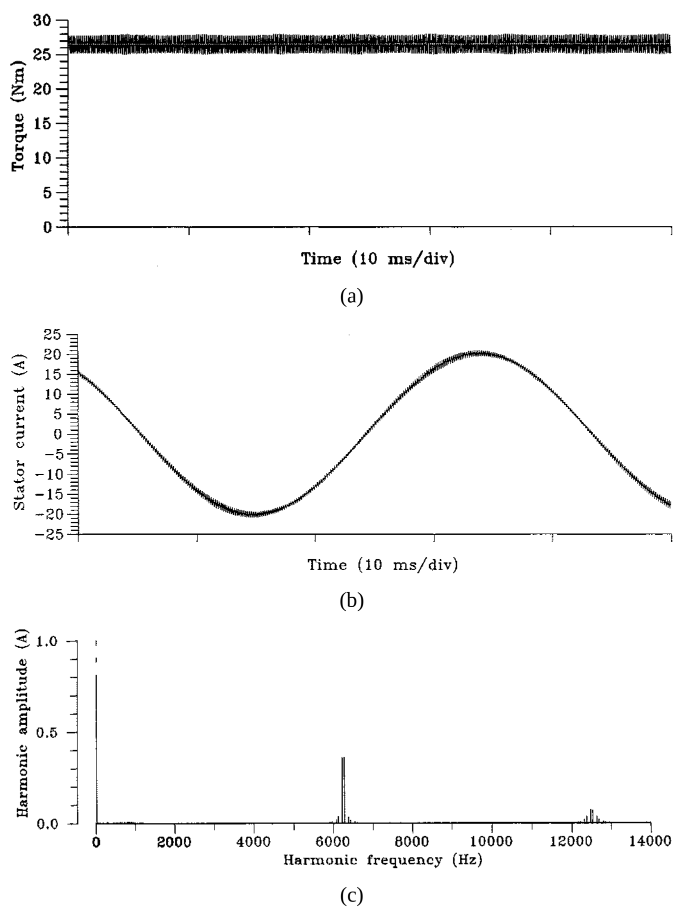


Fig. 7. (a) Torque (DFOC), 1440 rpm, 26.5 Nm. (b) Stator current (DFOC), 1440 rpm, 26.5 Nm. (c) Stator current harmonic spectrum (DFOC), 1440 rpm, 26.5 Nm.

inverter switching frequency practically equal to that of DFOC scheme.

The characteristics of the motor under test are shown in Table II.

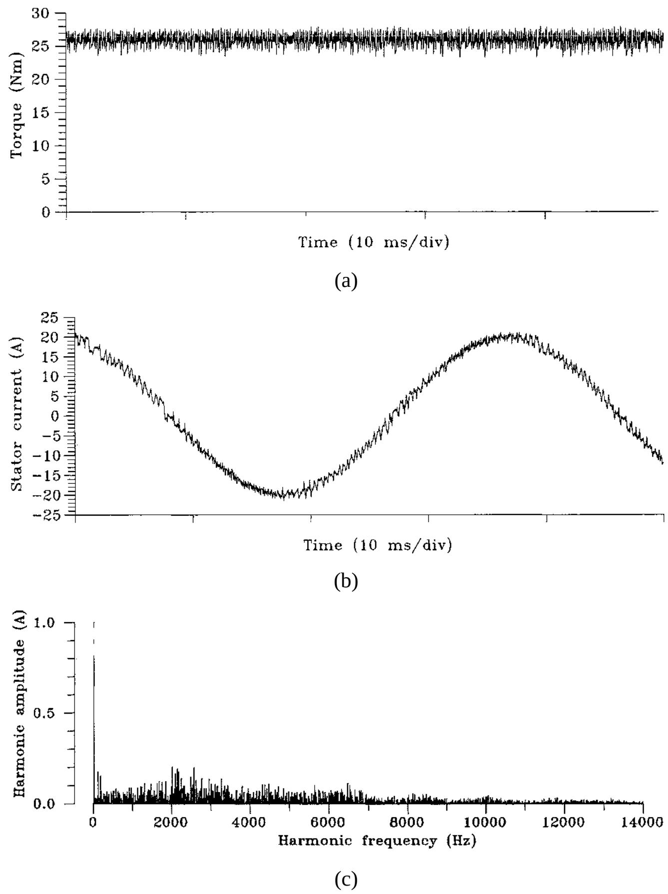


Fig. 8. (a) Torque (DTC), 1440 rpm, 26.5 Nm. (b) Stator current (DTC), 1440 rpm, 26.5 Nm. (c) Stator current harmonic spectrum (DTC), 1440 rpm, 26.5 Nm.

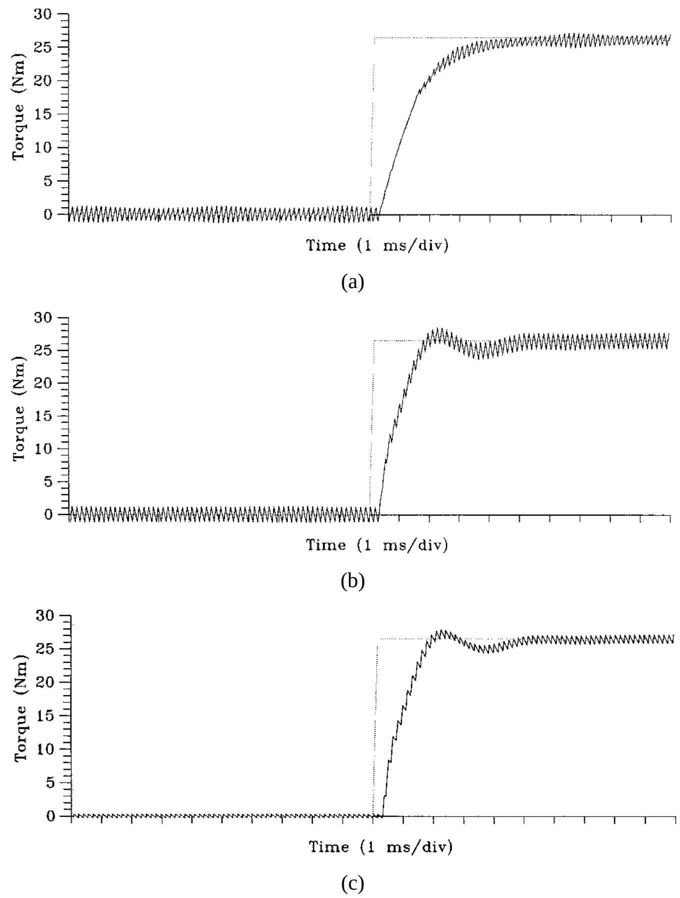


Fig. 9. (a) Torque response (DFOC), 1200 rpm. (b) Torque response (DFOC), 600 rpm. (c) Torque response (DFOC), 100 rpm.

A. Steady-State Performance

The steady-state performance of DFOC and DTC schemes has been compared evaluating the three-phase rms current ripple in different operating conditions.

The results obtained using DFOC and DTC schemes are summarized in Tables III and IV, respectively. The considered operating conditions are related to rotor speed values of 100%, 50%, and 10% of the rated value, and torque values of 100%, 50%, and 0% of the rated value.

As it is possible to see, in all the operating conditions the behavior of DFOC scheme is characterized by lower values of the three-phase rms current ripple with respect to the DTC scheme.

The torque, the stator current waveform and the stator current harmonic spectrum obtained with DFOC scheme are shown in Fig. 7(a)–(c), respectively. The rotor speed is 1440 rpm and the reference torque is 26.5 Nm (rated torque). Fig. 8(a)–(c) shows the same quantities obtained when using DTC scheme.

It should be noted that in the high-speed range the DTC scheme operates at a switching frequency lower than 4.1 kHz, even if the amplitude of the hysteresis bands is reduced. This is due to the moderate effect produced by the voltage vectors $\overline{V}_2$ and $\overline{V}_3$ when the torque has to be increased at high speed (see Figs. 5 and 6).

Under the assumption made of the same mean inverter switching frequency, the amplitude of the torque ripple in DTC is slightly higher than that of DFOC. However, the oscillations in DFOC scheme are more regular and uniform.

With reference to the current waveforms it can be noted that the harmonic spectrum of DFOC shows only the harmonic component corresponding to the modulation cycle period, whereas with DTC scheme the spectrum shows a series of harmonics with lower values, but distributed all over the frequency range. For a more clear representation of the harmonic amplitudes, the fundamental component has been truncated.

According to the current spectrum, DFOC generates a high frequency uniform noise, whereas DTC produces an irregular noise level, which is particularly maddening at low speed.

B. Transient Performance

The transient performance of the two schemes has been compared analyzing the response to a step variation of the torque command from 0 Nm to 26.5 Nm (rated torque), at different rotor speeds.

Fig. 9(a)–(c) illustrate the torque responses obtained using DFOC scheme, at 1200, 600, and 100 rpm, respectively. Fig. 10(a)–(c) illustrate the same quantities obtained using DTC scheme.

These results show that using the DTC scheme a better torque response can be achieved in terms of settling time and maximum overshoot. The settling times for the two cases are summarized in Table V.

The different dynamic behavior is due to the presence of PI regulators in DFOC scheme, which delay the torque response.

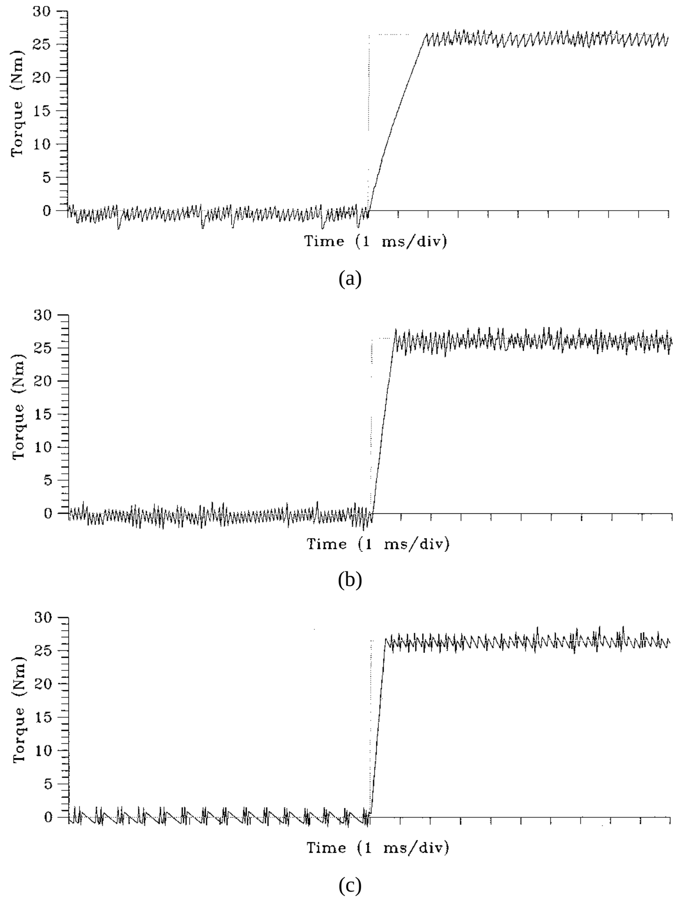


Fig. 10. (a) Torque respone (DTC), 1200 rpm. (b) Torque response (DTC), 600 rpm. (c) Torque response (DTC), 100 rpm.

TABLE V
SETTLING TIME OF THE TORQUE RESPONSE

	FOC	DTC
1200 rpm	3.8 ms	1.8 ms
600 rpm	1.8 ms	0.7 ms
100 rpm	1.7 ms	0.5 ms

C. DTC Behavior for Step Variations of Torque and Stator Flux Commands

In DTC scheme a direct control of the stator currents is not present and this may determine over currents when step variations of torque and flux are applied to the input commands. With reference to the torque, an indirect current control can be obtained introducing a limit to the maximum torque value. With reference to the stator flux, it can be noted that even a small variation of the stator flux command causes a large variation of the stator current. This behavior is clearly represented in Fig. 11(a) and (b), which shows the transient caused by a step variation of the stator flux command. In this case, an indirect control of the stator current can be easily obtained forcing the flux command to change slowly, according to a prefixed ramp waveform.

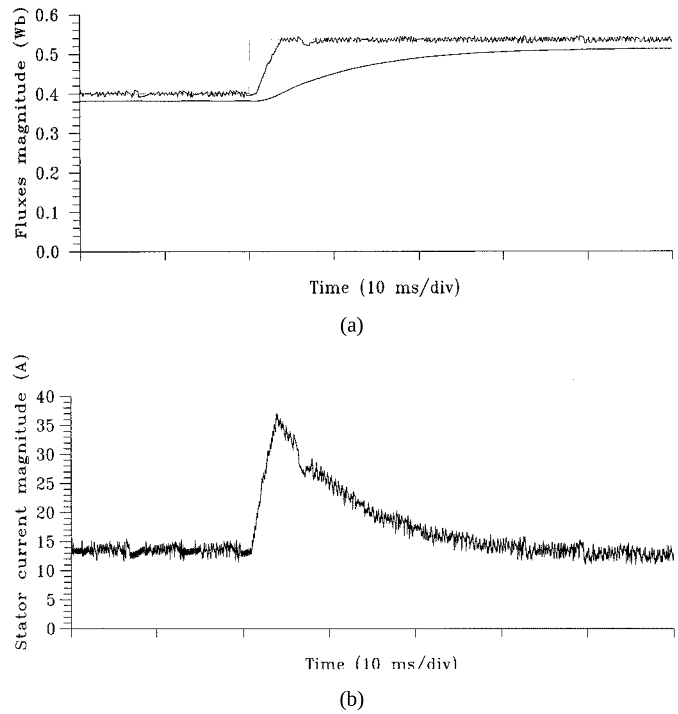


Fig. 11. (a) Stator and rotor flux responses to a step variation of the stator flux command. (b) Response of the stator current magnitude to a step variation of the stator flux command.

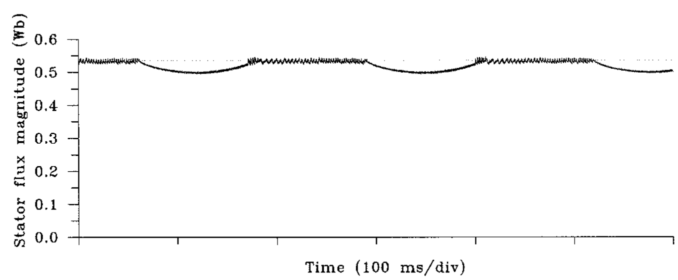


Fig. 12. Stator flux magnitude in DTC, 10 rpm, 5 Nm.

D. DTC Behavior at Low Speed

It is known that the basic DTC scheme is affected by undesired flux weakening phenomena at low speed. In these operating conditions the control system selects many times zero voltage vectors, determining a reduction of the flux level owing to the effects of the stator resistance voltage drop. Fig. 12 shows the stator flux variations obtained by numerical simulations at a rotor speed of 10 rpm, and with a torque of 5 Nm. Also, this drawback can be avoided changing the basic switching table in order to utilize all the available voltage vectors according to suitable criteria [29]–[31].

VI. NEW DTC SCHEME (DSVM)

A substantial reduction of current and torque ripple in DTC scheme could be obtained using a preview technique in the calculation of the stator flux vector variation required to exactly compensate the flux and torque errors at each cycle period. In order to apply this principle, the control system should be able to generate any voltage vector (e.g., using the space vector modulation technique). This ideal behavior can be approximated ap-

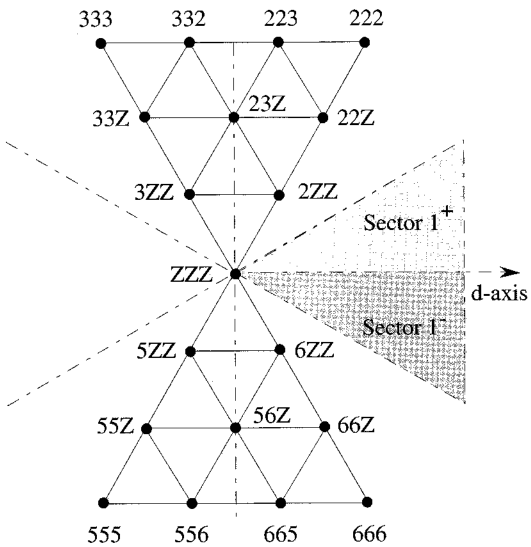
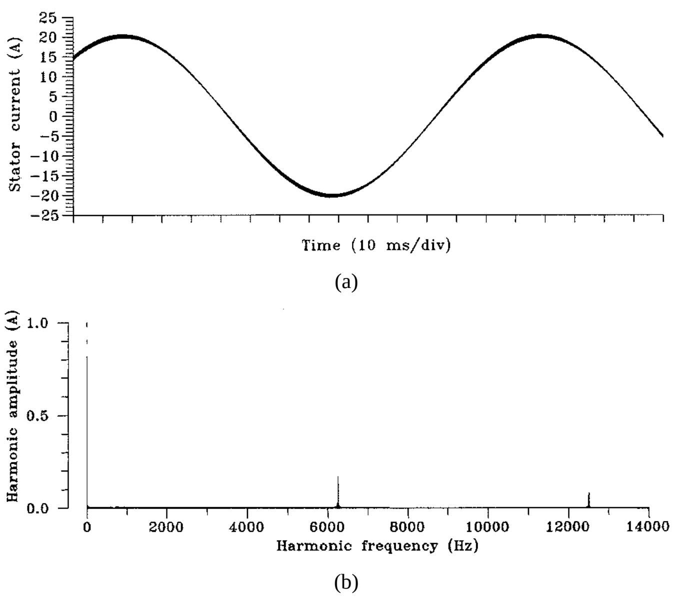


Fig. 13. Voltage vectors generated by using DSVM with three equal time intervals per cycle period.



(a)

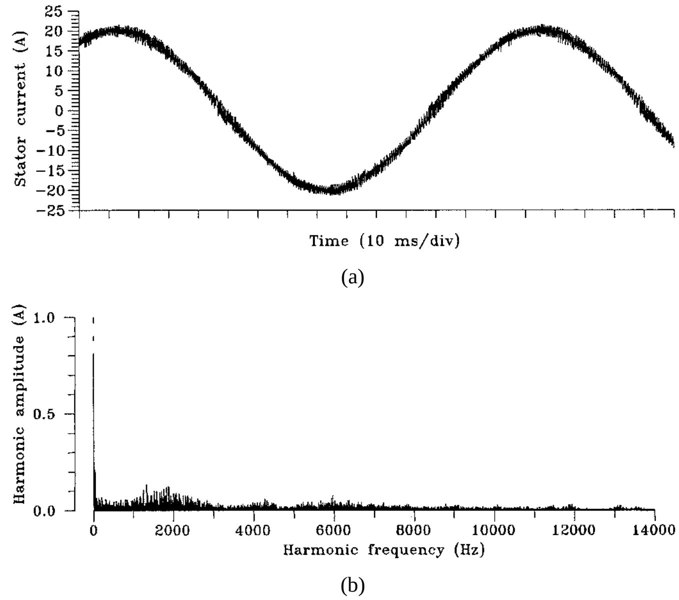
(b)

Fig. 14. (a) Stator current (DFOC). (b) Stator current harmonic spectrum (DFOC).

plying, at each cycle period, different voltage vectors for prefixed time intervals, leading to a discrete space vector modulation (DSVM) technique, which requires only a small increase of the computational time [32]. According to this principle of operation, new voltage vectors can be synthesized with respect to those used in basic DTC technique.

It has been verified that subdividing the cycle period in three equal time intervals leads to a substantial reduction of torque and current ripple without the need of too complex switching tables. Using the DSVM technique, with three equal time intervals, 19 voltage vectors can be generated, as represented in Fig. 13.

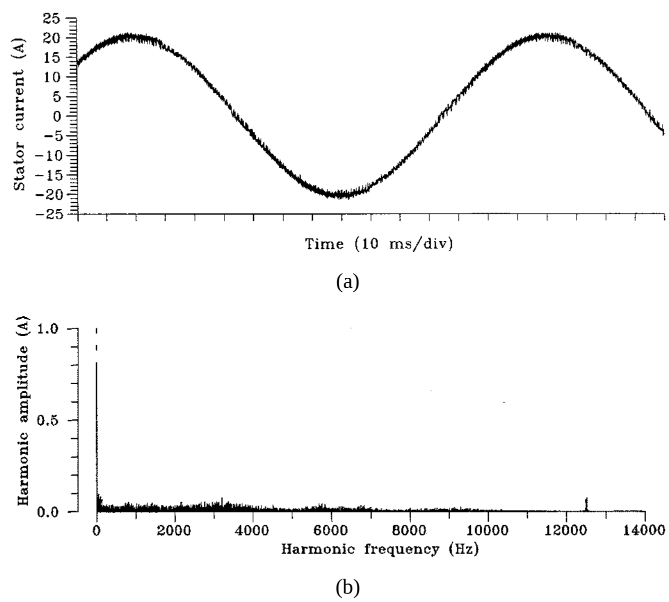
The black dots represent the ends of the synthesized voltage vectors. As an example, the label "332" denotes the voltage vector which is synthesized by using the voltage space vectors $\overline{V}_3$, $\overline{V}_3$ and $\overline{V}_2$, each one applied for one third of the cycle period.



(a)

(b)

Fig. 15. (a) Stator current (DTC). (b) Stator current harmonic spectrum (DTC).



(a)

(b)

Fig. 16. (a) Stator current (DSVM). (b) Stator current harmonic spectrum (DSVM).

The increased number of voltage vectors allows the definition of more accurate switching tables in which the selection of the voltage vectors can be made according to the rotor speed. The switching tables can be derived from the analysis of the equations linking the applied voltage vector to the corresponding torque and flux variations [32].

In order to show the effectiveness of this new DTC scheme, some numerical simulations have been performed, and the results obtained in terms of current waveform and current spectrum are given in Fig. 16. For comparison purposes, the same quantities are presented for DFOC and DTC in Figs. 14 and 15, respectively. The rotor speed is 144 rpm and the torque 26.5 Nm. The cycle period has been assumed equal to 80 μs. The difference with respect to 40 μs in DTC is not justified by a so large increase of the computational time, but by the need to keep the mean switching frequency equal to that of DFOC and DTC. It can be noted that the quality of the stator current is similar to that of DFOC scheme. It has been verified that also the torque ripple is similar to that of DFOC scheme.

VII. Conclusion

The aim of the paper was to give a fair comparison between DFOC and DTC techniques, to allow the users to identify the more suitable solution for any application that requires torque control. Several numerical simulations have been carried out in steady-state and transient operating conditions. A new DTC scheme has been also presented in order to improve the performance of the basic DTC scheme. The conclusion is that the whole performance of the two schemes is comparable. DTC might be preferred for high dynamic applications, but, on the other hand, shows higher current and torque ripple. This last drawback can be partially compensated by the new DTC scheme (DSVM).

The DTC scheme is simpler to be implemented, requiring a very small computational time. As a consequence, low cost DSP boards can be utilized. The implementation of DSVM technique requires only a small increase (25%–30%) of the computational time required by basic DTC scheme. Then, using a cycle period of 80 μs, as in numerical simulations, a large amount of time is available for parameter adaptation, protection and diagnostic facility.

References

[1] F. Blaschke, "A new method for the structural decoupling of A.C. induction machines," in *Conf. Rec. IFAC*, Duesseldorf, Germany, Oct. 1971, pp. 1–15.

[2] A. Nabae, K. Otsuka, H. Uchino, and R. Kurosawa, "An approach to flux control of induction motors operated with variable-frequency power supply," *IEEE Trans. Indust. Applicat. Syst.*, vol. IAS-16, pp. 342–349, May/June 1980.

[3] G. Kaufman, L. Garces, and G. Gallagher, "High performance servo drives for machine-tool applications using AC motors," in *Conf. Rec. IEEE-IAS*, 1982, pp. 604–609.

[4] R. Gabriel and W. Leonhard, "Microprocessor control of induction motor," in *Conf. Rec. IEEE Int. Semicond. Power Conv. Conf.*, Orlando, FL, 1982, pp. 385–395.

[5] K. B. Nordin, D. W. Novotny, and D. S. Zinger, "The influence of motor parameter deviations in feedforward field orientation," in *Conf. Rec. IEEE-IAS*, 1984, pp. 525–531.

[6] T. Matsuo and T. A. Lipo, "A rotor parameter identification scheme for vector controlled induction motor drives," in *Conf. Rec. IEEE-IAS*, 1984, pp. 538–545.

[7] R. Krishnan and F. C. Doran, "Study of parameter sensitivity in high performance inverter-fed induction motor drives," in *Conf. Rec. IEEE-IAS*, 1984, pp. 510–524.

[8] R. DeDoncker and D. W. Novotny, "The universal field oriented controller," in *Conf. Rec. IEEE-IAS*, 1988, pp. 450–456.

[9] X. Xu, R. DeDoncker, and D. W. Novotny, "A stator flux oriented induction machine drive," in *Conf. Rec. PESC*, 1988, pp. 870–876.

[10] J. Holtz and E. Bube, "Field oriented asynchronous PWM for high performance A.C. machine drives operating at low switching frequency," *IEEE Trans. Indust. Applicat.*, vol. 27, pp. 574–581, May/June 1991.

[11] I. Boldea and S. A. Nasar, *Vector Control of AC Drives*. Orlando, FL: CRC Press, 1992.

[12] T. Ohtani, N. Takada, and K. Tanaka, "Vector control of induction motor without shaft encoder," *IEEE Trans. Indust. Applicat.*, vol. 28, pp. 157–164, Jan./Feb. 1992.

[13] R. De Doncker, F. Profumo, and A. Tenconi, "The universal field oriented (UFO) controller in the airgap reference frame," *J. Inst. Elect. Eng. D*, vol. 113-D, no. 4, pp. 477–486, 1993.

[14] P. L. Jansen, R. D. Lorenz, and D. W. Novotny, "Observer based direct field orientation and comparison of alternative methods," *IEEE Trans. Indust. Applicat.*, vol. 30, pp. 945–953, July/Aug. 1994.

[15] L. Kwindler, J. C. Moreira, A. Testa, and T. A. Lipo, "Direct field orientation controller using the stator phase voltage third harmonics," *IEEE Trans. Ind. Applicat.*, vol. 30, pp. 441–447, Mar./Apr. 1994.

[16] R. De Doncker, F. Profumo, and M. Pastorelli, "Self tuning of induction motor servo drives using the universal field oriented controller," *IEEE Trans. Power Electron.*, vol. 9, pp. 357–366, July 1994.

[17] F. Profumo, G. Griva, J. Moreira, M. Pastorelli, and R. De Doncker, "Universal field oriented controller based on air gap flux sensing via third harmonic stator voltage," *IEEE Trans. Ind. Applicat.*, vol. 30, pp. 448–455, Mar./Apr. 1994.

[18] S. H. Kim and S. K. Sul, "Maximum torque control of an induction machine in the field weakening region," *IEEE Trans. Ind. Applicat.*, vol. 31, pp. 784–794, July/Aug. 1995.

[19] F. Profumo, R. DeDoncker, P. Ferraris, and M. Pastorelli, "Comparison of universal field oriendted (UFO) controllers in different reference frames," *IEEE Trans. Power Electron.*, vol. 10, pp. 205–213, Mar. 1995.

[20] T. Noguchi and I. Takahashi, "Quick torque response control of an induction motor based on a new concept" (in Japanese), *IEEJ Tech. Meeting Rotating Mach.*, vol. RM84–76, pp. 61–70, Sept. 1984.

[21] I. Takahashi and T. Noguchi, "A new quick-response and high efficiency control strategy of an induction machine," *IEEE Trans. Ind. Applicat.*, vol. 22, pp. 820–827, Sep./Oct. 1986.

[22] I. Takahashi and Y. Ohmori, "High-performance direct torque control of an induction motor," *IEEE Trans. Ind. Applicat.*, vol. 25, pp. 257–264, Mar./Apr. 1989.

[23] M. Depenbrock, "Direkte selbstregelung (DSR) für hochdynamische drehfeldantriebe mit stromrichterspeisung" (in German), *ETZ Archive*, no. 7, pp. 211–218, 1985.

[24] ——, "Direct self-control (DSC) of inverter-fed induction machine," *IEEE Trans. Power Electron.*, vol. 3, pp. 420–429, Oct. 1988.

[25] M. Depenbrock and A. Steimel, "High power traction drives and convertors," in *Proc. Elect. Drives Symp.'90*, Capri, 1990, pp. I 1–9.

[26] I. Boldea and S. A. Nasar, "Torque vector control (TVC)–A class of fast and robust torque speed and position digital controller for electric drives," in *Proc. EMPS'88 Conf.*, vol. 15, 1988, pp. 135–148.

[27] D. Casadei, G. Grandi, and G. Serra, "Study and implementation of a simplified and efficient digital vector controller for induction motors," in *Conf. Rec. EMD'93*, Oxford, U.K., Sept. 8–10, 1993, pp. 196–201.

[28] D. Casadei, G. Grandi, G. Serra, and A. Tani, "Effects of flux and torque hysteresis band amplitude in direct torque control of induction machines," in *Conf. Rec. IECON'94*, Bologna, Italy, Sept. 5–9, 1994, pp. 299–304.

[29] ——, "Switching strategies in direct torque control of induction machines," in *Conf. Rec. ICEM'94*, Paris, France, Sept. 5–8, 1994, pp. 204–209.

[30] P. Tiitinen, P. Pohkalainen, and J. Lalu, "The next generation motor control method: Direct torque control (DTC)," *EPE J.*, vol. 5, no. 1, pp. 14–18, Mar. 1995.

[31] J. N. Nash, "Direct torque control, induction motor vector control without an encoder," *IEEE Trans. Ind. Applicat.*, vol. 33, pp. 333–341, Mar./Apr. 1997.

[32] D. Casadei, G. Serra, and A. Tani, "Improvement of direct torque control performance by using a discrete SWM technique," in *Conf. Rec. PESC'98*, Fukuoka, Japan, May 17–22, 1998, pp. 997–1003.

[33] T. G. Habetler, F. Profumo, M. Pastorelli, and L. M. Tolbert, "Direct torque control of induction machines using space vector modulation," *IEEE Trans. Ind. Applicat.*, vol. 28, pp. 1045–1053, Sept./Oct. 1992.

[34] T. G. Habetler, F. Profumo, and M. Pastorelli, "Direct torque control of induction machines over a wide speed range," in *Conf. Rec. IEEE-IAS'92*, Houston, Oct. 1992, pp. 600–606.

[35] T. Abe, F. Profumo, G. Griva, and T. Habetler, "Evaluation of a high performance motor drive using direct torque control," in *Conf. Rec. PCC'93*, Yokohama, Japan, Apr. 1993, pp. 444–449.

[36] G. Griva, T. Habetler, M. Pastorelli, and F. Profumo, "Performance evaluation of a direct torque controlled drive in the continuous PWM-square wave transition region," *IEEE Trans. Power Electron.*, vol. 10, pp. 464–471, July 1995.

[37] D. Casadei, G. Serra, and A. Tani, "Stator flux vector control for high performance induction motor drives using space vector modulation," *Electromotion J.*, vol. 2, no. 2, pp. 79–86, 1995.

[38] C. Lascu, I. Boldea, and F. Blaabjerg, "A modified direct torque control (DTC) for induction motor sensorless drive," in *Conf. Rec. IEEE-IAS'98*, vol. 1, Oct. 12–15, 1998, pp. 415–422.

[39] D. Casadei, G. Serra, A. Tani, and L. Zarri, "Theoretical and experimental analysis of an induction motor drive based on stator flux vector control," *Electromotion J.*, vol. 6, no. 1–2, pp. 43–48, 1999.

[40] S. A. Mir, S. Zinger, and M. E. Elbuluk, "Fuzzy controller for inverter fed induction machines," *IEEE Trans. Ind. Applicat.*, vol. 30, pp. 78–84, Jan./Feb. 1994.

[41] P. Z. Grabowski and F. Blaabjerg, "Direct torque neuro-fuzzy control of induction motor drive. DSP implementation," in *Conf. Rec. IECON'98*, Aachen, Germany, Aug.–Sept. 31–4, 1998, pp. 657–661.

[42] D. Casadei, C. Rossi, G. Serra, and A. Tani, "Inverter state selection by neural network in DTC induction motor drives," in *Proc. SPEEDAM'00 Conf.*, Ischia, Italy, June 13–16, 2000, pp. C413–C418.

[43] D. Casadei, G. Serra, and A. Tani, "Sensitivity investigation of a speed sensorless induction motor drive based on stator flux vector control," in *Conf. Rec. PESC'97*, St. Louis, MI, June 22–27, 1997, pp. 1055–1060.

[44] K. D. Hurst, T. G. Habetler, G. Griva, and F. Profumo, "Zero speed tacho-less I.M. torque control: Simply a matter of stator voltage integration," *IEEE Trans. Ind. Applicat.*, vol. IA-34, pp. 970–975, July/Aug. 1998.

Domenico Casadei (M'75) was born in Rimini, Italy, in 1949. He received the Ph.D. degree (with honors) in electrical engineering from the University of Bologna, Bologna, Italy, in 1974.

He joined the Institute of Electrical Engineering, University of Bologna, in 1975. From 1975 to 1985, he was a Research Assistant, and since 1985, he has been an Associate Professor of Electrical Drives. He is Professor of Electrical Drives at the Department of Electrical Engineering, University of Bologna. His scientific work is related to electrical machines and drives, linear motors, Maglevs, and power electronics. He has published more than 100 papers in technical journals and conference proceedings. His present research interests include direct torque control of induction motors, brushless motors, matrix converters, and power quality.

Dr. Casadei is a member of the IEEE Industrial Electronics Society, the IEEE Power Electronics Society, and the Italian Electrotechnical and Electronic Association (AEI). Since 1994, he has been a member of the international editorial board of *Electromotion*. He is a Registered Professional Engineer in Italy.

Francesco Profumo (M'88–SM'90) was born in Savona, Italy, in 1953. He received the Ph.D. degree in electrical engineering from the Politecnico di Torino, Torino, Italy, in 1977.

From 1978 to 1984, he was a Senior Engineer for the R&D Ansaldo Group, Genova, Italy. In 1984, he joined the Department of Electrical Engineering, Politecnico di Torino, where he was Associate Professor until 1995. He is now a Professor of Electrical Machines and Drives at Politecnico di Torino and Adjunct Professor at the University of Bologna. He was a Visiting Professor at the Department of Electrical and Computer Engineering, University of Wisconsin, Madison, from 1986 to 1988 and at the Department of Electrical Engineering and Computer Science, Nagasaki University, Nagasaki, Japan, from 1996 to 1997. He has been the Coordinator or partner of several Projects in the frame of the European Commission activities (Tempus, Comett, Joule, Human Capital and Mobility, Alfa, European Union S&T Grant Programme in Japan, Leonardo da Vinci). He published more than 180 papers in international conferences and technical journals. His fields of interest are power electronics conversion, high-power devices, applications of new power devices, integrated electronic/electromechanical design, high-response speed servo drives, and new electrical machines structures.

Dr. Profumo received the IEEE-IAS second prize paper in 1991 and 1997 and the IEEE-IAS first prize paper in 1992. He is an active member of the IEEE-IAS Drives Committee and serves as Co-Chairman of the same Committee. He was also AdCom member of the IEEE PELS. He is a member of the Technical Program Committee of several International Conferences in the power electronics and motor drives field and he will be the Technical Co-Chairman of the PCC'02, Osaka, Japan, 2002. He is a Registered Professional Engineer in Italy.

Giovanni Serra (M'75) was born in Bologna, Italy, in 1950. He received the Ph.D. degree (with honors) in electrical engineering from the University of Bologna, Bologna, Italy, in 1975.

Following service in the Italian Army, he joined the Department of Electrical Engineering, University of Bologna, first as a recipient of a Fellowship of the Consiglio Nazionale delle Ricerche, then as a Research Associate and, since 1987, as Associate Professor. He is currently Professor of Electrical Machines at the Department of Electrical Engineering, University of Bologna. He has published more than 80 papers in technical journals and conference proceedings. His fields of interests are electrical machines, electrical drives, and power electronic converters. His current activities include direct torque control of ac machines, linear motors, and ac/ac matrix converters.

Dr. Serra is a member of the IEEE Industry Applications Society, the IEEE Dielectrics and Electrical Insulation Society, and the Italian Electrotechnical and Electronic Association (AEI). He is a Registered Professional Engineer in Italy.

Angelo Tani was born in Faenza, Ravenna, Italy, in 1963. He received the Ph.D. degree (with honors) in electrical engineering from the University of Bologna, Bologna, Italy, in 1988.

He joined the Department of Electrical Engineering, University of Bologna, in 1990, where he is currently a Research Associate. His scientific work is related to electrical machines and drives, power electronics, and Maglevs. He has published more than 40 papers in technical journals and conference proceedings. His current activities include ac/ac matrix converters and direct torque control of induction motors.