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Direct Torque Control of Induction Motor with Stator Flux Correction

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Original scientific paper

Direct torque control (DTC) method with correction of stator flux vector is presented in the paper. The correction is made by means of appropriate component of stator current vector. Thus, controlled quantities (electromagnetic torque and stator flux) are estimated only from stator parameters and measured stator quantities, and there is no need to use rotor parameters, which are dependent on the operating condition, and rotor quantities, which cannot be measured. With the proposed method stable operation in whole speed range, robust start-up with slow change of the torque and fast torque response are achieved. Simulations and experimental tests verify the validity of the method.

Key words: induction motors, estimation techniques, vector control

1 INTRODUCTION

The DTC method is one of the most recently researched induction motor control methods. It is based on the decoupled control of flux and torque without the need of coordinate transformation and the inner current regulation loops. This type of control was introduced as direct self-control [1] and independent hysteresis control of torque and flux using switching table [2]. The voltage vector selection using switching table is nowadays widely commercialised [3, 4, 5].

The estimated values of the torque and the flux vector are compared with the referent ones and one of the 8 possible stator voltage vectors generated by a voltage source inverter is selected. The optimum switching is determined for every control cycle. The limited number of voltage vectors that can be applied and the use of hysteresis controllers cause current and torque ripples. Therefore, short control cycle period (about 25 μs [3, 4]) is required to achieve good performance. Large torque ripples are generated especially in a low speed range. Basic DTC method, in which the torque and the flux vector are calculated only from stator parameters and measured stator quantities, cannot operate stable at low speeds. In that case, stator flux is corrected by means of rotor quantities and rotor parameters (estimation of the stator flux vector with current model) [3, 4], or instead of the stator flux vector the rotor flux vector is assumed as a reference [6, 7]. The use of rotor parameters and rotor quantities increases the computational time and produces additional errors in estimation because rotor parameters are strongly dependent on temperature and saturation effects and rotor quantities cannot be measured.

Mismatch between estimated flux vector and accurate flux vector would lead to incorrect control and undesirable torque and current ripples. Stator currents as well as stator fluxes are consequences of supplied voltage (its value and frequency) and are functions of load torque. Hence, it is possible to correct the estimated stator flux vector by means of appropriate component of stator current vector. In the paper, the proposed method, the simulation and experimental results are presented. Simulations and experimental tests were carried out on a model of a drive with 37 kW induction motor and IGBT inverter with digital signal processor (DSP).

2 PROPOSED METHOD FOR STATOR FLUX CORRECTION

2.1 Basic Induction Motor Equations

The stator flux vector and the electromagnetic torque are calculated as follows:

$$\vec{\Psi}_s = \int(\vec{u}_s - R_s\vec{i}_s)\,\mathrm{d}t \qquad (1)$$

$$t_{\mathrm{elm}} = \frac{2}{3}p(\vec{\Psi}_s \otimes \vec{i}_s) \qquad (2)$$

where:

- $\vec{\Psi}_s$ – stator flux vector,
- $\vec{u}_s$ – stator voltage vector,
- R_s – stator resistance,
- $\vec{i}_s$ – stator current vector,
- t_{elm} – electromagnetic torque,
- p – pole pairs of the motor.

2.2 Direct Torque Control Principle

Voltage source inverter can generate 6 nonzero and 2 zero stator voltage vectors. The influence of each nonzero voltage vector on absolute length and angle of the stator flux vector $\vec{\Psi}_s$ depends on the position of $\vec{\Psi}_s$ in the complex plane. The movement of $\vec{\Psi}_s$ when one of the zero voltages is applied depends on the stator current vector $\vec{i}_s$ and operating speed. Figure 1 shows the voltage vectors and the stator flux vector in the complex plane. The plane is divided in six sectors.

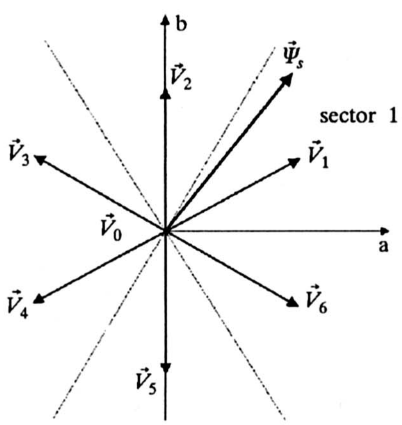

Fig. 1 The voltage vectors and the stator flux vector in the complex plane

The values of flux and torque are controlled by means of hysteresis controllers. Selection of control signals for the switches in the inverter and corresponding voltage vector are determined for every control cycle. The selection is made according to the outputs of torque and flux hysteresis controllers and position of the stator flux vector.

Switching table proposed in [2, 8] is represented in Table 1, where states of the switches in inverter and corresponding stator voltage vector are presented. τ and ϕ are outputs of the torque and the flux controllers, respectively.

The main feature of DTC is its simplicity because the flux and the torque are calculated only from stator parameters and measured stator quantities. However, the discrete number of voltage vector generated by a voltage source inverter and the use of hysteresis controllers lead to torque and current ripples. In the low speed range basic DTC method cannot operate stable without correction of estimated stator flux vector with rotor parameters and rotor quantities [3, 4], or the rotor flux vector is used in the method [6, 7].

2.3 Stator Flux Correction

The basic idea of stator flux correction is the use of stator currents. Both stator currents and stator fluxes are consequences of supplied voltage. Currents are measured, not estimated quantities, and therefore they contain information on real fluxes in the machine. A difference in the absolute length and/or in the position in the complex plane between estimated stator flux vector and accurate stator flux vector would result in unstable operation with large torque and current ripples. Estimated torque and estimated stator flux vector may be within the limits of hysteresis bands, but current ripples indicate that there is error in the estimation of stator flux.

Figure 2 shows the stator current vector $\vec{i}_s$ and the stator flux vector $\vec{\Psi}_s$. $\vec{i}_s$ is divided in 2 components: component $\vec{i}_{s\Psi}$ is collinear with $\vec{\Psi}_s$ and component $\vec{i}_{sT}$ is perpendicular to $\vec{\Psi}_s$. $\vec{i}_{sT}$ is component of the stator current vector which produces the electromagnetic torque because (2) can be written also as:

Table 1 **Switching table**

Sector		1	2	3	4	5	6
$\phi=1$	$\tau=1$	V_2 (1, 1, 0)	V_3 (0, 1, 0)	V_4 (0, 1, 1)	V_5 (0, 0, 1)	V_6 (1, 0, 1)	V_1 (1, 0, 0)
	$\tau=0$	V_1 (1, 0, 0)	V_2 (1, 1, 0)	V_3 (0, 1, 0)	V_4 (0, 1, 1)	V_5 (0, 0, 1)	V_6 (1, 0, 1)
	$\tau=-1$	V_6 (1, 0, 1)	V_1 (1, 0, 0)	V_2 (1, 1, 0)	V_3 (0, 1, 0)	V_4 (0, 1, 1)	V_5 (0, 0, 1)
$\phi=0$	$\tau=1$	V_3 (0, 1, 0)	V_4 (0, 1, 1)	V_5 (0, 0, 1)	V_6 (1, 0, 1)	V_1 (1, 0, 0)	V_2 (1, 1, 0)
	$\tau=0$	V_0 (0, 0, 0)	V_7 (1, 1, 1)	V_0 (0, 0, 0)	V_7 (1, 1, 1)	V_0 (0, 0, 0)	V_7 (1, 1, 1)
	$\tau=-1$	V_5 (0, 0, 1)	V_6 (1, 0, 1)	V_1 (1, 0, 0)	V_2 (1, 1, 0)	V_3 (0, 1, 0)	V_4 (0, 1, 1)

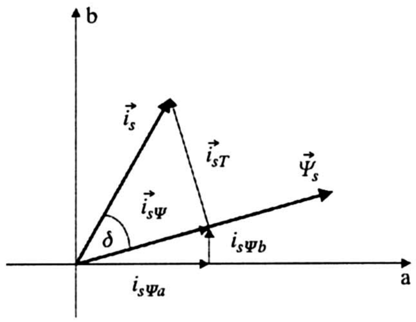

Fig. 2 The stator current vector and the stator flux vector

$$t_{\mathrm{elm}} = \frac{2}{3} p \left|\vec{\Psi}_s\right| \left|\vec{i}_s\right| \sin(\delta) \tag{3}$$

where:

δ – angle between $\vec{i}_s$ and $\vec{\Psi}_s$.

$\vec{i}_{s\Psi}$ is flux component of $\vec{i}_s$. It can be analysed as a vector with its real and imaginary part:

$$\vec{i}_{s\Psi} = i_{s\Psi a} + j i_{s\Psi b}. \tag{4}$$

Vectors $\vec{i}_{s\Psi}$ and $\vec{\Psi}_s$ are collinear. Hence, $i_{s\Psi a}$ and the real part of $\vec{\Psi}_s$ as well as $i_{s\Psi b}$ and the imaginary part of $\vec{\Psi}_s$ are, in the case of correct control and stable operation, in the phase and all quantities have sinusoidal waveform. These components are compared and used for correction of the stator flux vector.

$\vec{\Psi}_s$ estimated according to (1) is corrected as follows:

$$\Delta\vec{\Psi}_s = k_i \vec{i}_{s\Psi} - \vec{\Psi}_s \tag{5}$$

$$\vec{\Psi}_{sc} = \vec{\Psi}_s + k_{\Psi} \Delta\vec{\Psi}_s \tag{6}$$

where:

$\Delta\vec{\Psi}_s$ – delta stator flux vector,
k_i – scalar with dimension of inductance,
$\vec{\Psi}_{sc}$ – corrected stator flux vector,
k_{Ψ} – scalar.

k_i in (5) ought to be chosen in such a way that both real and imaginary part of the vector $\Delta\vec{\Psi}_s$ have sinusoidal waveform and that the amplitudes of vectors $\Delta\vec{\Psi}_s$ and $\vec{\Psi}_s$ are approximately equal. The difference between the amplitudes of vectors $\vec{\Psi}_{sc}$ and $\vec{\Psi}_s$ should not be greater than 0.5 % and that determines the value of scalar k_{Ψ} in (6).

The electromagnetic torque is also corrected:

$$t_{\mathrm{elmc}} = \frac{2}{3} p(\vec{\Psi}_{sc} \otimes \vec{i}_s) \tag{7}$$

where:

t_{elmc} – corrected electromagnetic torque.

A block diagram of the DTC scheme with proposed correction method is shown in Figure 3. FHC and THC are flux and torque hysteresis controllers, respectively.

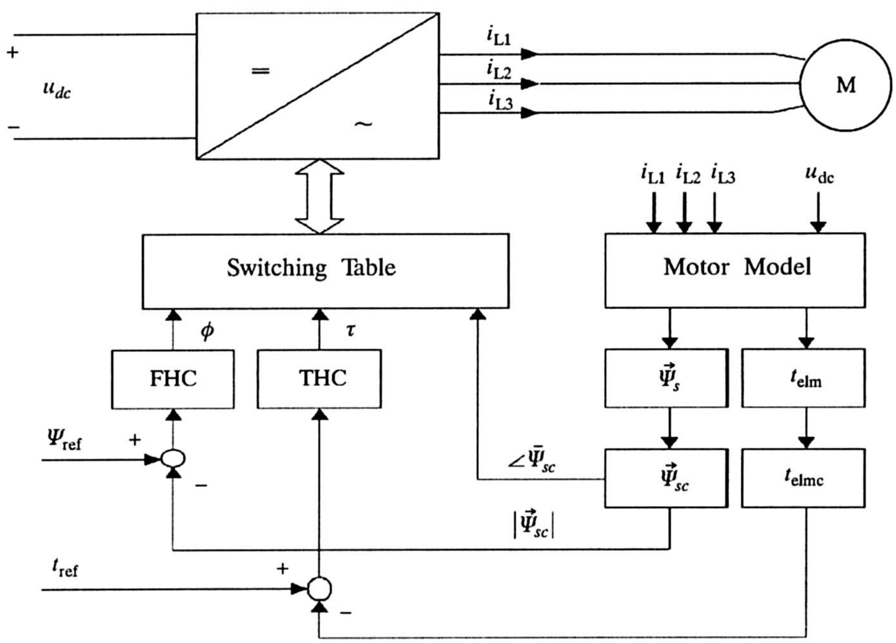

Fig. 3 Block diagram of the DTC scheme with stator flux correction

3 SIMULATION AND EXPERIMENTAL RESULTS

Simulation and experimental tests were carried out on a model of the drive with traction induction motor manufactured by »KONČAR«, IGBT inverter with 20 MHz DSP TMS320F240 and DC machine as a load. Motor data are listed in Table 2.

Simulation results take into account effects of time discretisation, A/D conversion and integer arithmetic. The control cycle period is 60 μs both in simulation and in experiments. Figure 4 shows simulation and Figure 5 shows experimental results at 2 % the rated speed and 50 % the rated torque without flux correction, i. e. the basic DTC method is applied. Estimated stator current component $i_{s\Psi a}$ and stator phase current are presented. $i_{s\Psi a}$ differs considerably from the sinusoidal waveform and there are undesirable oscillations in the current. Higher harmonics in developed electromagnetic torque (due to the hysteresis controllers and control cycle period) are inherent to DTC method. The electromagnetic torque, which is result of the simulation (Figure 4), has also low harmonic at frequency equal frequency of the fundamental voltage component and its amplitude is approximately 20 % of the reference torque value.

Table 2 **Motor data**

Type	4AZV 200La-4
Connection	Δ
Power	37 kW
Rated voltage	470 V
Rated current	56 A
Rated frequency	60 Hz
Pole pairs	2
Rated speed	1758 r/min

Figure 6 and Figure 7 show results under the same conditions when the proposed method of stator flux correction is applied. The values of scalar k_i in (5) and k_Ψ in (6) are 80 mH and 0.005, respectively. Current and torque ripples are diminished.

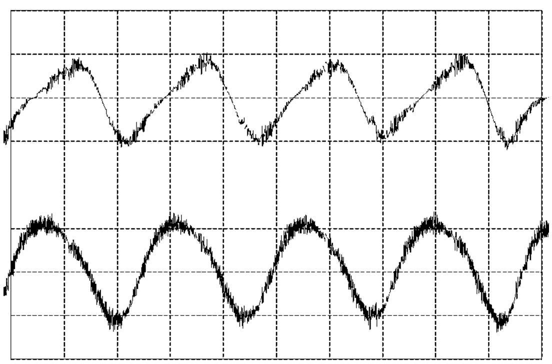

Fig. 4 Simulation results (basic DTC method): estimated current component $i_{s\Psi a}$ (upper trace), motor phase current (lower trace), 2 % rated speed, 50 % rated torque, 200 ms/div, 25 A/div

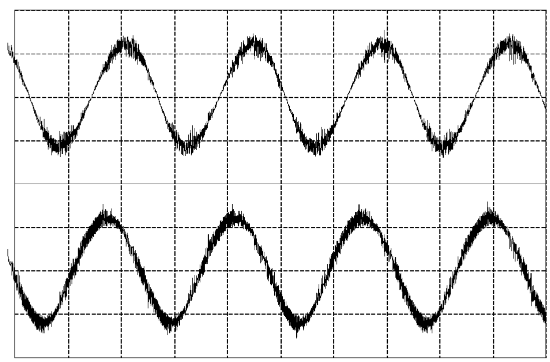

Fig. 6 Simulation results (method with stator flux correction): estimated current component $i_{s\Psi a}$ (upper trace), motor phase current (lower trace), 2 % rated speed, 50 % rated torque, 200 ms/div, 25 A/div

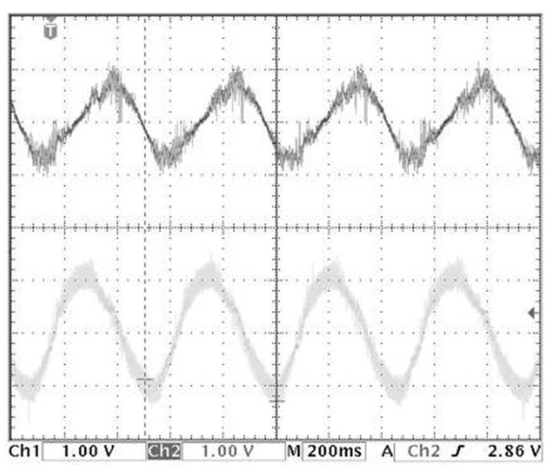

Fig. 5 Experimental results (basic DTC method): estimated current component $i_{s\Psi a}$ (upper trace), measured motor phase current (lower trace), 2 % rated speed, 50 % rated torque, 25 A/div

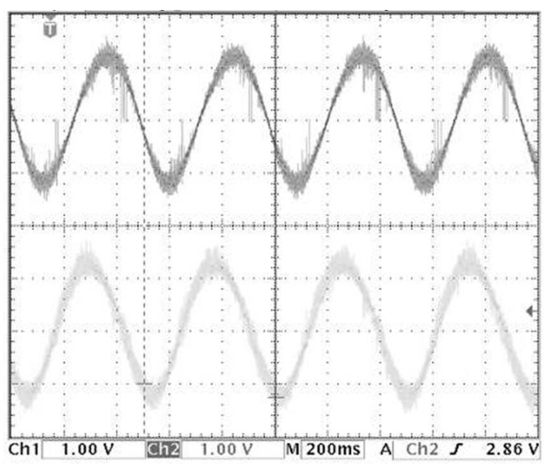

Fig. 7 Experimental results (method with stator flux correction): estimated current component $i_{s\Psi a}$ (upper trace), measured motor phase current (lower trace), 2 % rated speed, 50 % rated torque, 25 A/div

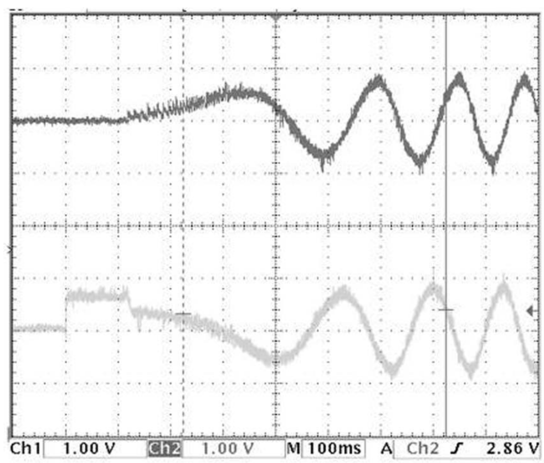

Fig. 8 Experimental results (method with stator flux correction): measured motor phase currents, start-up, 50 A/div

The developed electromagnetic torque contains only higher harmonics that are consequence of the hysteresis controllers and control cycle period. Although the speed is low, the drive operation is stable.

Fast torque response is not required in traction drives (e. g. tram drive) because that would lead to an uncomfortable drive. In drives with basic DTC method, start-up with slow change of torque reference is critical due to the demagnetisation phenomena [9]. The presented method of stator flux correction enables robust start.

Figure 8 shows start-up of the drive, i. e. motor phase-currents are showed. After DC magnetisation (the reference value of the stator flux vector was set that the duration of initial magnetisation was 120 ms), the torque reference (75 % rated torque) with slow rate of change (300 Nm/s) is applied.

Experiments with correction method were also carried out with step change of the torque command and at high speeds. Excellent dynamic torque control performance (torque response in few ms) and stable operation in field weakening region are achieved.

4 CONCLUSION

The performance of DTC method with correction of stator flux is analysed in the paper. The stator flux vector is corrected by means of stator currents. The method improves highly operation at low speeds (torque and current oscillations are diminished), enables robust start-up of the drive even with slow change of torque reference, fast torque response and stable operation in whole speed region. In this way, very simple control without use of rotor parameters and rotor quantities is achieved.

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Direktno upravljanje momentom asinkronog motora s korekcijom statorskog toka. U članku je prikazana metoda direktnog upravljanja momentom asinkronog motora s korekcijom vektora statorskog toka. Korekcija je provedena pomoću odgovarajuće komponente vektora statorske struje. Tako su upravljane veličine (elektromagnetski moment i statorski tok) određene samo preko statorskih parametara i mjerenih statorskih veličina, te je time izbjegnuto korištenje rotorskih parametara, koji ovise o pogonskim uvjetima i rotorskih veličina, koje se ne mogu mjeriti. Predloženom metodom omogućen je stabilan rad u čitavom području brzine vrtnje, pokretanje sa sporom promjenom zadanog momenta te brzi odziv razvijenog momenta. Simulacije i eksperimentalna ispitivanja potvrđuju ispravnost predložene metode.

Ključne riječi: asinkroni motori, metode estimacije, vektorska regulacija

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