EXPERIMENTAL EVALUATION OF THE HIGH PERFORMANCE VECTOR CONTROLLED DOUBLY-FED INDUCTION MACHINE WITH MATRIX CONVERTER

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Анотація **– Виконано експериментальні випробування машини подвійного живлення (МПЖ) з керуванням від 6 кВА матричного перетворювача (МП). Всі алгоритми керування для МП і МПЖ виконувались в реальному часі, використовуючи контролер DSP, і успішно випробувані на експериментальному стенді. Експериментально продемонстровано, що алгоритми керування МП і МПЖ гарантують точне слідкування за моментом позитивної і негативної траєкторій заданого моменту за умови одиничного коефіцієнту потужності статорної ланки. Досягнено задовільних форм кривих струмів в ланці МПЖ і в ланці МП.**

Ключові слова **– машина подвійного живлення, матричний перетворювач, векторне керування, експеримент.**

INTRODUCTION

In some technological applications such as centrifugal pumps, fans, wind generators desired control performance can be achieved using restricted speed regulation range (less than 20-25%). Doubly fed induction machine (DFIM) has been found as an attractive solution for these applications. DFIM allows to get control effect using bi-directional rotor power converter whose power is proportional to required slip range [1].

The two approaches are possible to supply the DFIM rotor circuit: standard AC-DC-AC converters with vector controlled input rectifier and direct frequency converters known as matrix converters (MC). Back-to-back AC-DC-AC converters have been intensively studied [1] and now they established the industrial standard for medium and high power applications. Recently matrix converters have been found as attractive alternative to AC-DC-AC converters [2]. Vector control techniques allows decoupled control of active and reactive power at stator side. Some results of MC application for DFIM control has been already reported in literature [3]. Nevertheless as far as authors know MC never has been tested in vector controlled DFIM.

In this paper we present results of intensive experimental study of the high dynamic performance vector controlled doubly-fed induction machine with matrix converter. For both MC and DFIM control we use recently developed by authors novel control algorithms.

A new space vector modulation (SVM) and improved commutation strategy [4] have been implemented for matrix converter control. The main features of the proposed SVM control are: linear loading of the line source (MC is viewed by the line source as linear load); high precision tracking of the reference voltage vector. No information about output current direction and relation between input phase voltages are required for implementation of the MC commutation.

The paper is organized as follows. Section II presents general configuration of torque tracking control algorithm for DFIM. In Section III the short description of MC control algorithm is given. Results of experimental testing of the DFIM with MC are given in Section IV.

TORQUE TRACKING CONTROL ALGORITHM FOR DFIM

In [5], [6] authors proposed to use a stator voltage vector oriented reference frame instead of the stator flux oriented one for the control of DFIM. The line voltage-vector angle can be easily measured with negligible errors, avoiding the stator current measurement.

The equivalent two-phase model of the symmetrical DFIM with connected to line stator, represented in stator voltage-vector oriented frame (d-q) is

$$\begin{aligned}
&\dot{\varepsilon} = \omega \\
&\dot{\omega} = \frac{1}{J}\left[\mu p_n\left(\psi_{1q} i_{2d} - \psi_{1d} i_{2q}\right) - T_L\right] \\
&\dot{\psi}_{1d} = -\alpha_1 \psi_{1d} + \omega_0 \psi_{1q} + \alpha_1 L_m i_{2d} + U \\
&\dot{\psi}_{1q} = -\alpha_1 \psi_{1q} - \omega_0 \psi_{1d} + \alpha_1 L_m i_{2q} \\
&\dot{i}_{2d} = -\gamma_2 i_{2d} + \omega_2 i_{2q} + \alpha_1 \beta \psi_{1d} - \beta p_n \omega \psi_{1q} - , \qquad (1) \\
&-\beta u_{1d} + \frac{1}{\sigma_2} u_{2d} \\
&\dot{i}_{2q} = -\gamma_2 i_{2q} - \omega_2 i_{2d} + \alpha_1 \beta \psi_{1q} + \beta p_n \omega \psi_{1d} - \\
&-\beta u_{1q} + \frac{1}{\sigma_2} u_{2q}
\end{aligned}$$

where $(u_{2d}, u_{2q}), (i_{2d}, i_{2q}), (\psi_{1d}, \psi_{1q})$ are rotor voltages, rotor currents and stator fluxes, T_L is a moving torque, generated by the primary mover, U and ω_0 are stator (line) voltage amplitude and angular frequency, ε and ω are angular position and rotor speed, $\omega_2 = \omega_0 - \omega$ is sleep angular frequency, p_n is number of pole pair. Positive constants related to DFIM electrical parameters are defined as:

$$\alpha_1=\frac{R_1}{L_1};\ \sigma_2=L_2\left(1-\frac{L_m^2}{L_1L_2}\right);\ \beta=\frac{L_m}{L_1\sigma_2};$$

$$\gamma_2=\frac{R_2}{\sigma_2}+\alpha_1\beta L_m,\ \mu=\frac{3}{2}\frac{L_m}{L_1},$$

where R_1, R_2, L_1, L_2 - resistance and inductance of stator and rotor respectively, L_m - mutual inductance.

The complete equations of the torque tracking stator side power factor stabilizing controller are given by:
Stator flux vector controller:

$$i_{2q}^*=\frac{1}{\alpha_1 L_m}\left(\alpha_1\psi^*+\dot{\psi}^*\right)$$
$$\psi^*=\frac{-U-\left(U^2-4\left(\frac{2}{3}\right)\omega_1 R_1 T^*\right)^{\frac{1}{2}}}{2\omega_1} \tag{2}$$

Torque controller:

$$i_{2d}^*=\frac{T^*}{\mu\psi^*} \tag{3}$$

Rotor current controller:

$$u_{2d}=\sigma_2\left[\gamma_2 i_{2d}^*-\omega_2 i_{2q}^*+\beta\omega\psi^*+\right.$$
$$\left.+\beta U+\dot{i}_{2d}^*-k_1\tilde{i}_{2d}+x_d\right]$$
$$u_{2q}=\sigma_2\left[\gamma_2 i_{2q}^*+\omega_2 i_{2d}^*-\alpha_1\beta\psi^*+\right. \tag{4}$$
$$\left.+\dot{i}_{2v}^*-k_1\tilde{i}_{2q}+x_q\right]$$

$$\dot{x}_d=-k_{ii}\tilde{i}_{2d}$$
$$\dot{x}_q=-k_{ii}\tilde{i}_{2q}$$
$$\tilde{i}_{2d}=i_{2d}-i_{2d}^*$$
$$\tilde{i}_{2q}=i_{2q}-i_{2q}^*,$$

where i_{2d}^*, i_{2q}^* are rotor currents reference in (d-q) reference frame; k_1 and k_{ii} are positive proportional and integral gains of current controllers; ψ^* - stator flux reference; x_d, x_q are integral components of current controllers.

Control task is asymptotic torque tracking control under condition of unity stator side power factor.

The block diagram of the proposed controller is shown in Fig. 1.

MATRIX CONVERTER CONTROL ALGORITHM

The matrix converter generates appropriate voltage waveforms for DFIM rotor supply. The averaged values of the voltage reference vector $\mathbf{u}_{ref}$ are obtained as the result of synthesis from the five stationary vectors (four non-zero and one zero) [7], [8]. As a result of alternate operation on each SVM period the line voltages form "averaged" voltage, which transformed to output voltage vector.

At the beginning of the carrier frequency period is formed MC output voltage vector. Two adjacent vectors alternately participate in forming of the output voltage in each sector on SVM period. Thus, each of vectors is involved in two adjacent sectors (Fig.2).

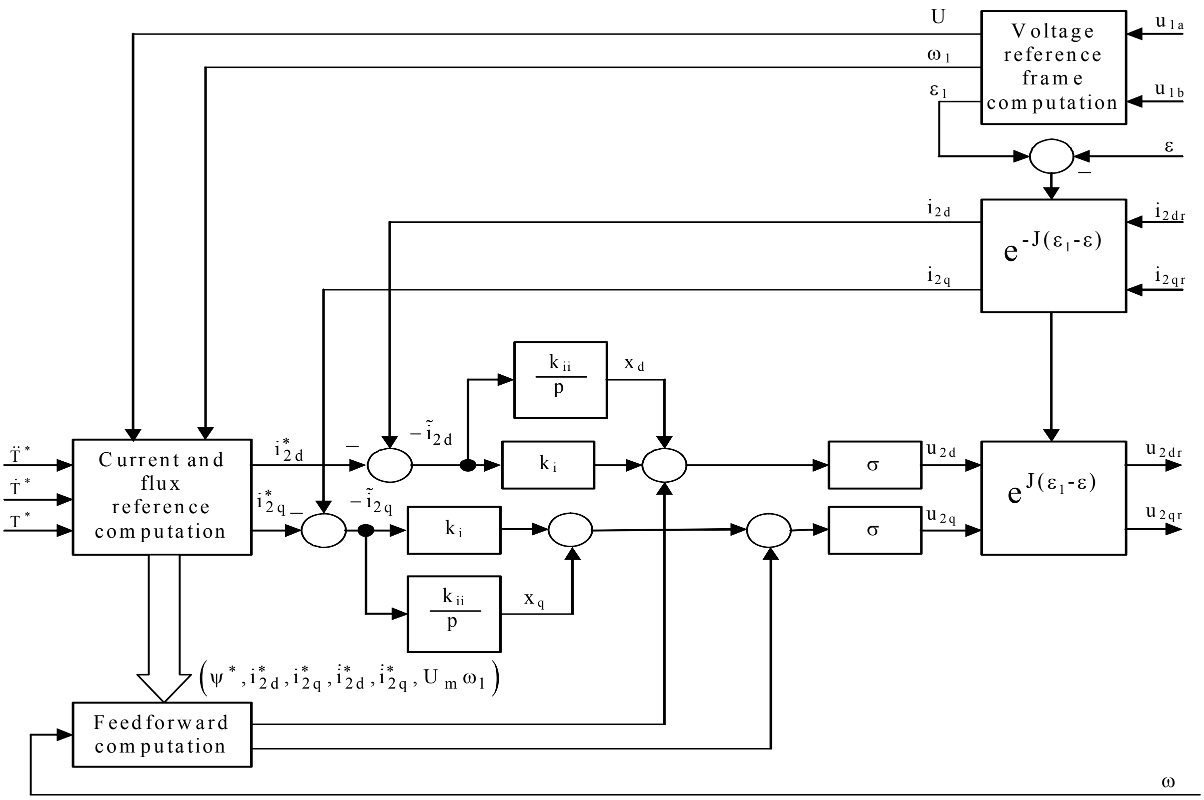

Fig. 1. Block diagram of the torque tracking stator side power factor stabilizing controller.

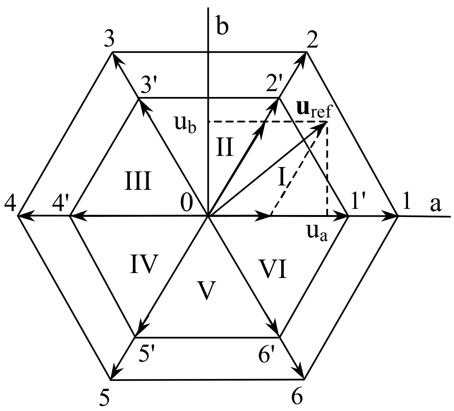

Fig. 2. Output space voltage vector diagram

Calculation of the on-time ratios (the interval duration, in which four non-zero stationary vectors are acting during current SVM period) are defined as follows [9]:

$$\mu_{nA(B,C)} = \sqrt{3}\,\varepsilon_{A(B,C)}\,\varepsilon_n\,\mathbf{u}_{ref}\,, \quad (5)$$

where

$$\varepsilon_{A(B,C)} = \frac{\left|u_{A(B,C)}\right|}{u_A^2 + u_B^2 + u_C^2}\,, \quad (6)$$

$$\varepsilon_n = \sin(n\frac{\pi}{3} - \psi)\,, \quad (7)$$

$$\varepsilon_{n+1} = \sin[\psi - (n-1)\frac{\pi}{3}]\,, \quad (8)$$

$$\mathbf{u}_{ref} = \sqrt{{u_a}^2 + {u_b}^2}\,, \quad (9)$$

n and n+1 are vector indexes (Fig.2), which bound sector with the MC reference voltage vector $\mathbf{u}_{ref}$. On the rest of SVM period a zero vector is generated.

In total 6*6=36 of possible states for non-zero vectors and three for zero is included. During one cycle of SVM period five states are implemented. As an example the control algorithm of MC output voltage vector for the first reference sector (n=1) is presented:

$$\left|\mathbf{u}_{ref}\right| = \frac{2}{3}\left|\begin{matrix}\mu_{1A}u_{AB} + \mu_{2A}u_{AB} + \\ + \mu_{2C}u_{CB} + \mu_{1C}u_{CB} + \mu_0 0\end{matrix}\right| \quad (10)$$

where

$$\begin{aligned}
\mu_{1A} &= \frac{\sqrt{3}\left|u_A\right|\left|\mathbf{u}_{ref}\right|}{u_A^2 + u_B^2 + u_C^2}\sin(n\frac{\pi}{3} - \psi),\\
\mu_{1C} &= \frac{\sqrt{3}\left|u_C\right|\left|\mathbf{u}_{ref}\right|}{u_A^2 + u_B^2 + u_C^2}\sin(n\frac{\pi}{3} - \psi),\\
\mu_{2A} &= \frac{\sqrt{3}\left|u_A\right|\left|\mathbf{u}_{ref}\right|}{u_A^2 + u_B^2 + u_C^2}\sin(\psi),\\
\mu_{2C} &= \frac{\sqrt{3}\left|u_C\right|\left|\mathbf{u}_{ref}\right|}{u_A^2 + u_B^2 + u_C^2}\sin(\psi),\\
\mu_0 &= 1 - \mu_{1A} - \mu_{1C} - \mu_{2A} - \mu_{2C}.
\end{aligned} \quad (11)$$

Thus, MC vector control algorithm is realized in following steps:

- during execution of the previous reference on the current SVM cycle the moment of transition from one combination of voltages to other and its identification is defined on base of instantaneous voltages of mains;
- reference components u_a, u_b of the output voltage vector are read out, and the corresponding sector of the vector diagram is determined;
- with help of expression (11) on-time ratios are calculated.

In this work the commutation strategy, based on measuring the AC input phase voltages relationship, is used. As compared with the other approaches it requires no current direction determination, and a relation of the input phase voltages in each commutation moment, but only their polarity [4], [9].

EXPERIMENTAL TESTING OF THE DOUBLY-FED INDUCTION MACHINE WITH MATRIX CONVERTER

The proposed torque tracking control algorithm has been experimentally tested using 1.4kW wound rotor induction machine, whose rated data are listed in Appendix [10]. The experimental tests were carried out using an experimental set-up, whose block diagram is shown in Fig. 3.

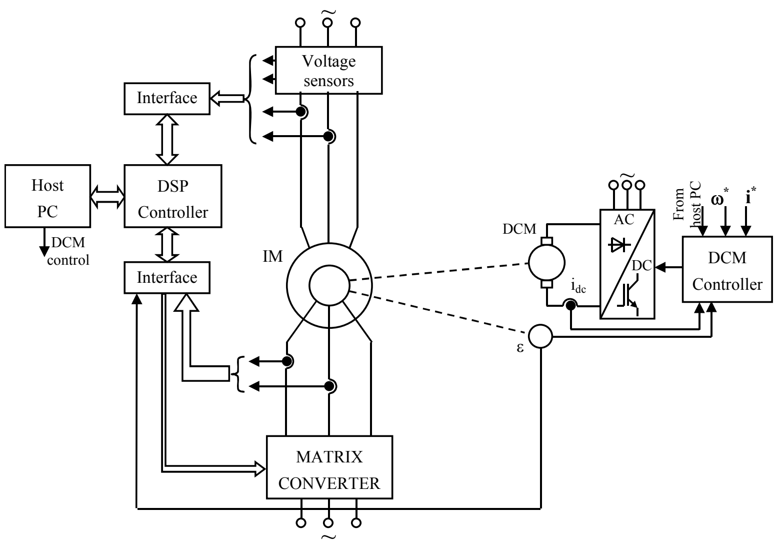

Fig. 3. Block diagram of experimental set-up

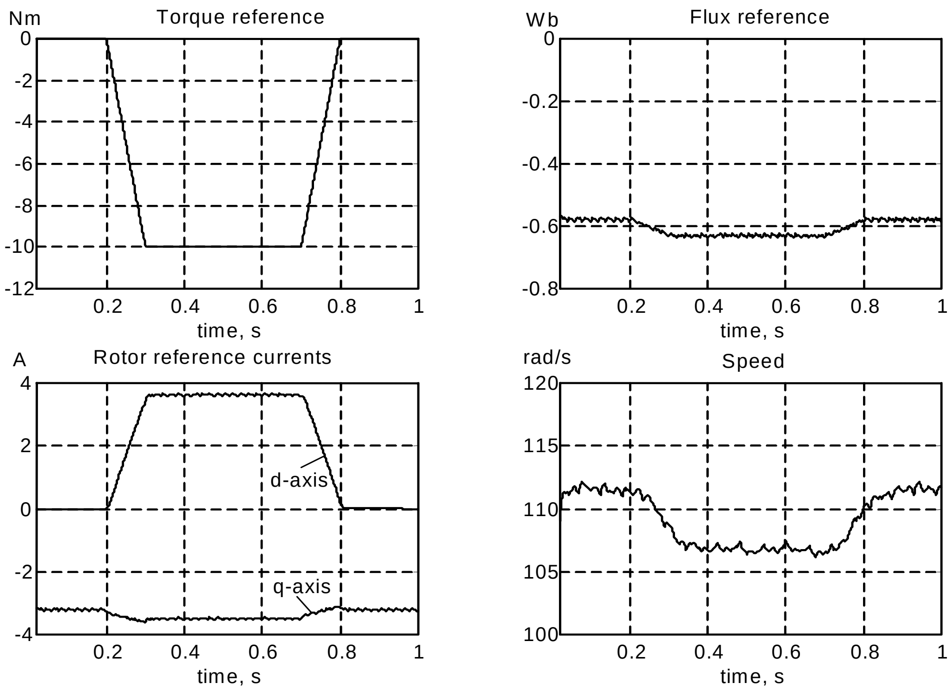

Fig. 4a.

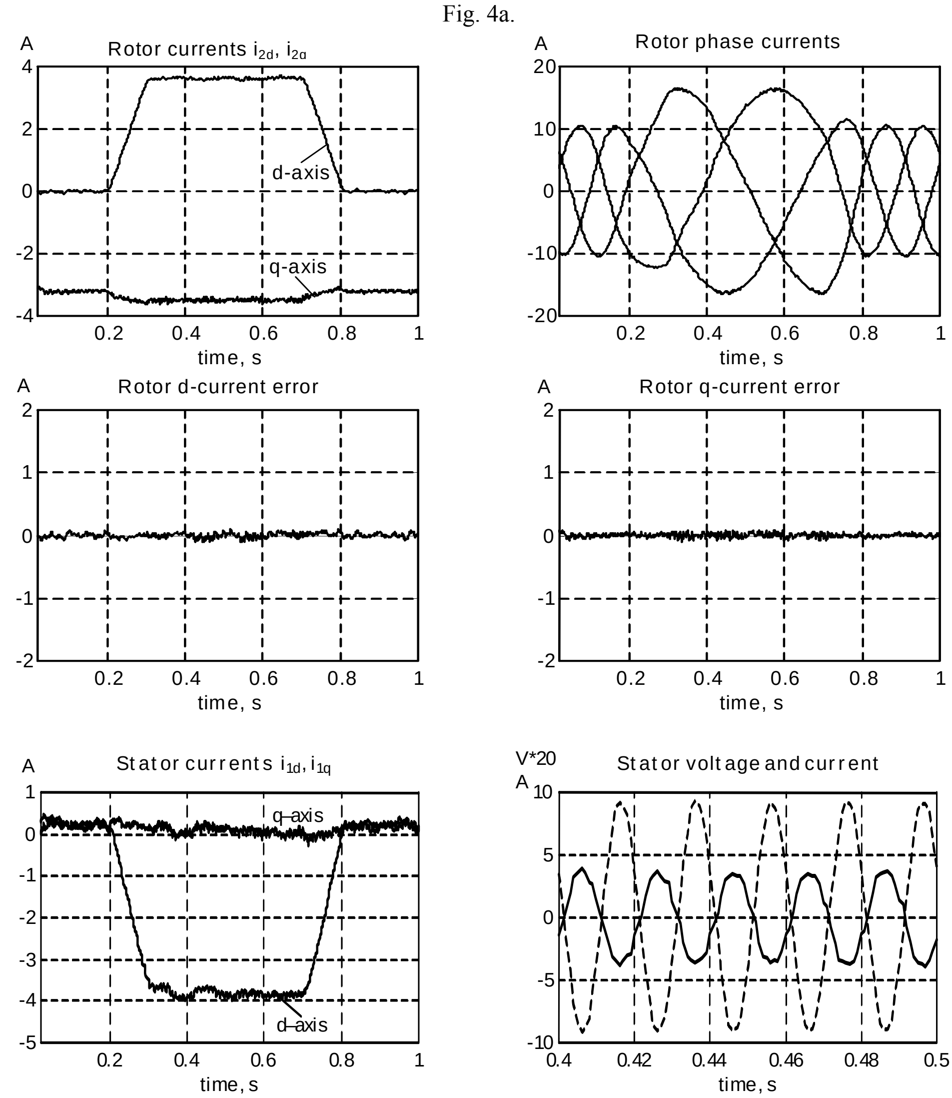

Fig. 4b.

Fig. 4. Transient performance during torque tracking (generator mode).

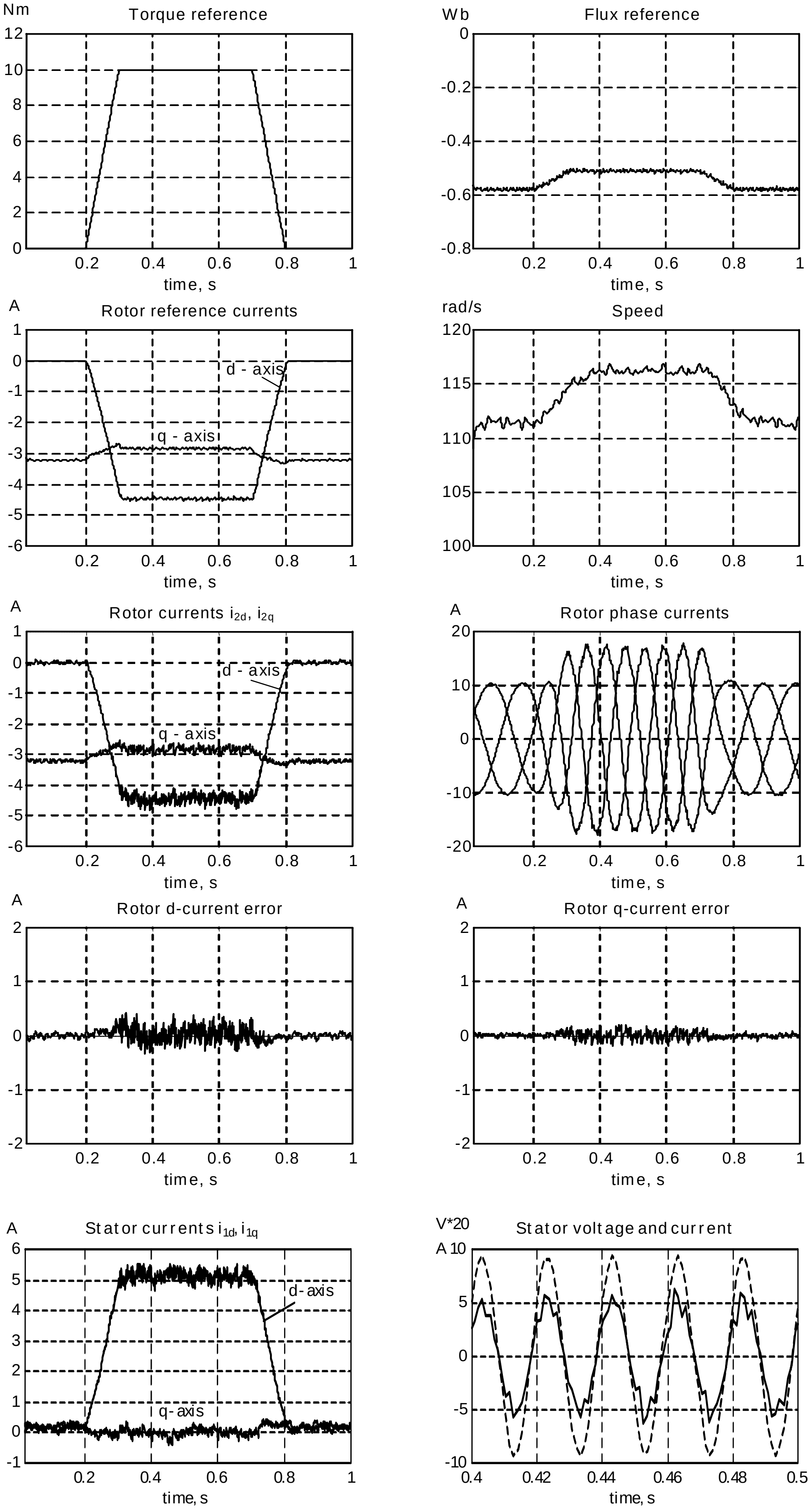

Fig. 5. Transient performance during torque tracking (motor mode).

The experimental set-up includes:

1. A wound rotor induction machine supplied by a 6kW matrix converter (MC), operating at 5kHz switching frequency, with dead-time equal to 2μs.
2. A current (speed) controlled DC motor, used to stabilize the speed of the rotor shaft, when the DFIM is used as a generator.
3. A DSP-based, real-time controller implemented using dSPACE DS1102 control board (TMS320C31) directly connected to PC bus. The sampling time for control implementation has been set to 200μs, the visualization and acquisition system of DS1102 were used for real time tracing of selected variables and data storage.
4. LEM current and voltage sensors for measuring all of the analog signals. Analog filters with a cut-off frequency of 2kHz have been adopted for filtering of all analog signals.
5. An incremental encoder with 5000ppr, used to measure rotor position and speed.
6. A personal computer, acting as operator interface for programming, debugging, program downloading, virtual oscilloscope and automation function during the experiments.

The proportional and integral gains of the rotor current controllers in (4) have been set at $k_1 = 10^3$, $k_{ii} = 25 \cdot 10^4$. All programs for controller implementation have been written using C^{++} language. The discrete-time version of the algorithm proposed has been obtained applying simple backward derivative discretization method.

Experiments, reported in Figs.4a and 4b was performed to investigate system behaviour during torque tracking in "generator mode". The sequence of operation during this test is shown in Fig.4a. The DFIM, already connected to the line grid, is required to track a trapezoidal torque reference, which starts at t = 0.2s from zero initial value and reaches the rated value of -10 Nm at t = 0.3 s. Note that flux value, required to track torque trajectory with unity power factor at stator side is not a constant, as it is usually assumed neglecting stator resistance in field oriented solutions. Fig.4b reports transients of DFIM variables during torque tracking. Rotor current errors are controlled at zero level. The reactive component of the stator current is almost null during all the time (a non-zero value is theoretically admissible only when the torque reference derivative is not null). As result, the stator phase current, reported in Fig.4b, has a phase angle opposite to the line voltage one and shows a low content of high order harmonics. The same transients during torque tracking in "motor mode" are show in Fig.5. One of the important conclusion from the performed experimental tests of the MC-fed DFIM is that MC does not have any limitation for such kind of high performance applications, where low output voltage is required with high level of output current. Condition of DC output current during operation of DFIM with the synchronous speed is easily achievable.

CONCLUSIONS

The main conclusions from the results of experimental study can be summarized as follows: a) matrix converter control algorithms provide high precision voltage tracking suitable for implementation in high dynamic performance doubly-fed induction machines; b) safe commutation of the MC switching is achieved in all condition of DFIM operation without of detection of the output current direction; c) high performance torque tracking is guaranteed under condition of unity stator side power factor; d) satisfactory waveforms of input DFIM stator side currents and MC input currents are obtained.

APPENDIX

Rated power	1.4 kW
Rotor resistance	R_2=5.3 Ω;
Rated current	5.2 A
Stator inductance	L_1=0.161 H;
Rated voltage	380 V
Rotor inductance	L_2=0.161 H;
Rated torque	15 Nm
Mutual inductance	L_m=0.138 H;
Rated speed	880 rev/min
Number of pole pair	p_n=3;
Stator resistance	R_1=4.7 Ω;
Viscous friction coefficient	ν=0.45;

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