УДК 621.313

SPEED CONTROL OF A MATRIX CONVERTER EXCITED DOUBLY-FED INDUCTION MACHINE

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Speed control algorithm based on full doubly-fed induction machine model has been investigated. Experimental testing of the doubly-fed induction machine control algorithm with matrix converter at rotor side has been performed. Speed control algorithm of the doubly-fed induction machine has been implemented in real time using DSP-controller and successfully tested on the experimental rig. Refereces 12, figures 6.
Key words: doubly-fed induction machine, matrix converter, speed control.

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 [7]. DFIM allows to get control effect using bi-directional rotor power converter whose power is proportional to required slip range.

The fundamentals of DFIM vector control are presented in [3] and widely used in different developments [1−3, 8−11]. In both motor and generator applications the DFIM is able to provide torque production together with stator side power factor control. If suitably controlled AC/AC converter is used to supply the rotor side of the DFIM, the power components of the overall system can be controlled with low harmonic distortion in the stator and rotor sides. Moreover, when the DFIM is used as a variable-speed drive, the slip power is regenerated during motor operating conditions by the converter to the line grid, resulting in highly efficient energy conversion.

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).

General theoretical solution of torque tracking and speed tracking control of the DFIM under stabilization of the stator-side power factor at unity level is presented in [9], [1]. The torque tracking controller has also been extended for speed tracking under condition of constant load torque. The control development is based on line voltage vector oriented reference frame, which is more robust with respect to direct stator-flux oriented one [9].

The aim of this paper is to present results of experimental testing of the speed control algorithm of MC excited DFIM. The paper is organized as follows. Section II presents general configuration of speed 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.

DFIM Speed Control Algorithm. The equivalent two-phase model of the symmetrical DFIM, represented in stator voltage-vector oriented reference frame (*d-q*) is [9]:

$$
\begin{aligned}
&\dot{\varepsilon} = \omega, \qquad \dot{\omega} = \frac{1}{J}\Big(\mu\big(\psi_{1q} i_{2d} - \psi_{1d} i_{2q}\big) - \nu\omega - T_L\Big),\\
&\dot{\psi}_{1d} = -\alpha_1 \psi_{1d} + \omega_1 \psi_{1q} + \alpha_1 L_m i_{2d} + U_m,\\
&\dot{\psi}_{1q} = -\alpha_1 \psi_{1q} - \omega_1 \psi_{1d} + \alpha_1 L_m i_{2q},\\
&\dot{i}_{2d} = -\gamma_2 i_{2d} + \omega_2 i_{2q} + \alpha_1 \beta \psi_{1d} - \beta\omega\psi_{1q} - \beta U_m + \frac{1}{\sigma_2} u_{2d},\\
&\dot{i}_{2q} = -\gamma_2 i_{2q} - \omega_2 i_{2d} + \alpha_1 \beta \psi_{1q} + \beta\omega\psi_{1d} + \frac{1}{\sigma_2} u_{2q},
\end{aligned} \qquad (1)
$$

where $\left(u_{2d}, u_{2q}\right), \left(i_{2d}, i_{2q}\right), \left(\psi_{1d}, \psi_{1q}\right)$ are rotor voltages, rotor currents and stator fluxes, T_L is a moving torque, generated by the primary mover, U_m and ω_1 are stator (line) voltage amplitude and angular frequency, ε and ω are rotor angular position and speed, $\omega_2 = \omega_1 - \omega$ is slip angular frequency, one pole pair is assumed without loss of generality. Positive constants related to DFIM electrical parameters are defined as:
$\alpha_1 = \frac{R_1}{L_1}$, $\sigma_2 = L_2\left(1 - \frac{L_m^2}{L_1 L_2}\right)$, $\beta = \frac{L_m}{L_1 \sigma_2}$, $\gamma_2 = \frac{R_2}{\sigma_2} + \alpha_1 \beta L_m$, $\mu = \frac{3}{2}\frac{L_m}{L_1}$, where R_1, R_2, L_1, L_2 − resistances and inductances of stator and rotor respectively, L_m − mutual inductance.

Assuming the rotor current-fed condition, the following torque-flux control algorithm is constructed:

− flux level control algorithm

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

− torque control algorithm

$$i_{2d}^* = T^*\left(\mu\psi^*\right)^{-1}. \tag{3}$$

Following [6] the current controller control algorithm is defined as

$$\begin{aligned} u_{2d} &= \sigma\left(\gamma i_{2d}^* - \omega_2 i_{2q}^* + \beta\omega\psi^* + \beta U_m + \dot{i}_{2d}^* - k_i \tilde{i}_{2d} - x_d\right), \qquad \dot{x}_d = k_{ii}\tilde{i}_{2d}, \\ u_{2q} &= \sigma\left(\gamma i_{2q}^* + \omega_2 i_{2d}^* - \alpha\beta\psi^* + \dot{i}_{2q}^* - k_i \tilde{i}_{2q} - x_q\right), \qquad \dot{x}_q = k_{ii}\tilde{i}_{2q}, \end{aligned} \tag{4}$$

where T^* – torque reference; k_i and k_{ii} are positive proportional and integral gains of current controllers; x_d, x_q are integral components of current controllers.

In [9] it is shown that speed control algorithm (2) – (4) guarantees global torque tracking and asymptotic stator side reactive power stabilization on the zero level during steady state condition.

Reference for torque, which is formed by the speed controller, is defined as

$$T^* = J\left(\hat{T}_L + \dot{\omega}^* - k_\omega \eta + \frac{\nu}{J}\omega^*\right), \tag{5}$$

$$\hat{T}_L = -\dot{\tilde{T}}_L = -k_{\omega i}\xi, \qquad \dot{\eta} = -\frac{1}{\tau}\eta + \frac{1}{\tau}\xi, \qquad \xi = -\frac{1}{\tau}\xi + \frac{1}{\tau}\tilde{\omega}, \tag{6}$$

where $(k_\omega, k_{\omega i})>0$ are proportional and integral gains of speed controller, τ is time constant of the filter of angular speed measurement.

Complete speed control algorithm is specified by expressions of flux level control and torque control algorithms (2), (3) and current controller control algorithm (4), in which derivatives are calculated from (2), (3), (5), (6), and by speed controller (5), (6).

Actual control voltages, applied to the rotor, are defined by means of coordinate transformation

$$\begin{pmatrix} u_{2dr} \\ u_{2qr} \end{pmatrix} = \begin{bmatrix} \cos(\varepsilon_1 - \varepsilon) & -\sin(\varepsilon_1 - \varepsilon) \\ \sin(\varepsilon_1 - \varepsilon) & \cos(\varepsilon_1 - \varepsilon) \end{bmatrix} \begin{pmatrix} u_{2d} \\ u_{2q} \end{pmatrix}, \tag{7}$$

where ε_1 is angular position of the voltage vector.

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

Matrix converter control algorithm. Space vector modulation (SVM) of the MC is based on the instantaneous space-vector representation of output voltage and input current [4, 12]. Through SVM, the matrix converter generates appropriate voltage waveforms for exciting the DFIM rotor. The averaged values of the voltage reference vector are obtained as the result of synthesis from five adjacent stationary vectors (four non-zero and one zero) [4, 12]. As a result of alternate operation on each SVM period the line voltages form an "averaged" voltage to create the output voltage vector.

The SVM algorithm has the following steps:

− first, on the basis of information about the instantaneous input voltage during each SVM cycle the moment of switching from one combination of voltage to another is determined;

− after that on the basis of output voltage vector the required sector is determined;

− duty-cycles and the corresponding time intervals are computed;

− finally, the reference space output voltage vector is formed at the beginning of the next SVM cycle.

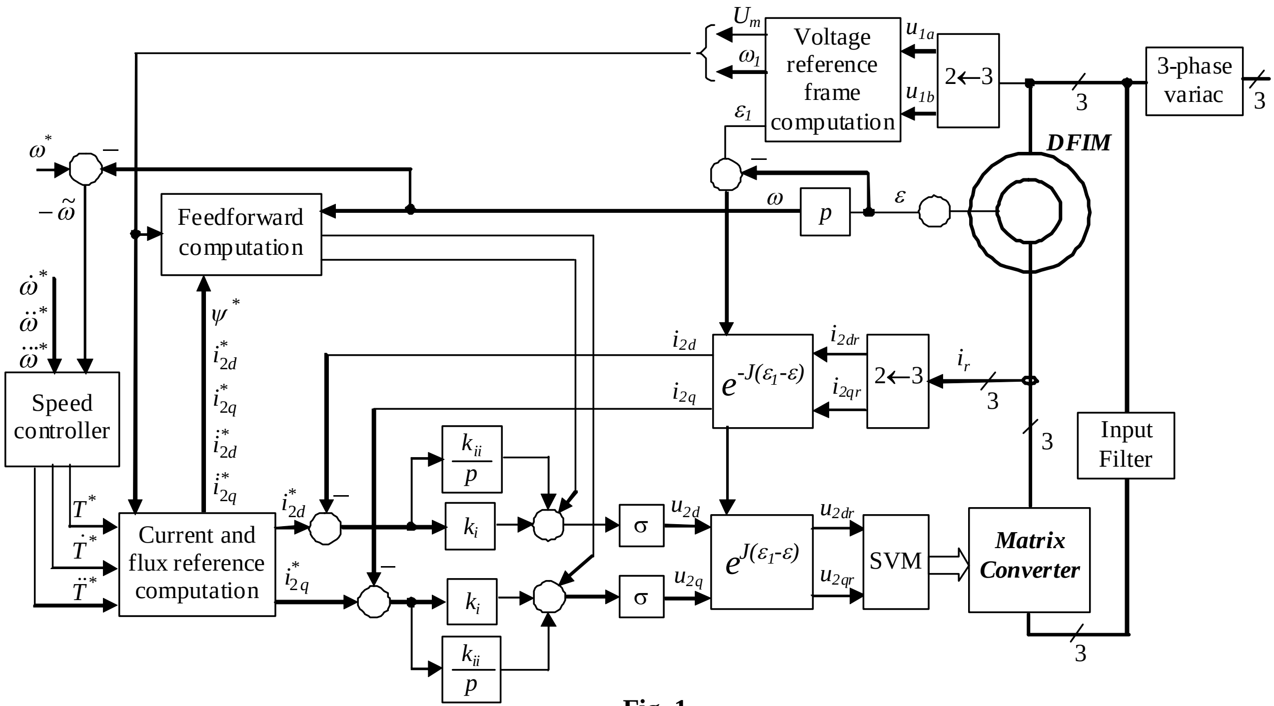

Fig. 1

Commutation strategies for a MC can be based on two approaches. The first, based on the current direction information and the second, based on measured AC input phase voltages relationship [4,12]. In this work a commutation strategy based on the current direction information is used.

*Experimental rig***.** Speed control algorithm have been experimentally tested using a slip-ring induction motor with ratings: power 7.5 kW; current 17.5 A; voltage 380 V; speed 1460 rpm; stator resistance R_1=0.45 Ω; rotor resistance R_2=0.2 Ω; stator inductance L_1=0.161 H; rotor inductance L_2=0.095 H; mutual inductance L_m=0.088 H; number of pole pairs p_n=2.

The experimental tests were carried out using an experimental rig, whose overall layout is shown in Fig. 2. The experimental rig includes:

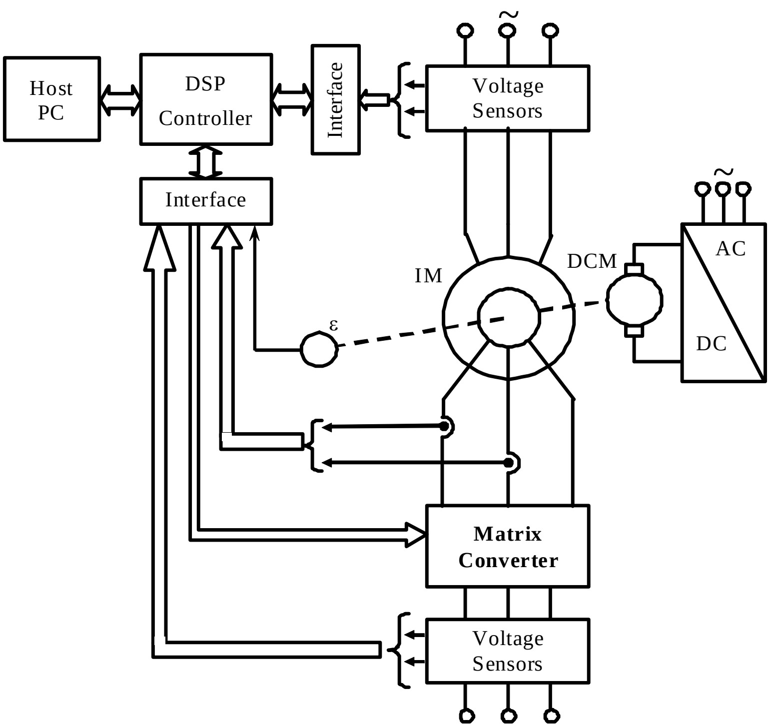

Fig. 2

1. A 7.5 kW slip-ring induction motor supplied by a matrix converter, operating at 12.5 kHz switching frequency.

2. A current (speed) controlled DC motor, used to provide the load torque to the DFIM, during drive operation, or 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 FPGA MC control board with TMS320C6711 DSK connected to PC.

4. LEM current and voltage sensors for measuring the analogue signals.

5. An incremental encoder with resolution 2500ppr, used to measure rotor position and speed.

6. A personal computer, acting as operator interface for programming, debugging, program downloading, vir-

tual oscilloscope and automation function during the experiments.

The power circuit of the matrix converter has been developed and built in the Power Electronics, Machines and Control (PEMC) Group of the University of Nottingham around the EUPEC FM35R12KE3 Matrix Converter module [6, 12]. The 18 IGBTs and 18 diodes in this module are rated at 1200V and 35Amps. The Matrix Converter requires an input filter uses three 2uF capacitors and three 1mH inductors. This filter has not been optimized for the matrix converter operating conditions and, hence, the input current waveform quality is lower than expected. In order to protect the matrix converter power devices during experimental tests, stator voltages and hence rotor voltages were limited to 120V line-to-line through a 3-phase variac on the supply, as shown in Fig. 1.

*Control Platform***.** The control of the MC is implemented with the help of interaction between a digital signal processor (TMS320C6711 DSK board) and a field programmable gate array (FPGA board). For fast data processing Texas Instruments TMS320C6711 DSP board with Actel ProASIC A500K050 FPGA is used in the control board. The C6711 DSK features a 150 MHz clock and is capable of executing 900 million floating-point operations per second. It has a parallel port controller which is able to interface to standard parallel port on a host PC. The host PC provides the user interface to the DSP. The DSP and FPGA based control platform used in the MC is developed by the PEMC group. The FPGA on this board is operated with 10 MHz clock frequency. The FPGA board connected to the DSP board via an expansion port connector.

All the calculations related to the space vector modulation, data manipulations and host interfacing were performed in the DSP. The PWM pulse generation, the commutation control, the watchdog and other software protection items were implemented in the FPGA. Data acquisition and pulse generation are coordinated by the FPGA. On the control platform the analog measurement signals are encoded to digital form. The FPGA is operated with 10 MHz clock frequency and is used to retrieve data from the nine analog-to-digital channels and communicate with the DSP. These digital data are read by the DSP. The output signals resulting from the calculation performed by the DSP are the switching control signals. The switching signals are stored in the FPGA register in the format of the switching state vector and time. The major function of the FPGA is to output the switching state vector and time when the next interrupt occurs (the interrupt occurs every 80μs). Then the PWM pulses are generated and transmitted to the gate driver board.

The control system also includes hardware protection circuits in case of overload. The hardware-based instantaneous overcurrent protection circuit is built in the FPGA board. This protection circuit is based on the use of comparators in which the reference voltage can be adjusted to the maximum peak current allowed in the system to protect the IGBTs under the short circuit or loss of controls. When the measured current is higher than the maximum peak current, the comparator will provide an instantaneous trip signal to the FPGA board and stop the switching pulses. Also the FPGA board has a watchdog timer circuit to protect the MC if the DSP-FPGA network experiences deadlock.

The input data required by the control system is supplied from the measurement boards. This data includes the two line-to-line input MC voltages, two line-to-line mains/stator voltages, three output MC currents. The current measurements use LEM LA55-P current transducers to measure all instantaneous currents: the three output MC currents. In order to measure the line-to-line voltages, the voltage transducer LEM LV25-P is used.

The software for all control algorithms of the DFIM and MC is written in C programming language using Code Composer Studio [5]. Code Composer Studio (CCStudio) software is a fully integrated development environment (IDE) supporting Texas Instruments DSP platforms.

The host PC provides the user interface to the network with a link to the DSP. While the DSP is performing a routine calculation the control reference can be set and also the instantaneous control variable can be monitored via the host PC. In addition, it is used to capture and transfer the data variables passed back to the computer for monitoring purposes. The host program in C programming language is developed by the PEMC group.

Experimental results. Experimental results, reported in Figs. 3 and 4, were performed to investigate system behaviour during speed trajectory tracking. The sequence of operation during this test is shown in Fig. 3. During this test the speed control algorithm has been preliminary actuated with the speed reference equal to 1500 rpm. At t = 1.5s speed reference trajectory is applied (Fig. 3), requiring the unloaded motor to operate below and above the synchronous speed. The adopted speed trajectory requires a dynamic torque. Speed tracking capabilities, together with the stabilization of the stator side reactive power on zero level, are shown in Fig. 4. Satisfactory waveforms of input DFIM stator side currents and MC input currents are obtained which are considered in Figs. 5 and 6. The spectrum of the current waveforms of the previous pictures is shown in the same Figures.

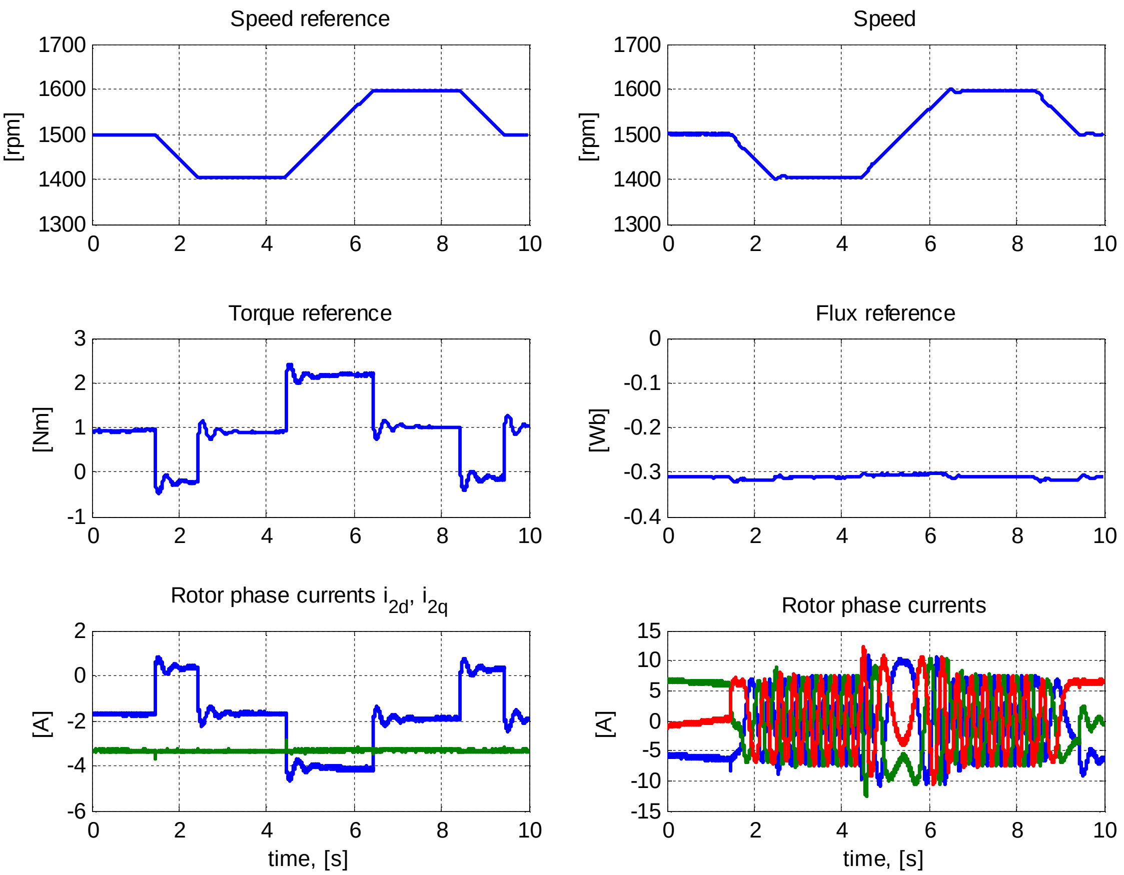
Speed reference
[rpm]
Speed
[rpm]
Torque reference
[Nm]
Flux reference
[Wb]
Rotor phase currents i_{2d}, i_{2q}
[A]
time, [s]
Rotor phase currents
[A]
time, [s]

Fig. 3

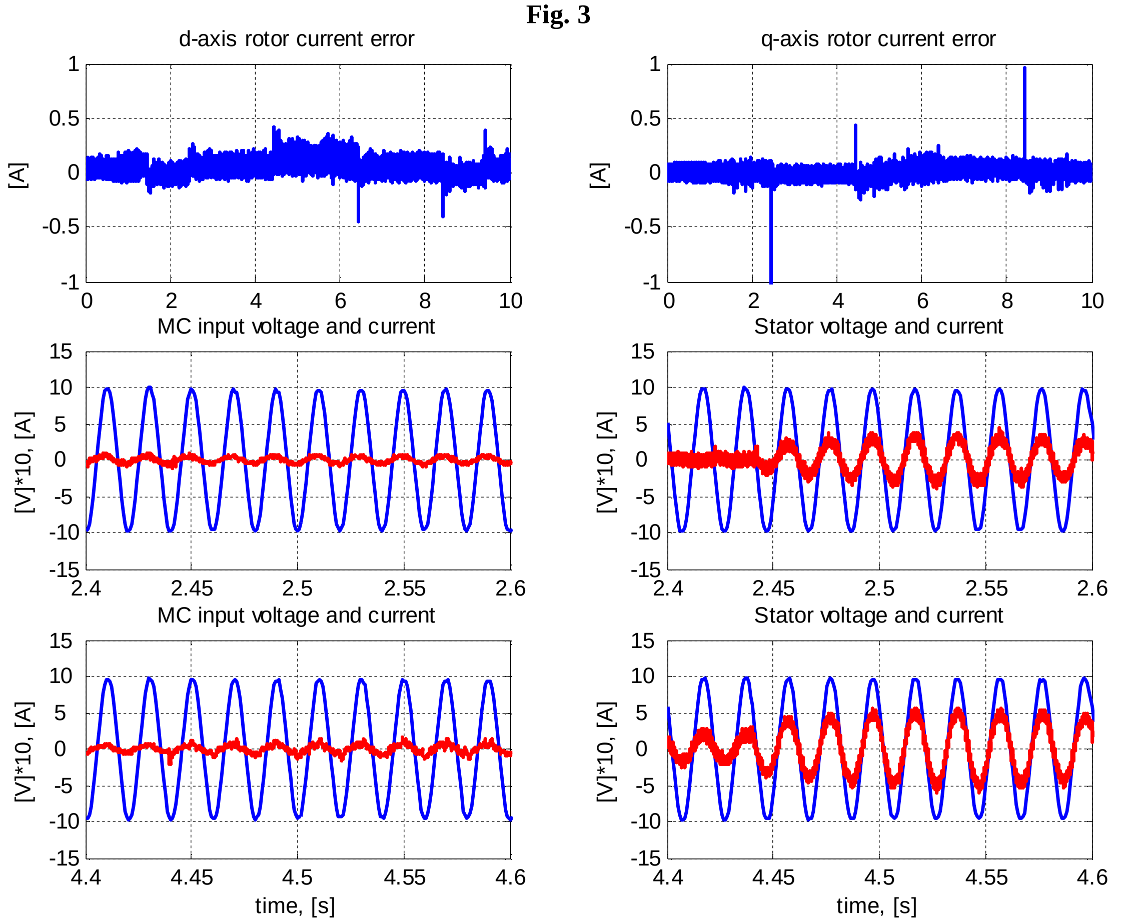
d-axis rotor current error
[A]
q-axis rotor current error
[A]
MC input voltage and current
[V]*10, [A]
Stator voltage and current
[V]*10, [A]
MC input voltage and current
[V]*10, [A]
time, [s]
Stator voltage and current
[V]*10, [A]
time, [s]

Fig. 4

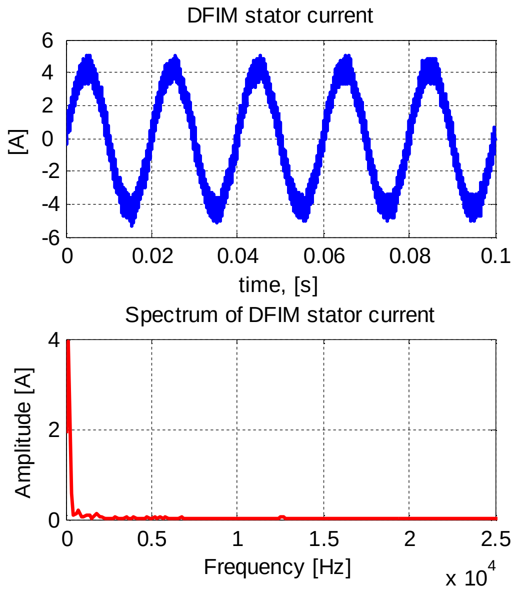

Fig. 5

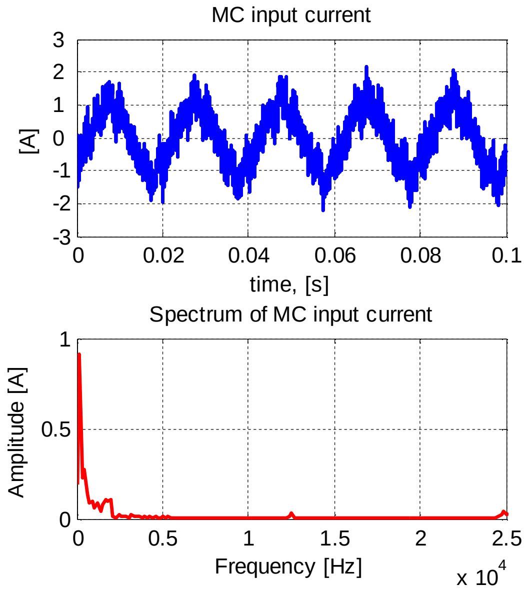

Fig. 6

Conclusions. Results of experimental testing of the MC-fed DFIM are presented. Control algorithms (MC and DFIM) have been implemented in real-time using DSP-controller. The experimental rig used to control DFIM has been presented. The rig was used to confirm the control methods proposed for the DFIM. The structure of the rig including all hardware and circuits were described.

It is demonstrated by experiments that: high performance speed tracking is guaranteed under condition of unity stator side power factor and that satisfactory waveforms of input DFIM stator side currents and MC input currents are obtained. The main conclusion from the performed experimental study is that control proposed control algorithm and technical solutions for MC and DSP controller development are suitable for practical application in high performance DFIM based electromechanical systems.

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УДК 621.313

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Керування швидкістю машини подвійного живлення з матричним перетворювачем

Досліджено алгоритм керування кутовою швидкістю машини подвійного живлення. Виконано експериментальні дослідження алгоритму керування машини подвійного живлення з матричним перетворювачем. Алгоритм керування кутовою швидкістю машини подвійного живлення реалізовано за допомогою цифрового сигнального контролера і успішно випробувано на експериментальному стенді. Бібл. 12, рис. 6.

Ключові слова: машина подвійного живленння, матричний перетворювач, керування швидкістю.

УДК 621.313

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Управление скоростью машины двойного питания с матричным преобразователем

Исследован алгоритм управления угловой скоростью машины двойного питания. Выполнены экспериментальные исследования алгоритма управления машины двойного питания с матричным преобразователем. Алгоритм управления угловой скоростью машины двойного питания реализован с помощью цифрового сигнального контроллера и успешно испытан на экспериментальном стенде. Библ. 12, рис. 6.

Ключевые слова: машина двойного питания, матричный преобразователь, управление скоростью.

Надійшла 09.02.2011
Received 09.02.2011