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HIGH PERFORMANCE ELECTROMECHANICAL ENERGY CONVERSION USING MATRIX CONVERTER.
PART 2: VECTOR CONTROL OF INDUCTION MOTOR

1. Introduction

Vector controlled Induction Motor (IM) drives are wide spread electromechanical systems suitable for high dynamic performance applications. During last two decades they established an industrial standard for high performance IM drives. The typical configuration of such electromechanical systems includes: AC-DC-AC power converter supplying the IM, vector speed-flux controller based on concept of field orientation [1] and vector DC-link voltage-power factor controller of input rectifier [2].

Matrix converters (MC) first introduced in [3], [4] have been found as interesting alternative to standard AC-DC-AC converters [5], [6]. Number of promising results on application of MC for control in electromechanical systems are reported in literature: IM drives [5], synchronous motor drives [6], doubly-fed induction machine [7], autonomous wound rotor induction generator [8]. Nevertheless as far as authors know MC never has been tested in heavy dynamic conditions of operation, which are typical for vector controlled IM drives.

In this paper a new development of vector control for IM using MC is proposed. Our development includes:

- design of new high performance speed-flux tracking control algorithm, based on concept of direct field orientation;
- new space vector PWM control algorithm for MC;
- new safe commutation strategy for MC switches;
- intensive experimental testing.

2. Speed-flux tracking controller

A new direct field-oriented vector control algorithm for IM is proposed. Controller development is based on novel design strategy for indirect field-orientation presented in [9]. This design approach has been modified in order to build observer-based output feedback controller based on stator currents and speed measurements. Specifically, the problem of flux-speed tracking with no singularities is addressed, in presence of unknown constant load torque and under the requirement of achieving new features for the closed loop dynamics:

1. Global exponential asymptotic speed-flux tracking.
2. Asymptotic speed-flux decoupling.
3. Asymptotic linearization of the speed subsystem.
4. Robustness with respect to IM parameter (especially rotor resistance) variations.

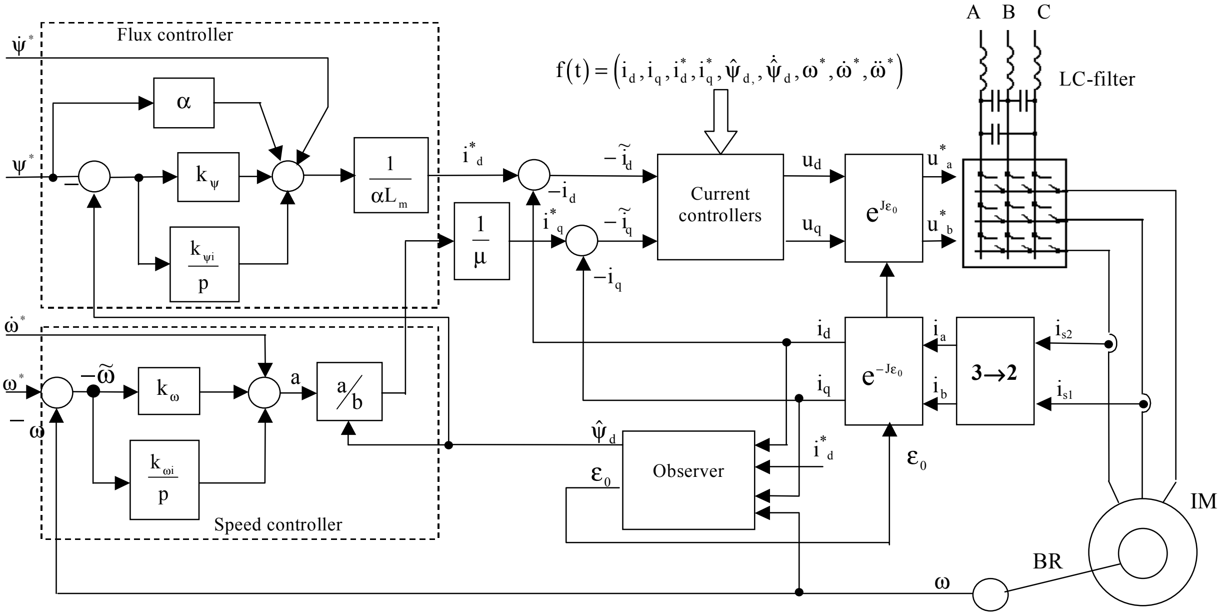


Fig. 1. Block-diagram of the vector controlled IM fed by MC.

Following the same conceptual line as in [9] we design direct field-oriented controller with reduced order (second order), but closed loop flux observer. The two interconnected (electromechanical and electromagnetic) subsystems are designed, whose outputs are torque (speed) and flux vector, respectively, with the two transformed stator voltages responsible for control objectives in each subsystem. Based on the concept of field-oriented decomposition, special coupling conditions are defined for speed and flux subsystems which allow to design a observer-based flux-vector control algorithm providing closed loop exponential asymptotic flux vector tracking as well as asymptotic speed-flux decoupling via asymptotic field orientation. The property of asymptotic linearization of the speed subsystem (even with time-varying flux level) allows the use of well-known linear optimization technique and speed controller parameters tuning procedure, commonly used in standard cascaded systems. Robustness of the speed subsystem is guaranteed by the two-level cascaded structure with astatic inner and outer loops having nonlinear current and speed controllers.

The flux subsystem, which is an open-loop system when standard field-oriented control with reduced order observer (equations of rotor circuit) is used, is designed to get closed-loop properties. As result, significant improvement of the robustness with respect to rotor circuit parameters variation is achieved, when rotor speed is different from zero. The proposed observer-based flux controller is simpler as compared with controllers based on full order observers and does not require the information about stator voltages.

The proposed speed-flux controller has a simple physically based structure and provides significant improvement of the dynamic performance and energy efficiency during the speed-flux tracking, as compared to standard solutions. The block-diagram of the proposed system is shown in Fig. 1.

3. Experimental testing of the matrix converter fed induction machine

In order to justify the performance of the matrix converter and its implementability for high dynamic performance induction machine control an intensive experimental study have been performed. Our main interests of investigation have been concentrated on the evaluation of the dynamic capabilities of the MC during heavy dynamic conditions of operation, line current dynamics and availability to achieve zero speed induction machine operation when almost zero voltage of the MC is required.

Experimental set-up. The experimental tests have been carried out using a Rapid Prototyping Station developed for testing the matrix converter fed electric machines. The Rapid Prototyping Station, whose block diagram shown in Fig.1, includes:

1. A wound rotor IM, whose rated data are listed in Appendix A, supplied by MC. During investigation of vector controlled induction machine the IM stator is fed by MC and rotor circuit is shortened. An additional rotor resistance can be added to rotor in order to investigate the sensitivity with respect of rotor parameter variations.
2. A current controlled DC motor is used to provide the load torque for induction motor drive or to stabilize the speed of DFIM rotation.
3. A 6 kVA matrix converter, operating at 5 kHz switching frequency with 4 μs "dead time".
4. 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 at 200 μs, the visualization and extended acquisition system of DS1102 were used for real time tracing of selected variables and data storage.
5. All analog signals have been measured using LEM current and voltage sensors and filtered with first order analog filters having cut-off frequency of 2 kHz. For speed and position measurements an incremental encoder with 5000 lines per revolution is used.
6. A personal computer acting as Operator Interface for programming, debugging, program downloading, virtual oscilloscope and automation function during the experiments.

Controller tuning and implementation. The tuning parameters of the speed and flux subsystems [9] are proportional and integral gains of the speed and flux controllers $\left(k_{\omega}, k_{\omega i}, k_{\psi}, k_{\psi i}\right)$ as well as proportional and integral gains of the current controllers $\left(k_{i}, k_{ii}\right)$. According to the structure of the cascaded system we use the standard tuning relation

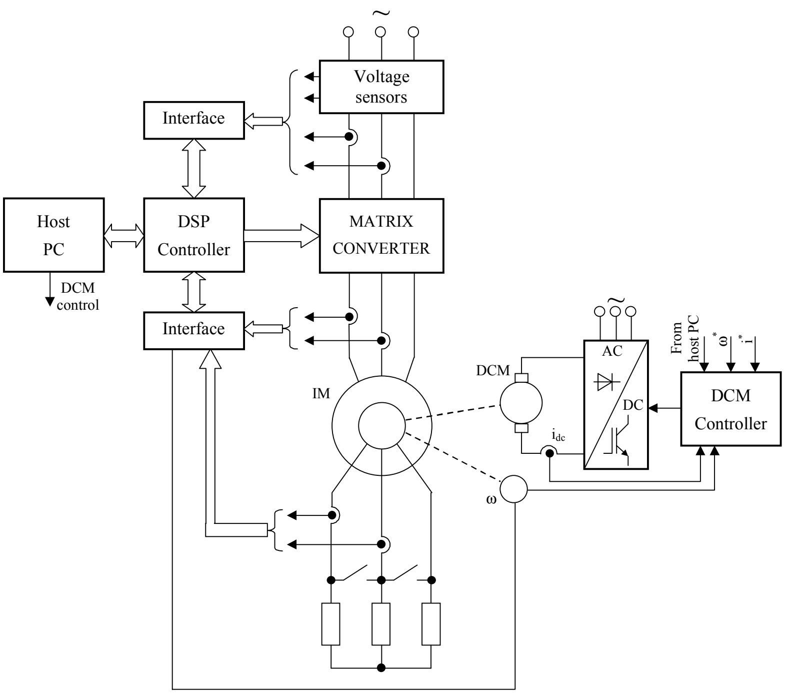


Fig. 2. Block diagram of the experimental set-up.

$$k_i = \frac{k_p^{\,2}}{2} = \frac{1}{\tau^2}; \xi = 0.707 \tag{1}$$

where τ and ξ are the time constant and damping factor imposed for the second order error dynamics and k_i, k_p are the proportional and integral gain in each loop. The time scale separation is achieved with $\tau_s \geq (2-4)\tau_i$, where indexes s and i stand for speed, flux and currents loops. To get the discrete time version of control algorithm the simple backward derivative (Euler) method is used. The controllers parameters, selected according to (1) were set at:

$$k_\omega = 100; k_{\omega i} = 5000; k_i = 500; k_{ii} = 125000; k_\psi = 50, k_{\psi i} = 650$$

All programs for controllers implementation have been written using C^{++} language.

Operating sequences. The operating sequences, reported in Fig. 3, are the following:

1. The machine is exited during the initial time interval 0 – 0.25 s using a flux reference trajectory starting at $\psi^*(0) = 0.02$ Wb and reaching the motor rated value of 0.7 Wb with the first derivative equal to 2.72 Wb/s.
2. The unloaded motor is required to track the speed reference trajectory, starting at time t=0.5 s from zero initial value and reaching the speed of 50 rad/s (60% of rated) with the first and second derivatives equal to 420 rad/s^2 and 8239 rad/s^3.
3. During time interval of constant speed rotation the step load torque, equal to rated value, is applied and removed.
4. The final time interval is given for unloaded motor breaking to zero speed.

Tracking of the speed reference trajectory adopted requires a dynamic torque, which is equal to double of rated value of the IM. Flux and speed reference trajectories are presented in Fig. 3 using solid lines; dashed line in the same figure represents the load torque profile.

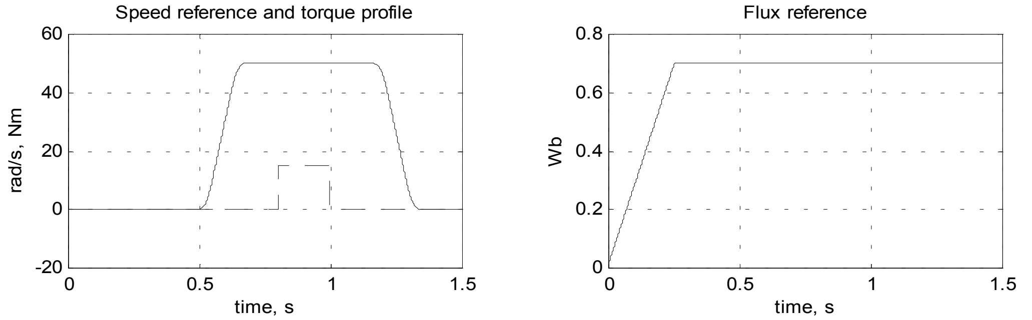


Fig. 3. Speed, flux references and load torque profile.

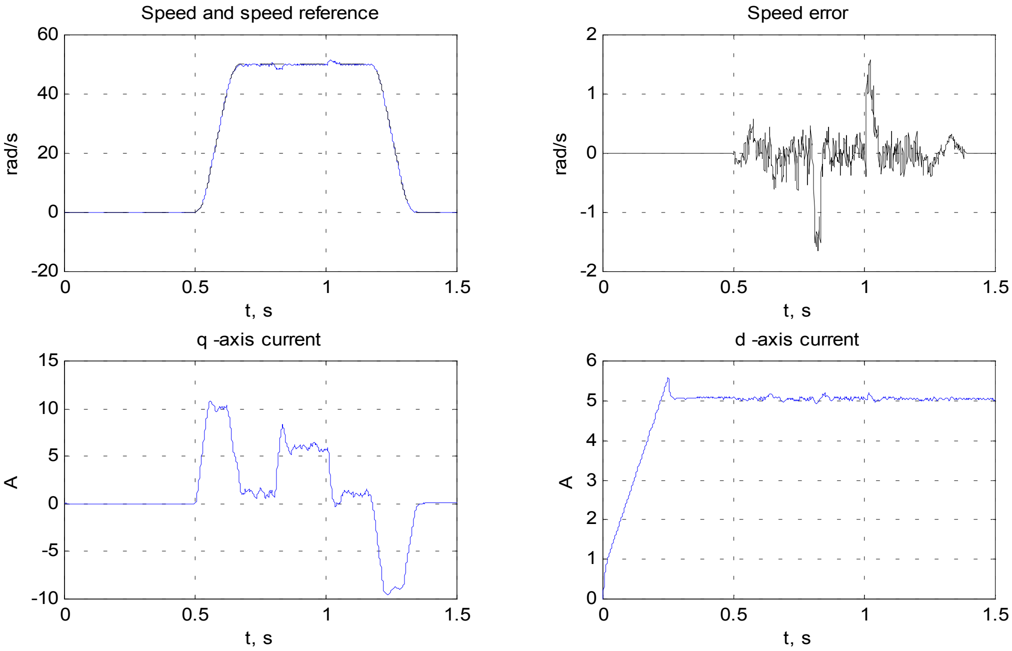
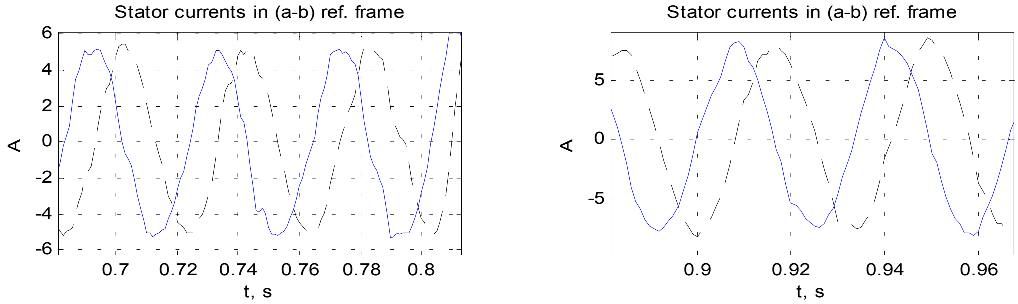


Fig. 4. Transient performance of the proposed controller.

The Figs. 5a and 4b demonstrate the waveforms of the stator current during steady state condition ω=50 rad/s without load and with rated load.

Experimental results. The experimental results presented in Fig. 4 demonstrate the dynamic performance of the proposed controller adopting the standard controller tuning according to (1). The speed tracking performance (maximum speed error of about 0.3 rad/s) satisfied the requirements of any high dynamic performance applications.



a) b)

Fig. 5. Stator currents waveforms during steady state condition ω=50 rad/s: a) no load torque; b) rated load torque.

The operation near by zero speed with $\omega^* = 0.05\,\mathrm{rad/s}$ is shown in Fig. 6. Excellent steady state performance and dynamics during load torque rejection is achieved during this regime of operation in low MC voltage region.

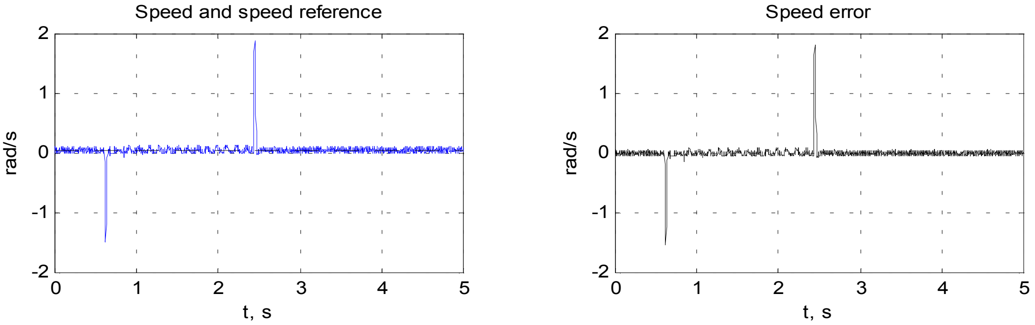


Fig. 6. Operation near by zero speed: $\omega^* = 0.05\,\mathrm{rad/s}$, rated load is applied at t=0.6 s and removed at t=2.4 s.

4. Conclusions

From intensive experimental study we conclude that proposed solutions for matrix converter control and control algorithms for matrix converter fed IMs are suitable for any high dynamic performance applications. As far as authors know it is first experimental results related to MC application with such high dynamic requirements.

Appendix A

Rated power	1.4 kW	Stator inductance	L_1=0.161 H;
Rated current	5.2 A	Rotor inductance	L_2=0.161 H;
Rated voltage	380 V	Mutual inductance	L_m=0.138 H;
Rated torque	15 Nm	Number of pole pair	pn=3;
Rated speed	880 rev/min	Viscous friction coefficient	ν=0.45;
Stator resistance	R_1=4.7 Ω;	Total inertia	J=0.07 kg·m^2;
Rotor resistance	R_2=5.3 Ω;		

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