Direct Torque Control of Induction Machine Using Fuzzy Logic MRAS Speed Estimator Implemented for Electric Vehicle

Abderrahmane Ouchatti, Ahmed Abbou, Mohammed Akherraz and Abderrahim Taouni

Abstract This paper discusses a sensorless speed control of an induction machine, used for traction application in electric vehicle. The controller allows operating the machine in all four quadrants. The implemented controller is based on classical Direct Torque and Flux Control (DTC) technique, due to its simplicity and good performance. The speed rotor and stator flux-linkage components are estimated by using a model reference adaptive system (MRAS). All regulators are based on conventional fuzzy-logic. The performance obtained by variable-speed drive system are presented first by simulation results, and secondly by the experimental results based on a dSPACE DS1104 platform.

Keywords Induction motor · Direct torque and flux control (DTC) · Fuzzy logic controller (FLC) · Electric vehicle · Model reference adaptive systems (MRAS)

1 Introduction

The induction machine is widely used as motor in industrial applications for its high reliability, relatively low cost and modest maintenance requirements. However, the problem is that control of the induction machine is more complex since its dynamic and highly nonlinear model, and most state variables are not measurable. Scalar-controlled drives have been widely used in industry due to their easier

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A. El Oualkadi et al. (eds.), *Proceedings of the Mediterranean Conference on Information & Communication Technologies 2015*, Lecture Notes in Electrical Engineering 381, DOI 10.1007/978-3-319-30298-0_3

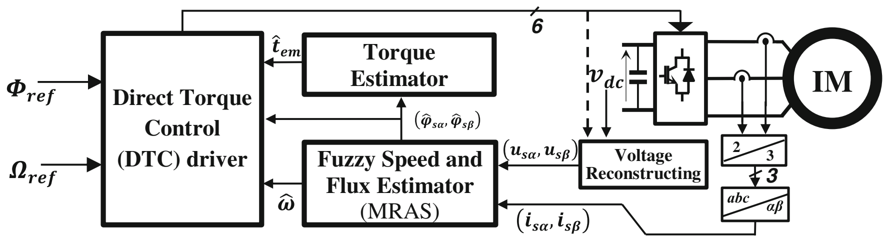


Fig. 1 Proposed control scheme

implementation. However, the superior performances (demanded in many recent applications) of vector-control, have diminished the use of scalar control.

In the literature there are many papers which discuss and propose various vector drives. Only a few papers discuss implementations and mainly concentrate on simulations. To this end, induction machine control was treated according to different approaches. These include simple linear techniques such as Field Oriented Control (FOC), Direct Torque Control (DTC) and more involved nonlinear techniques like input-output linearization, Backstepping [1, 2], passivity, sliding mode [3, 4] etc. Most of the proposed controllers use speed sensor, for economical and maintenance reasons, the sensorless control constitutes one of the main preoccupations of industry, and so there are several techniques to estimate the rotor speed [5, 6, 7].

The purpose of this paper is sensorless speed control of an induction machine using a classical DTC technique associated with fuzzy rotor speed estimator based on Fuzzy MRAS method. The inertia of the rotor and the load torque are considered unknown parameters. In this paper it will be shown that the control performs well with Fuzzy Logic. Figure 1 shows the block diagram of the proposed control design.

As mentioned above the IM controller's objective is to motorize the electric vehicle, the power supply is composed of a main storage battery (e.g. battery pack lead acid) and an ultra-capacitor bank.

This paper is organized as following: induction motor model and fuzzy speed controller based on classical DTC are presented in the second section. Section 3 treats the fuzzy technique used to estimate the rotor speed. The Sect. 4 is devoted to simulation and experimental results.

2 Direct Torque Control (DTC) of Induction Machine

In direct-torque-controlled (DTC) induction motor drive, supplied by a voltage source inverter, it is possible to control directly the stator flux linkage and the electromagnetic torque by the selection of optimum inverter switching modes (see Sect. 2.2).

2.1 Induction Machine Model

The induction motor is described by the following model in the (α, β) axis (where magnetic saturation effect is neglected)

$$\dot{\omega} = \frac{1}{J}(t_{em} - t_l) \tag{1}$$

$$t_{em} = p(\varphi_{s\alpha} i_{s\beta} - \varphi_{s\beta} i_{s\alpha}) \tag{2}$$

$$\dot{\varphi}_{s\alpha} = u_{s\alpha} - R_s i_{s\alpha} + \omega_s \varphi_{s\beta} \tag{3}$$

$$\dot{\varphi}_{s\beta} = u_{s\beta} - R_s i_{s\beta} - \omega_s \varphi_{s\alpha} \tag{4}$$

$$\dot{\varphi}_{r\alpha} = -\frac{1}{T_r}\varphi_{r\alpha} + \frac{L_m}{T_r} i_{s\alpha} + \omega_{slp}\varphi_{r\beta} \tag{5}$$

$$\dot{\varphi}_{r\beta} = -\frac{1}{T_r}\varphi_{r\beta} + \frac{L_m}{T_r} i_{s\beta} - \omega_{slp}\varphi_{r\alpha} \tag{6}$$

$$\omega_{slp} = \omega_s - p\omega \tag{7}$$

$$T_r = \frac{L_r}{R_r} \tag{8}$$

where u_s is the terminal voltage of the machine, i_s is the stator current, φ_s is the stator flux linkage, t_{em} is the electromagnetic torque, ω_s is the synchronous angular speed of the stator flux vector, ω_{slp} is the angular slip frequency, R_s is the stator winding resistance, L_m is the machine magnetizing self-inductance, T_r is the rotor time-constant and p is the number of pole-pairs.

2.2 Stator-Flux-Based DTC Induction Machine Drive

Direct torque controller consist calculating an estimate of the stator flux and electromagnetic torque based on the measured stator current and stator voltage. The simplified schematic of stator-flux-based DTC induction motor drive with voltage source inverter is shown in Fig. 2. It consists of two-level stator flux hysteresis comparator, and three-level torque hysteresis comparator.

After determining the stator flux and electromagnetic torque errors, the adequate switching-vector is selected using an optimal voltage switching look-up table. In DTC induction machine drive, a decoupled control of torque and flux can be achieved by two independent control loops. However, the estimation of stator voltage when the machine is operating at low speed introduces error in flux

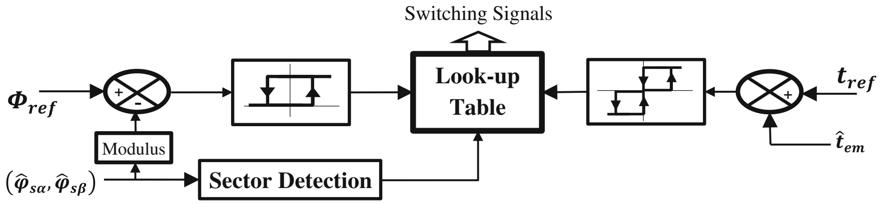
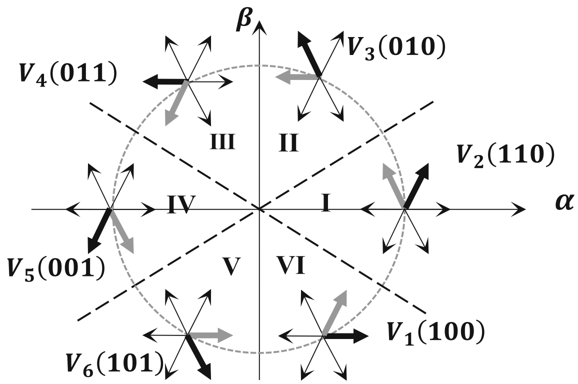


Fig. 2 Stator-flux-based DTC induction machine drive

Fig. 3 Sectors and required switching-voltage space vector



estimation which also affects the estimation of torque and speed in case of sensorless drive [8, 9].

There are eight states whose two of them have null voltage. The six states are illustrated in Fig. 3. It shows that the stator flux plane is divided into six sectors where each one has a set of voltage vectors. Therefore, the stator flux is controllable according to actual sector of flux vector [7]. As shown In Fig. 3, the bold arrow increases the stator flux, while light arrow decreases it. Similarly, it can be seen that, if an increase of the torque is required, then the torque is controlled by applying voltage vectors that advance the flux-linkage space vector in the direction of rotation, and if a decrease of torque is required, voltage vectors are applied which oppose the direction of the torque. If zero torque is required then zero switching vector V_0 or V_7 is applied. According to previous inverter state, the zero switching vector (V_0 or V_7) to be applied is chosen so as to switch one only arm of inverter.

2.3 Flux and Torque Estimator

The electromagnetic torque can be estimated easily by using Eq. (2). However, we must firstly have the stator flux-linkage components.

It was not convenient to use flux sensors; that is why the stator flux-linkage components must be estimated. In the DTC induction machine drive the stator flux-linkage has a double interest: First, stator flux-linkage components are required for the estimation of the electromagnetic torque as mentioned above. Secondly they are also required in the optimum switching vector selection table discussed in the previous section. It should be noted that, in general, the stator flux follows the applied stator voltage vector during an interval of time (dt) according to Eq. (9).

$$\varphi_s = \begin{pmatrix} \varphi_{s\alpha} \\ \varphi_{s\beta} \end{pmatrix} = \begin{pmatrix} \int (u_{s\alpha} - R_s i_{s\alpha})dt \\ \int (u_{s\beta} - R_s i_{s\beta})dt \end{pmatrix} \tag{9}$$

It should be noted that the performance of the DTC drive using Eq. (9) depend greatly on the accuracy of the estimated stator flux components, and these depend on the accuracy of the measured voltages and currents, and also of stator resistance. This method qualified as an open-loop flux linkage estimator is simple and work well excepting at very low frequency [7].

2.4 Rotor Speed Controller

In order to control the rotor speed, the reference torque t_{ref} is changed as following:

- If rotor speed is less than the reference speed, the torque must be increased;
- If the speed exceeds its reference the torque must be reduced.

The rotor speed is obtained by using a fuzzy MRAS estimator. The following section provides a description of the fuzzy controller.

3 Fuzzy MRAS Speed Estimator

The proposed scheme of the MRAS-based rotor speed observer is shown in Fig. 4. It should be noted that a linear state observer for the rotor flux can then be derived as follows by considering the mechanical time-constant is much greater than the electrical time-constants [7].

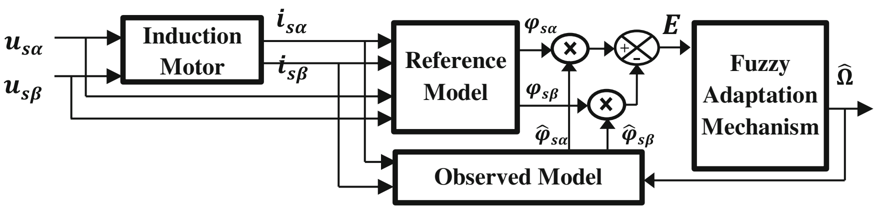


Fig. 4 Structure of the fuzzy MRAS speed estimator

The reference model is a model that doesn't depend on the rotation speed; it allows calculating the components of rotor flux (in the stationary reference frame) from stator voltage equations:

$$\frac{d\Phi_{r\alpha}}{dt} = \frac{1}{a}\left(u_{s\alpha} - R_s i_{s\alpha} - \frac{1}{\delta}\frac{di_{s\alpha}}{dt}\right); \; \frac{d\Phi_{r\beta}}{dt} = \frac{1}{a}\left(u_{s\beta} - R_s i_{s\beta} - \frac{1}{\delta}\frac{di_{s\beta}}{dt}\right) \tag{10}$$

The observer model uses the speed of rotation in its equations and permits to estimate the components of rotor flux and thus:

$$\frac{d\hat{\Phi}_{r\alpha}}{dt} = -k\Phi_{r\alpha} - p\hat{\Omega}\Phi_{r\beta} + kL_m i_{s\alpha}; \; \frac{d\hat{\Phi}_{r\beta}}{dt} = -k\Phi_{r\beta} + p\hat{\Omega}\Phi_{r\alpha} + kL_m i_{s\beta} \tag{11}$$

where the subscript ^ denotes the estimated value of the specified signal. Figure 4 shows the schematic of the rotor speed estimator. The adaptation mechanism is derived by using Popov's criterion of hyperstability. This results in a stable and quick response system [7], where the differences between the state-variables of the reference model and adaptive model (state errors) are manipulated into a speed tuning signal (E), which is then an input into a fuzzy-type of controller (shown in Fig. 5), which outputs the estimated rotor speed.

kE, kdE, kdU are gains called "scale factor". They can change the sensitivity of the controller without changing its structure. The fuzzy controller is composed of three blocks: Fuzzification, rule bases, and Defuzzification. The fuzzy subsets are as following: NB (Negative Big), NM (Negative Medium), NS (Negative Small), Z (Zero), PS (Positive Small), PM (Positive Medium), PB (Positive Big). As shown in Table 1, there are 7 fuzzy subsets for each variable, which gives 49 possible rules.

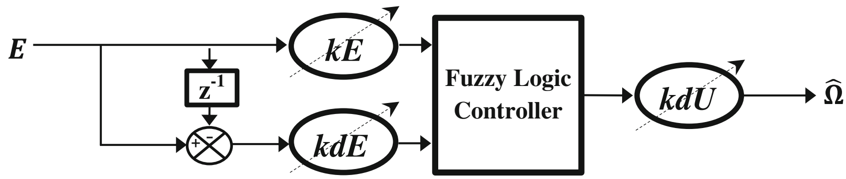


Fig. 5 Fuzzy logic controller elements

Table 1 Fuzzy rule base with 49 rules

dE/E	NB	NM	NS	Z	PS	PM	PB
PB	Z	PS	PM	PB	PB	PB	PB
PM	NS	Z	PS	PM	PB	PB	PB
PS	NM	NS	Z	PS	PM	PB	PB
Z	NB	NM	NS	Z	PS	PM	PB
NS	NB	NB	NM	NS	Z	PS	PM
NM	NB	NB	NB	NM	NS	Z	PS
NB	NB	NB	NB	NB	NM	NS	Z

4 Experimental and Simulation Result

The experimental setup arrangement is based on dSPACE DS1104 board (based on a Texas Instruments TMS320F240 DSP) and a SEMIKRON inverter switching at 10 kHz (noted by VSI). The load torque of the induction motor is controlled by the DC machine (see Fig. 6).

The induction machine parameters are mentioned in Table 2. The simulation and experimental results are shown in Fig. 7.

The applied speed reference profile is shown in Fig. 7b. During start-up the load torque is maintained at 10 Nm; at t = 1 s, the load torque value changes to −10 Nm.

We can see a fast speed response during start-up and during fast changes of speed reference or load torque. The stator currents and stator flux are approximately sinusoidal. The driver has the capability of four-quadrant operation (it should be noted that between 0.75 and 0.83 s, (see Fig. 7e): the induction machine operates in the regenerating mode and the kinematic energy stored in the system inertia is converted into electrical energy).

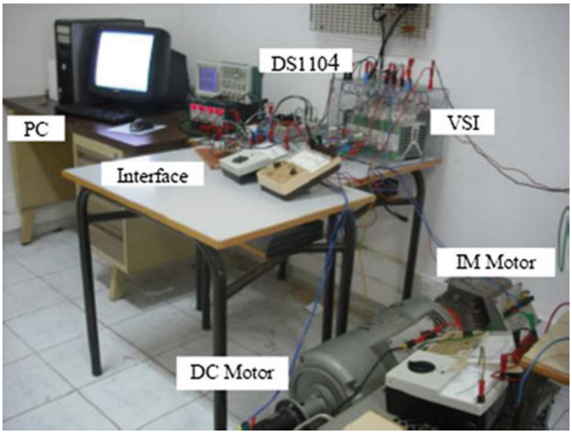


Fig. 6 Experimental setup test

Table 2 Induction machine parameters

Parameter	Symbol	Rating value
Rated power	*Pn*	1.5 kW
stator voltage/frequency	*U*/*f*	380 V/50 Hz
Number of pole-pairs/rated speed	*P*/*n*	2/1460 rpm
Resistance (stator/rotor)	*Rs*/*Rr*	5.7/3.4 Ω
Inductance (stator/rotor)	*Ls*/*Lr*	0.23 H/0.22 H
Mutual inductance	*Lm*	0.21 H
Polar moment of inertia	*J*	0.18 kg m^2

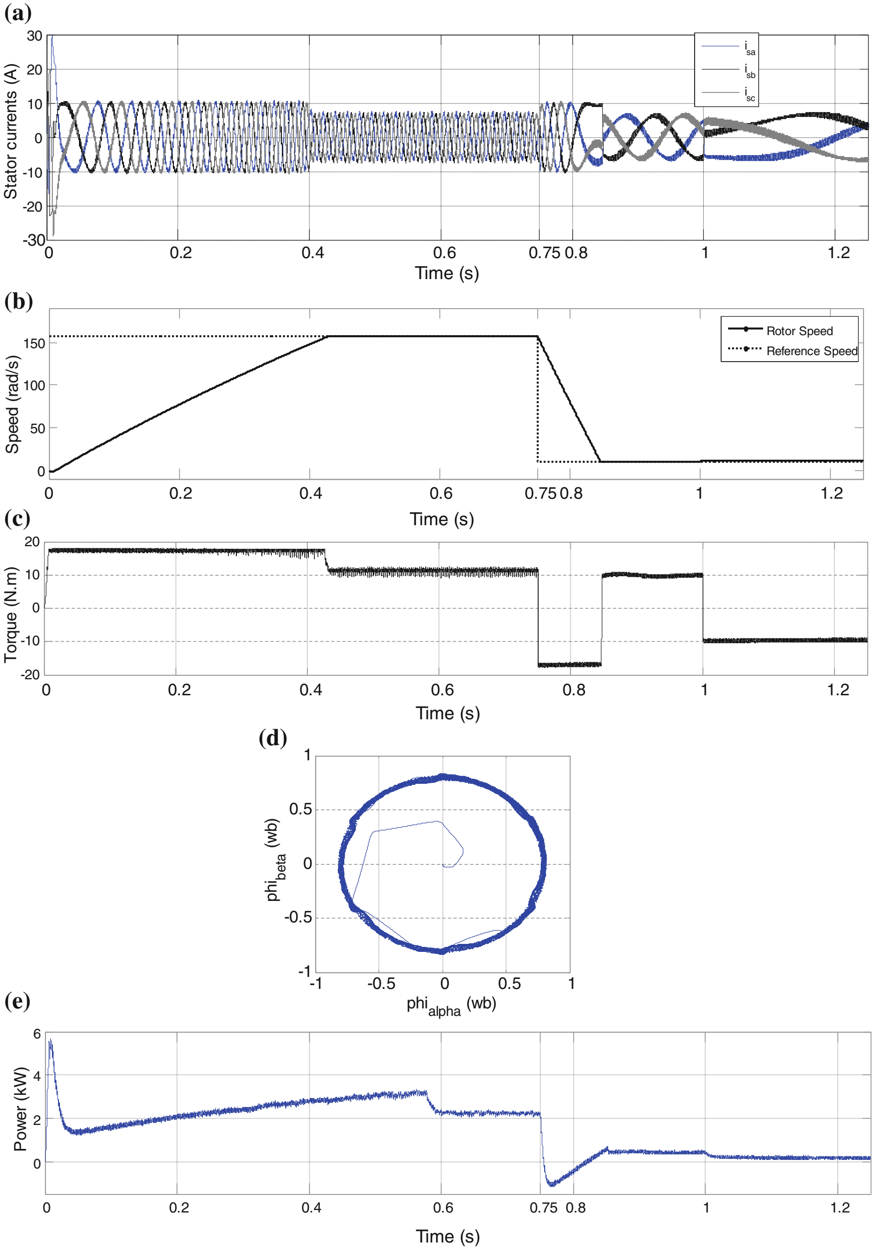


Fig. 7 Simulation and experimental results: **a** Stator currents; **b** Rotor speed; **c** Estimated electromagnetic torque; **d** Stator flux trajectory; **e** Instantaneous power supply

5 Conclusion

In this paper we have presented the study of the classical direct torque and flux controller of induction machine. The main advantages of the DTC are:

- Direct control of flux and torque (by the selection of optimum inverter switching vectors);
- Very quick response;
- Indirect control of stator currents and voltages (current regulators not required);
- Absence of coordinate transformations (which are required in most of the vector-controlled drive implementations);

From simulation results, it can be shown that the DTC combined with fuzzy logic speed controller ensures robust start and operation in the zero-speed region. And the adaptive control can be achieved by stator resistance estimation.

Our future research work would take into account the variation of the rotor resistance and the implementation of this control strategy using a 16-bit Fixed-point DSP.

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