Induction Motor Drive Predictive Control Method Analysis and Comparison with Fundamental Direct Torque Control Method

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Abstract— The authors propose new modification of the direct torque control method based on voltage vector prediction. The principle of the method is explained and the mathematical description of the system is provided. The control algorithm is implemented in simulation environment MatLab/Simulink and its behaviour is tested on the mathematical model of an induction motor drive. Then, the control algorithm is verified on the real drive with induction motor with dSPACE control system. The results from the simulations and measurements are presented and compared with those when using the fundamental direct torque control method.

1. INTRODUCTION

In 1986 Isao Takahashi and Toshihiko Noguchi presented a new control strategy of induction motor control algorithm called direct torque control (DTC) [1]. The method is based on transistor switching according to table uses hysteresis torque and magnetic flux controllers. One of the disadvantages is the relatively high torque ripple. A lot of modifications were performed since then. The most important are DTC with space vector modulation [2], multilevel inverter application [3] and predictive algorithms of DTC [4, 5]. The method described in the paper presents another modification using prediction of voltage vector. It is based on the calculations of changes in stator and rotor magnetic fluxes and motor parameters.

2. PRINCIPLE OF VOLTAGE VECTOR PREDICTIVE DTC

The basic theory of the proposed method firstly predicts the stator magnetic flux for the next cycle and then the voltage vector that should be switched on the inverter. The calculations are based on the every cycle motor state values (measured or estimated), motor parameters and reference values. Because the requirement of the method is the rotor flux value knowledge, the estimator have to calculate with adequate precision and parameters of the induction machine must be known. The block diagram of the controlled system is depicted in Fig. 1 on the left hand side.

The calculation of voltage for the next cycle is based on the induction motor stator voltage Equation (1). After discretisation it results in (2)

$$\vec{u_s} = R_s \cdot \vec{i_s} + \frac{d\vec{\Psi}_s}{dt} \tag{1}$$

$$u_s(\vec{k+1}) = \frac{[\Psi_s(\vec{k+1}) - \Psi_s\vec{(k)}]}{T_s} + R_s \cdot i_s\vec{(k)} \tag{2}$$

where $\vec{u_s}$ is stator voltage vector, $\vec{i_s}$ stator current vector, $\vec{\Psi}_s$ stator magnetic flux vector, R_s is stator resistance, and T_s is sampling time constant. The only unknown variable in equation (2) is stator magnetic flux vector in next step $\Psi_s(\vec{k+1})$. The vector is defined as (3)

$$\Psi_s(\vec{k+1}) = \Psi_s^* \cdot e^{j\theta_s(k+1)} \tag{3}$$

where Ψ_s^* is desired value of stator magnetic flux amplitude that can be considered as next cycle value of Ψ_s. The angle $\theta_s(k+1)$ is the next cycle angle of stator magnetic flux vector and it can be expressed by (4)

$$\theta_s\,(k{+}1) = \theta_r\,(k) + \Delta\theta_r\,(k) + \theta_{sr}\,(k{+}1) \tag{4}$$

where θ_r is the angle of rotor magnetic flux vector, $\Delta\theta_r$ is the angle change in rotor magnetic flux in course of one step and θ_{sr} is the angle between the stator and rotor magnetic fluxes. The graphical representation of space relationships among the vectors is shown in Fig. 1 on the right hand side. The rotor magnetic flux vector is calculated in estimator and its angle is expressed in (5).

$$\theta_r\,(k) = arctan\left(\frac{\theta_{r\beta}\,(k)}{\theta_{r\alpha}\,(k)}\right) \tag{5}$$

Induction motor has the electromagnetic torque equation as (6)

$$T = \frac{L_m}{L_\Delta} p_p \cdot \psi_s \times \psi_r = \frac{L_m}{L_\Delta} p_p \cdot |\psi_s| \cdot |\psi_r| \cdot sin\theta_{sr} \tag{6}$$

where T is generated torque, L_m is mutual inductance, $L_\Delta is expressed$ as $L_\Delta = L_s \cdot L_r - L_m^2$, L_s is stator inductance, L_r is rotor inductance. Assuming constant values of the magnetic flux amplitudes, the torque is determined only by the angle between stator and rotor flux vectors. Actual difference between stator and rotor magnetic flux angles is calculated from (7).

$$\theta_{sr}(k) = \arcsin\left[-\frac{L_\Delta \cdot T(k)}{p_p \cdot L_m \cdot |\Psi_s(k)| \cdot |\Psi_r(k)|}\right] \tag{7}$$

The value of $\theta_{sr}(k+1)$ is then expressed as (8). If we assume reaching the desired values immediately in the next cycle then it is possible to replace values of $(k+1)$th sample with desired values. Because the time constant of the rotor is much greater than constant of the stator all the changes from stator will occur in rotor with long time delay. With this assumption the rotor flux in next step $\Psi_r(k+1)$ can be replaced with $\Psi_r(k)$ if the sampling time is adequately short. The formula can be then simplified.

$$\theta_{sr}(k+1) = \arcsin\left[-\frac{L_\Delta \cdot T(k+1)}{p_p \cdot L_m \cdot \Psi_s(k+1) \cdot |\Psi_r(k+1)|}\right] = \arcsin\left[-\frac{L_\Delta \cdot T^*}{p_p \cdot L_m \cdot |\Psi_s^*| \cdot |\Psi_r(k)|}\right] \tag{8}$$

The change in the rotor flux vector angle during one cycle is by rearranging the rotor voltage equation of induction motor as (10)

$$\Delta\theta_r(k) = \left[\omega_r(k) + \frac{R_r \cdot T(k)}{p_p \cdot |\Psi_r(k)|^2}\right] \cdot T_s \tag{9}$$

where R_r is rotor resistance and ω_r is rotor electrical angular velocity.

The necessary angles for (4) have been calculated and if the angle $\theta_s(k+1)$ is put to (3) and (2) the optimal voltage vector $u_s(\vec{k+1})$ is then calculated. Once the optimal voltage vector is calculated, the most suitable combination of inverter transistors is switched. Since this method doesn't use any modulation, the nearest active or zero vector is selected for the whole next step.

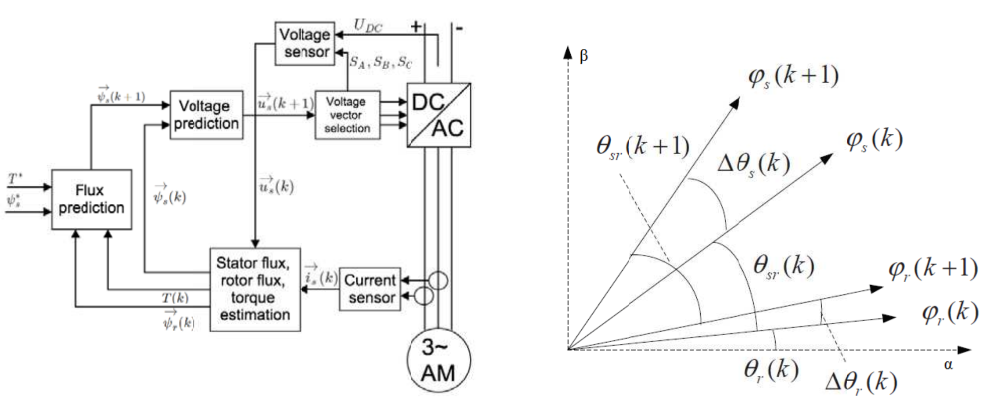


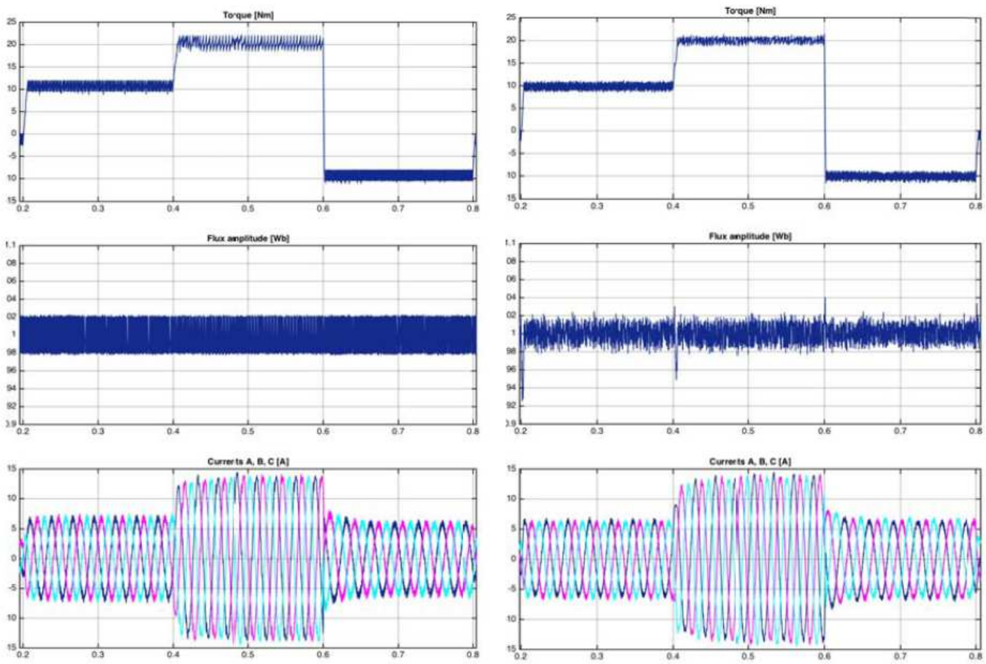
Figure 1: Block diagram of voltage vector predictive DTC and relationships of induction motor magnetic flux vectors.

3. SIMULATION AND EXPERIMENTAL RESULTS

In order to verify the control strategy, the proposed method was in the simulation environment MatLab/Simulink realized and its behaviour was tested on a 5.5 kW model of induction motor. The nominal values of the induction motor are summarized in Table 1. In the simulations, the average switching frequency of the inverter transistors was 2.5 kHz. The predictive control method was put to the contrast with the fundamental direct torque control method and the results of the

Table 1: Nominal values of induction motor.

U_n	230 V	Nominal voltage
I_n	11.8 A	Nominal current
P_n	5.5 kW	Nominal power
ω_n	145 rad/s	Nominal speed
	Y	Star connected
p_p	2	Number of pole pairs



(a) (b)

Figure 2: System simulation at (a) fundamental DTC and (b) predictive DTC.

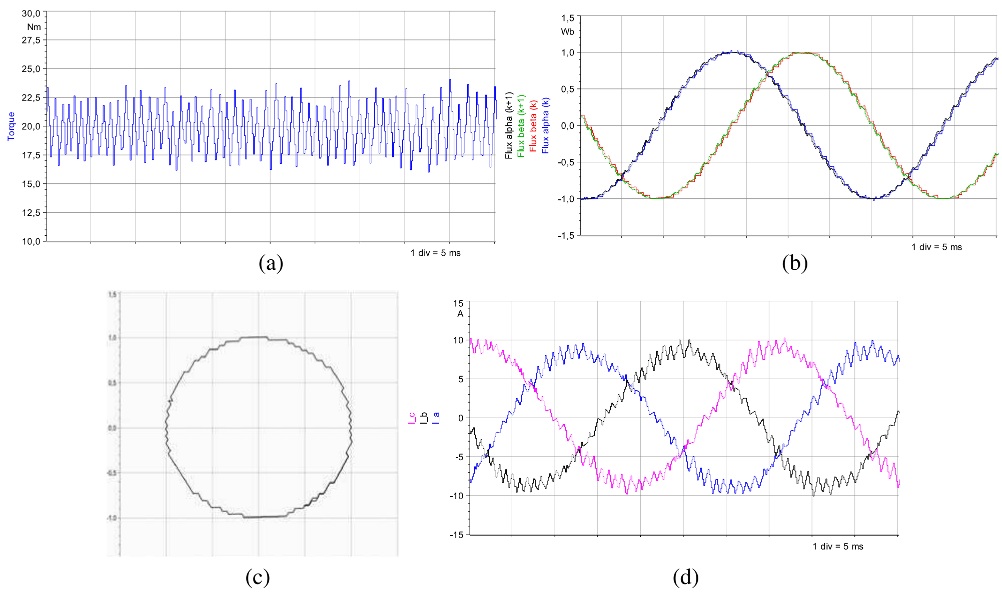


Figure 3: Measured results on the real drive at predictive DTC ((a) torque, (b) stator flux and predicted stator flux, (c) stator flux in alpha beta coordinates, (d) stator currents).

simulations are presented in Fig. 2. The waveforms for the fundamental method are depicted on the left hand side and for the predictive method on the right hand side.

In order to verify the control strategy feasibility, the method was also implemented on real drive with induction machine with parameters corresponding to the simulations. The method was implemented by means of the dSPACE control system. For the measured waveforms of torque, stator flux and currents see Fig. 3.

As can be seen from the presented waveforms, the evaluation can be summarized as follows.

1. The stator magnetic flux vector tip moves along a circular trajectory.
2. The induction motor torque ripple has reasonable small values in all cases.
3. The induction motor torque and stator flux amplitude waveforms are at the predictive DTC maintained at the reference values with smaller ripples than at fundamental DTC.
4. After the demanded torque value step changes the induction motor torques values reach quickly the reference values without overshoots at both strategies.

4. CONCLUSION

Voltage vector predictive direct torque control method of induction motor was derived in this paper and the mathematical description of the control system was provided. The controlled system model was created in the simulation environment MatLab/Simulink and its behaviour was tested and compared with fundamental DTC with hysteresis controllers. From the contrast between these methods the smoother run of the predictive DTC in the fields of torque and current waveforms was verified. Ultimately, the predictive DTC strategy was implemented on the real induction motor drive with the dSPACE control system and the simulation results were verified by the experiment.

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