Hysteresis Control and Constant-Switching Strategy in Direct Torque Control Drive – A Comparative Analysis

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Abstract: - Comparative analysis between to control strategies for direct torque control (DTC) of current converter fed (CSI) induction motor drive is presented. The well-known DTC strategy based on hysteresis type torque controller is compared with new proposed DTC algorithm. Contrary to the direct torque control of CSI drive presented in the known literature (without experimental results), proposed algorithm is based on constant switching frequency with modification of the inverter optimal switching table. The main idea is to develop robust, but simple for implementation algorithm without rotational transformation and parameter dependences that exist in vector control of the same drive. With such a solution, problems detected under basic DTC using torque hysteresis comparator are avoided (significant torque pulsations, requirement for filtering of the estimated torque and adaptation of hysteresis bandwidth in depend of motor speed). Analysis is performed using simulated mathematical model. Than, experimental verification is done through implementation in the realized drive prototype with a standard thyristor type frequency converter. Both simulation and experimental results confirm the performance of the proposed control algorithm.

Key-Words: - DTC, hysteresis comparator, constant switching, CSI, induction motor

1 Introduction

The direct torque control (DTC) is one of the actively researched control schemes of induction machines, which is based on the decoupled control of flux and torque. DTC provides a very quick and precise torque response without the complex field-orientation block and the inner current regulation loop [1], [2]. DTC is the latest AC motor control method [3], developed with the goal of combining the implementation of the V/f-based induction motor drives with the performance of those based on vector control. It is not intended to vary amplitude and frequency of voltage supply or to emulate a DC motor, but to exploit the flux and torque producing capabilities of an induction motor when fed by an inverter [4].

Although the traditional DTC is developed for voltage-source inverters, for synchronous motor drives the current-source inverter (CSI) is proposed [5], [6]. This type of converter can be also applied to DTC induction motor drive, and in the paper such an arrangement is presented. The induction motor drives with thyristor type current-source inverter (CSI, also known as auto sequentially commutated inverter) possess some advantages over voltage-source inverter drive. CSI permits easy power regeneration to the supply network under the breaking conditions, what is favorable in large-power induction motor drives. In traction applications bipolar thyristor structure is replaced with gate turn-off thyristor (GTO). Nowadays, current source inverters are popular in medium-voltage applications, where symmetric gate-commutated thyristor (SGCT) is utilized as a new switching device with advantages in PWM-CSI drives [7].

DTC of a CSI-fed induction motor involves the direct control of the rotor flux linkage and the electromagnetic torque by applying the optimum current switching vectors. Furthermore, it is possible to control directly the modulus of the rotor flux linkage space vector through the rectifier voltage [5]. Instead of triggering the rectifier voltage by the applied flux error [6], the current controller is used.

The reference current is formed from the components in synchronous frame – i_{sd}* obtained from the output of rotor flux PI controller and i_{sq}* calculated from the torque and rotor flux references. Similarly to the stator flux field-oriented control and DTC with constant switching frequency (space vector modulation – SVM [8]), current components i_{sd}* and i_{sq}* and reference rotor flux ($\Psi_{rd}* = \Psi_r*$, $\Psi_{rq}* = 0$) are used to calculate reference stator flux.

Since flux estimator operates in stationary reference frame, it is necessary to convert input variables from synchronous to stationary frame. This coordinate transformation is only performed when reference is changed and there is no influence to the dynamics of the control algorithm. To avoid some drawbacks of torque hysteresis controller (larger torque ripples, necessity to adopt torque hysteresis bandwidth depend on the motor speed), a phase angle between current components i_{sd}* and i_{sq}* is applied as a control variable. This angle is added to the rotor flux position and introduced to the flux sector seeker. As a result, the same current vector will be chosen as in the case of vector control algorithm [11], where coordinate transformation is employed to activate the inverter switches.

2 Comparison between two different DTC approaches

In a direct torque controlled induction motor drive supplied by current source inverter it is possible to control directly the modulus of the rotor flux-linkage space vector through the rectifier voltage, and the electromagnetic torque by the supply frequency of the CSI.

2.1 Hysteresis control DTC strategy

Basic DTC algorithm for CSI induction motor drive is derived using analogy from voltage source inverter (VSI) drive [5]. The inputs to the optimal switching table are the output of a 3-level hysteresis comparator and the position of the rotor flux-linkage space vector. As a result, the optimal switching table determines the optimum current switching vector of current source inverter (Table 1).

Table 1: Optimum current switching-vector look-up table

ΔT_e	S_1	S_2	S_3	S_4	S_5	S_6
1	i_2	i_3	i_4	i_5	i_6	i_1
0	i_0	i_0	i_0	i_0	i_0	i_0
-1	i_6	i_1	i_2	i_3	i_4	i_5

Block diagram of this control strategy is shown in Fig. 1.

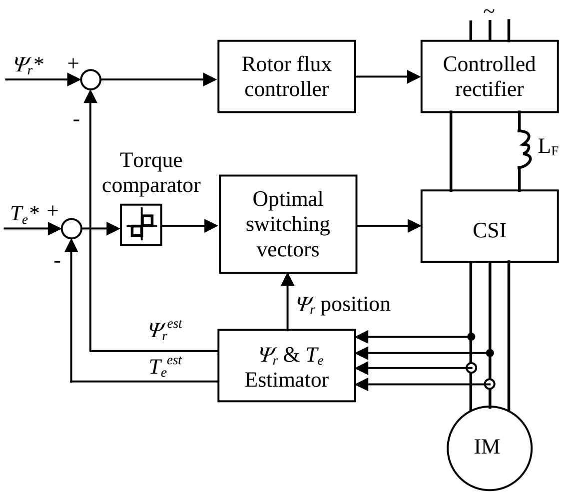

Fig. 1. DTC of CSI drive based on hysteresis control

It is necessary to emphasize the importance of zero space vectors. In VSI there are two zero voltage vectors: u_0 denotes case when all three switches from the one half of inverter are switched ON while u_7 represent state when switches are OFF. Contrary, in CSI (using analogy to the VSI) zero current vector i_0 represent case when all thyristors are OFF. That could lead to both torque and motor speed decrease. Due to the nature of commutation in CSI, it is convenient to keep the selected current vector at instants when zero current vector is chosen. Torque response of the drive is shown in Fig. 2.

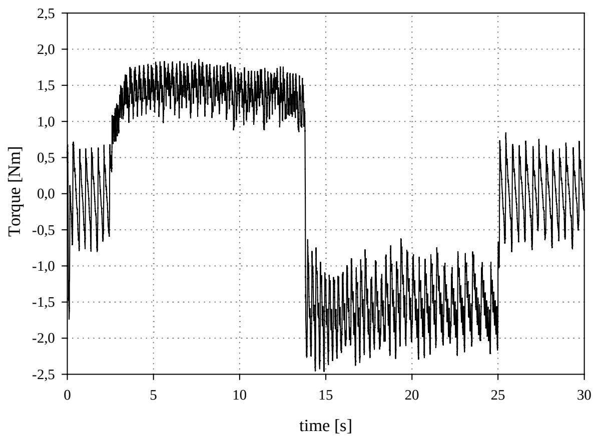

Fig. 2. Torque response in basic DTC drive

It could be observed that initial torque response is slower when the reference is lower, but it is fast during reversal since the torque reference change is doubled. On the other side, torque ripples are higher when torque changes its sign because torque-decreasing voltage vectors are stronger than the torque-increasing voltage vectors [8]. In that case, situation could be somewhat improved with modification of hysteresis comparator where positive part of hysteresis are larger then negative as shown in Fig. 3 [9].

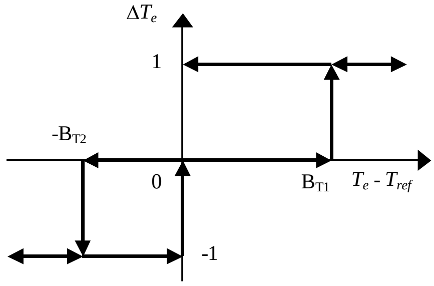

Fig. 3. Modified hysteresis comparator

2.2 Constant-switching DTC strategy

In DTC schemes, the presence of hysteresis controllers for flux and torque determines variable-switching-frequency operation for the inverter. Furthermore, using DTC schemes a fast torque response over a wide speed range can be achieved only using different switching tables at low and high speed. The problem of variable switching frequency can be overcome by different methods [5], [8]. In [8], a solution based on a stator flux vector control (SFVC) scheme has been proposed. This scheme may be considered as a development of the basic DTC scheme with the aim of improving the drive performance. The input commands are the torque and the rotor flux, whereas the control variables are the stator flux components. The principle of operation is based on driving the stator flux vector toward the corresponding reference vector defined by the input commands. This action is carried out by the space-vector modulation (SVM) technique, which applies a suitable voltage vector to the machine in order to compensate the stator flux vector error. In this way it is possible to operate the induction motor drive with a constant switching frequency.

In proposed DTC CSI drive shown in Fig. 4 the inputs are rotor flux and torque as in VSI presented in [8], but as a control variable the stator flux angle α_s is used. Although this configuration could remind on field-oriented control, the main difference is absence of coordinate transformation since it is not necessary to use coordinate transformation to achieve correct firing angle as in vector control of the same drive [11]. Identical result would be obtained when phase angle Φ_s between d-q current references and rotor flux vector angle $\theta_e = \arctan(\Psi_{r\beta}/\Psi_{r\alpha})$ are summed and resulting angle α_s is than used to determine sector of 60 degrees where resides rotor flux vector. In that way, phase angle Φ_s acts as a torque control command, since when reference torque is changed, i_{sq}* is momentary changed.

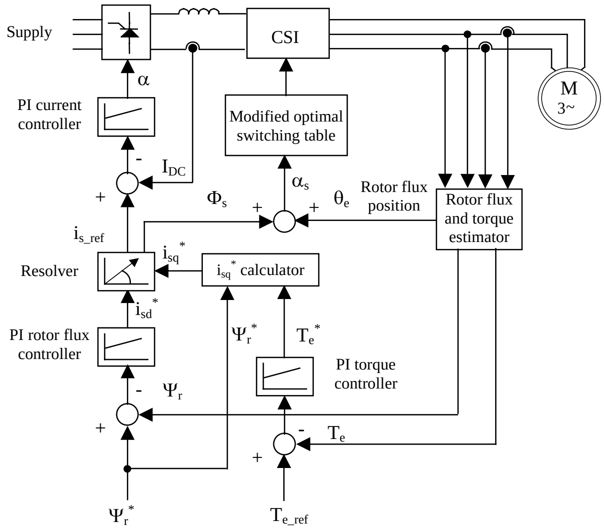

Fig. 4. Constant-switching DTC strategy in CSI fed induction motor drive

Fig. 5 represent phasor diagram with reference current vector, rotor flux vector and corresponding angles.

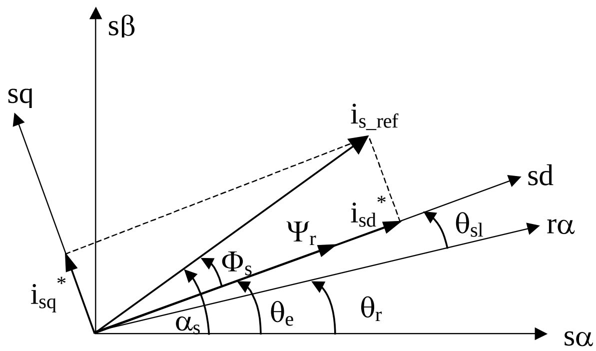

Fig. 5. Position of stator current and rotor flux vectors

Phase angle Φ_s "moves" stator current vector i_s in direction determined by the sign of torque reference and its value accelerate or decelerate flux vector movement according to the value of the reference torque.

This modification implies somewhere different switching table for activating inverter switches, as shown in Table 2, where α_s is angle between referent α-axis and reference current vector i_s. That angle determines which current vector should be chosen: i_2 for torque increase, i_6 for torque decrease or i_1 for keeping torque at the current value.

Table 2: Optimal switching table in proposed DTC

Current vector	Angle range (degrees)
i_1	$\alpha_s > 0°$ and $\alpha_s \leq 60°$
i_2	$\alpha_s > 60°$ and $\alpha_s \leq 120°$
i_3	$\alpha_s > 120°$ and $\alpha_s \leq 180°$
i_4	$\alpha_s > 180°$ or $\alpha_s \leq -120°$
i_5	$\alpha_s > -120°$ and $\alpha_s \leq -60°$
i_6	$\alpha_s > -60°$ and $\alpha_s \leq 0°$

Results from the simulation model of the proposed strategy developed in Matlab/SIMULINK is shown in Fig. 6, where torque reference was changed from +10Nm to –10Nm after the rated rotor flux is established.

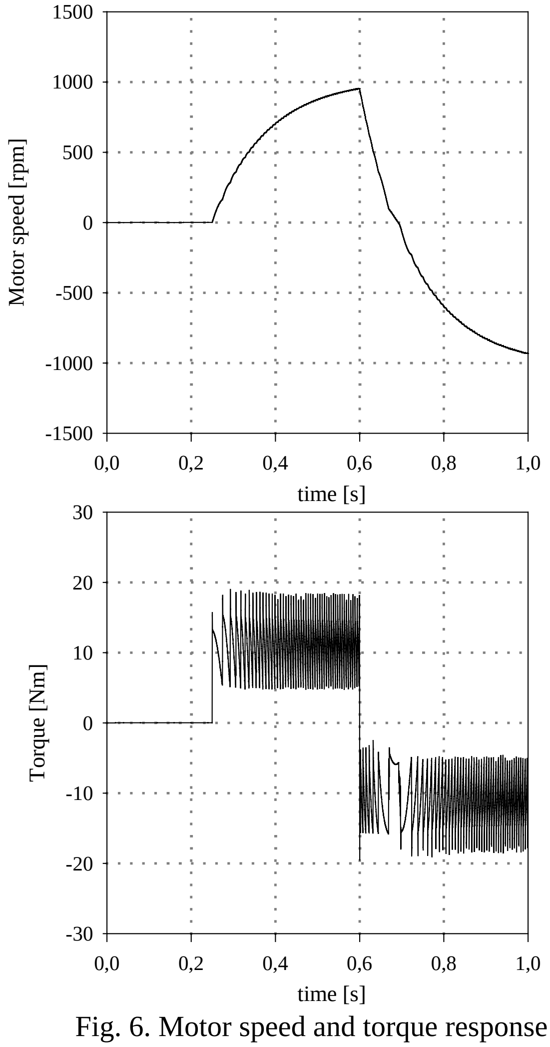

Fig. 6. Motor speed and torque response in open-loop speed control

3 Experimental results

For experimental purposes a standard thyristor type frequency converter (three-phase bridge rectifier, dc link inductor and auto sequentially commutated inverter) is used. The CSI feeds a 4kW induction motor and, as a mechanical load, the DC machine with controlled armature current is used [11], [12]. The algorithm presented in this paper is not dependent on the motor power or the type of switching devices and it could be applied to any current source converter topology. The low-power induction motor and standard type thyristors are used just for the simplicity of the laboratory tests.

Fig. 7 shows speed reversal when torque command is changed from 1.5Nm to –1.5Nm and vice versa. Torque response is fast and accurate, with small ripples due to the nature of CSI operation.

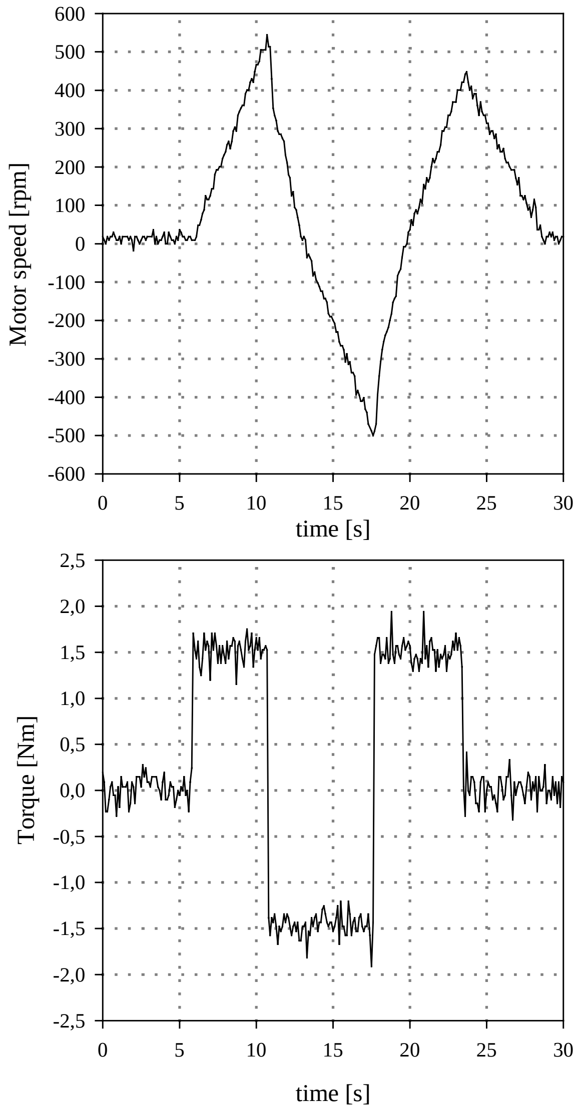

Fig. 7. Motor speed and torque response under square torque command

4 Conclusion

Two types of direct torque control strategies in CSI fed induction motor drive are presented in the paper. Contrary to the well-known hysteresis control derived from VSI drive, authors proposes new DTC algorithm based on the constant switching frequency.

Advantage of such a solution in comparison to the vector control of the same drive is absence of coordinate transformation and speed sensor on the motor shaft. In this case, by combination of vector control and basic DTC, a robust algorithm is developed that has a faster torque response and it is simpler for implementation. Furthermore, algorithm is less sensitive to the parameter variation than standard FOC on the same drive. Only deterioration of drive performance could be expected under the speed of 100rpm due to the known problems of flux estimation. But, since CSI drive is not intended for low or zero-speed operation, this should not be treated as disadvantage.

Results obtained by simulations and experiments on laboratory prototype have proved the validity of the proposed algorithm.

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