A Novel Direct Torque Controlled IM Drives Fed from CSI with Minimum Ripple Torque

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Abstract— **This paper proposes a novel vector control strategy for Direct torque controlled current source inverter fed induction motor drives. The choice of the inverter switching vector is based on angular position of stator flux or rotor flux and on the reference and the motor current vectors in the switching vector plane. The performance of this control method has been demonstrated by simulations performed using a versatile simulation package, MATLAB / SIMULINK. The results prove the excellent characteristics for torque response and efficiency, which confirm the validity of this control scheme.**

Keywords— **Induction motor**, **Current Source Inverter, Direct Torque Control,**

INTRODUCTION

Variable speed AC motor drives have been continuously developed during the last decades owing to the advances in power electronics, control theory and microprocessors technology. In recent industrial development, induction motor is widely used for variable speed control system, which requires a precise and quick torque response. An improvement of the drive performance can be obtained using a new direct torque control algorithm based on the application of the space vector modulation [1-3]. The Direct Torque Control (DTC) technique has been recognized as viable method to provide a very quick and precise response, where minimum switching frequency and hence maximum efficiency is guaranteed and fully de-coupled control loops as well. Direct torque control is one of the actively researched control schemes which are based on the de-coupled control of flux and torque when the exact vector of stator flux is known. The basic concept of direct torque control of induction machines is investigated in order to emphasize the effects produced by a given current vector on stator flux and torque variations. In DTC, the torque and stator flux are regulated to their command values by selecting the switching state which gives the proper changes in the torque and flux. There have been some DTC-based strategies, e.g. current-vector selection using switching table, direct self-control, and space-vector modulation [4-7]. Among them, the current-vector selection strategy using a switching table is widely researched and commercialized, because it is very simple in concept and easy to be implemented. The proper current vector selection is based on the error in electromagnetic torque, error in stator flux and the position of the stator flux vector. In the conventional DTC scheme the system makes no difference between a very small and relatively large error of torque and/or flux. The switching states chosen for the large error that occurs during the startup or during a step change in torque command or even flux command are the same that have been chosen for the fine control during normal operation. This may cause a lightly slower response during the start-up and during a step change in electric torque or stator flux. This was the reason of attempting to propose a new approach for direct torque control (DTC) based on "If the ranges in which the torque error exists and the range in which the flux error exists are considered when choosing the switching state, the system response can be improved using different error levels".

To overcome above mention drawbacks different solutions are discussed here in section II basic concept of CSI Direct Torque Control principles with advanced flux-torque estimator. In section III a new dynamic torque control for induction motor with direct torque control is introduced. The simulation circuit models and results are discussed in section

1. DIRECT TORQUE CONTROL PRINCIPLES

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A Conventional DTC for CSI-fed induction motor

In a direct torque controlled induction motor drive supplied by current source inverter (Figure 1) 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 [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.

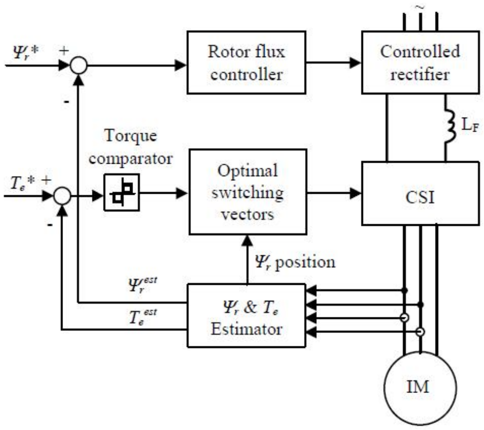

Fig. 1 Conventional DTC CSI-fed IM drive

In the classical DTC, there are several drawbacks. Some of them can be summarized as follows:

− Sluggish response (slow response) in both start up and changes in either flux or torque.
− Large and small errors in flux and torque are not distinguished. In other words, the same vectors are used during start up and step changes and during steady state. In order to overcome the mentioned drawbacks, there are different solutions, which can be classified as follows:
− Non artificial intelligence methods, mainly "sophisticated tables".
− Predictive algorithms, used to determine the switching voltage vectors. A mathematical model of the induction motor is needed. Electromagnetic torque and stator flux, are estimated for sampling period for all possible inverter states. Then, the predictive algorithm selects the inverter switching states to give minimum deviation between the predicted value of the electromagnetic torque and the reference torque.
− Fuzzy logic based systems.

Algorithm proposed in this paper could be classified in the first category since the same flux vector sector seeker is used, but with some other modifications that will be explained in the next sections.

B Input and Control Variables

The input variables of the proposed algorithm are motor torque *Te** and rotor flux amplitude λ_r*, as in the case of basic DTC. Control variables are current components in synchronous reference frame i_{sd}* and i_{sq}* and phase angle between them (θ_s). D-axis component i_{sd}* is determined as the output of the PI rotor flux controller, while q-axis component i_{sq}* is calculated from the input variables and motor parameters:

$$i_{qs}^* = \frac{2L_r}{3pL_m} T_e^* \qquad (1)$$

Where L_r is rotor inductance, L_m is mutual inductance and *p* denotes pair of poles.

Phase angle θ_s and rectifier reference current i_{ref} are obtained as a result of rectangular to polar coordinate transformation:

$$\theta_s = tan^{-1}\left(\frac{i_{ds}^*}{i_{qs}^*}\right) \qquad (2)$$

$$i_{ref} = \sqrt{\left[(i_{ds}^*)^2 + (i_{qs}^*)^2\right]} \qquad (3)$$

$$\lambda_s^* = \frac{L_m}{L_r}\lambda_r^* + \frac{L_sL_r - L_M^2}{L_r} i_s^* \qquad (4)$$

C Flux and Torque Estimator

The main feedback signals in DTC algorithm are the estimated flux and torque. They are obtained as outputs of the estimator operating in stator reference frame. This estimator at first performs EMF integration to determine the stator flux vector:

$$\lambda_{ds}^s = \int (V_{ds}^s - R_s i_{ds}^s)dt \qquad (5)$$

$$\lambda_{qs}^s = \int (V_{qs}^s - R_s i_{qs}^s)dt \qquad (6)$$

$$\Theta_e = tan^{-1}\left(\frac{\lambda_{ds}^s}{\lambda_{qs}^s}\right) \qquad (7)$$

$$T_e = \frac{3}{2} p\left(\lambda_{ds}^s i_{qs}^s - \lambda_{qs}^s i_{ds}^s\right) \qquad (8)$$

and then calculates the flux amplitude and find the sector of 60 degrees in α-β plane where flux vector resides, according to the partition shown in Figure 2.

In that case six intervals of 60 degrees can be defined in which the current and the voltage changes its values. In every interval the current from DC link flows through two inverter legs and two motor phase windings.

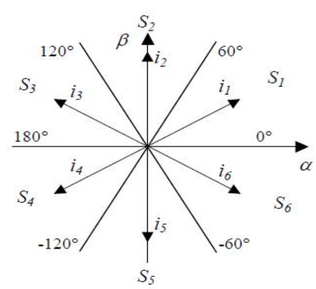

Fig. 2 Sectors in $\alpha - \beta$ plane where rotor flux resides

From the stator output current and voltage, pure integrator in (5) and (6) yields flux vector.

The trajectory of λ_s is exactly circular, it is important to note that the dynamics of stator flux estimation do not depend on the response of the offset estimator. The estimated rotor flux is calculated from the stator flux estimate using motor parameters and reconstructed stator current:

$$\lambda_s = \sqrt{\left[(\lambda_{ds}^s)^2 + \left(\lambda_{qs}^s\right)^2\right]} \qquad (9)$$

and its position in α-β reference frame is determined by:

$$\theta_e = tan^{-1}\left(\frac{\lambda_{ds}^s}{\lambda_{qs}^s}\right) \qquad (10)$$

Finally, from the estimated stator flux and current vector the motor torque is:

$$T_e = \frac{3}{2}p\left(\lambda_{ds}^s i_{qs}^s - \lambda_{qs}^s i_{ds}^s\right) \qquad (11)$$

Where the stator flux and current vectors are given in synchronous α-β frame and *p* denotes the number of poles.

2. PROPOSED DTC CONTROL SCHEME FOR CSI FED DRIVES

In high power electrical drives the semiconductor devices cannot operate at high switching frequency. As a consequence it is not possible to achieve full control of flux and torque. The DSC strategy presented in [2] is aimed at minimizing the number of commutation in each cycle of the supply to the detriment of the flux control. Since the flux error is not introduced to the switching table in conventional CSI fed induction motor drive, the torque error is the only one input in the basic DTC scheme. In proposed system the flux error is introduced to the switching table.

The stator flux and Torque calculated from the machine terminal voltage and current. The signal computation block also calculate the sector number **S(k)** (where k= 1,2,3…6) in which the flux vector **λs** lies. There are six vectors (each π/3 angle wide)as indicated in figure.2 The current vector table block for the proposed DTC system receive the signals **Δλs** and **ΔTe** and **S(k)** and generates the approximate control voltage vector (switching states) for the inverter by a lookup table which is shown in Table1. for the proposed DTC strategy shown in Figure 3. Table 1 applies the selected current vector which essentially affects both torque and flux simultaneously.

For example an operation in sector 2 the Δλs = -1 and ΔTe = +1 the flux is too high and torque is too low generate current I_4. In same sector 2 the Δλs = +1 and ΔTe = +1 and this will generate the I_3vector from the table.

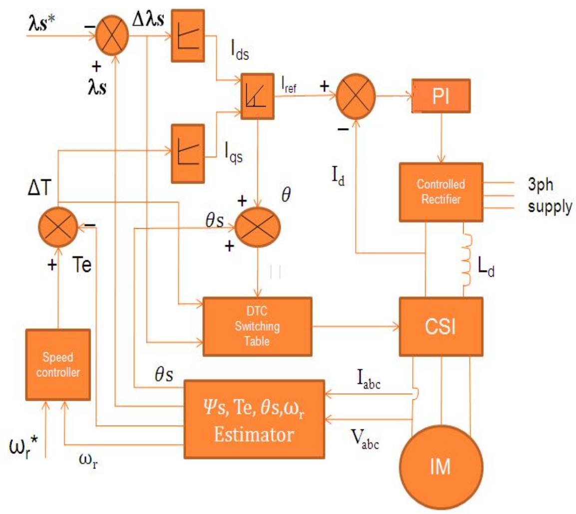

Fig.3 Proposed DTC-SVM Control scheme for CSI fed IM drive

TABLE I
OPTIMUM CURRENT SWITCHING-VECTOR LOOK-UP TABLE

Δλs	ΔTe	S1	S2	S3	S4	S5	S6
1	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
-1	1	i_3	i_4	i_5	i_6	i_1	i_2
	0	i_0	i_0	i_0	i_0	i_0	i_0
	-1	i_5	i_6	i_1	i_2	i_3	i_4

3. SIMULATION RESULTS

A complete drive system has been simulated to study the proposed method performance. The proposed current control is quite simple and it is not rotated to the machine parameter. The investigated speed range 500 rpm with the flux reference λ* set its rated value.

The inverter switching frequency has been set at 5 KHz. The comparison results for conventional and proposed DTC are shown in figure 4 and 5 in terms of stator current Is, stator flux (φ_s), Torque and speed.

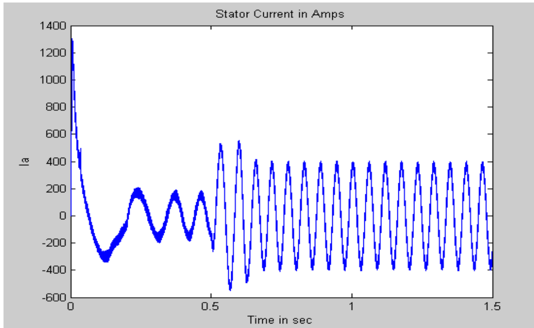

Fig. 4 (a) Stator current for Conventional DTC

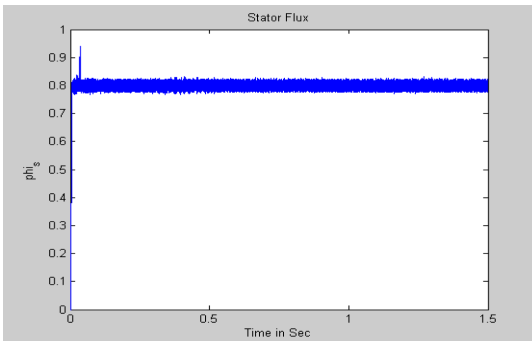

Fig. 4 (b) Stator Flux for Conventional DTC

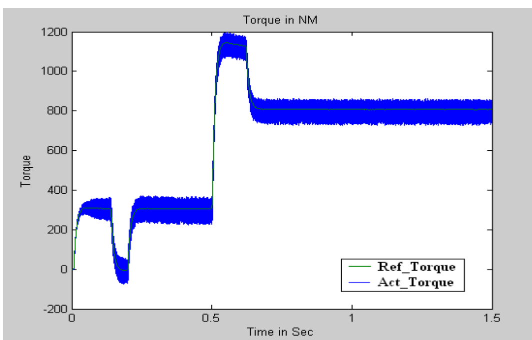

Fig. 4 (c) Torque for Conventional DTC

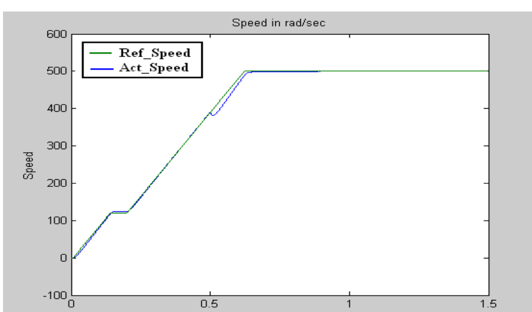

Fig. 4 (d) Speed for Conventional DTC

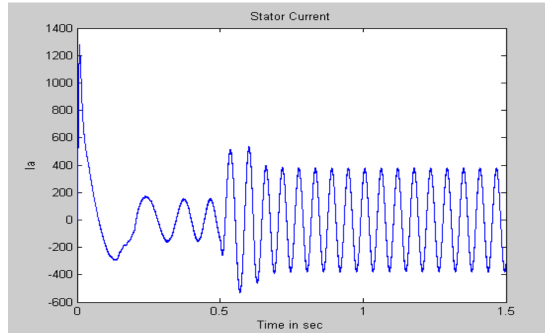

Fig. 5 (a) Stator current for Proposed DTC

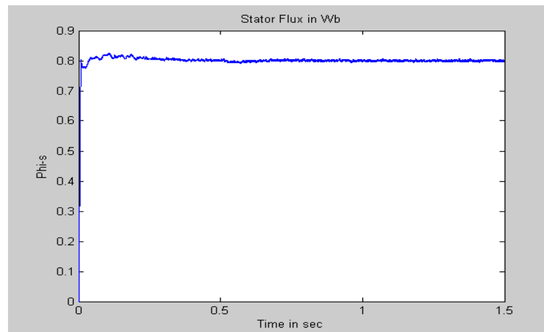

Fig. 5 (b) Stator Flux for Proposed DTC

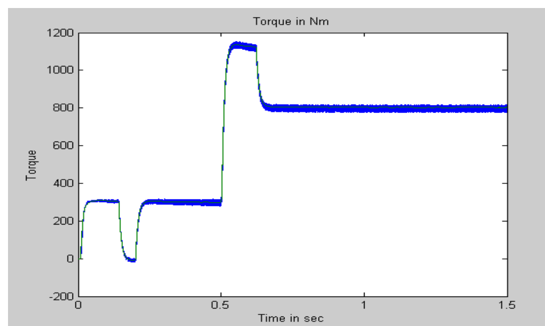

Fig. 5 (c) Torque for Proposed DTC

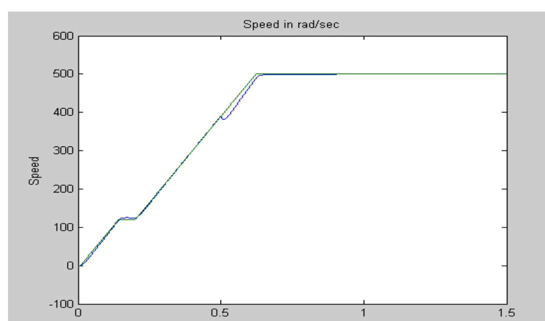

Fig. 5 (d) Speed for Proposed DTC

SIMULINK Outputs for Conventional and Proposed DTC - (a) Stator current (b) Stator Flux (c) Torque (d) Speed

4. Conclusions

In this paper a new method of Direct Torque Controlled CSI fed IM drives has been presented. The simulation results prove that the proposed control strategy allows higher efficiency and the control loop gains reduced current and voltage phase error with torque ripple reduction comparison with other methods in the literature. This drive can easily operate in the four quadrants. The torque response of the drive is claimed to be comparatable with that of a vector controlled drive.

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