DIRECT TORQUE CONTROL OF INDUCTION MOTOR USING TORQUE FLUX PLANE

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Abstract- Direct Torque Control (DTC) is a preferred method for its fast torque response and easy implementation in induction motor (IM) applications. However varying switching frequency and current harmonics are the drawback of the method. There are many industrial applications already using DTC. In this study novel switching table is proposed to reduce current harmonics based on torque-flux plane that can be applied to current motor drives with software modification, rather than a hardware advancement. The study is illustrated with Simulink model and motor output graphics.

Keywords- Direct Torque Control, Torque-Flux plane, Vector Selection Table, Total Harmonic Distortion.

I. INTRODUCTION

Today Field Oriented Control (FOC) and Direct Torque Control (DTC) are the preferred vector control method to drive IM among industrial applications [1],[2]. The most well-known superiority of DTC over FOC is, it has fast torque and flux control property even with its simplicity. Other advantages of DTC are being precise and rotor parameter free. The basic DTC algorithm aims to control both torque and stator flux linkage of motor by selecting appropriate voltage vector and using stator resistance as motor parameter, voltage and current measurement as feedback, that's how it works independent of rotor parameters and without need for speed or position feedback. [3],[4]. One disadvantage of this method is high harmonic distortion causing acoustic noise and EMI interference.

In order to enhance DTC method, there are several methods proposed in the literature. Deadbeat control [5], Sliding Mode Control [6], neural network based direct torque control [7], self-tuned neural fuzzy controller [8].While, all these methods improves side effects of the DTC, they also lead the control technique become more complicated and cause a longer adaptation time delay to adopt to the current motor drive systems. Some of the developed control methods can be expressed with switching tables with the purpose of easy implementation [9], [10],[11]. Switching table based DTC are not complicated to apply which leads less application time delay on motor drive systems. Regarding the phase of developing new algorithms for DTC, the three phase system is transformed to α, β plane so as to illustrate the voltage vector selection in a two dimensional plane. In this plane stator flux linkage is defined as a vector and the variation of it is defined as the flux ripple. And torque is visualized with the magnitude of both rotor and stator flux vector and the angle between them. In order to decrease the torque ripple, it is aimed to move the stator and rotor flux vector more harmoniously and smoother.

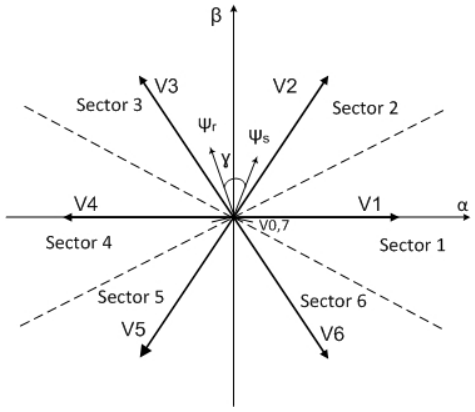


Fig. 1 Voltage vector representation on α,β plane

On Fig.1 The existing voltage vectors, which is needed to drive the inverter in DTC algorithm, can be seen in α, β plane. In this study the main focus is to define motor operating point on torque-flux plane, which gives the designer a different perspective so that the designer can develop/consider different design options for a control concept. In the following sections, the classical Switching Table Based DTC (ST-DTC) algorithm and our proposed method which is basically a new interpretation of the switching table, the simulation study and the comparison of the simulation results will be discussed respectively.

II. BASIC ST-DTC SCHEME

DTC is a feedback control method where the voltage vector and phase currents applied to the induction motor are required as feedback. Stator flux linkage and motor torque are calculated so that they are used as the input for the control algorithm for the next time interval.

Voltage vector selection as the stator flux linkage is determined by the equation (1). In DTC algorithm, defining inverter control signals is basically the main core in order to keep the motor torque and the flux linkage around the control reference points given by the user.

$$\frac{d}{dt}\overline{\psi_s} = \overline{V_s} - r_s\overline{I_s} \quad (1)$$

Rotor flux vectors and stator flux vectors are interrelated therefore a change in stator flux is followed with a delay by the rotor flux therefore stator or rotor flux magnitudes are crucial to control motor torque. Thus, torque at the induction motor output is determined as a function of both flux magnitudes in equation (2).

$$T_e = \frac{3}{2}P\frac{L_m}{\sigma L_s L_r}\psi_s\psi_r \sin\gamma \quad (2)$$

In equation (2) the terms are expressed as:
Te: the induction motor output torque,
ψS: stator flux magnitude, ψr: rotor flux magnitude,
γ: torque angle between stator and rotor flux,
P: Number of poles, Ls: Stator inductance,
Lr: Rotor inductance, Lm: Mutual inductance,
σ: leakage factor.

Conventional ST-DTC scheme is depicted in Fig.2. In this method, the difference between reference and calculated flux linkage are processed by a two level hysteresis comparator. Similarly, the difference between reference torque and the calculated torque values are processed by a three level comparator. The outcomes of these are inputs for voltage vector selection function. In conventional ST-DTC method, voltage vector selection is determined by table I on which present stator flux linkage sector (Fig.1), digitized torque and stator flux linkage error are the inputs. As the vector selection table I denotes, when torque values reach to hysteresis comparator set values, in order to keep torque and flux around the reference points and to prevent violation of limits, voltage vectors are changed between V0 and V7. Thus, all possible voltage vectors regarding DTC algorithm can be seen on Fig. 1.

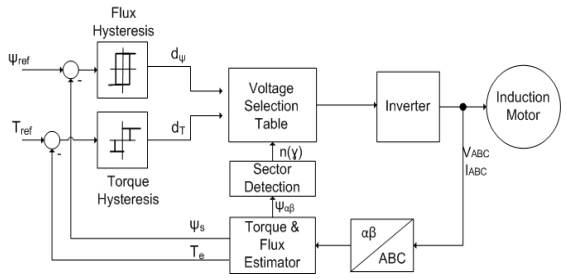


Fig. 2 Conventional ST-DTC scheme.

TABLE I. DTC VOLTAGE VECTOR SELECTION TABLE [12]

dDψ	dTe	S1	S2	S3	S4	S5	S6
1	1	V2	V3	V4	V5	V6	V1
	0	V7	V0	V7	V0	V7	V0
	-1	V6	V1	V2	V3	V4	V5
-1	1	V3	V4	V5	V6	V1	V2
	0	V0	V7	V0	V7	V0	V7
	-1	V5	V6	V1	V2	V3	V4

To understand the conventional ST-DTC algorithm Table I can be approached in detail. S1-S6 determines the sector number of the stator flux linkage. Likely, V0-7 determines the voltage vector numbers which are needed to bring the motor outputs around the reference points. V0 and V7 are zero voltage vectors. dψ and dTe defines the digitized flux and the torque errors on controller side. '+1' illustrates the variable need to be increased, '-1' illustrates the variable which processed by the controller need to be decreased and '0' is to define the control parameters are already around the reference points.

III. NOVEL ST-DTC SCHEME

Proposed method does not use hysteresis controller as depicted in Fig.3. Instead, stator flux linkage and torque output is traced and compared with the reference magnitudes continuously instead of using hysteresis controller.

Motor stator flux linkage and torque outputs are defined as an operating point in torque-flux plane. Voltage vector selection is done in order to move the operating point of motor inside a hypothetical region in torque-flux plane. In this study, It is aimed to keep the motor operating point in rectangular shaped region, that size of the rectangular is defined as allowed torque and stator flux linkage error as in Fig.4.

In that manner, torque-flux plane is divided into nine zones. Selected voltage vector forces the motor operating point to a different direction as in Fig.4. For instance, if motor torque and flux linkage values are both below the defined error limit, this express that motor is operating in zone 7. Similarly, if both values are in limits, motor is operating in zone 5. When the motor is in zone 7, and if the stator flux linkage sector number is `k`, then `k+1`th voltage vector needs to be applied so that motor operating point can be forced towards zone 5.

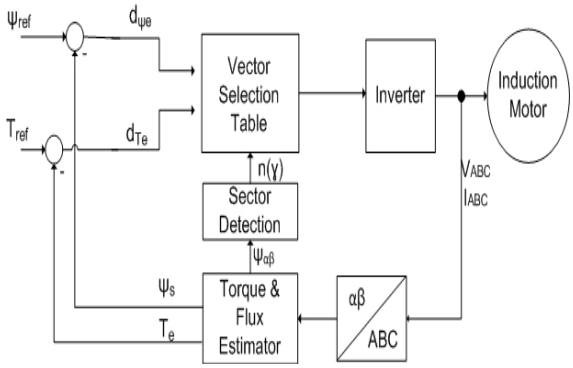


Fig. 3 Proposed ST-DTC scheme.

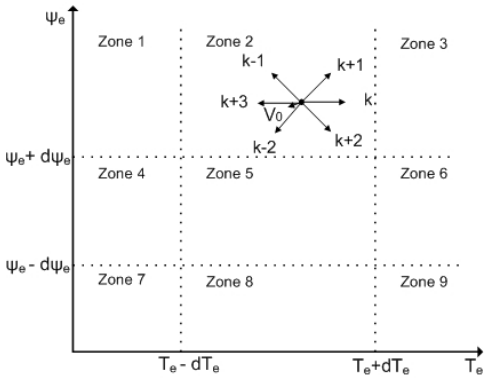


Fig. 4 Effect of voltage vectors to operating point in torque flux plane.

IV. PROPOSED VECTOR SELECTION TABLE

The basis of this study is to reduce current harmonic distortion without any lack of control for an induction motor output parameters such as torque and flux linkage errors. For this purpose, an implementation of a new vector selection table based DTC algorithm is designed based on torque flux plane to define the selection of the voltage vectors which will be applied to.

After the torque and flux hysteresis band are determined as shown in Fig.4, one has to decide the related action for the nine zones in the torque-flux plane. After trails of different choices, the vector selection table in Table II is determined so as to keep the phase current harmonics lower

TABLE II. DTC VOLTAGE VECTOR SELECTION TABLE

Zone	1	2	3	4	5	6	7	8	9
Vector	k+2	0/7	0/7	k+1	NC	0/7	k+1	k+1	k-1

Table II can explained in detail as, if the motor is operating in zone 1 and the stator flux linkage is in sector 'k' apply 'k+2th' voltage vector till motor operating point moves to a different zone. When the motor comes to zone 5, do not change the voltage vector as NC states 'No Change'. For zones 2/3 and 6 apply zero voltage, V0 or V7 in a manner to keep the switching frequency lower.

In the simulation while using the texture in Fig.4, one problem with the method was high frequency swinging of motor operating point between zone 4 and 2, and between zone 8 and 6, Thus result inevitable high frequency switching while still keeping the torque and flux linkage in the limit. To overcome this issue, texture is adjusted to avoid swinging while keeping the motor in zone 5. The texture after adjustment is as shown in Fig.5.

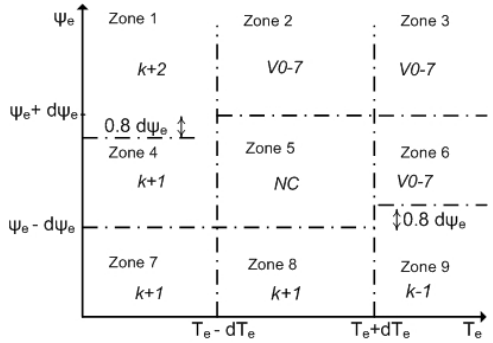


Fig. 5 Modified motor operating zones in torque flux plane.

This adjustment is an example to show how the design can be visualized in an easy way.

V. SIMULATION STUDY

To show the effectiveness of the proposed method, a test scheme is constructed using a predetermined induction motor model in the Simulink environment using the motor parameters below.

4KW, 50 Hz, 1430 Rpm, Squirrel Cage IM
Stator Resistance : 1.405 Ohm
Stator Inductance : 0.005839 H
Rotor Resistance : 1.395 Ohm
Rotor Inductance : 0.005839 H
Mutual Inductance : 0.1722 H
Pole Pair : 2

To compare the both method, control parameters and input voltage are assigned same. Simulation parameters are:
DC link Voltage : 400 Volt
Torque error limit : ±0.5Nm
Flux error limit : ±0.01 Wb
Torque reference : 10 Nm
Flux linkage reference : 0.5 Wb.

Thence, a model is formed for induction motor drive system with the principle of conventional ST-DTC scheme by Matlab/Simulink. In continuation the conventional ST-DTC algorithm is compared to the proposed algorithm with new voltage vector selection table. The simulation results depicts lower phase current harmonics, lower total harmonic distortion (THD), better flux trajectory follow as compared to the conventional ST-DTC scheme.

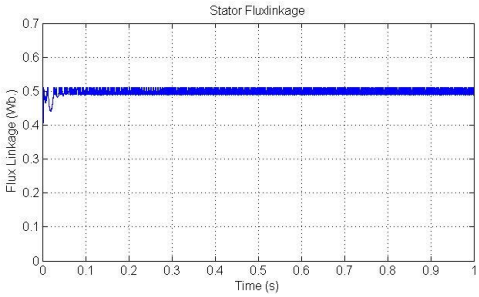


Fig. 6 Conventional ST-DTC Stator flux linkage variation in time.

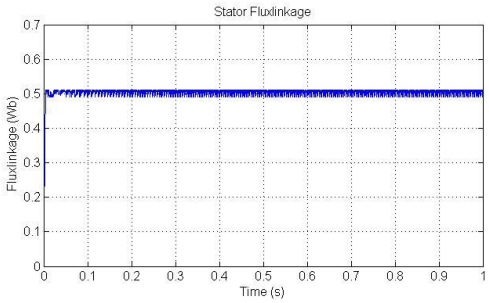


Fig. 7 Proposed ST-DTC Stator flux linkage variation in time.

When the two method is compared by means of flux linkage, both method achieves to keep the flux linkage in the set band at steady state. However at start up, thefluxlinkage of the conventional ST-DTC needed more duration to settle in the band than proposed method. That is because conventinal DTC aims to keep the torque in the band as a priority while the proposed method does not assign a priority between torque and flux linkage as a result of determined texture on the torque flux plane.

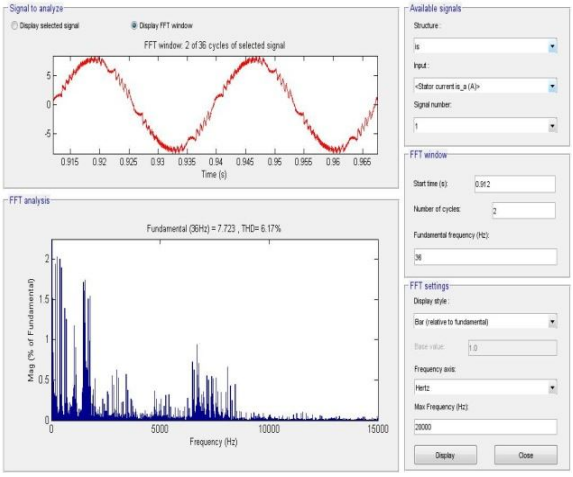


Fig. 8 Conventional ST-DTC phase current and phase current THD.

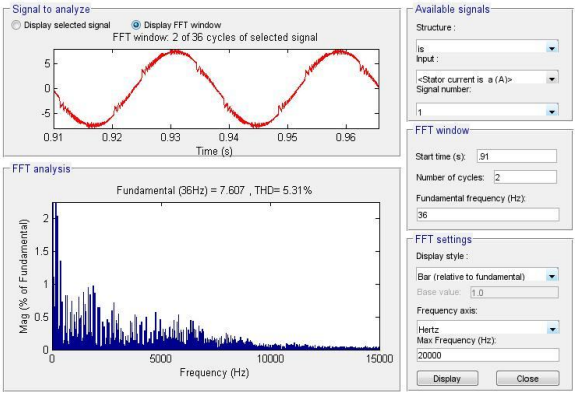


Fig. 9 Proposed ST-DTC phase current and phase current THD.

The fluxlinkage of the motor is controlled with lower distortion than conventional ST-DTC thus leading a better total harmonic distortion in phase current. THD value for the conventional method is %6.17 while it is %5.31 for the proposed method.

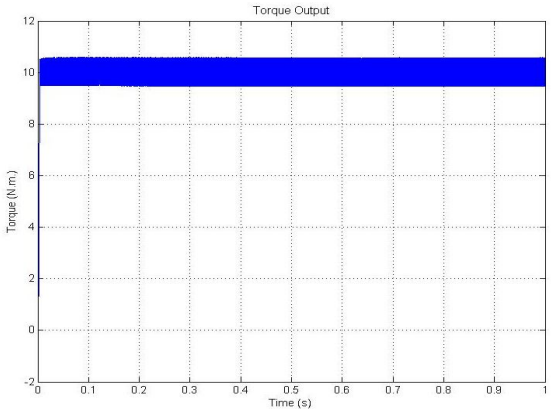


Fig. 10 Conventional ST-DTC torque variation in time

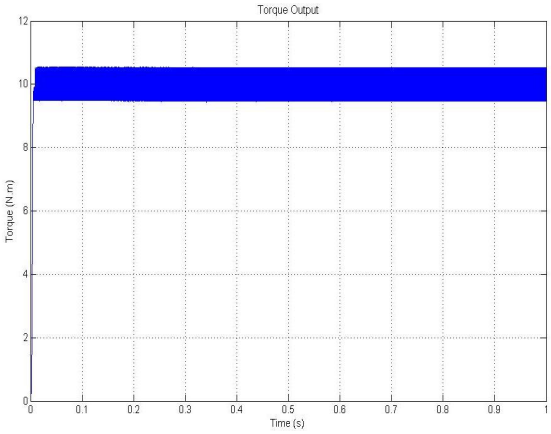


Fig. 11 Proposed ST-DTC torque variation in time.

The torque response of the both method are similar. The proposed method achieved a better flux linkage results whilepreserving torque response characteristic of the motor.

CONCLUSION

In this study Switching table based DTC application of Induction motor in torque flux plane is explained. Proposed torque flux plane achieved a visual platform to construct a switching table defined by the operation point of induction motor. Motor flux-linkage and torque output is traced continuously, instead of using flux and torque controller in a hysteresis band manner. An improvement in the phase current total harmonic distortion is achieved without any degradation in the torque and flux band. The proposed method can be applied to the current motor drives by software upgrade. The study is carried on rectangular shaped band, thus different geometrical shapes can be investigated for better THD values and switching frequency as future work.

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