TORQUE-FLUX PLANE BASED SWITCHING TABLE IN DIRECT TORQUE CONTROL

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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 drawbacks of the method. There are many industrial applications already using DTC. In this study, a 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 results.

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

INTRODUCTION

Today Field Oriented Control (FOC) and Direct Torque Control (DTC) are the preferred vector control method to drive Induction motor (IM) among industrial applications (Farid, Sebti, Mebarka, & Tayeb 2007; Mumcu, Aliskan, Gülez, & Tuna, 2013). 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 free from rotor parameters. The basic DTC algorithm aims to control both torque and stator flux linkage of motor by selecting appropriate voltage vector and use 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. (Takahashi, & Noguchi, 1986, Depenbrock, M. 1988). 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. Kenny & Lorenz (2003) used deadbeat control, Ahammad, Beig & Al-Hosani (2013) preferred sliding mode control, Kumar, Gupta, Bhangale and Gothwal (2007) studied neural network based DTC. Hafeez, Uddin, Rahim & Hew (2013) used self-tuned neuro-fuzzy control. 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 (Casadei, Serra, Tani, & Zarri, 2013; Ludtke, & Jayne, 1995; Gulez, Adam, & Pastaci, 2007). Switching table based DTC (ST-DTC) is not complicated to apply which leads less application time delay on motor drive systems.

Regarding the phase of developing new algorithms for DTC, induction motor voltage vectors, which are in three phase system, is transformed to α, β plane as in Fig. 1, so as to illustrate the voltage vector selection in a two dimensional plane. In this plane, the stator flux linkage is defined as a vector and the variation of it is defined as the flux ripple. And, the 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.

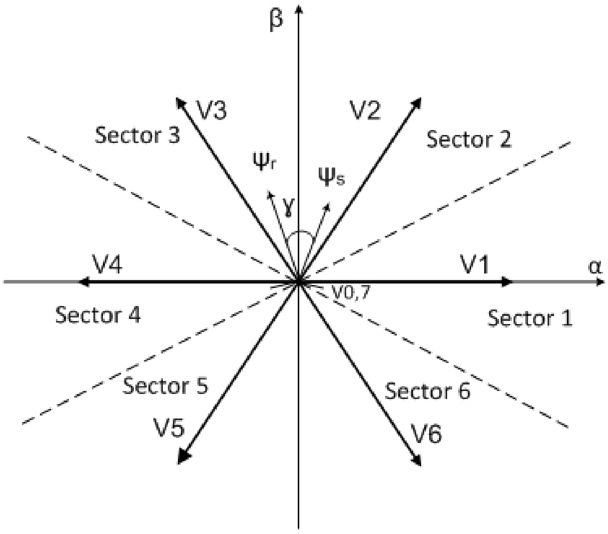


Fig. 1 Voltage vector representation on α-β plane (Buja, & Kazmierkowski. 2004).

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

BASIC ST-DTC SCHEME

DTC is a feedback control method where the voltage vectors and phase currents applied to the induction motor are required as feedback signals. Stator flux linkage and motor torque are calculated so that they can be applied in the next time interval to the motor in algorithm.

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.

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

Rotor and stator flux vectors are interrelated in induction motor, that a change in stator flux is followed with a delay by the rotor flux, both 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).

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

In equation (2) the terms are expressed as:

T_e: the induction motor output torque,
ψ_S: stator flux magnitude, ψ_r: rotor flux magnitude,
γ: torque angle between stator and rotor flux,
P: Number of poles, L_s: Stator inductance,
L_r: Rotor inductance, L_m: 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.

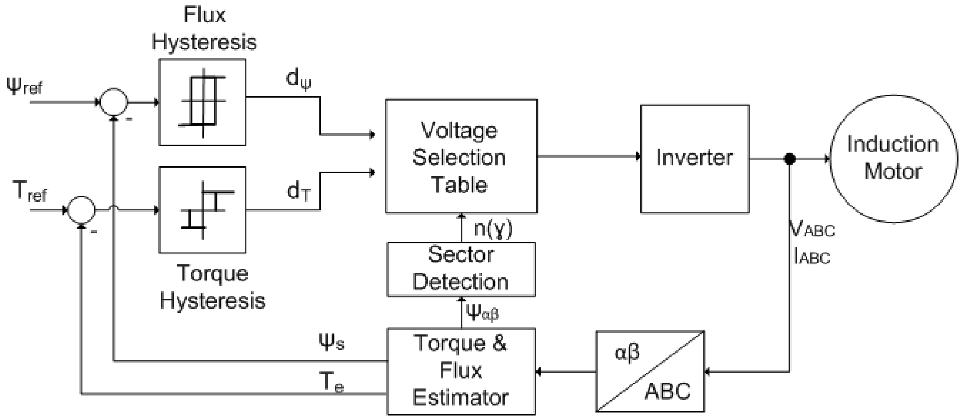


Fig. 2 Conventional ST-DTC scheme.

TABLE 1. DTC VOLTAGE VECTOR SELECTION TABLE [12]

dD_ψ	dT_e	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 explained 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 point. V0 and V7 are zero voltage vectors. d_ψ and dT_e defines the digitized flux and the torque errors on controller side. '+1' illustrates that torque or flux parameter need to be increased, '-1' illustrates the parameters which are processed by the controller need to be decreased and '0' is to define the control parameters are already around the reference point.

NOVEL ST-DTC SCHEME

The 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.

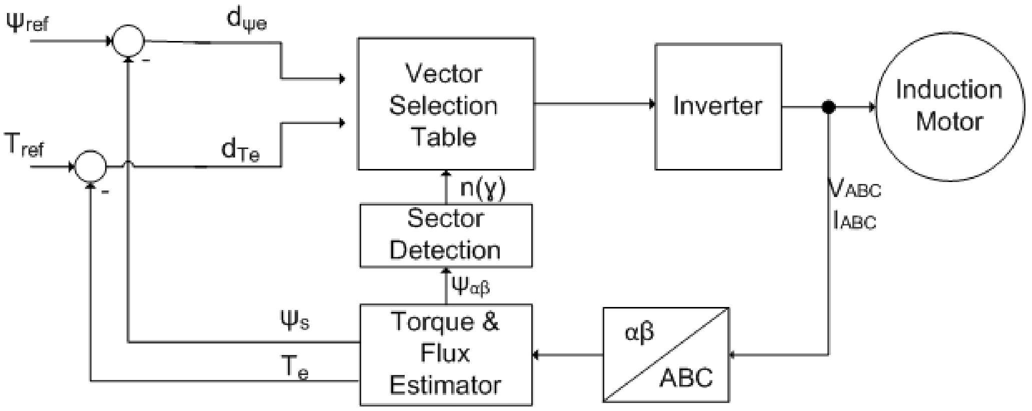


Fig. 3 Proposed ST-DTC scheme.

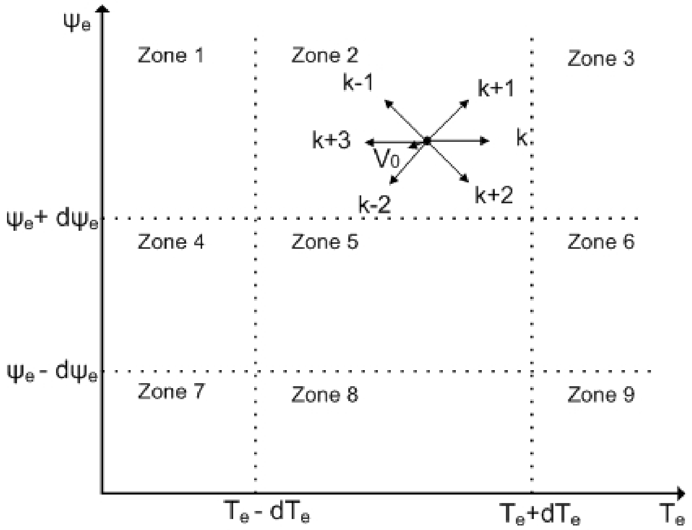


Fig. 4 Effect of voltage vectors to operating point in torque flux plane.

THE 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 among different choices, the vector selection table in Table II is determined so as to decrease the phase current harmonics.

TABLE 2. 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 be 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 is high frequency swinging of motor operating point between zone 4 and 2, and between zone 8 and 6, Thus, the result is inevitable with 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. Zone 1 is expanded as 0.8 times flux band by experience. Mathematical expressions for torque flux plane are a future work.

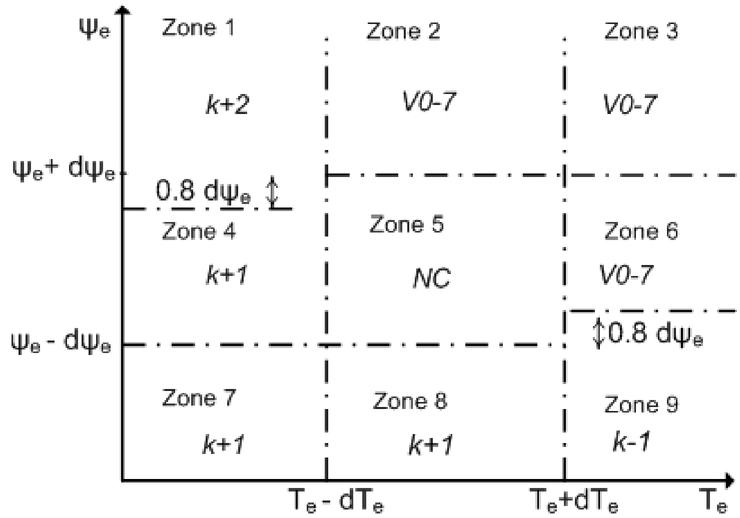


Fig. 5 Modified motor operating zones in torque flux plane.

This adjustment is an example to show how the design can be visualized clearly.

SIMULATION RESULTS

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.

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

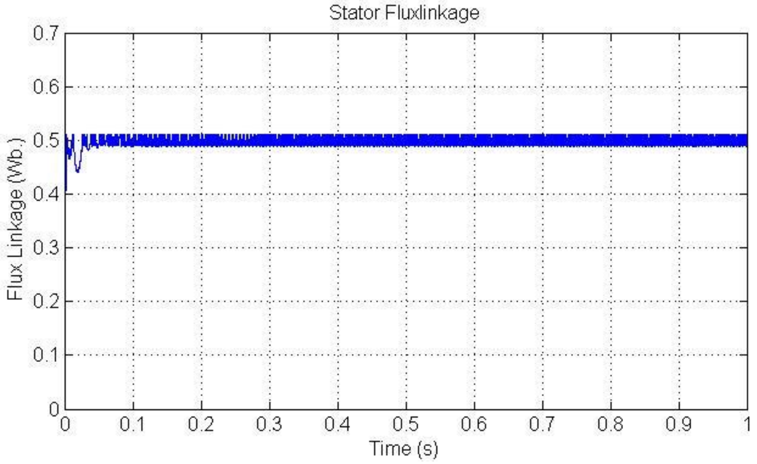


Fig. 6 Conventional ST-DTC Stator flux linkage variation in time.

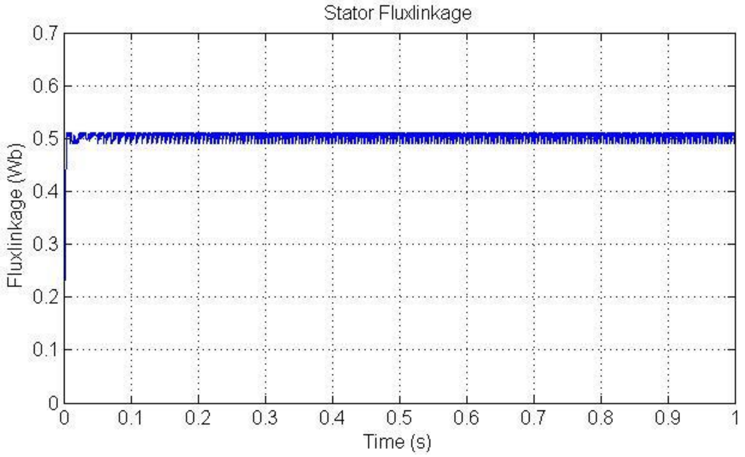
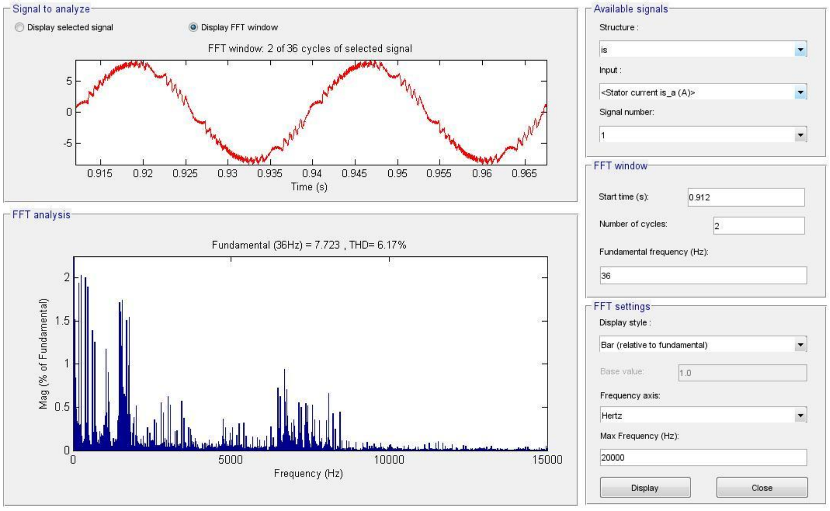


Fig. 7 Proposed ST-DTC Stator flux linkage variation in time.

When the two method is compared by means of flux linkage, both method achieves to keep the flux linkage in the set band at the steady state. However at the start up, the fluxlinkage of the conventional ST-DTC needed more duration to settle in the band than proposed method as shown in Fig. 6 and Fig 7. 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 determined by the proposed switching table.



Signal to analyze

○ Display selected signal ● Display FFT window

FFT window: 2 of 36 cycles of selected signal

FFT analysis

Fundamental (36Hz) = 7.723 , THD= 6.17%

Available signals

Structure : is

Input : <Stator current is_a (A)>

Signal number: 1

FFT window

Start time (s): 0.912

Number of cycles: 2

Fundamental frequency (Hz): 36

FFT settings

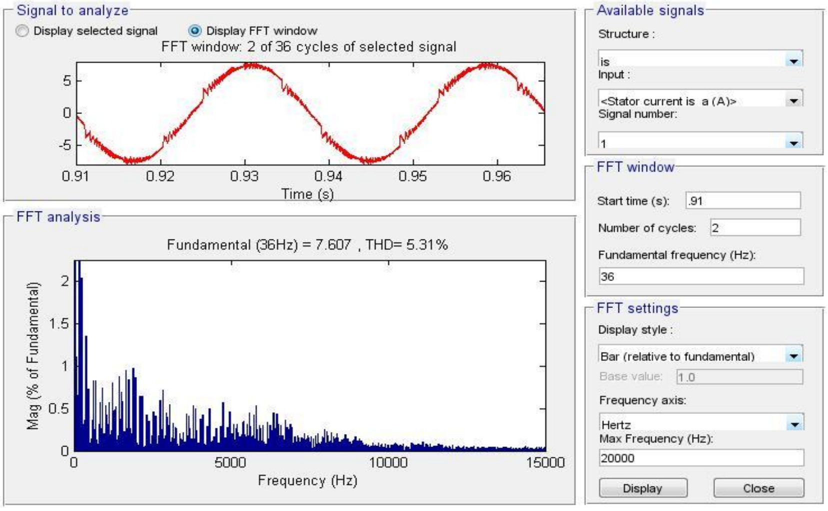
Display style : Bar (relative to fundamental)

Base value: 1.0

Frequency axis: Hertz

Max Frequency (Hz): 20000

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



Signal to analyze

○ Display selected signal ● Display FFT window

FFT window: 2 of 36 cycles of selected signal

FFT analysis

Fundamental (36Hz) = 7.607 , THD= 5.31%

Available signals

Structure : is

Input : <Stator current is_a (A)>

Signal number: 1

FFT window

Start time (s): .91

Number of cycles: 2

Fundamental frequency (Hz): 36

FFT settings

Display style : Bar (relative to fundamental)

Base value: 1.0

Frequency axis: Hertz

Max Frequency (Hz): 20000

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

The flux linkage 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 as in Fig. 8 while it is %5.31 for the proposed method as in Fig 9.

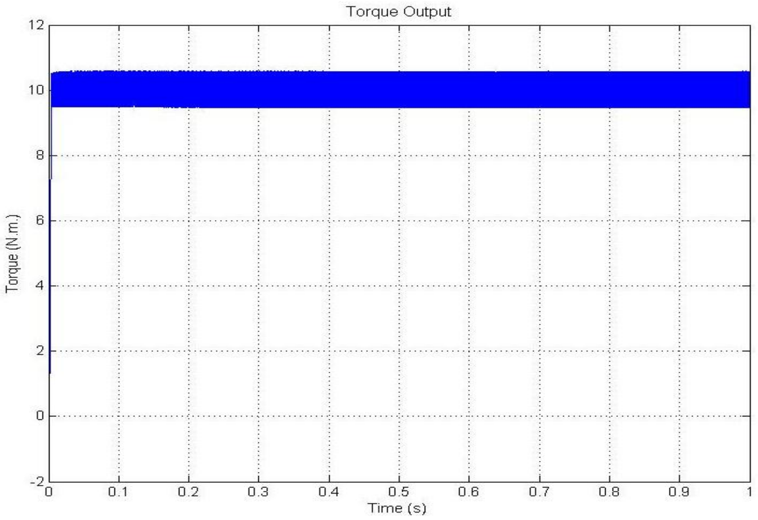


Fig. 10 Conventional ST-DTC torque variation in time

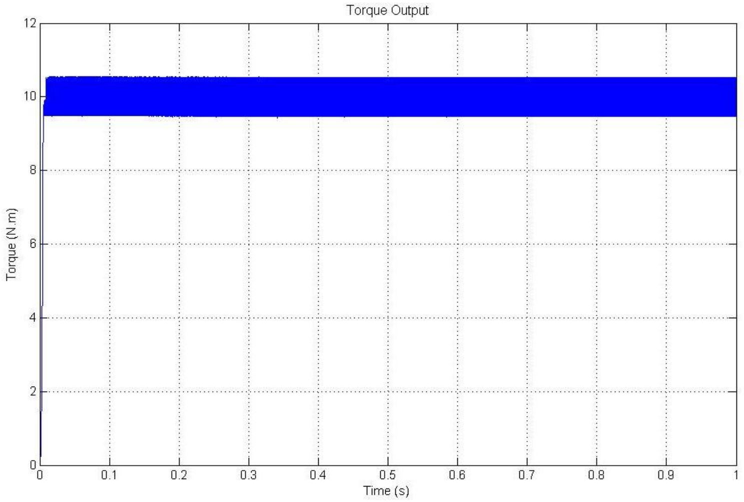


Fig. 11 Proposed ST-DTC torque variation in time.

The torque response of the both method are similar. The proposed method achieved a better flux linkage results while preserving torque response characteristic of the motor as can be depicted in Fig 10 and Fig 11 respectively.

CONCLUSION

In this study, the switching table based DTC application of Induction motor in torque-flux plane is explained. The proposed torque-flux plane achieved a visual platform to construct a switching table which is 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 torque and flux band, thus different band approaches can be investigated for improved THD values and reduced switching frequency as a future work.

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