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Torque Ripple Reduction in Direct Torque Control of Induction Motor Drives by Improvement of the Switching Table

Eng.Ahmed Hassan Adel, Dr.Amr Refky, Dr.Salama Abo-Zaid, Prof.Mahmoud Elwany
Dept. of Electrical Engineering
Al-Azhar University
Cairo, Egypt
ahmedhassanadel@yahoo.com

***Abstract*— This paper proposes design and analysis of a direct torque control (DTC) of induction motor drives using the switching table, hysteresis controllers and flux and torque estimator. This paper also proposes the improvement of the conventional DTC using the modified and twelve sector DTC. In the end of this paper there is a comparative study between the mentioned types of conventional DTC.**

Keywords—Induction Motor Drives; Direct Torque Control (DTC); Modified DTC; switching table; flux and torque estimator.

I. INTRODUCTION

In many variable speed drive applications(e.g. traction drives for electric vehicles), torque control is required or desired, but precise, closed-loop control of speed is not necessary. Torque control provides greatly improved transient response, avoidance of nuisance over-current trips, and elimination of load dependent controller parameters[1]. DTC was introduced by Takahashi (1984) in Japan and then in Germany by Depenbrock (1985)[2].

Direct Torque Control has the following main advantages: simplicity and fast electromagnetic torque response[3], less computational requirements, current controller and coordinate transformations are not required[4], a modulation technique for the inverter is not needed[3]. Common disadvantages of conventional DTC are: high torque ripple [4], It also needs flux and torque estimators and therefore, accurate machine parameters are required[5].

II. STRATEGY OF DIRECT TORQUE CONTROL

The DTC technique can be easily implemented using two hysteresis controllers (one for flux and the other for torque), torque and flux estimators and a switching table to select the proper voltage vector[6],[7]. The basic functional blocks used to implement the DTC scheme are represented in Fig.1.

A. *Hysteresis controllers*

According to the principle of operation of DTC, the selection of the proper voltage vector is made to maintain the torque and stator flux within the limits of two hysteresis bands[3]. Superior motor performance is achieved by narrower hysteresis bands especially in the high- speed region[8]. Decreasing the width of hysteresis bands can increase the switching frequency only to some level[9].

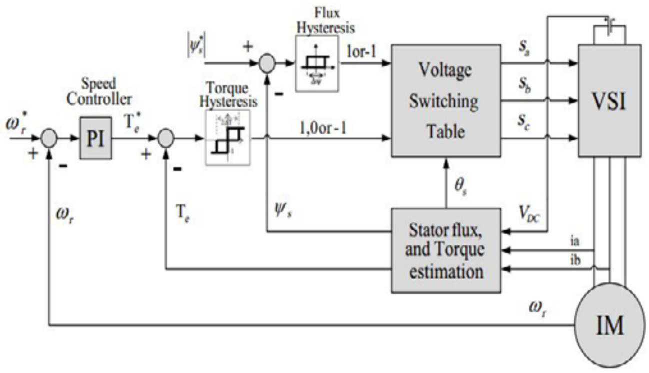

Fig. 1. Block Diagram of DTC of I.M Drive

B. *Voltage Source Inverter and Switching Table*

The torque control of the inverter fed machine is carried out by hysteresis control of magnitude of stator flux and torque that selects one of the six active and two zero inverter voltage vector $V_s(i)$ [10]. The use of a switching table for voltage vector selection provides fast torque response, low inverter switching frequency and low harmonic losses without the complex field orientation by restricting the flux and torque errors within respective flux and torque hysteresis bands with the optimum selection being made[7].

In a voltage fed three phases, the switching commands of each inverter leg are complementary So for each leg a logic state C_i (i=a,b,c) can be defined. C_i is 1 if the upper switch is commanded to be closed and 0 if the lower one in commanded to be close (first)[3]. The following equation give the voltage vectors:

$$V_s = \sqrt{\frac{2}{3}}U_0\left[C_1 + C_2 e^{\frac{j2\pi}{3}} + C_3 e^{\frac{j4\pi}{3}}\right] \qquad (1)$$

Eight switching states can be taken according to equation (1): two zero voltage vectors and six non-zero voltage vectors show by Fig. 2[3].

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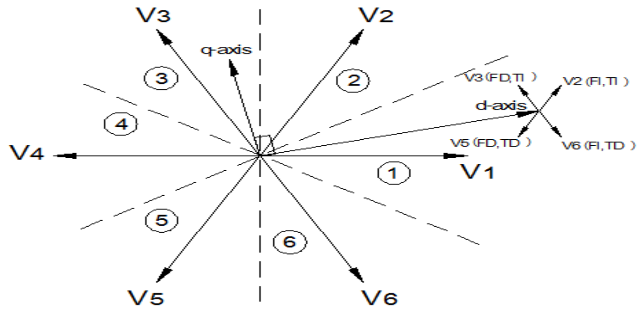

Fig. 2. Partition of the dq plane into 6 angular sectors

In Fig. 2 the stator flux is represented by the direct axis and the torque is represented by the quadrature axis ,It can be seen that selecting the proper voltage vector results in maintaining the torque and stator flux within the limits. For example in sector 1 the use of V_2 and V_3 will increase the torque ,the use of V_2 and V_6 will increase the stator flux, V_1 and V_4 aren't used.

The switching table proposed by Takahashi is given by Table I.

TABLE I. SWITCHING TABLE FOR CLASSICAL DTC

Sector		1	2	3	4	5	6
H_ψ	H_{Te}						
1	1	V_2	V_3	V_4	V_5	V_6	V_1
	0	V_0	V_7	V_0	V_7	V_0	V_7
	-1	V_6	V_1	V_2	V_3	V_4	V_5
-1	1	V_3	V_4	V_5	V_6	V_1	V_2
	0	V_0	V_7	V_0	V_7	V_0	V_7
	-1	V_5	V_6	V_1	V_2	V_3	V_4

The voltage vector table receives the flux level H_ψ , the torque level H_{Te} and the sector number and generates appropriate control for the inverter from a look-up table as in Table 1[10].

C. *Voltage Source Inverter and Switching Table*

According to [3], Stator voltage components (V_{sd},V_{sq}) are determined from measured value U_0 and Boolean switching controls (C_1,C_2,C_3) by:

$$V_{sd} = \sqrt{\frac{2}{3}} U_0 [C_1 - \frac{1}{2}(C_2 + C_3)] \quad (2)$$

$$V_{sq} = \frac{1}{\sqrt{2}} U_0 (C_2 - C_3) \quad (3)$$

And stator current components (I_{sd} , I_{sq}) are determined from :

$$I_{sd} = \sqrt{\frac{2}{3}} I_{sa} \quad (4)$$

$$I_{sq} = \frac{1}{\sqrt{2}} (I_{sb} - I_{sc}) \quad (5)$$

And stator flux (ϕ_s)is determined from:

$$\overline{\phi_s} = \int_0^t (\overline{V_s} - R_s \overline{I_s}) dt \quad (6)$$

The stator resistance R_s can be assumed constant during a large number of converter switching periods Ts . The voltage vector applied to the induction motor remains also constant over the time period Ts. Therefore, on resolving equation (6) leads to:

$$\phi_s(t) \approx \phi_{so} + V_s T_s \quad (7)$$

In equation; ϕ_{so} stands for the initial stator flux condition.

In fact, we have $\frac{d\phi_s}{dt} = V_s$

The components of the stator flux can be estimated by :

$$\overline{\phi_{sd}} = \int_0^t (\overline{V_{sd}} - R_s \overline{I_{sd}}) dt \quad (8)$$

$$\overline{\phi_{sq}} = \int_0^t (\overline{V_{sq}} - R_s \overline{I_{sq}}) dt \quad (9)$$

The stator flux linkage per phase is given by :

$$\phi_s = \sqrt{\phi_{sd}^2 + \phi_{sq}^2} \quad (10)$$

Electromagnetic torque for P, pair-pole number of the induction machine can be determined from :

$$T_{em} = p(\phi_{sd} I_{sq} - \phi_{sq} I_{sd}) \quad (11)$$

III. IMPROVEMENT OF THE SWITCHING TABLE

It can be seen that the states V_1 and V_4 , are not used in the Conventional DTC (CDTC). The reason of this; is that they can increase or decrease the torque at the same sector depending on if the position is in its first 30 degrees or in its second ones[3]. Which lead to modify the Switching Table and use the modified DTC (MDTC).

A. Modified DTC

In the modified DTC (MDTC), the vectors V_3 and V_6 are not used. However, now the reason is the ambiguity in flux instead of torque, as it was in the CDTC. This considered being an advantage in favour of the MDTC as the main point it to control the torque. Therefore, it is better to lose the usage of two for flux ambiguity that for torque one [3]. The modified DTC and its new six sectors is given in Fig.3.

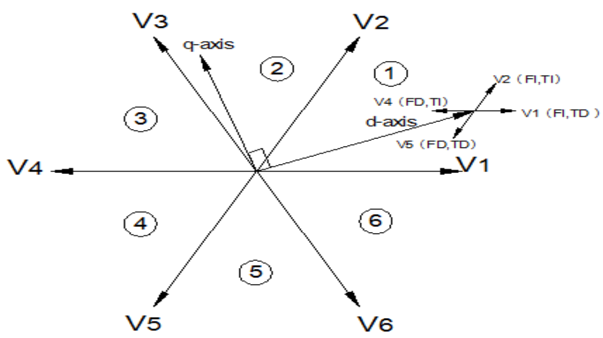

Fig. 3. Partition of the dq plane into 6 angular sectors (Modified)

The modified switching table is given by Table II.

TABLE II. SWITCHING TABLE FOR MODIFIED DTC

Sector		1	2	3	4	5	6
H_{Te}	H_{ψ}						
1	1	V2	V3	V4	V5	V6	V1
	0	V0	V7	V0	V7	V0	V7
	-1	V1	V2	V3	V4	V5	V6
-1	1	V4	V5	V6	V1	V2	V3
	0	V0	V7	V0	V7	V0	V7
	-1	V5	V6	V1	V2	V3	V4

B. *DTC Twelve Sector Table*

In Conventional DTC there are two states per sector that present a torque ambiguity. Therefore they are never used. In a similar way, in the modified DTC there are two states per sector that introduce flux ambiguity, so they are never used either. It seems a good idea that if the stator flux locus is divided into twelve sectors as shown in Fig. 4 instead of just six, all six active states will be used per sector Consequently, it is arisen the idea of the twelve sector modified DTC [3].

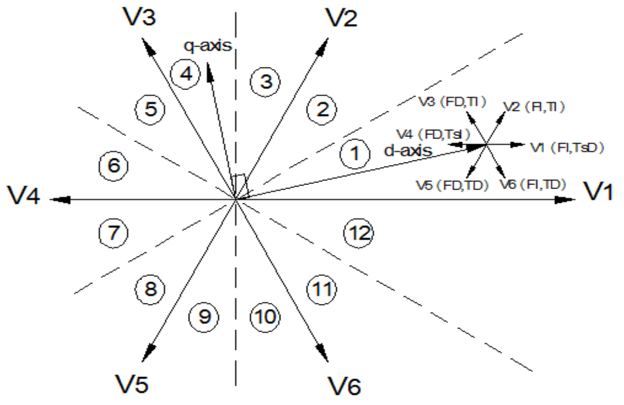

Fig. 4. Twelve sector modified DTC and its sectors. FD/FI: flux decrease/increase. TD/TI: torque decrease/increase. TsD/TsI: torque small decrease/increase. Notice how all six voltage vectors can be used in all twelve sectors, disappearing all ambiguities.

The twelve sector switching table is given by Table III.

C. *Modified Classical DTC*

Table 1 can be simply modified by applying zero voltage vectors (V_0 , V_7) for the torque decrease states (-1) ,and this modification will result in decreasing the torque ripple largely , a considerable reason for this decrease is that applying the zero voltage vectors result in reducing the inertia of the motor at this instant and this result in reducing the torque with a percent which is more suitable than the percent given by applying the vectors in table I for the torque decrease states. Table IV. illustrates this modification.

TABLE III. SWITCHING TABLE FOR THE TWELVE SECTOR DTC (* THERE IS NO SUITABLE STATE IT HAS BEEN CHOSEN THE SECOND MOST SUITABLE)

Φ	FI				FD			
τ	TI	TsI	TsD	TD	TI	TsI	TsD	TD
S1	V2	V2*	V1	V6	V3	V4	V7	V5
S2	V3	V2	V1*	V1	V4	V4*	V5	V6
S3	V3	V3*	V2	V1	V4	V5	V0	V6
S4	V4	V3	V2*	V2	V5	V5*	V6	V1
S5	V4	V4*	V3	V2	V5	V6	V7	V1
S6	V5	V4	V3*	V3	V6	V6*	V1	V2
S7	V5	V5*	V4	V3	V6	V1	V0	V2
S8	V6	V5	V4*	V4	V1	V1*	V2	V3
S9	V6	V6*	V5	V4	V1	V2	V7	V3
S10	V1	V6	V5*	V5	V2	V2*	V3	V4
S11	V1	V1*	V6	V5	V2	V3	V0	V4
S12	V2	V1	V6*	V6	V3	V3*	V4	V5

TABLE IV. SWITCHING TABLE FOR MODIFIED CLASSICAL DTC

Sector		1	2	3	4	5	6
H_{Te}	H_{ψ}						
1	1	V2	V3	V4	V5	V6	V1
	0	V0	V7	V0	V7	V0	V7
	-1	V0	V7	V0	V7	V0	V7
-1	1	V3	V4	V5	V6	V1	V2
	0	V0	V7	V0	V7	V0	V7
	-1	V0	V7	V0	V7	V0	V7

D. *Modified Twelve Sector DTC*

A simple modification on table 3 by cancelling the small increase and small decrease states (TsI,TsD) and applying zero voltage vectors (V_0 , V_7) for the torque decrease states (TD) will result in reducing the torque ripple in the Twelve Sector DTC for the reason mentioned in part (C) .Table V. illustrates this modification.

TABLE V. SWITCHING TABLE FOR MODIFIED TWELVE SECTOR DTC

Φ	FI			FD		
τ	TI	T=	TD	TI	T=	TD
S1	V2	V0	V0	V3	V0	V0
S2	V3	V7	V7	V4	V7	V7
S3	V3	V0	V0	V4	V0	V0
S4	V4	V7	V7	V5	V7	V7
S5	V4	V0	V0	V5	V0	V0
S6	V5	V7	V7	V6	V7	V7
S7	V5	V0	V0	V6	V0	V0
S8	V6	V7	V7	V1	V7	V7
S9	V6	V0	V0	V1	V0	V0
S10	V1	V7	V7	V2	V7	V7
S11	V1	V0	V0	V2	V0	V0
S12	V2	V7	V7	V3	V7	V7

IV. Simulation of Direct torque control

A. *Model and Parameters*

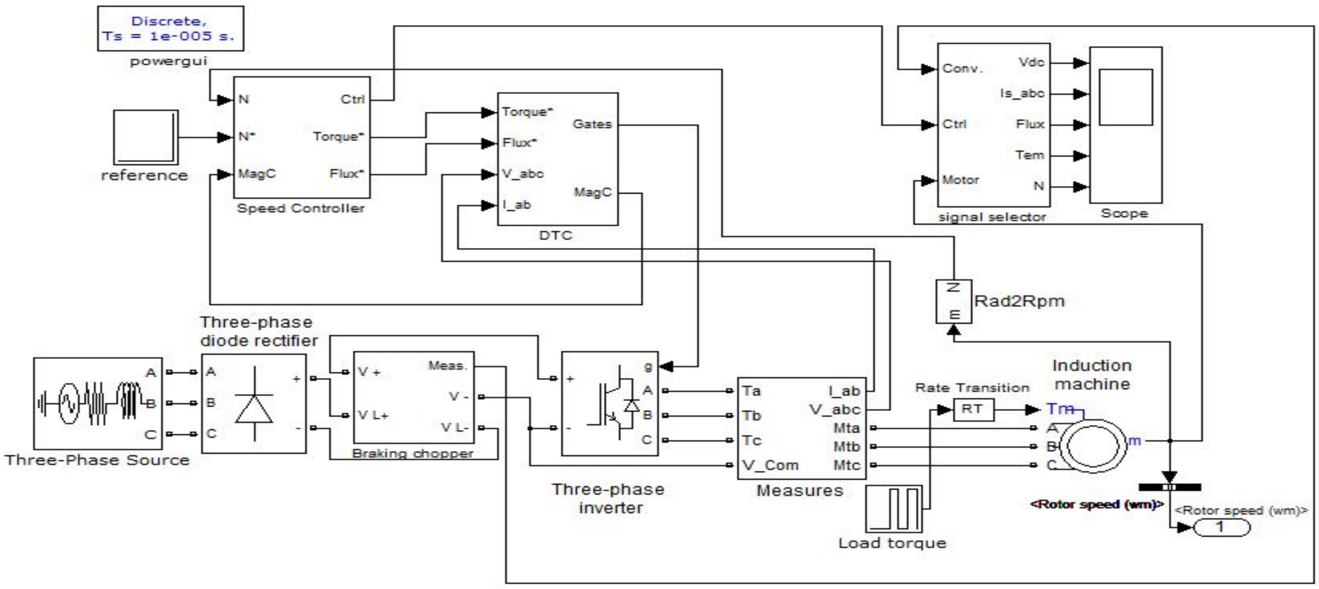

Fig. 5. Simulink model of DTC

TABLE VI. PARAMETERS FOR INDUCTION MOTOR

Rated voltage	Rated power	Rated frequency	Pole pairs	Stator resistance	Stator inductance	Rotor resistance	Rotor inductance	Mutual inductance
220	2238	60	2	0.435	2	0.816	2	69.3
V	VA	Hz	—	Ω	mH	Ω	mH	mH

TABLE VII. PARAMETERS FOR DIRECT TORQUE CONTROL

Sampling time	Hysteresis torque band width	Hysteresis flux band width	Max. switching frequency	Intial flux
20	0.5	0.01	20	0.3
µs	N.m	wb	KHz	wb

TABLE VIII. PARAMETERS FOR SPEED CONTROLLER

Upper limit torque	Lower limit torque	Sampling time	Cut off frequency	Ki	Kp	Ramp 2 speed	Ramp 1 speed
17.8	-17.8	7*20	100	10	5	1800	-1800
N.m	N.m	µs	Hz	–	–	r.p.m	r.p.m

Tables VI. ,VII. and VIII. show the parameters of the induction motor drive. The following simulation results is drawn in per unit values for a base values of 12.5 N.m for the torque and 1705 r.p.m for the speed.

B. Results

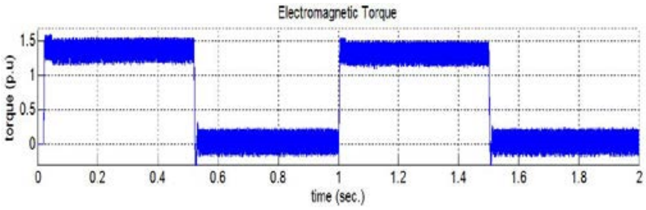

Fig. 6. electromagnetic torque in per unit for the classical DTC

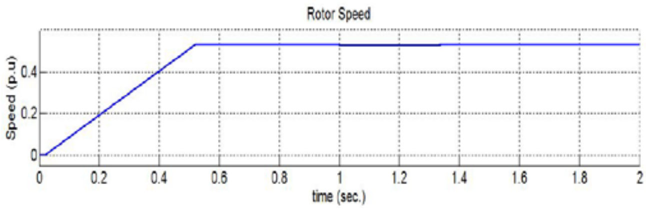

Fig. 7. rotor speed in per unit for the classical DTC

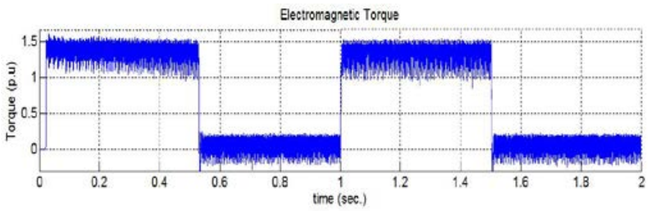

Fig. 8. electromagnetic torque in per unit for the modified DTC

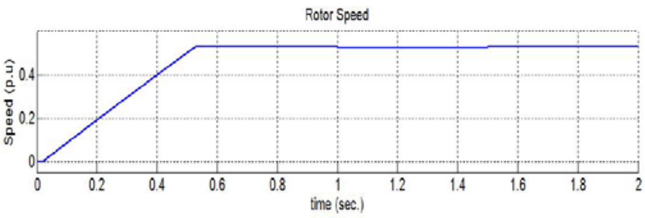

Fig. 9. rotor speed in per unit for the modified DTC

As shown in figures, at time t = 0.02 s the speed set point is 900 rpm, the torque attains its maximum value (17.8 N.m). At t = 0.52 s, the motor speed attains its steady state value and the torque value reaches zero. At t=1s a load torque of 16 N.m is applied, then removed at t =1.5 s. It is clear that the torque ripple of both CDTC and MDTC are unacceptable (0.38 p.u).

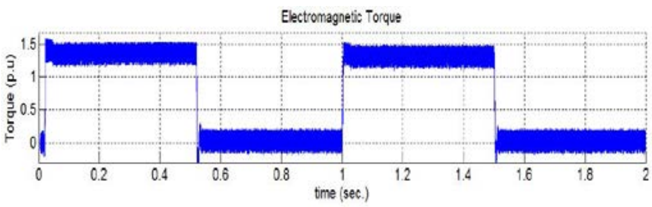

Fig. 10. electromagnetic torque in per unit for the 12-sec. DTC

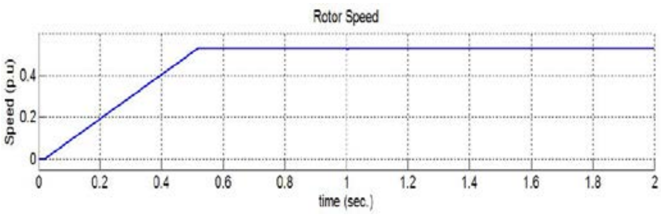

Fig. 11. rotor speed in per unit for the 12-sec. DTC

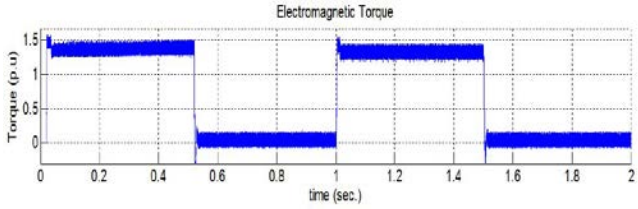

Fig. 12. electromagnetic torque in per unit for the modified CDTC

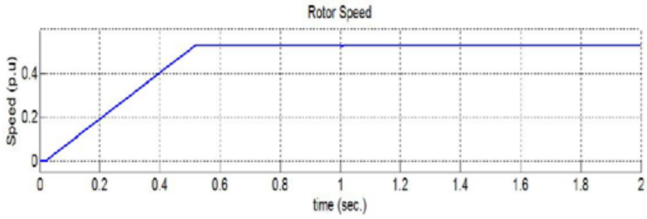

Fig. 13. rotor speed in per unit for the modified classical DTC

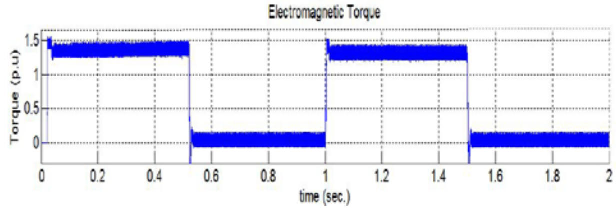

Fig. 14. electromagnetic torque in per unit for the modified 12-sec. DTC

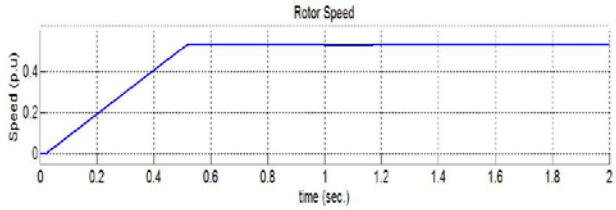

Fig. 15. rotor speed in per unit for the modified 12-sec. DTC

As shown in Fig. 10. The ripple of torque for the twelve sector is reduced compared with CDTC and MDTC and the value of it about 0.32 p.u. Fig. 12 and Fig. 14 show the simulation results for both Modified classical and Modified twelve sector DTC and show that the torque ripple is reduced remarkably and the ripple value is around 0.2 p.u .

V. CONCLUSION

This paper proposes improvement of DTC using modification of the switching table. It can seen from the simulation results above for the simulation model given and the parameters mentioned above that both Classical and Modified DTC have the same torque ripple but the Modified DTC overcomes the ambiguity in Torque ,but it is obvious that the torque ripple is reduced in the Twelve sector DTC and there is no ambiguity in both Torque and flux , More reduction in ripple using Modified classical and Modified twelve sector DTC as mentioned in part III and as shown in Fig. 12. and Fig. 14, so an improved performance is achieved. The simulation results show that the torque has very good dynamic response for the mentioned DTC methods, the following table show comparison between ripple values (in per unit) for the different mentioned DTC methods.

TABLE IX. COMPARISON BETWEEN RIPPLE VALUES

DTC	Classical & Modified	12-sector	Modified Classical	Modified 12-sec.
Ripple	0.38	0.32	0.22	0.22

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