Torque ripple reduction in direct torque controlled five-phase induction motor using modified five-level torque comparator

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Abstract. The five-phase induction motor inherently has the minimal torque ripple. However, when it is controlled by direct torque control (DTC) technique, the torque ripple increases due to the presence of a hysteresis torque comparator. The classical five-level torque comparator is presented in the previous literatures to control the torque ripple. However, this comparator has the drawback of wrong selection of zero voltage vectors inside the inner band on the positive side of the comparator, which enables the torque ripple to increase and dc-link utilization to decrease. In this paper, in order to reduce the torque ripple and to increase the dc-link utilization, a modified five-level torque comparator is proposed, which selects either medium or small voltage vectors instead of zero voltage vectors inside the inner band on the positive side of the comparator. In addition to torque ripple reduction and improvement in dc-link utilization, the proposed comparator significantly improves the quality of phase current. All the available 32 voltage vectors are selected through the proposed five-level torque comparator based on the location of x - y stator flux in order to eliminate the x - y stator flux so as to obtain reduced distortion in the phase current. By employing all the available voltage vectors, the freedom of utilization of all voltage vectors in the five-phase induction motor DTC drive is availed. The proposed five-level torque comparator is compared to its classical five-level counterpart through simulation and experimental results in order to validate the proposed DTC strategy.

Keywords. Direct torque control; five-phase induction motor; torque ripple; dc-link utilization; x - y stator current.

1. Introduction

The five-phase induction motor (IM) is introduced with its inherent advantages of reduced torque ripple, fault tolerance, reduction of current per phase, etc. [1–3]. Owing to these advantages, direct torque control (DTC) based on the classical hysteresis controller for three-phase IM [4] is extended for five-phase IM [5]. However, this DTC of five-phase IM based on the classical hysteresis controller [5] has the drawback of torque ripple, like in case of three-phase DTC scheme, because of the involvement of hysteresis torque controller. Some modifications are presented in the classical structure of the DTC scheme to reduce the torque ripple in case of three-phase IM [6–9]. In case of five-phase IM, some developments are presented in the classical DTC scheme to improve its performance in the context of torque ripple reduction, x - y stator flux elimination, improvement in dc-link utilization, improvement in speed response and reduction in demagnetization of stator flux during low-speed operation [10–12]. In [10], a sensorless DTC-controlled five-phase

IM drive is proposed, wherein the voltage vectors are selected so that the x - y stator flux is eliminated with full utilization of dc-bus voltage. In [11], the predictive torque control technique is introduced as an alternative to classical DTC, wherein the torque ripple minimization, x - y component elimination and improvement in speed response are achieved. In [12], the performance of the five-phase IM in low-speed region is significantly improved using the DTC technique.

The classical three-level torque comparator is implemented in [10, 11] and the classical five-level torque comparator is implemented in [12] for designing the DTC method for five-phase IM. Since the classical five-level torque comparator has more bands compared with the classical three-level torque comparator, it reduces the torque ripple. However, the classical five-level torque comparator selects the zero voltage vectors inside the inner band on positive side, which enables the torque ripple to be increased and dc-link utilization to be reduced. By carefully selecting the voltage vectors inside the inner band on positive side of the five-level torque comparator, the reduction in torque ripple and improvement in dc-link utilization can be achieved.

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In this paper, the voltage vector selection through the classical five-level torque comparator is modified such that the zero voltage vectors inside the inner band on the positive side of the comparator are replaced either by medium or by small voltage vectors in order to reduce the torque ripple. The selection of voltage vectors through the proposed five-level torque comparator improves the dc-link utilization. In the proposed DTC technique the obtained stator current waveform is significantly improved compared with current waveform in the DTC technique with the classical torque comparator. This is the bonus advantage of using the proposed five-level torque comparator in the DTC scheme. The virtual voltage vectors of [12] are implemented in the proposed DTC scheme to eliminate the x - y stator flux. In order to check the capability of proposed five-level torque comparator in reducing the torque ripple and improving the dc-link utilization, a comparative investigation with its classical counterpart [12] is carried out. Simulation and experimental results are presented to validate the proposed modified DTC strategy.

This paper is organized as follows. Section 2 discusses the modelling of five-phase IM. Section 3 focuses on the formation of virtual voltage vectors. Section 4 gives the design of proposed modified five-level torque comparator. Simulation and experimental results are provided in sections 5 and 6, respectively. Section 7 deals with the conclusions from the presented work.

2. Modelling of five-phase IM

The d - q stator flux (λ_{dq}^s), d - q rotor flux (λ_{dq}^r), x - y stator flux (λ_{xy}^s) and x - y rotor flux (λ_{xy}^r) of the motor considering stationary reference frame can be written as [13]

$$\lambda_{dq}^s = \int (V_{dq}^s - i_{dq}^s r_s) dt \quad (1)$$

$$\lambda_{dq}^r = \int (V_{dq}^r - i_{dq}^r r_r) dt \quad (2)$$

$$\lambda_{xy}^s = \int (V_{xy}^s - i_{xy}^s r_s) dt \quad (3)$$

$$\lambda_{xy}^r = \int (V_{xy}^r - i_{xy}^r r_r) dt \quad (4)$$

$$\lambda_{dq}^s = (L_{ls} + L_m) i_{dq}^s + L_m i_{dq}^r \quad (5)$$

$$\lambda_{dq}^r = (L_{lr} + L_m) i_{dq}^r + L_m i_{dq}^s \quad (6)$$

$$\lambda_{xy}^s = L_{ls} i_{xy}^s \quad (7)$$

$$\lambda_{xy}^r = L_{lr} i_{xy}^r \quad (8)$$

where V_{dq}^s , V_{dq}^r , V_{xy}^s , V_{xy}^r represent, respectively, the stator and rotor voltage complex vectors representing d - q and x - y

axis and i_{dq}^s , i_{dq}^r , i_{xy}^s , i_{xy}^r represent the stator and rotor current complex vectors representing d - q and x - y axis; r_s is stator resistance, r_r is rotor resistance, L_{ls} is the leakage stator inductance, L_{lr} is the leakage rotor inductance and L_m is the mutual inductance. The electromagnetic torque can be expressed as

$$T_e = \frac{5}{2} P \frac{L_m}{\sigma L_s L_r} \text{Im} [\lambda_{dq}^s \lambda_{dq}^{r*}] \quad (9)$$

where P is the number of pole pairs, “*” denotes the complex conjugate, L_s is the stator inductance, L_r is the rotor inductance and leakage coefficient (σ) = $1 - \frac{L_m^2}{L_s L_r}$. A schematic of five-phase IM drive is shown in figure 1a and in a balanced five-phase IM, the five stator phase groups are distributed with spacing of 72° as shown in figure 1b. The five-phase inverter has $2^5 = 32$ switching voltage vectors consisting of 30 active and 2 zero. The switch function of these voltage vectors is represented as $S = [S_A S_B S_C S_D S_E]^T$, where $S_i = 0$ or 1, state 1 represents turning ‘ON’ of upper switch and for the same state, lower switch will be turned ‘OFF’. State 0 represents turning ‘ON’ of lower switch and for the same state, upper switch will be turned ‘OFF’.

3. Formation of virtual voltage vectors group

The x - y space plane exists in the five-phase IM, which is decoupled and orthogonal to already existing d - q space plane. The fundamental supply component and supply harmonics of the order $10n \pm 1$ ($n = 0, 1, 2, 3, \dots$) map into d - q space plane and the supply harmonics of the order $10n \pm 3$ ($n = 0, 1, 2, 3, \dots$) map into x - y space plane. The electromagnetic torque is produced by d - q component only (Eq. (9c)) and x - y component (Eq. (3)) simply causes losses in the machine by distorting the phase current. Hence, it becomes necessary to eliminate the x - y stator flux while designing the DTC scheme for the five-phase IM. It is observed in figure 2a and b that the voltage vectors that have the same direction in d - q space plane are located at different positions in x - y space plane. For example, the voltage vectors V_1 , V_{11} and V_{21} have the same direction in d - q space plane as shown in figure 2a. However, in x - y space plane, the voltage vectors V_1 and V_{21} are located in the same direction, but voltage vector V_{11} is located in exactly opposite direction as shown in figure 2b. This peculiarity of location of voltage vectors in d - q and x - y space plane is used to eliminate the x - y stator flux. In order to eliminate the x - y stator flux, the virtual voltage vectors are formed. The large voltage vectors V_1 - V_{10} and medium voltage vectors V_{11} - V_{20} are represented by a group of large virtual voltage vectors V_{LX} , where $X = 1$ -10. The medium voltage vectors V_{11} - V_{20} and small voltage vectors V_{21} - V_{30} are represented by a group of small virtual voltage vectors

Figure 1. (a) Schematic of five-phase induction motor drive and (b) phasor diagram of five-phase system representing winding position.

V_{SX} , where $X = 1-10$. The zero voltage vectors V_0 and V_{31} remain as they are. These 20 virtual voltage vectors and two zero voltage vectors are divided into 10 sectors as shown in figure 2c [12]. Once V_{LX} is selected by the control strategy, either large or medium voltage vector will be selected, depending upon the location of x - y stator flux. For example, if large virtual voltage vector V_{L3} is selected and if x - y stator flux is located in left half of x - y space plane, the actual voltage vector V_3 will be selected as depicted in figure 2d, because V_3 is located opposite to left half of x - y space plane. The selection of V_3 or V_{13} will be done by the following procedure:

- check the location of x - y stator flux ($\alpha = \tan^{-1}(\lambda_y^s/\lambda_x^s)$);
- If x - y stator flux lies in sector (V-IX), V_3 will be selected.
- If x - y stator flux lies in sector (X-IV), V_{13} will be selected.

Similarly, actual voltage vectors from the small virtual voltage vectors will be selected. The selection of opposite voltage vectors to the location of x - y stator flux eliminates the x - y stator flux [12].

4. Implementation of proposed five-level torque comparator from classical five-level torque comparator

In this section, firstly the formation of classical five-level torque comparator from classical three-level torque comparator is addressed; then the evolution of the proposed five-level torque comparator from the classical five-level torque comparator is focussed. It is already presented in the literatures [9, 12] that with increasing number of levels of torque comparator the torque ripple of machine can be reduced. The

classical five-level torque comparator is therefore presented in [9, 12] to minimize the torque ripple compared with its three-level counterpart. The bands on both sides of the classical three-level torque comparator [10, 11] as shown in figure 3a are divided into two parts in each side in order to convert the classical three-level torque comparator into classical five-level torque comparator [12] as shown in figure 3b. Out of five levels of the classical five-level torque comparator, outer two levels on both sides of the comparator, i.e., HB_2 and $-HB_2$ are used for increasing the torque and decreasing the torque, respectively, at fast rate, for which the large virtual voltage vectors are selected, inner two levels on both sides, i.e., HB_1 and $-HB_1$ are used for increasing the torque and decreasing the torque, respectively, at slow rate, for which the small virtual voltage vectors are selected, and the centre level is used when the torque error lies in between the inner two levels, for which the zero voltage vectors are selected. The outer bands (levels) guarantee the dynamic performance of the motor and the inner bands reduce the torque ripple.

The torque variation is expressed as [6-9]

$$\frac{dT_e}{dt} = -T_{e0} \left(\frac{r_s}{L_s} + \frac{r_r}{L_r} \right) \frac{1}{\sigma} + \frac{5}{2} P \frac{L_m}{\sigma L_s L_r} \text{Im} \left[(V_{dq}^s - j\omega_m \lambda_{dq}^s) j \lambda_{dq}^r \right] \quad (10)$$

where T_{e0} is the torque at current instant and ω_m is the motor angular velocity. It is investigated in [6-9] that the torque variation (Eq. (10)) is influenced by the length of applied voltage vector. The length of large, medium and small voltage vectors is, respectively, 0.647, 0.4 and 0.2472 V_{dc} .

The virtual large voltage vectors consisting of large and medium voltage vectors have the dc-bus length of

$$(0.647 + 0.4) V_{dc} / 2 = 0.5235 V_{dc}. \quad (11)$$

The virtual small voltage vectors consisting of medium and small voltage vectors have the dc-bus length of

Figure 2. Mapping of the voltage vectors: (a) d - q space plane, (b) x - y space plane, (c) mapping of virtual voltage vectors in d - q space plane and (d) oppositely located voltage vectors.

$$(0.4 + 0.2472)V_{dc}/2 = 0.3236V_{dc}. \quad (12)$$

The reason behind taking the average of dc-bus length of large and medium voltage vectors in case of large virtual voltage vectors and medium and small in case of small virtual voltage vectors is that both the types of actual voltage vectors in each virtual voltage vector group are employed for equal duration. From Eqs. (10)–(12), the comparison between the absolute values of torque variation due to virtual large voltage vectors (δV_{LX}) and virtual small voltage vectors (δV_{SX}) for incrementing the torque is

$$\delta V_{LX} > \delta V_{SX}. \quad (13)$$

The comparison between the absolute values of torque variation due to virtual large voltage vectors, virtual small

voltage vectors and zero voltage vectors (δV_0) for decrementing the torque is

$$\delta V_{LX} > \delta V_{SX} > \delta V_0. \quad (14)$$

Both the types of virtual voltage vectors are responsible for incrementing as well as decrementing the torque, whereas zero voltage vectors are responsible for only decrementing the torque due to their zero dc-link utilization.

4.1 Design of the proposed five-level torque comparator

In the classical five-level torque comparator, the zero voltage vectors are used in the inner bands on both sides of

Figure 3. Representation of torque comparator: (a) classical three-level, (b) classical five-level and (c) proposed five-level torque comparator.

the comparator. If the zero voltage vectors are employed several times, the dc-link utilization will be affected. The small virtual voltage vectors can be employed instead of zero voltage vectors. This modification serves both the objectives, i.e., 1) torque ripple reduction and 2) improvement in dc-link utilization. Therefore, in order to gain these objectives, there are two corrections that need to be incorporated in the classical five-level torque comparator.

- (a) When the torque error comes in the positive inner band from the positive end of the classical five-level torque comparator, the zero voltage vector ($dT = 0$) is selected as shown in figure 3b. Due to selection of zero voltage vector, the torque error does not reach its zero value; rather, it moves again towards positive end (torque error increases), because the actual torque is decreased. If zero voltage vector in the positive inner band is not replaced by small virtual voltage vector, the actual torque will never reach its reference value. If zero voltage vectors in the positive inner band are replaced by the small virtual voltage vectors ($dT = 1$), the actual torque will surely reach its reference value. Due to this, the torque error gets reduced and hence the torque ripple will be reduced. This modification is done in the proposed five-level torque comparator as shown in figure 3c.
- (b) When the torque error progresses from negative end, crosses its zero position and comes into the positive inner band of the classical five-level torque comparator, again zero voltage vector is selected as shown in figure 3b.

After crossing the zero position by the torque error, the torque error needs to be reduced (actual torque needs to be increased) immediately in order to reduce the torque ripple. However, selection of zero voltage vector here again decreases the torque, which enables the torque ripple to increase. The torque can be increased when the zero voltage vector is replaced by small virtual voltage vector ($dT = 1$) in the positive inner band. By selecting the small virtual voltage vectors the torque error gets reduced and hence the torque ripple gets reduced. This modification is done in the proposed five-level torque comparator as shown in figure 3c.

There are three rules that need to be followed while designing the proposed five-level torque comparator.

- 1) The small virtual voltage vectors should be employed as many times as possible, but only within the outer bands [14]
The function of small virtual voltage vectors is to reduce the torque ripple. In the classical five-level torque comparator, the small virtual voltage vectors are utilized four times while incrementing and decrementing the torque error as shown in figure 3b. In case of proposed five-level torque comparator, number of times the small virtual voltage vectors are utilized is increased from four to six as shown in figure 3c. It is observed in figure 3c that all the six small virtual voltage vectors are employed in the proposed comparator inside the outer band on both sides.

Figure 4. Selection of virtual voltage vectors for all the possible torque and flux comparator outputs for sector I.

Table 1. Virtual voltage vectors selection table.

		Sector									
$d\lambda$	dT	I	II	III	IV	V	VI	VII	VIII	IX	X
1	2	V_{L3}	V_{L4}	V_{L5}	V_{L6}	V_{L7}	V_{L8}	V_{L9}	V_{L10}	V_{L1}	V_{L2}
	1	V_{S3}	V_{S4}	V_{S5}	V_{S6}	V_{S7}	V_{S8}	V_{S9}	V_{S10}	V_{S1}	V_{S2}
	0	V_0	V_{31}	V_0	V_{31}	V_0	V_{31}	V_0	V_{31}	V_0	V_{31}
	-1	V_{S9}	V_{S10}	V_{S1}	V_{S2}	V_{S3}	V_{S4}	V_{S5}	V_{S6}	V_{S7}	V_{S8}
	-2	V_{L9}	V_{L10}	V_{L1}	V_{L2}	V_{L3}	V_{L4}	V_{L5}	V_{L6}	V_{L7}	V_{L8}
0	2	V_{L4}	V_{L5}	V_{L6}	V_{L7}	V_{L8}	V_{L9}	V_{L10}	V_{L1}	V_{L2}	V_{L3}
	1	V_{S4}	V_{S5}	V_{S6}	V_{S7}	V_{S8}	V_{S9}	V_{S10}	V_{S1}	V_{S2}	V_{S3}
	0	V_{31}	V_0	V_{31}	V_0	V_{31}	V_0	V_{31}	V_0	V_{31}	V_0
	-1	V_{S8}	V_{S9}	V_{S10}	V_{S1}	V_{S2}	V_{S3}	V_{S4}	V_{S5}	V_{S6}	V_{S7}
	-2	V_{L8}	V_{L9}	V_{L10}	V_{L1}	V_{L2}	V_{L3}	V_{L4}	V_{L5}	V_{L6}	V_{L7}

- 2) The zero voltage vectors should be used inside the inner band on negative side of the comparator only
In the classical five-level torque comparator the zero voltage vectors are employed in the inner bands on both sides of the torque comparator as shown in figure 3b, whereas in the proposed five-level torque comparator, the zero voltage vectors are used inside the inner band on the negative side only as shown in figure 3c, which justifies that the zero voltage vectors should be employed for decrementing the torque only. Since the zero voltage vectors have zero dc-bus length, it obviously affects the dc-link utilization. The proposed five-level torque comparator is designed keeping in mind that the maximum possible dc-link utilization should be obtained while reducing the torque ripple. Therefore, the zero voltage vectors are employed in proposed five-level comparator only where they are required (inside the inner band on the negative side of the comparator only).
- 3) The large virtual voltage vectors should be used outside the outer band on both sides of the comparator
Equations (13) and (14) show that the torque variation due to utilization of large virtual voltage vectors is more

than the torque variation due to utilization of small virtual voltage vectors. Therefore, the large virtual voltage vectors are employed outside the outer band on both sides of the comparator to fasten the torque response while incrementing or decrementing the actual torque.

4.2 Selection of virtual voltage vectors through proposed five-level torque comparator

The virtual voltage vectors are selected based on the information of the torque, d - q stator flux and its location for increasing or decreasing the flux (FI and FD) and the torque (TI and TD) as shown in figure 4. This is further illustrated in much detail for sector I. For example, when the stator flux enters the first sector and when increase of the flux (FI_1) and increase of the torque (TI_2) are required, the virtual voltage vector V_{L3} is selected for a very short time T_s (sampling time). The selection of virtual voltage vector V_{L3} increases the stator flux, because the resultant stator flux λ_2^s is greater than the previous stator flux λ_{dq}^s advances the stator flux in forward

direction (assume that anticlockwise is the forward direction). Similarly, other virtual voltage vectors will be selected. The selection of voltage vectors in all the sectors for all the possible conditions of torque and flux comparator is provided in table 1.

4.3 Selection of actual voltage vectors

Table 2 selects the actual voltage vector based on the output from table 1 and the location of x - y stator flux. For example, if V_{L3} is selected by table 1 and if x - y stator flux lies in third sector, the actual medium voltage vector V_{13} is selected by table 2. The voltage vector V_{13} is selected when the x - y stator flux lies in sector X-IV (X-I-II-III-IV), because the voltage vector V_{13} lies exactly opposite to the x - y stator flux location X-IV (X-I-II-III-IV). For opposite half, i.e., when the x - y stator flux lies in sector V-IX (V-VI-VII-VIII-IX), the large voltage vector V_3 is selected, because the voltage vector V_3 lies exactly opposite to the x - y stator flux location V-IX (V-VI-VII-VIII-IX). Similarly, remaining actual voltage vectors will be selected. The selection of opposite voltage vectors to the location of x - y stator flux does not allow the x - y stator flux to increase. Therefore, by selecting the opposite voltage vectors to the x - y stator flux, the magnitude of x - y stator current can be controlled, which reduces the distortion in the d - q stator current waveform. Once the virtual voltage vector is selected by table 1, table 2 sees the location of x - y stator flux (θ) and accordingly selects the actual voltage vector. The control block diagram of the proposed DTC method is shown in figure 5, which mainly consists of proposed five-level torque comparator, classical two-level flux comparator, virtual voltage vector selection table 1 and actual voltage vector selection table 2, which initiates the switching action in the inverter for satisfying the required condition of torque while maintaining the stator flux constant.

5. Simulation results

The operation of five-phase IM controlled by the DTC scheme with the classical and proposed five-level torque comparator is carried out through MATLAB simulation. The sampling frequency used for the simulation is 20 kHz. The motor has the rated torque of 6 Nm and the rated flux of 0.54 Wb. The outer and inner bands on both sides of both the classical and proposed five-level torque hysteresis controller are set, respectively, to $\pm 6.66\%$ and $\pm 3.33\%$ of the rated torque. For the two-level flux hysteresis controller, the bands are set to $\pm 0.55\%$ of the rated flux. The data and parameters of the machine are depicted in table 3.

Figures 6 and 7 summarize the performance of five-phase IM controlled by DTC method with the classical five-level torque comparator [12] and the proposed five-level torque comparator, respectively. For the operation, the motor speed is fixed to 1000 rpm. It is seen that the proposed torque comparator has significantly reduced the

Table 2. Actual voltage vectors selection table.

Virtual large voltage vectors	V_{L1}	V_{L2}	V_{L3}	V_{L4}	V_{L5}	V_{L6}	V_{L7}	V_{L8}	V_{L9}	V_{L10}
x - y stator flux location (sectors)	(IX-III)	(II-VI)	(V-IX)	(VIII-II)	(I-V)	(IV-VIII)	(VII-I)	(X-IV)	(III-VII)	(VI-X)
Actual large voltage vectors	V_1	V_2	V_3	V_4	V_5	V_6	V_7	V_8	V_9	V_{10}
x - y stator flux location (sectors)	(IV-VIII)	(VII-I)	(X-IV)	(III-VII)	(VI-X)	(IX-III)	(II-VI)	(V-IX)	(VIII-II)	(I-V)
Actual medium voltage vectors	V_{11}	V_{12}	V_{13}	V_{14}	V_{15}	V_{16}	V_{17}	V_{18}	V_{19}	V_{20}
Virtual small voltage vectors	V_{S1}	V_{S2}	V_{S3}	V_{S4}	V_{S5}	V_{S6}	V_{S7}	V_{S8}	V_{S9}	V_{S10}
x - y stator flux location (sectors)	(IX-III)	(II-VI)	(V-IX)	(VIII-II)	(I-V)	(IV-VIII)	(VII-I)	(X-IV)	(III-VII)	(VI-X)
Actual small voltage vectors	V_{21}	V_{22}	V_{23}	V_{24}	V_{25}	V_{26}	V_{27}	V_{28}	V_{29}	V_{30}
x - y stator flux location (sectors)	(IV-VIII)	(VII-I)	(X-IV)	(III-VII)	(VI-X)	(IX-III)	(II-VI)	(V-IX)	(VIII-II)	(I-V)
Actual medium voltage vectors	V_{11}	V_{12}	V_{13}	V_{14}	V_{15}	V_{16}	V_{17}	V_{18}	V_{19}	V_{20}

Figure 7. Simulation results of five-phase DTC with proposed torque comparator: (a) torque, (b) torque ripple, (c) stator flux magnitude, (d) stator a, b phase current and (e) trajectory of x - y stator current.

controllers are the same as in the simulation. The motor data and motor parameters are the same as those given in table 3.

Figures 9 and 10 summarize the experimental results of DTC schemes with the classical torque comparator and with the proposed torque comparator, respectively. The motor speed is fixed to 1000 rpm throughout the operation. Since the torque sensors are not used due to their very high cost, the estimated torque is obtained from DSP through JTAG emulator. It is observed that by implementing the classical five-level torque comparator, the DTC scheme suffers from the torque ripple. The proposed torque comparator modifies the classical torque comparator and its effect can be observed in the form of torque ripple reduction as shown in figure 10a compared with figure 9a. The stator flux of the rated value is maintained constant throughout the operation in both DTC schemes as shown in figures 9b and 10b. With the proposed comparator, the trajectory of d - q stator current is better controlled, especially during steady-state operation (inner dense circle) as shown in figure 10c compared with trajectory of d - q stator current as shown in figure 9c. It is seen from the trajectories of x - y stator current as shown in figures 9c and 10c that the magnitude of x - y stator current is reduced, which proves the effective implementation of x - y stator flux elimination algorithm in both cases.

Figures 11 and 12 summarize the experimental results of DTC schemes for the loading operation under the normal speed condition of 1000 rpm with the classical torque comparator and with the proposed torque comparator, respectively. A load of 2.5 Nm is applied to the motor. It is seen that the proposed comparator has effectively reduced the torque ripple during loading operation. It is observed that the current THD is reduced in the proposed DTC method. Therefore, the waveform of phase current is significantly improved. Since the same two-level flux comparator is implemented in both DTC schemes, the stator flux trajectory exhibits the same performance. It is inevitable that the stator flux in the x - y space plane needs to be eliminated; otherwise the phase current will be distorted. Therefore, the virtual voltage vectors formation technique [12] has been implemented in both schemes to eliminate the x - y stator flux. It is clearly seen that virtual voltage vectors formation technique did its function by almost eliminating the x - y stator flux. Figures 13 and 14 show the steady-state and transient operation for classical and proposed comparator DTC methods. For the steady-state operation, the motor reference speed is fixed to 300 rpm (almost 20% of the rated speed). It is seen that the proposed DTC scheme considerably did its work by reducing the torque ripple. Along with steady-state operation, transient operation is also carried out. Under this operation, a load of 3 Nm is applied to the motor. As soon as the load is applied, the reference torque suddenly increases to the value set by the PI controller. The actual torque needs to immediately track the reference value in order to have the rapid dynamic

Figure 8. Block diagram of experimental set-up of five-phase inverter-fed DTC-controlled five-phase induction motor drive.

Figure 9. Experimental results of no-load operation of five-phase DTC with classical torque comparator: (a) torque, (b) stator flux and (c) trajectory of d - q and x - y stator current.

Figure 10. Experimental results of no-load operation of five-phase DTC with proposed torque comparator: (a) torque, (b) stator flux and (c) trajectory of d - q and x - y stator current.

Figure 11. Experimental results of loaded steady-state operation of five-phase DTC with classical torque comparator: (a) torque, (b) stator a, b phase current, (c) current THD and (d) trajectory of d - q and x - y stator flux.

response. Since the large virtual voltage vector varies the torque faster as compared with small virtual voltage vector and zero voltage vector, large virtual voltage vector is applied in both DTC schemes during the transient period. Under transient operation, the speed reversal test is also conducted. When the speed reversal command is given, suddenly the PI controller generates negative torque command and hence the actual torque tries to follow the negative torque reference.

Figure 12. Experimental results of loaded steady-state operation of five-phase DTC with proposed torque comparator: (a) torque, (b) stator a, b phase current, (c) current THD and (d) trajectory of d - q and x - y stator flux.

Table 4 shows the comparison between the DTC schemes through experimental results during loading (2.5 Nm) operation. It is observed that DTC with proposed five-level torque comparator has reduced the torque ripple by 38.89% compared with DTC with classical five-level torque comparator. It is seen that by implementing the proposed torque comparator, the dc-link utilization of the drive is improved by 7%. It is also observed that with the proposed comparator the THD of current is significantly reduced. Figure 15 shows the average switching frequency under the

(I)

(II)

(III)

Figure 13. Experimental results for the classical comparator: (I) steady-state condition (CH. 1, torque 2 Nm/div. and 0.5 s/div., CH.2 rotor speed 100 rpm/div. and 0.5 s/div.), (II) transient condition of application of load (CH. 1, torque 2 Nm/div. and 0.5 s/div., CH.2 rotor speed 500 rpm/div. and 0.5s/div.) and (III) transient condition of speed reversal operation (CH. 1, torque 2 Nm/div. and 0.5 s/div., CH.2 rotor speed 500 rpm/div. and 0.5 s/div.).

operation of change in speed from 200 to 1400 rpm. It is seen that in both of the presented DTC schemes the average switching frequency remains almost the same. It is also observed that with increase in speed, the average switching frequency increases in both cases.

(I)

(II)

(III)

Figure 14. Experimental results for the proposed comparator: (I) steady-state condition (CH. 1, torque 2 Nm/div. and 0.5 s/div., CH.2 rotor speed 100 rpm/div. and 0.5 s/div.), (II) transient condition of application of load (CH. 1, torque 2 Nm/div. and 0.5 s/div., CH.2 rotor speed 500 rpm/div. and 0.5 s/div.) and (III) transient condition of speed reversal operation (CH. 1, torque 2 Nm/div. and 0.5 s/div., CH.2 rotor speed 500 rpm/div. and 0.5 s/div.).

Table 4. Comparison of DTC schemes based on experimental data.

DTC schemes	Peak-peak torque ripple (Nm)	dc-link utilization RMS value of V_{LL}/V_{dc}	Max. x - y stator flux (Wb)	Current THD (%)
Classical	1.8	0.58	0.016	21.63
Proposed	1.1	0.621	0.017	11.61

Figure 15. Experimental result of average switching frequency with respect to different speed conditions.

7. Conclusion

The paper proposed a modified five-level torque comparator against the classical five-level torque comparator in order to minimize the torque ripple and to improve the dc-link utilization. The voltage vector selection through the classical five-level torque comparator affects the torque ripple and the dc-link utilization. The proposed torque comparator modifies the voltage vector selection inside the inner band on the positive side of the classical five-level torque comparator, which significantly reduces the torque ripple and improves the dc-link utilization. The x - y stator flux magnitude has been eliminated in the proposed DTC scheme, which enables the stator phase current to follow the sinusoidal nature. The advantage of the DTC based on a hysteresis controller, i.e., the simplicity of the control algorithm, is retained through the proposed five-level torque comparator.

Nomenclature

DTC	direct torque control
λ_{dq}^s	d - q stator flux
λ_{dq}^r	d - q rotor flux
λ_{xy}^s	x - y stator flux
λ_{xy}^r	x - y rotor flux
V_{dq}^s	d - q stator voltage vector
V_{dq}^r	d - q rotor voltage vector
V_{xy}^s	x - y stator voltage vector
V_{xy}^r	x - y rotor voltage vector
i_{dq}^s	d - q stator current vector
i_{dq}^r	d - q rotor current vector
i_{xy}^s	x - y stator current vector
i_{xy}^r	x - y rotor current vector
r_s	stator resistance
r_r	rotor resistance
L_{ls}	leakage stator inductance
L_{lr}	leakage rotor inductance
L_m	mutual inductance
P	pole pairs
L_s	stator inductance
L_r	rotor inductance

σ	leakage coefficient
V_{LX}	large virtual voltage vectors
V_{SX}	small virtual voltage vectors
$\frac{dT_e}{dt}$	torque variation
δV_{LX}	absolute value of torque variation due to virtual large voltage vectors
δV_{SX}	absolute value of torque variation due to virtual small voltage vectors
δV_0	absolute value of torque variation due to zero voltage vectors
T_{e0}	torque at current instant
ω_m	motor angular velocity

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