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TORQUE RIPPLE MINIMIZATION BY MODIFIED DTC ALGORITHM BASED ON DUTY RATIO CONTROL FOR ELECTRIC VEHICLE APPLICATIONS.

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Abstract: This paper is dedicated to torque ripple minimization by different duty ratio control techniques for electric vehicle applications. Conventional duty ratio control techniques with modified look up Tables are discussed in detail. Implementation of different variants of duty ratio control technique based on introduction of intermediate voltage vectors is also included in this paper.

1 INTRODUCTION

The direct torque control method for an induction motor drive involves controlling both the stator flux and electromagnetic torque of the motor simultaneously using six active full voltage vectors and two zero voltage vectors from an inverter. To accomplish this objective, a combination of two hysteresis comparators and a heuristic switching table is employed to guarantee that the stator flux and torque stay within their desired reference values. [1-2]. Additionally, when implementing this method with digital controllers. To address this issue, it becomes essential to partition the process into smaller sampling intervals, which, in turn, can introduce undesired fluctuations in torque and current. [3-4].

According to literature, in recent decades, DTC-SVM (Direct Torque Control based on Space Vector Modulation) has become a popular solution for addressing the limitations of conventional DTC drives mentioned earlier [5-6].

However, it too had the limitations of complex control algorithm in the form of different switching Tables for different operating speed range [7]. Introduction of artificial intelligence [8-10], injection of high frequency dither signals [11] and adjustment of torque and flux hysteresis comparator bands [4, 12] are some of the simplified solutions reported for torque ripple reduction. One effective strategy for mitigating these disturbances involves expanding the repertoire of voltage vectors and carefully selecting the most suitable vector based on the torque error's magnitude. (MLI-DTC) [13].

To minimize these oscillations, a viable approach is to augment the quantity of voltage vectors and determine the suitable vector by considering the torque error magnitude. Duty ratio control, as explained in citations [14-15], is a method that enables the expansion of the pool of accessible voltage vectors without the need for additional semiconductor switches in the inverter. This is achieved by synthesizing additional voltage vectors through the application of the selected inverter voltage vector for only a portion of the switching period, rather than for the entire period.

2 DUTY RATIO CONTROL SWITCHING TECHNIQUES

In every Direct Torque Control (DTC) system, it is achievable to independently regulate the flux and torque by choosing appropriate voltage vectors. Equations (1) to (5) demonstrate the correlation between these two significant parameters of an induction motor drive and the voltage vectors applied.

$$\lambda_s = \frac{1}{s}(E_s) \qquad (1)$$

Where$E_s = V_s - i_s R$ (2)

Neglecting the drop in resistance, (2) can be expressed in discrete by (3)

$$\lambda_s(k) = \Delta t_s . V_s(k) + \lambda_s(k-1) \qquad (3)$$

The torque ripples (ΔTe) in a conventional DTC (Direct Torque Control) system can be divided into two components, as stated in equations (4) and (5).

$$\Delta T_{e1} = -T_e \left(\frac{1}{\tau_s} + \frac{1}{\tau_r}\right) \frac{\Delta t_s}{\sigma} \qquad (4)$$

$$\Delta T_{e2} = P \frac{L_m}{\sigma L_s L_r} \left[\left(\overline{V_s} - j\omega_m \overline{\lambda_s}\right) . j\overline{\lambda_r} \right] \Delta t_s \qquad (5)$$

Research paper UGC CARE Listed (Group -I) Journal Volume 10, Iss 3, 2021

Equation (4) includes several parameters, such as τ_s and τ_r, which refer to the stator and rotor time constants, Δts, which is the sampling period, $\overline{V}_s$ which is the applied voltage vector, and $\overline{\lambda}_r$ which is the rotor flux vector.

The various forms of duty ratio control employed in the study, as illustrated in Figure 1, include the following variants.

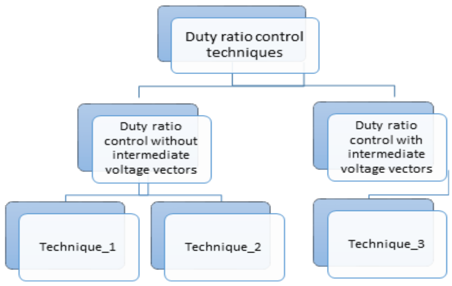

Fig.1 duty ratio control based torque ripple reduction techniques.

The evaluation of these parameters can be performed using the Root Mean Square Torque Error (RMSTE) and Root Mean Square Flux Error (RMSFE), as defined in equations (6) and (7) correspondingly. In these equations, $\lambda_s(k)$ and $T_e(k)$ denote the flux and estimated torque at the kth sampling moment, while $\lambda_s(k)$ a represents the reference stator flux, and T_e^{avg} signifies the calculated mean torque.

$$RMSFE = \frac{1}{N}\sqrt{\sum_{k=1}^{N}\left(\lambda_s^{ref} - \lambda_s(k)\right)^2} \quad (6)$$

$$RMSTE = \frac{1}{N}\sqrt{\sum_{k=1}^{N}\left(T_e^{avg} - T_e(k)\right)^2} \quad (7)$$

3.DUTY RATIO CONTROL WITH HALF VOLTAGE VECTORS

The conventional DTC drive switching strategy is shown in Fig. 2 (a) and (b), along with Table 1, When the stator flux resides within sector 1, spanning from $-\pi/3$ to $\pi/3$ radians, the process involves selecting voltage vectors in accordance with the desired torque and flux specifications. The DTC drive is powered by a two-level inverter, which offers six active voltage vectors (V_1-V_6) and two zero vectors (V_7 and V_8) for selection.

On the other hand, an alternative switching technique that employs duty ratio control and offers a greater number of available voltage vectors is demonstrated in Fig. 2 (c) and (d). Table 2 explains the principle of voltage vector selection using technique_1 control when the stator flux is in sector 1

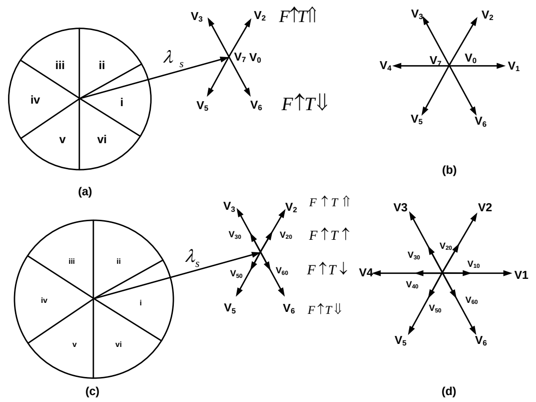

Fig.2 The selection of voltage vectors in both the Conventional and Technique_1 approaches follows a similar strategy. In contrast, when employing the duty ratio control method, the pool of accessible voltage vectors expands to encompass a total of six complete vectors. (V_1-V_6) and six half vectors (V_{10}-V_{60}). Fig. 2(a) and Table 1 can be understand as follows.

Table.1 Voltage vector selection Table for conventional DTC drive

Flux	Torque	Voltage Vector	Flux	Torque	Voltage Vector
$F\uparrow$	$T\uparrow\uparrow$ (large increase)	V_2	$F\downarrow$	$T\uparrow\uparrow$ (large increase)	V_3
	$T\leftrightarrow$ (no change)	V_0, V_7		$T\leftrightarrow$ (no change)	V_0, V_7
	$T\downarrow\downarrow$ (large decrease)	V_6		$T\downarrow\downarrow$ (large decrease)	V_5

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Research paper UGC CARE Listed (Group -I) Journal Volume 10, Iss 3, 2021

Flux	Torque	Voltage	Flux	Torque	Voltage
$F\uparrow$	$T\uparrow\uparrow$ (large incr	$V2$	$F\downarrow$	$T\uparrow\uparrow$ (large increase)	$V3$
	$T\leftrightarrow$ (no change	$V0, V7$		$T\leftrightarrow$ (no change)	$V0, V7$
	$T\downarrow\downarrow$ (large decr	$V6$		$T\downarrow\downarrow$ (large decrease)	$V5$

Table.2 Switching Table for Technique_1

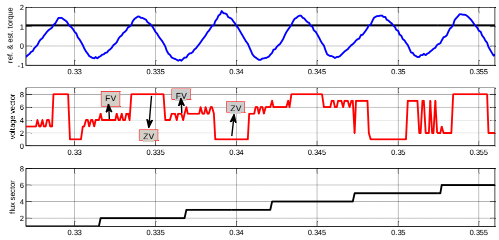
Flux	Torque	Voltage Vector	Flux	Torque	Voltage Vector
$F\uparrow$	$T\uparrow\uparrow$	V_2	$F\downarrow$	$T\uparrow\uparrow$	V_3
	$T\uparrow$	V_{20}		$T\uparrow$	V_{30}
	$T\leftrightarrow$ (no change)	V_0, V_7		$T\leftrightarrow$ (no change)	V_0, V_7
	$T\downarrow$	V_{60}		$T\downarrow$	V_{50}
	$T\downarrow\downarrow$	V_6		$T\downarrow\downarrow$	V_5

While the technique_1 involves choosing the appropriate voltage vectors based on specific torque and flux requirements as given in Fig. 2 (c) and Table 2 can be interpreted as follows.

A large increment in torque with flux increment can be achieved by V_2 (full vector) while a small increment in torque with increased flux can be achieved by V_{20} (half vector). Application of V_{60} results in a flux increment and small decrement in torque and large torque decrement with increased flux is accomplished by V_6. A very small decrement in torque or no change is achieved by zero vectors. Application of voltage vector V_3, V_{30}, V_{50} and V_5 results in large increment, small increment, large decrement and small decrement in torque respectively with reduced flux.

This statement explains that it is possible to create a half voltage vector called V_{k0} using a full vector V_k and a zero vector. The duty ratio control method is different from conventional DTC drives because it distinguishes between large and small torque errors (ΔT_e) using a five-level hysteresis comparator. The magnitude of torque hysteresis comparator bandwidth (H_t) is used to categorize torque errors as either large or small. If the torque error is greater than 2*$H_{t.}$$|\Delta T_e| \geq 2 * H_t$, it is considered a large torque error, while errors ranging from $|0 \leq \Delta T_e \leq H_t|$ are considered small.

By referring to Figure 3 and Figure 4, one can compare the patterns of torque variation slope. These figures illustrate the changes in estimated torque corresponding to the applied voltage vectors in both the conventional and proposed techniques. These real time results can be used to compare the torque variation between the two techniques.



time (secs)

Fig. 3 Torque variation with applied voltage vector in conventional DTC

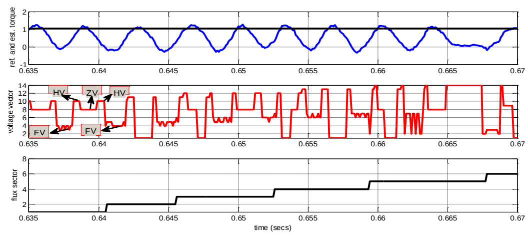


Fig. 4 Torque variation with applied voltage vector in duty ratio controlled DTC in Technique_1

This statement compares two switching strategies based on the observations made from Fig. 3 & 4. In the conventional switching strategy shown in Fig. 3, a full vector is selected for a large torque increment, and a zero vector is used for a small decrement when the actual torque exceeds the reference torque.

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The proposed switching technique can be elaborated from Fig. 5 (a) and (b), which is an enlarged view of Fig.4 between the sampling instants 0.64 and 0.644 secs. Fig. 4 confirms that in situations where the actual torque falls considerably below the required reference torque (resulting in a large positive torque error), the selection of full vectors is employed to mitigate the error.

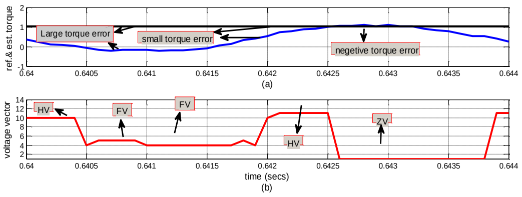

Fig. 5 Real time results showing relationship between torque errors and applied voltage vectors

Conclusion: The results demonstrate that the modified DTC algorithm effectively reduces torque ripple, resulting in improved vehicle performance and drivability. The use of duty ratio control techniques and intermediate voltage vectors allows for more precise control of torque, leading to smoother operation and enhanced efficiency. This research contributes to the advancement of torque control strategies for electric vehicles, paving the way for more optimized and refined drive systems.

Overall, the proposed modified DTC algorithm based on duty ratio control offers a promising approach to mitigate torque ripple in electric vehicle applications. The results of this investigation offer significant knowledge for scholars, researchers, engineers, and manufacturers working on the development of electric vehicle drivetrains to achieve better performance and customer satisfaction.

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