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Reducing Torque Oscillations in Induction Motor Drives for Electric Vehicle Applications.

Survesh Pratap Singh
Research Scholar, *Department of Electrical and Electronics Engineering, University Institute of Technology RGPV, Bhopal, Madhya Pradesh 462033, India.*
Sarvesh786singh@gmail.com

Bhoopendra Singh
Department of Electrical Engineering
UIT, Rajiv Gandhi Proudyogiki Vishwavidyalaya, Bhopal(M.P.) India
bhoopendrasingh1@gmail.com

Abstract: - Transportation plays a vital role in societal progress, but its current reliance on finite and polluting fossil fuels necessitates a shift towards electric vehicles. This transition is crucial for reducing environmental damage and decreasing dependence on fossil fuels. Induction motors are widely favored in electric vehicles due to their durability and minimal maintenance requirements. Among various control techniques, Direct Torque Control (DTC) is recognized as the most efficient method for regulating induction motors in electric and hybrid vehicles. DTC accurately calculates flux, torque, and speed, resulting in faster response times and fewer machine settings. However, it does exhibit a drawback in the form of high torque ripples. To address this issue, the paper proposes a straightforward control strategy for three-phase induction motors that maintains performance while effectively mitigating torque ripples, utilizing techniques such as duty ratio control..

Keywords: electric vehicle (E.V.), direct torque control (DTC), induction motor (I.M.), field-oriented control (FOC).

I. INTRODUCTION

The world consumes nearly 79% of fossil fuels for transportation services. This will increase pollution through the emission of toxic gases [1]. Since they are independent of fossil fuels and emit no harmful gases, electric vehicles (E.V.s) appear as a viable solution to the oil crisis/use of oil and environmental issues [2]. Induction motors (I.M.) are widely accepted for use in electric cars, according to [3], which compares a variety of engines. I.M. drives are therefore regarded as one of the most excellent options for driveline topology. However, there are numerous difficulties in developing the electric vehicle drive to compete with internal combustion engines, including efficiency, a reduced top speed, and transient and dynamic responses to a fast change in starting, stopping and running conditions. Advanced and improved control solutions are required to mitigate or alleviate the abovementioned issues. In recent literature, various novel control techniques have been suggested by researchers to enhance the utilization of induction motor drives in electric vehicles. For induction motor drive systems, it can be verified that a FOC and DTC are the best control strategies that can be implemented on a typical drive motor [4]. Torque and flux can be separated and adjusted separately in both methods. F. Blaschke first suggested FOC for induction motor control in 1971[5]. FOC transforms I.M. control into a separately excited D.C. motor. The three-stator current is converted into the αβ components that provide flux and torque, allowing for separate control of torque and flux. [6]. In FOC, precise motor parameter estimation is necessary. FOC can be applied in two different ways: directly (DFOC) and indirectly (IFOC) [7]. The method has been evolving for a while and is now mature from an industrial standpoint. After thirteen years, M. Depenbrock and I. Takahashi created and presented a novel method of controlling torque as direct self-control (DSC) [8]–[10] and DTC [11]–[13]. When comparing DSC with DTC, the only key characteristic is the orientation of such flux vector controller. In contrast to DSC, which has a hexagonal path, DTC has a quasi-circular way, increasing the switching frequency of DTC. DTC abandons the stator's present control philosophy. The voltage of the stator is quickly adjusted to rectify errors in torque and flux [14].

DTC has a benefit above FOC in that it does not require a pulse width modulation (PWM) generator. It provides better torque control and is simple to implement in steady-state and dynamic operations. This controller does not need any coordinate transformation; hence it is less sensitive to parameter variations. The main drawbacks of DTCs are high torque and current ripples, a variable switching frequency, and intense noise, especially at low speeds [15-16]. Various modifications have been made to DTC systems to resolve the previously mentioned problems.

References [17-18] show that it is possible to produce improved switching tables without modifying the basic design of the architecture. Space-vector modulation (SVM) techniques were used to develop solutions in [19-22]. In [23-24], solutions based on neural networks and fuzzy logic are implemented. [25] Introduces the DTC EMC switching table, a novel switching table to address electromagnetic compatibility and lessen standard mode emissions (Electromagnetic ally compatible). A nonlinear system with uncertainties can be effectively controlledP using variable structure control (VSC). It is strong and has quick response control, but it also displays regulated chattering. The authors in [26] compared and recommended control by enhancing the performance of several variable structure systems to reach flux estimating methods for improving flux response using voltage model-based estimation in a DTC drive. In [27-28], authors suggested reducing torque ripple by using a modified lookup table in conventional and duty ratio control DTC drives. This research suggested modified duty ration control of I.M. for lowering torque and current ripples. The primary factor in producing ripple content is the coupling between the elements. This study suggested using a DTC system to decouple the components of the α & β axis and improve the induction motor's stability and rapid responsiveness. So this enhances the control scheme's dynamic response, quick transient response, resilience, and simplicity.

The following five sections make up this manuscript: System modelling and an explanation of the conventional control method are covered in section II, modified DTC with duty ratio control of voltage vectors is covered in section III, and the outcomes for the examined model using the conventional and proposed systems are covered in section IV. The study's conclusions and their long-term ramifications are summarized in section V.

II. MODELLING OF DTC INDUCTION MOTOR DRIVE

Equations in a stationary reference frame can represent the dynamic equation of a three-phase induction motor. (1 – 15)

$$V_s = R_s I_s + \frac{d\lambda_s}{dt} \quad (1)$$

$$0 = R_r I_r + \frac{d\lambda_r}{dt} - j\omega_m \lambda_r \quad (2)$$

$$\lambda_s = L_s I_s + L_m I_r \quad (3)$$

$$\lambda_r = L_m I_s + L_r I_r \quad (4)$$

$$T_e = \frac{3}{2} P \frac{L_m}{\sigma L_s L_r} \lambda_s x \lambda_r \quad (5)$$

Finally, electromagnetic torque can be expressed by

$$T_e = \frac{3}{2} P \frac{L_m}{\sigma L_s L_r} \lambda_s x \lambda_r \sin(\delta) \quad (6)$$

where δ is the flux vectors of the stator and rotor's phase angle, as shown in Figure 1.

$$\sigma = 1 - \frac{L_m{}^2}{L_s L_r} \quad (7)$$

A two-axis coordinate transformation further modifies to

$$V_{s\alpha} = R_s I_{s\alpha} + \frac{d\lambda_{s\alpha}}{dt} \quad (8)$$

$$V_{s\beta} = R_s I_{s\beta} + \frac{d\lambda_{s\beta}}{dt} \quad (9)$$

$$0 = R_r I_{r\alpha} + \frac{d\lambda_{r\alpha}}{dt} - j\omega_m \lambda_{r\alpha} \quad (10)$$

$$0 = R_r I_{r\beta} + \frac{d\lambda_{r\beta}}{dt} - j\omega_m \lambda_{r\beta} \quad (11)$$

$$\lambda_{s\alpha} = L_s I_{s\alpha} + L_m I_{r\alpha} \quad (12)$$

$$\lambda_{s\beta} = L_s I_{s\beta} + L_m I_{r\beta} \quad (13)$$

$$\lambda_{r\alpha} = L_m I_{s\alpha} + L_r I_{r\alpha} \quad (14)$$

$$\lambda_{r\beta} = L_m I_{s\beta} + L_r I_{r\beta} \quad (15)$$

Where λ_s stator flux linkage vector

λ_r Rotor flux linkage vector

V_s Stator voltage

L_s Stator inductances

L_r Rotor inductances

L_m Magnetizing inductances

R_s Stator resistance

R_r Rotor resistance

ω_m Mechanical angular speed. The induction motor can be modelled based on these equations to implement the DTCalgorithm.

(A) Direct torque-controlled I.M. drive.

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The three essential elements of DTC (Direct Torque Control) are a motor model, a switching voltage vector lookup table, and a hysteresis controller. The motor simulation computes the torque produced, stator flux, and rotor speed using measurements of the battery voltage and two stator phase currents. Using a hysteresis control technique, the torque and flux standards are evaluated to their predicted values to produce control signals. The switching voltage vector lookup table, shown in Table 1, helps choose appropriate voltage vectors for all possible stator flux and torque requirements for a given space-flux vector position.

The Stator flux vector λ_s is estimated by an induction motor's basic equation, which is given by

$$\lambda_s = \int (V_s - R_s I_s) dt \qquad (16)$$

The voltage drop is neglected in stator resistance, and hence

$$\Delta\lambda_s = \overline{V_s} \Delta t \qquad (17)$$

Where Δt is the applied voltage vector's time step. The motor's torque is calculated using (18)

$$T_e = P \frac{L_m}{\sigma L_s L_r} |\lambda_s| |\lambda_r| \sin(\delta) \qquad (18)$$

Where $\sigma = 1 - \frac{L_m{}^2}{L_s L_r}$ (19)

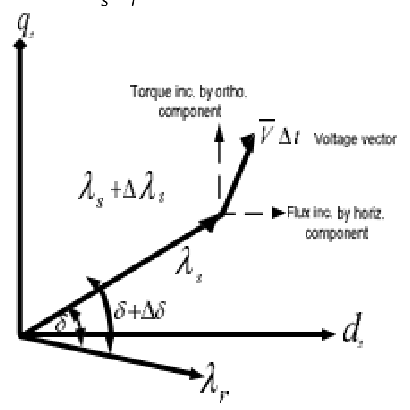

Fig.1 Torque and flux control in DTC drive

It is clear from (18) and Fig. 1 that as the flux vectors for the stator and rotor get more angled, the torque will rise. When the vector $\Delta\lambda s$ is divided into its horizontal and perpendicular components, as shown in Fig. 1 it can be observed that the vertical segment of $\Delta\lambda s$ governs the torque, while the horizontal component governs the flux. The induction motor is supplied with voltage vectors corresponding to the necessary torque and flux to sustain and regulate them. In Fig.2 voltage source inverter is shown, which produces voltage vectors according to switching of the switches S_1 to S_6.

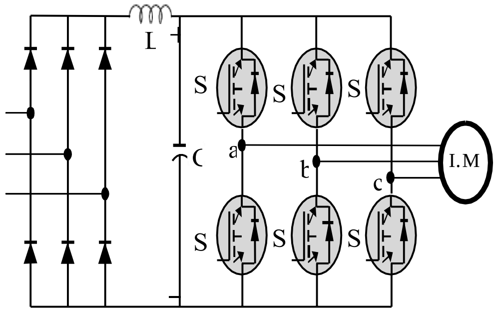

Fig. 2 Two-level VSI fed induction motor drive.

In a conventional DTC drive, the horizontal and perpendicular stator-voltage space vector components separately control the torque and stator-flux with the help of suitable inverter switching.

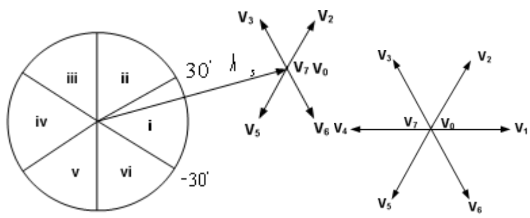

Fig. 3 Strategy for choosing voltage vectors for a conventional DTC drive

Fig. 3 shows a traditional DTC drive and its voltage vector selection. Six sectors of 60° totalling 360 degrees make up the stator flux plane. By applying voltage vector V_2, torque and flux can both rise if the stator flux vector is in the first sector (-30° to +30°).On the other hand, applying voltage vector V_6 causes an increase in flux while simultaneously reducing the torque. Vector V_3 produces a torque increase and a flux decrease, and vector V_5 does the opposite. The stator flux is unaffected by any applied zero voltage vectors (V_0 or V_7), the rotor flux vector continues to rotate clockwise because of its significant time constant, which reduces the angle between the stator and rotor flux vectors. The motor torque decreases as a result of this. However, operations at moderate and high speeds are the only ones that benefit from this torque reduction. The rotor flux movement is too sluggish at low speeds, so torque reduction is not effectively achieved. If the stator flux linkage vector is located in sector K, then to alter its position, the voltage vectors V_{k-2} (when rotating clockwise) and V_{k+2} (when rotating counterclockwise), as well as the the switch variables V_{k-1} (for rotation in a clockwise direction) and V_{k+1} (for rotation in a anticlockwise direction)

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are used. The magnitude of the torque error determines whether to raise or decrease the torque discrepancy between the reference and the calculated torque. To evaluate the control procedure, it is necessary to employ a torque hysteresis comparator, which can be described using equations 20-22.

If $\Delta Te \geq Ht$, then Htorque equals 1. (20)

If $-Ht < \Delta Te < Ht$, then Htorque equals 2. (21)

If $\Delta Te \leq - Ht$, then torque Ht = 3. (22)

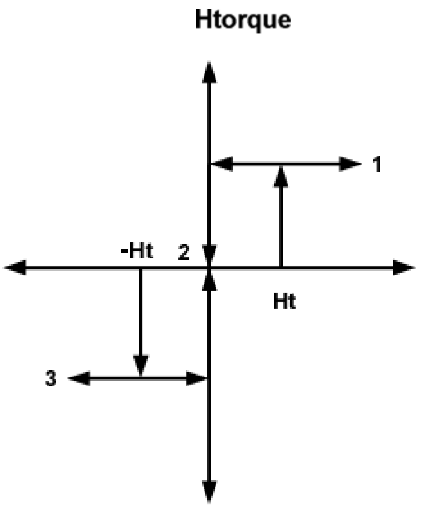

Fig.4.Torque hysteresis comparator

The following equations are also used in flux comparison.

Hflux=1, for $\Delta\lambda_{se} \geq H_{\emptyset}$ (23)

Hflux=2, for $\Delta\lambda_{se} \leq -H_{\emptyset}$ (24)

$\theta = \tan^{-1} \lambda_{\beta s} / \lambda_{\alpha s}$ (25)

Table. 1 conventional lookup table [13]

Hflux	Htorque	Sec I	Sec II	Sec III	Sec IV	Sec V	Sec VI
1	I	V_2	V_3	V_4	V_5	V_6	V_7
	II	V_0	V_7	V_0	V_7	V_0	V_7
	III	V_6	V_1	V_2	V_3	V_4	V_5
2	I	V_3	V_4	V_5	V_6	V_1	V_2
	II	V_7	V_0	V_7	V_0	V_7	V_0
	III	V_5	V_6	V_1	V_2	V_3	V_4

III MODIFIED DTC WITH DUTY RATIO CONTROL OF VOLTAGE VECTORS

Fig. 5(a) and (b) depict a typical DTC drive-switching procedure. The appropriate voltage vectors that meet a specific torque and flux requirement can be selected based on the position of the stator flux in a particular sector example, as shown in sector 1 (-30 to 30 deg), Fig. 5 (a) and (b) and Table 2. A DTC drive driven by a two-level inverter has six voltage vectors (V_1 to V_6) and two zero vectors (V_7 & V_8). An alternate switching method is shown in Figures 5(c) and (d), which makes use of duty ratio control and has the advantage of allowing access to more voltage vectors, Fig.5 (d). It can be seen in table 3, the voltage vector chosen for stator flux in sector 1 by the modified duty ratio control.

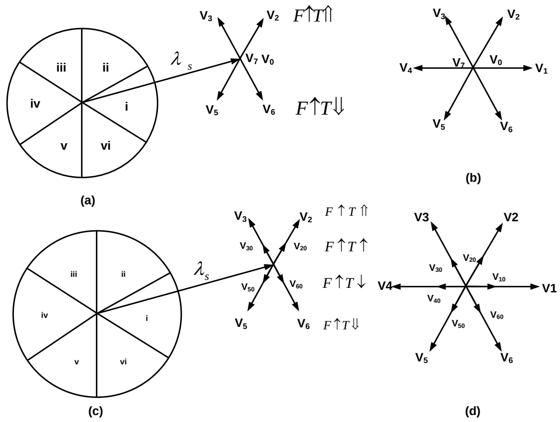

Fig.5. (a) Conventional methods' strategies for selecting among a limited set of voltage vectors. (b) Traditional DTC's vector availability (c) Using the modified duty ratio control method, a voltage vector is selected. (d) The voltage vectors for accessible duty ratio controls.

The interpretation of Table 2 and Fig. 5(a) is as follows. When the stator flux is in sector 1, use vector V_2 to increase torque and flux. For any given torque and flux demand, a typical DTC drive powered by a two-level inverter gives eight voltage vectors. In contrast, the number of voltage vectors rises to twelve, six full (V_1-V_6) and six half vectors using the duty ratio control approach (V_{10}-V_{60}).

Table.2 switching table of choosing voltage vectors for conventional DTC drives.

Flux	Torque	Voltage Vector	Flux	Torque	Voltage Vector
$F\uparrow$	$T\uparrow\uparrow$ (bigger rise)	V_2	$F\downarrow$	$T\uparrow\uparrow$ (bigger rise)	V_3
	$T\leftrightarrow$ (no change)	V_0,V_7		$T\leftrightarrow$ (no change)	V_0,V_7
	$T\downarrow\downarrow$ (big reduction)	V_6		$T\downarrow\downarrow$ (big reductio n)	V_5

Table.3 switching table of Modified DTC with duty ratio control of voltage vectors

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

When the stator flux is in sector 1, then for an increment in torque and flux, vector V_2 is to be selected. At the same time, V_6 is selected for flux increment and decrement in torque. V_3 results in a decrement in torque and an increment in flux. V_5 achieves reduced torque at reduced flux, and Zero vectors are selected for a slight decrement in torque or no change in it.

Modified duty ratio control is a method that can be employed to select the suitable voltage vectors for attaining the desired torque and flux in an electric motor. This selection process is illustrated in Figure 5 (c) and outlined in Table 3 and can be understood as follows. V_2 (full vector) can produce a large increase in torque with an increase in flux, whereas V_{20} can produce a small increase in torque with an increase in flux (half vector). By choosing V_{60} results in a flux increment and slight decrement in torque and a significant torque decrement with increased flux is accomplished by V_6. Zero vectors achieve a very small decrement in torque or no change. Application of voltage vectors V_3, V_{30}, V_{50} and V_5 results in significant increment, small increment, large decrement and slight decrement in torque, respectively, with reduced flux.

In contrast to conventional DTC drives, the proposed method categorizes torque errors into large and small errors using a five-level hysteresis comparator. This categorization is based on the bandwidth (H_t) of the torque hysteresis comparator, where torque errors larger than $2H\_t$ ($|\Delta T\_e| \geq 2H\_t$) are classified as significant errors, and errors ranging between 0 and H_t ($|0 \leq \Delta T\_e \leq H\_t|$) are considered as minor errors. This discrimination helps improve the accuracy of the torque control.

IV ANALYSIS OF TORQUE AND CURRENT RIPPLES:

For various reference torques (different operating speeds) at 80% loading in order to evaluate the performance of the suggested modified duty ratio controlled DTC driving. Furthermore, the performance parameters like RMSTE, RMSFE, stator current ripple, and mean torque at different operating speeds were recorded at two various torque hysteresis comparator bandwidth values (Ht), Ht=0.5Nm and Ht=1.0Nm.

The comparison of torque ripples at 400 rpm (0.6 Nm reference torque) and 1000 rpm (1.0 Nm reference torque) in Fig. 6. It can be verified from Table 4 that at a speed of 400 rpm, the calculated RMSTE for a conventional DTC drive is 280.61%, which reduces to 146% (Table 5) in a modified duty ratio controlled in Fig. 6 (a) and (b). Similarly, Fig. 7 shows confirmation of a decrease in steady-state current ripples at 400 and 1000 rpm.

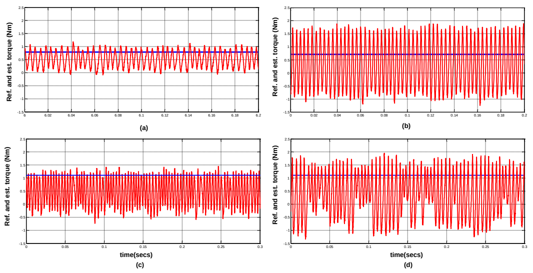

Fig.6 shows the comparison of torque ripples (a) modified duty ratio controlled DTC at 0.6Nm ref. torque (b) conventional DTC at 0.6Nm ref. torque (c) modified duty ratio controlled DTC at 1.0Nm ref. torque (d) conventional DTC at 1.0 Nm ref. torque

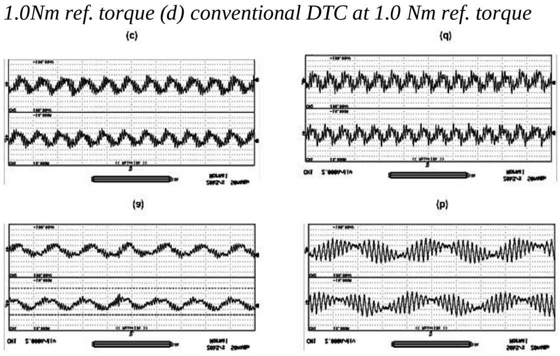

Fig. 7 shows the stator current ripple in four scenarios: (a) modified duty ratio controlled DTC operating at 400 rpm, (b) conventional DTC operating at 400 rpm, (c) modified duty ratio controlled DTC operating at 1000 rpm, and (d) conventional DTC operating at 1000 rpm.

Table 4 Performance parameters for conventional DTC drive for Ht=0.5Nm

Speed	**Mean torque (Nm)**	**RMSTE (Nm)**	**RMSTE (In perc. of mean torque)**	**RMSFE**	**Current ripple**
1500	0.8921	0.3260	36.5393	1.5005	10.13
1350	0.7375	0.6156	83.4690	1.5900	11.94
1250	0.6419	0.5972	93.0311	1.8135	17.24
1000	0.4569	0.6150	134.5902	1.8856	11.67
400	0.3268	0.9169	280.6108	1.5039	16.92
200	0.3210	0.9214	287.12	1.7042	17.01

Table 5Performance parameters for switching strategy based on modified duty cycle control with 5-level hysteresis control at Ht=0.5 Nm

Speed	**Mean torque (Nm)**	**RMSTE (Nm)**	**RMSTE (In perc. of mean torque)**	**RMSFE**	**Current ripple**
1500	0.8851	0.3205	36.12%	1.49	7.18
1430	0.8670	0.3131	36.10	1.48	1.42
1250	0.7007	0.5059	72.10	4.32	22.16
1100	0.6546	0.5111	78.07	5.28	10.77
700	0.66	0.5001	77.6	7.07	7.02
400	0.3558	0.5216	146%	7.74	16.02

Table 6 compares the performance of a conventional Direct Torque Control (DTC) drive with that of a modified duty ratio controlled drive for a torque value of Ht=0.5Nm.

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	Conventional		**Modified Duty ratio**	
Speed	**RMSTE (In perc. of mean torque)**	**Current ripple**	**RMSTE (In perc. of mean torque)**	**Current ripple**
1500	36.5393	10.13	36.12	7.18
1250	93.0311	17.24	72.10	22.16
400	280.6108	16.92	146.0	16.02

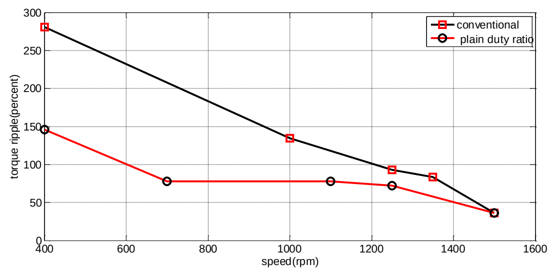

Fig. 8 shows a hysteresis comparator to compare the torque ripple caused by modified duty ratio control to conventional control for a torque value of 0.5 Nm.

Figure 8 demonstrates how the proposed duty ratio controlled switching technique can reduce torque ripple by comparing it with conventional duty ratio control using a hysteresis comparator for a torque level of 0.5 Nm. The comparison shows that the modified duty ratio control effectively decreases torque ripple.

V CONCLUSION:

The proposed I.M. drive system makes use of the suggested DTC control method. The results of the suggested and conventional DTC systems are compared in the same circumstance. Yet, the results are consistent with the I.M. drive system's better performance when using the suggested DTC technique.

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