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Research Article

A Novel space vector modulated DTC scheme of induction motor drive with a single PI controller for electric vehicles

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Abstract: Facilitating instantaneous torque and smooth speed of Electric vehicle (EV) largely relies on modulation scheme employed and type of controller used for motor drive system. The DTC-SVM (Space Vector Modulation) approach with two PI controllers has an excellent steady state and transient response. However, there is still a need to reduce stator current and torque ripples in induction motor for application in Electric vehicle. This paper presents a new approach to minimize stator current harmonics, torque ripple of an induction motor drive with appropriate gain value for torque PI controller. Good performance of the induction motor drive is achieved using a single PI controller. Both flux and torque are controlled effectively with less torque ripple. In this study, torque and current ripples are obtained at full, one-half and one-fourth of the rated speeds at rated torque value. This work analyzes the transient operation of the drive for unit step change in command torque at various rotor speeds. Space Vector Pulse Width Modulation (SVPWM) of the drive at constant switching frequency is presented. Modeling and Simulation is performed in the stationary reference frame theory. The performance is observed during steady state and transient operations. The settling time of torque responses and stator currents are obtained during transient conditions. Torque ripples are obtained during steady state. A comparison with DTC-SVM with two PI controllers for the same Torque commands is well understood. Total Harmonic Distortion (THD) in the motor input current at different reference fluxes are tabulated for classical, two PI controllers and a single PI controller. The proposed DTC-SVM scheme with single PI controller is found to be robust with good steady state and transient characteristics with less settling time and is validated with flux vector trajectories.

Keywords: *Direct Torque Control, Electric vehicle, Induction motor, Proportional plus integral control, Robust, Space vector modulation, Total harmonic distortion*

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1. INTRODUCTION

Three phase induction motors especially the squirrel cage induction motors are largely used in industries because of less cost, robustness, high reliability and less maintenance. The limitation of not possessing constant speed during load changes can be overcome using adjustable speed drives. There are different approaches by which an induction motor drive (IMD) can be controlled like Direct Torque Control (DTC), Scalar control, and Vector control etc. DTC is the widely accepted method and is suitable for commercial, industrial, traction and electric vehicle applications. However, high performance of an electric drive is not obtained due to variable inverter switching frequency behavior, high current ripples and high torque ripples [1-3].

Direct Torque control is recognized as being the simplest AC drive control technology and is suitable for commercial, industrial, traction and electric vehicle (EV) applications. Traditional controllers in the Direct Torque Control system were introduced by Takahashi and Depenbrock in the mid-1980s. Traditional DTC consists of hysteresis comparators with three level for output torque and two level for output flux. It does not possess any modulation algorithm and there exists no processing of feedback signals. This traditional method is easy to implement and it shows good response at transient conditions [4]. However, there is a major drawback of excessive current, torque ripples during steady state operation. Due to absence of modulation algorithms, this hysteresis control is not much suitable for application in EVs.

For obtaining an improved performance of DTC-SVM (Space Vector Modulation), hysteresis controller is replaced with two Proportional plus Integral (PI) controllers for torque and flux are proposed in [5,6]. This technique addressed the problem of high flux and high torque ripples during steady state and also it alleviates the dynamic response times during load variations. However, this system is unable to tolerate changes in motor parameters and is not robust against extraneous perturbations. The major problems in DTC are flux and torque ripples, low speed control and high Total Harmonic Distortion (THD) in stator current. PI controllers are sensitive to parameter variations and external disturbances. In the last 30 years, many researchers tried to solve the mentioned problems and the following solutions have been reported in the literature. Therefore, a need arises to minimize the current and torque ripples to a large extent possible while improving the robustness and efficiency using a single PI controller:

- *Variable amplitude control of Flux and Torque Hysteresis bands [7].*
- *Dynamic hysteresis Torque band for improving the performance of Lookup-Table-Based DTC of Induction Machines [8].*
- *A simple duty-cycle modulated direct torque control [9].*
- *Direct Torque Control of Induction Motor Drive with Space vector modulation using two PI Controllers at constant switching frequency [10].*
- *Induction Motor control using Non-Linear Sliding Mode theory [11].*
- *Fuzzy Sliding-Mode Speed Control with Torque Observer in Induction Motor Drive [12].*
- *Speed Control of Induction Motor Using Neural Network Sliding Mode Controller [13].*
- *Reduction of Torque and Flux Variations Using a Fuzzy Direct Torque Control System in Motor Drive [14].*
- *Induction Motor DTC Based on Adaptive SMC and Fuzzy Control [15].*
- *Implementation of Robust SVM-DTC for Induction Motor Drive Using Second-Order Sliding Mode Control [16].*
- *Super-Twisting Sliding Mode Direct Torque and Flux Control of Induction Machine Drives [17].*
- *Integral Super Twisting Sliding Mode Based Sensorless Predictive Torque Control of Induction Motor [18].*

The merits of using the method proposed here are (*i*) reference stator flux vector is obtained from torque PI controller and therefore optimum reference voltage space vector is supplied to terminals of motor for reduction in stator flux, current, torque ripples. (*ii*) co-ordinate transformation is not required (*iii*) a single PI controller is used to control both electromagnetic torque and stator flux instead of individual torque and flux PI controllers. This work distinguishes from the existing literature by replacing the number of PI controllers existing in SVM-DTC technique. The advantages of IMD using the proposed controller justify its better suitability in HEV applications. The merits of Space vector modulated DTC scheme over other classical schemes (Field oriented or Direct Torque Control) permits effective speed control particularly at low speeds and its novel application in HEVs justifies better steady state and dynamic torque responses with less ripples.

In this work, DTC-SVM with a single PI controller is proposed to reduce flux, current and torque ripples for an IMD during steady state operation. This proposed controller improves the response times during transient operations of IMD for meeting the load and speed variations [19,20]. The proposed DTC-SVM is much more efficient and cost-effective solution when compared to DTC-SVM with two PI controllers.

Entire Simulation work is executed for 4 kW induction motor considering run time as 1 s. In this work, steady state torque responses are obtained for full rated, one-half and one-fourth of nominated torque values under different rotor speeds [21]. Moreover, transient performance is analyzed for step change of load torque command in 0.5 s at full, one-half, one-fourth of rated load torque values under various commanding speeds. The proposed DTC scheme with single torque PI controller is analyzed with settling times acquired during transient operating conditions. The current and torque ripples are obtained during steady state. A comparison with DTC-SVM using two PI controllers for the same Torque commands is presented. The main contributions of the paper include (*i*) proposed single PI controller based DTC-SVM scheme, (*ii*) steady state and dynamic characteristics of IMD, (*iii*) THD at different loads with different flux references, (*iv*) stator flux vector during transient phenomenon and its comparison to conventional and DTC-SVM with two PI controllers, (*v*) flux ripple theoretical verification, (*vi*) comparison of current, torque ripples and settling times at different loads with respect to conventional DTC schemes.

The mathematical model of IMD for electromagnetic torque is presented in Sec. 2. Sec. 3 presents DTC-SVM scheme with two PI controllers. The DTC-SVM scheme with a single PI controller is explained in Sec. 4. Sec. 5 and 6 presents the simulation results and conclusions respectively.

2. DERIVATION OF ELECTROMAGNETIC TORQUE OF THREE PHASE IMD USING STATOR REFERENCE FRAME

The voltage equations in α, β coordinate system attached to stationary reference frame is given as

$$v^{s}{}_{s\alpha} = \frac{2}{3} \times \left(v_{sa} - \frac{1}{2} v_{sb} - \frac{1}{2} v_{sc} \right), \tag{1}$$

$$v^{s}{}_{s\beta} = \frac{2}{3} \times \left(\frac{\sqrt{3}}{2} v_{sb} - \frac{\sqrt{3}}{2} v_{sc} \right). \tag{2}$$

Resultant voltage space vector in a stator reference frame is presented in Eq. 3 and its magnitude is given by Eq. 4.

$$v_S^s = v^s{}_{s\alpha} + j v^s{}_{s\beta}, \tag{3}$$

$$\left| v_S^s \right| = \sqrt{\left(v^s{}_{s\alpha}{}^2 + v^s{}_{s\beta}{}^2 \right)}. \tag{4}$$

The Stator current equations in α, β coordinate system attached to stationary reference frame is given as Eq. (5) and Eq. (6) respectively.

$$i^{S}{}_{s\alpha} = \frac{2}{3} \times \left(i_{sa} - \frac{1}{2} i_{sb} - \frac{1}{2} i_{sc} \right), \tag{5}$$

$$i^{S}{}_{s\beta} = \frac{2}{3} \times \left(\frac{\sqrt{3}}{2} i_{sb} - \frac{\sqrt{3}}{2} i_{sc} \right). \tag{6}$$

Stator flux linkages in α, β coordinate system is given in Eq. (7) and Eq. (8) and magnitude of resultant stator flux linkage is given by Eq. (9).

$$\Psi^{S}{}_{s\alpha} = \int \left(V_{S\alpha} - r_a i_{S\alpha} \right), \tag{7}$$

$$\Psi^{S}_{S\beta} = \int \left(V_{S\beta} - r_a i_{S\beta} \right), \tag{8}$$

$$\left| \overline{\Psi}^{S}{}_{s} \right| = \sqrt{\left(\Psi^{S}{}_{s\alpha}{}^{2} + \Psi^{S}{}_{s\beta}{}^{2} \right)}. \tag{9}$$

The angular speed in (rad/sec) by which the resultant voltage space vector rotates is given by Eq. (10) where f is a fundamental frequency and t is time period in seconds.

$$\theta = \omega t = 2 \times \pi \times f \times t = \tan^{-1} \left(\frac{v^{S}{}_{s\beta}}{v^{S}{}_{s\alpha}} \right) \tag{10}$$

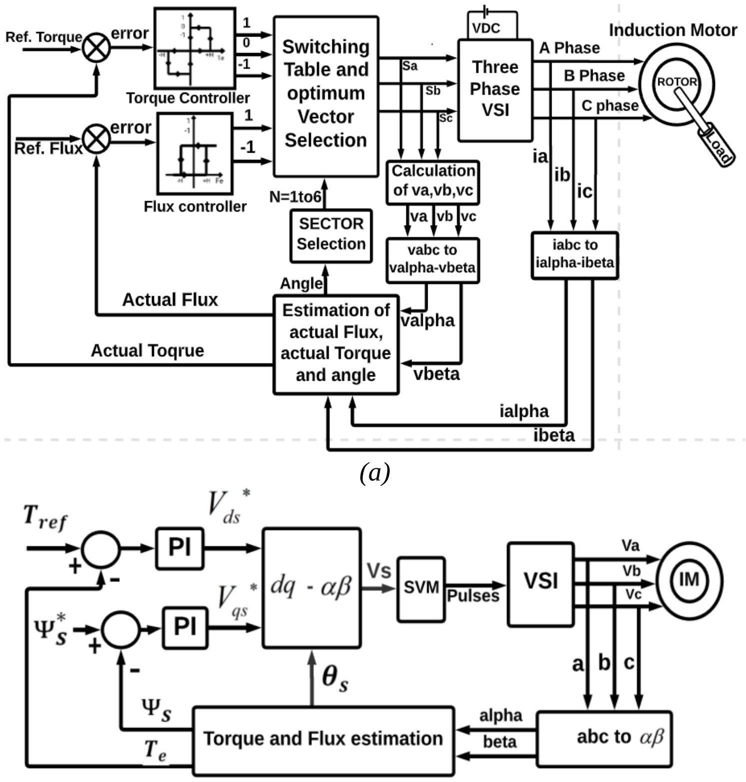
Electro-mechanical Torque of induction motor is given by Eq. (11), where P indicates the number of poles of the machine.

$$T_e = \frac{3}{2} \left(\frac{P}{2} \right) \left[\left(\Psi^{S}{}_{s\alpha} \times i^{S}{}_{s\beta} \right) - \left(\Psi^{S}{}_{s\beta} \times i^{S}{}_{s\alpha} \right) \right] \tag{11}$$

3. DTC-SVM USING TWO PI CONTROLLERS

DTC-SVM with two PI controllers comprises of separate PI controllers for Flux and torque, Space vector modulation block, estimation of actual flux, motor torque, stator reference voltage and space vector angle [22]. The conventional DTC-SVM scheme is shown in Fig. 1(a). DTC-SVM with two PI controllers is shown in Fig. 1(b).

In this technique, instantaneous torque is obtained directly by varying stator voltage vector based on torque and flux errors obtained using two separate control loops. The DC-Link voltage is maintained constant whereas constant switching frequency operation is performed for reduction in inverter switching losses. This scheme of control best reduces the current and torque ripples while preserving the merits of good dynamic response obtained with traditional control schemes. It is applicable to high power applications [23]. Fig. 2 shows sectors of operation of proposed DTC scheme in α-β coordinate system in stator fixed reference frame.



(a)

(b)

Figure 1. Conventional DTC-SVM with (a) Hysteresis control, and (b) two PI controllers.

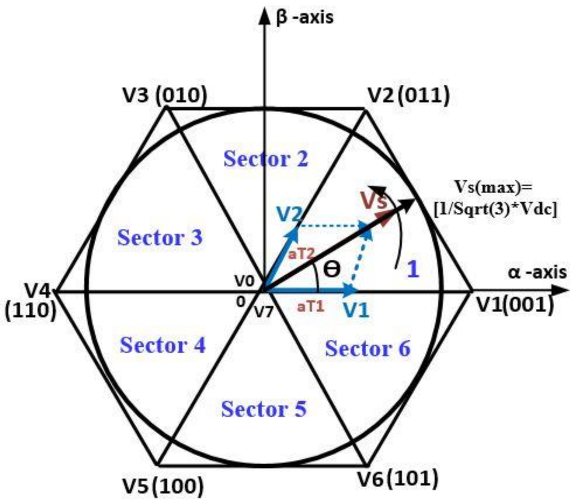


Figure 2. Sectors of operation.

In this method the estimated torque and desired torque command are compared in torque control loop whereas estimated stator flux and desired flux command are compared in flux control loop. The errors developed via control loops are given to torque and flux PI controller blocks [24]. The outputs of these controller blocks undergo d-q to α-β transformation for calculating the reference space vector. This calculated reference voltage meets the instantaneous torque requirement of IMD.

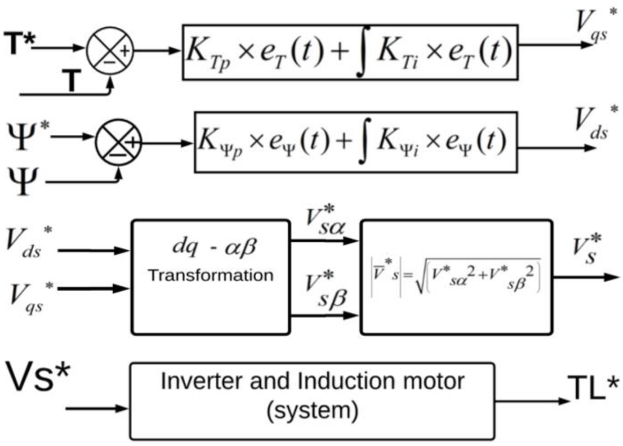


Figure 3. Closed loop operation.

Fig. 3 shows the closed loop operation where the reference voltage V_s^* and torque T_L^* are obtained. The increment in stator flux linkage obtained within an interval of time is directly proportional to change in the reference stator voltage space vector. Fig. 4 shows variation of stator flux linkage for a change in the reference voltage vector [25].

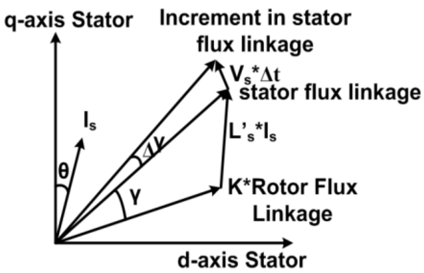


Figure 4. The variation in stator flux linkage for change in stator voltage reference vector.

4. A NOVEL SPACE VECTOR MODULATED DTC WITH SINGLE PI CONTROLLER

The DTC-SVM scheme with a single PI controller is shown in Fig. 5. Torque comparator produces differential torque from reference T_{ref} and estimated torque T_e as inputs. The output of the torque comparator is fed to torque PI controller and its output is taken as slip angle θ_{sl}. The slip angle is then added with rotor angle θ_r to obtain the reference stator angle θ_s. The complex form of the stator flux is obtained as output in the flux calculation block with the help of stator flux reference Ψ_s^* and flux angle θ_s. The complex form of stator flux is given as input to flux comparator whose output decides the stator reference voltage space vector V_s.

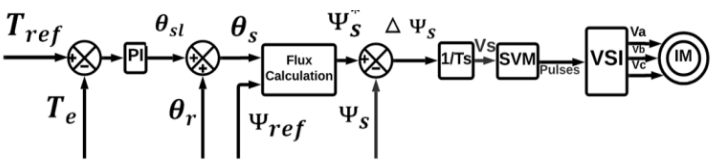


Figure 5. DTC-SVPWM with single PI controller

In this technique, the reference stator voltage V_s is obtained from a torque PI controller which is used to minimize the stator flux ripples and in turn reduce the torque ripples of a Three-Phase IMD. The proposed control scheme requires a single PI controller to control both stator flux and electromechanical Torque. As compared to conventional DTC-SVM, the computational burden on proposed controller reduces drastically by eliminating complex trigonometric calculations and sector identifier.

5. SIMULATION RESULTS

Simulation results using MATLAB Simulink are presented for single and two PI controllers DTC schemes. In this work both schemes are operated at the same working conditions for better comparison of flux and torque ripples during steady state. Table 1 represents specifications of the induction motor.

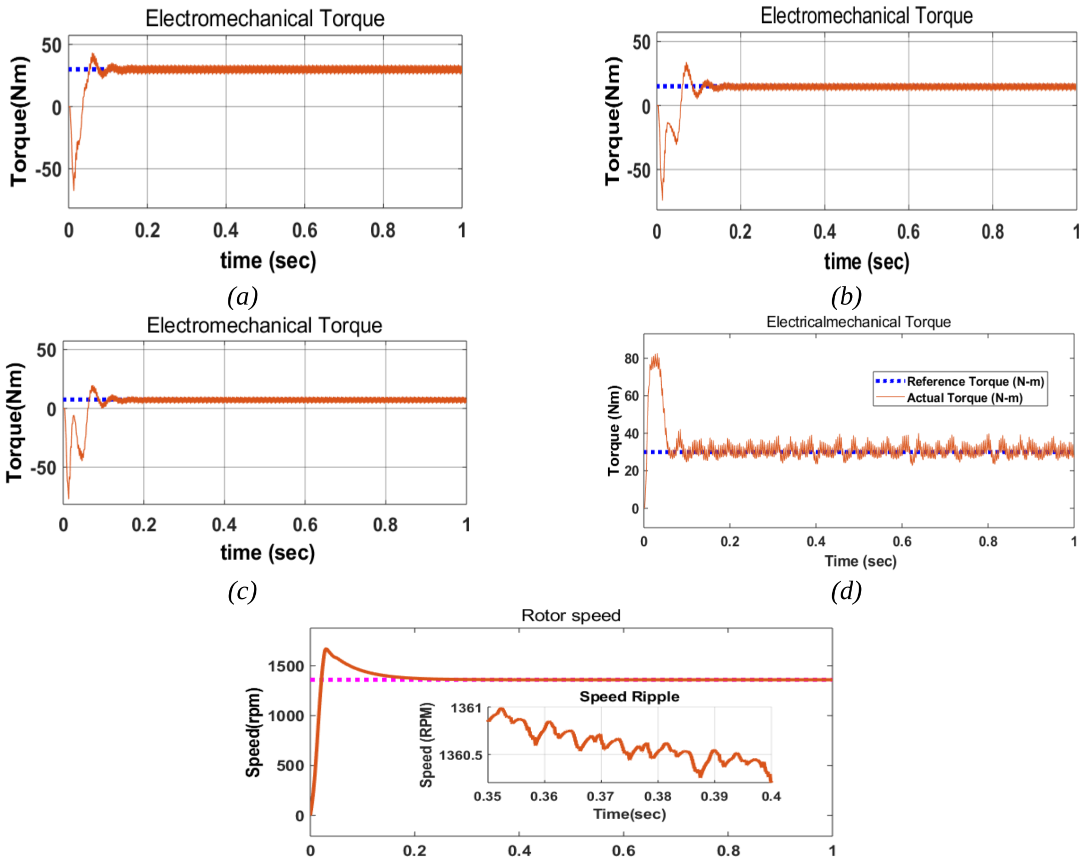
Table 1. Specifications of induction motor.

Variables	Simulated Value
Rating of the Induction motor, P	5.4 HP
Voltage (L-L), V_{rms}	440 V
Power frequency, f	50 Hz
Rated Torque, T	30 N-m
Rated Current (Peak)	16 A
Nominal Speed, N_{nom}	1430 rpm

5.1. DTC-SVM with two PI controller results

First the conventional DTC scheme with two PI controllers results have been presented. The results show good steady state and transient responses but with high current and torque ripples.

(i) Fig. 6 represents steady state torque responses at different loads. Using classical DTC-SVM method, at full load condition i.e. 30 Nm and rated speed of 1430 rpm, steady state response characteristics are presented in Fig. 6(a). For one-half and one-fourth loads, the corresponding characteristics are presented in Fig. 6(b) and Fig. 6(c). Excellent tracking of actual and estimated toques are realized from these waveforms.



(e)

Figure 6. Electromechanical torque obtained during steady state at (a) full load (b) Half load (c) one-fourth load. (d) Electromagnetic torque for the conventional DTC scheme and (e) Rated speed response for the conventional DTC scheme.

It is very clear that the conventional DTC-SVM scheme using Two PI controllers offers a poor performance in terms of ripple in the electromagnetic torque developed and speed response.

(ii) Fig. 7 shows the responses of torque during transient state at different loads. During sudden changes of torque at t=0.5 s, the operation is performed at full load condition. The full load condition is 30 Nm and rated speed is 1430 rpm. It is observed that the actual electromagnetic torque starts following the reference torque with less overshoots. Similar operation is performed at one-half and one-fourth loads using DTC-SVM controller. The operation of the inverter is at a constant 5 kHz switching frequency. The switching pulses to the complementary IGBT switches are presented in Fig. 8. The corresponding stator phase currents at 30 N-m load at 1430 rpm speed are presented during steady state and transient condition from 0.1 s to 0.5 s are presented in Figs. 9 and 10. The controller is said to be robust against load variations.

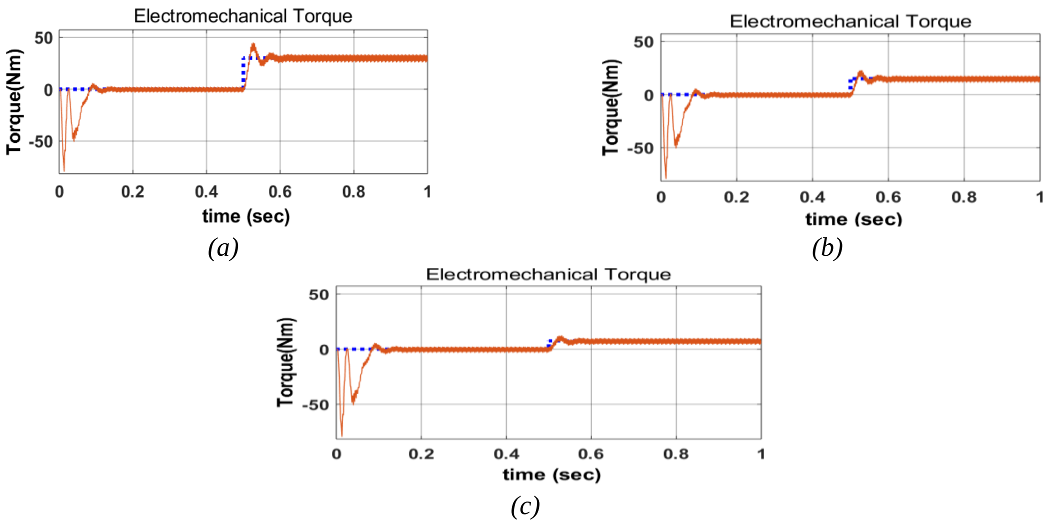


Figure 7. Electromechanical torque obtained during transient condition at (a) full load (b) 1/2 load (c) ¼thload.

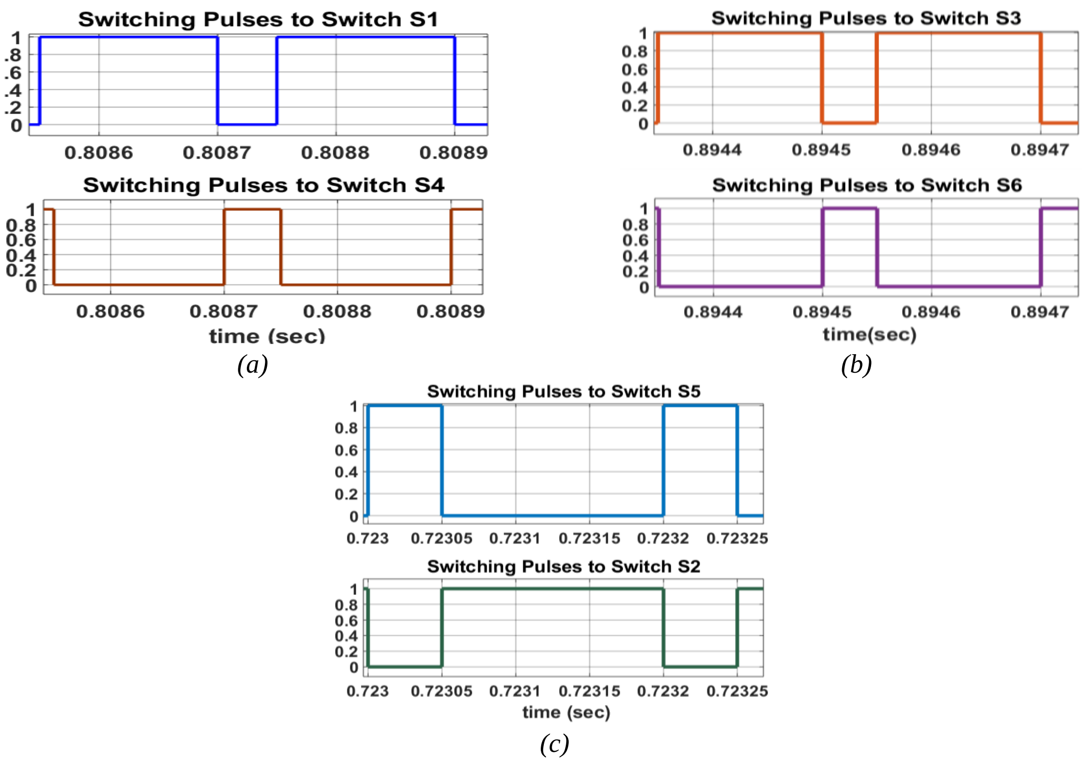


Figure 8. Complimentary gating pulses for IGBT switches(a) S_1, S_4, (b) S_3, S_6, (c) S_5, S_2 at 5 kHz switching frequency.

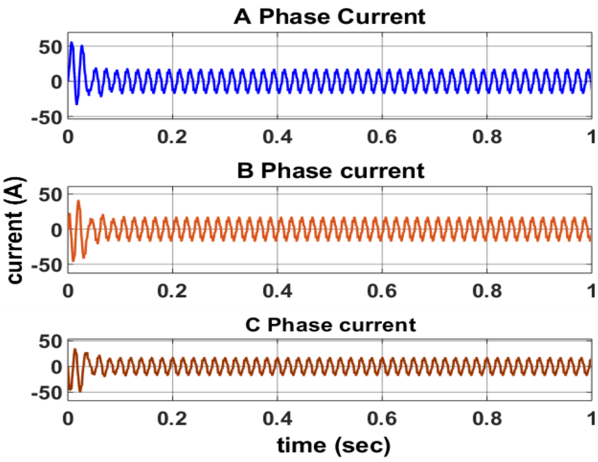


Figure 9. Stator currents during steady state operation at full load.

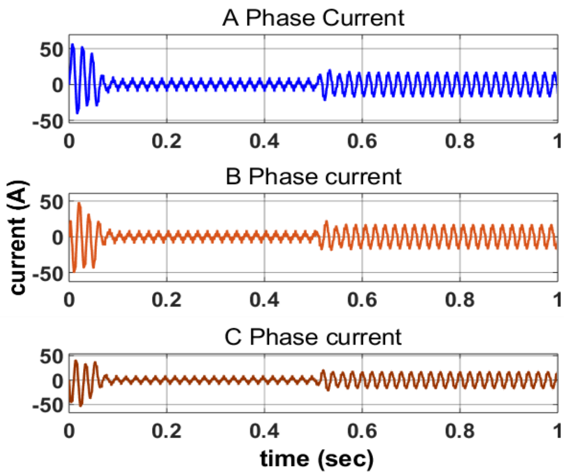
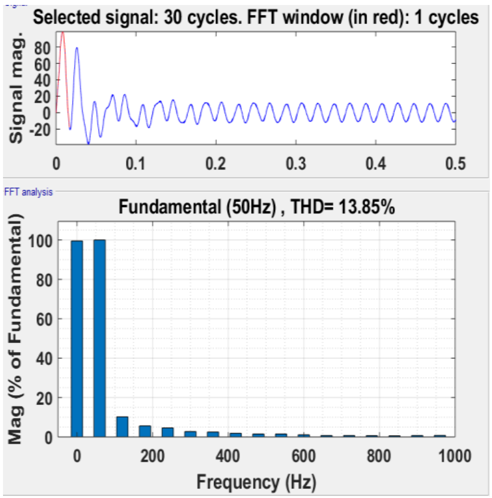
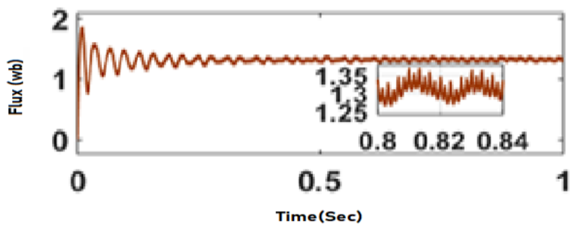


Figure 10. Stator currents during transient operation at full load.

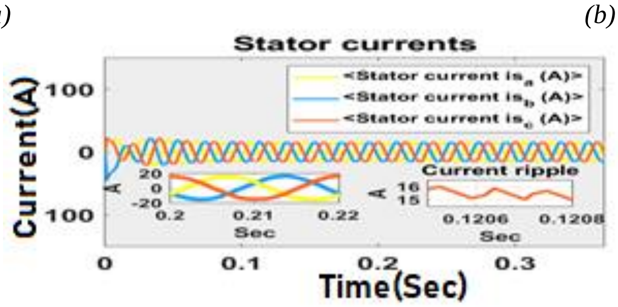
Fig. 11 (a) shows FFT analysis of stator current of a Three-Phase IM in a Classical DTC-SVM scheme with two PI controllers. It is observed that the stator current has a Total Harmonic Distortion of 13.85%. The 3rd harmonic component constitutes 5.13% of f undamental waveform and 5th Harmonic component constitutes 5.82% of fundamental. The remaining all other higher order harmonics are less than 3 percent of fundamental magnitude. Fig. 11(b) and (c) presents the stator flux and stator currents. It is seen that the waveforms have ripple content and disturbances.



(a)



(b)



(c)

Figure 11. (a) THD spectrum for the stator current of three phase induction motor, (b) stator flux waveform, (c) stator current waveforms.

5.2. Proposed Space Vector Modulated DTC with single PI controller Results

The simulation results are presented only at one-fourth loads so as to analyze the system performance at low speeds. The controller in Fig. 5 is used to obtain the results.

(i) The steady state torque response is shown in Fig. 12. The controller is able to track the reference torque with less distortions at one-fourth load i.e. 7.5 Nm and rated 1430 rpm. A torque ripple of 1 Nm is observed.

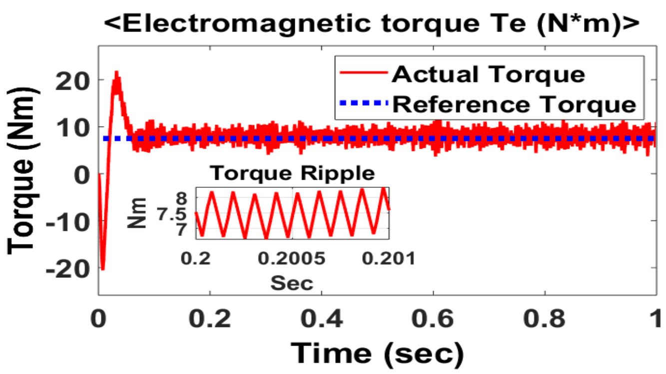


Figure 12. Steady state Torque response at Quarter load

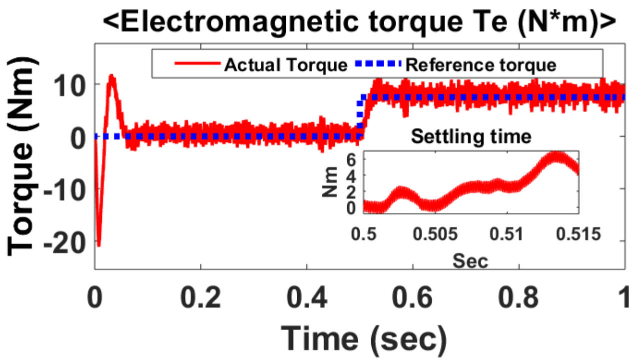


Figure 13. Electromagnetic torque response at 1430 rpm for Quarter load condition using proposed DTC-SVM control strategy.

(ii) Fig. 13 shows the torque response during transient operation. At one-fourth load condition and rated speed of 1430 rpm, the tracking of actual torque with the reference torque is obtained with less settling time.

(iii) Torque reversal is presented in Fig. 14. It shows the response from -7.5 Nm to +7.5 Nm at 1430 rpm. The ability of the controller to track the reference value with less ripples is realized.

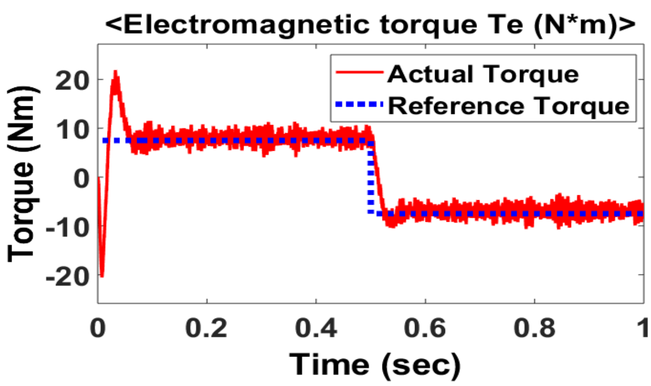


Figure 14. Reference and Actual torque tracking during torque reversal.

Fig. 15(a) shows FFT analysis and its list corresponding to stator current. With switching frequency of 5 kHz and output frequency of 50 Hz the stator current has a Total Harmonic Distortion of 13.72%. The 3rd harmonic component constitutes 3.5% of fundamental waveform and 5th harmonic component constitutes 2.84% of fundamental. The remaining all other higher order harmonics are less than 3 percent of fundamental magnitude. The proposed DTC-SVM with single PI controller has quick response during steady state and minimum torque ripple of 1.8 Nm and ripple current of 0.4 A as compared to 2 Nm and 0.6 A in DTC-SVM scheme with two PI controllers at the same operating conditions. The stator flux and stator currents in Figs. 15(b) and (c) are observed to be smooth as compared with two PI controllers.

Table 2. Torque and Current at varying speeds in DTC-SVM with two pi controllers and novel space vector modulated DTC with single PI controller.

Speed (rpm)	1430				715				357.5			
	Ripple Current (A)		Torque Ripple (Nm)		Ripple Current (A)		Torque Ripple (Nm)		Ripple Current (A)		Torque Ripple (Nm)	
Torque (Nm)	Two PI	One PI	Two PI	One PI	Two PI	One PI	Two PI	One PI	Two PI	One PI	Two PI	One PI
30	0.6	0.4	2	1.8	0.5	0.36	1.8	1.65	0.35	0.31	1.65	1.6
15	0.3	0.28	1.6	1.52	0.25	0.21	1.25	1.2	0.2	0.18	1.2	1.1
7.5	0.25	0.2	1.2	1	0.23	0.18	1.1	0.95	0.21	0.16	1	0.9

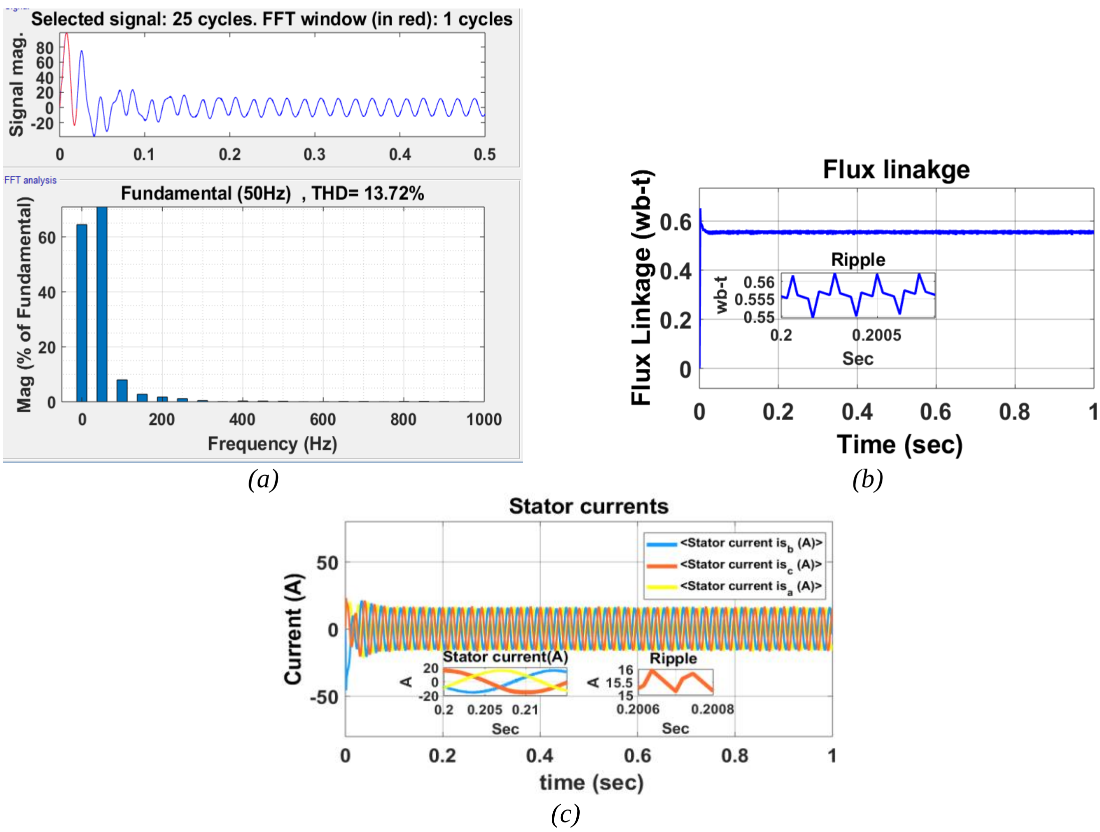
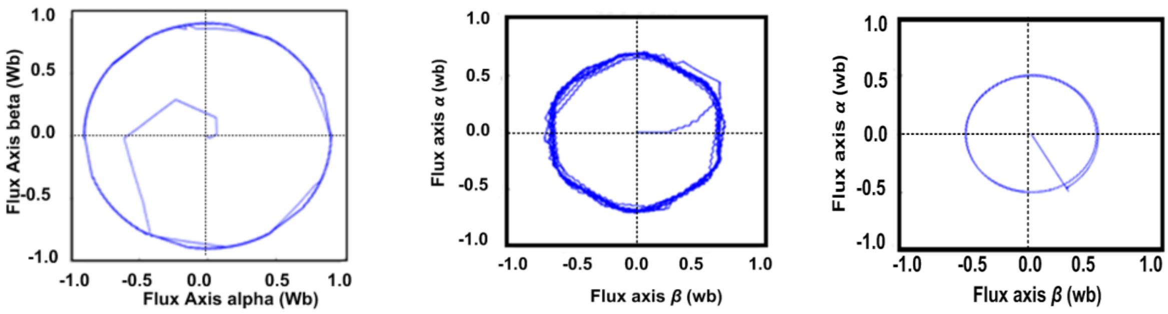


Figure 15.THD spectrum for the stator current of three phase induction motor using the proposed controller, (b) stator flux, (c) stator current waveforms with the ripple content.

During transient conditions, it shows quick response with 15 ms whereas DTC-SVM with two PI controllers takes 30 ms under the same dynamic conditions. This work is better than the existing control methods in minimizing torque ripple when compared to available classical control techniques. Table 2 presents the comparative analysis of stator current and output torque at different speeds in DTC-SVM using single and two PI controllers. Table 3 presents the settling times of torque. It is found that the proposed scheme performs much better than with two PI controllers. From Fig. 16, it is clear that the proposed controller with a single PI has a circular trajectory with less distortions as compared to few oscillations before reaching the reference value of flux in conventional and with two PI controllers.



(a) (b) (c)

Figure 16. Stator Flux trajectories for DTC-SVM (a) Classical, (b) two PI controllers, and (c) single PI controller at 25 % speed.

Table 3. Comparison of Settling times in obtaining Torque response using Single PI and Two PI controllers.

Induction Motor Speed (rpm)	Settling times in DTC-SVM with two PI controllers	Settling times in Proposed DTC-SVM with single PI controller
1430	30 ms	15 ms
715	18 ms	10 ms
357.5	15 ms	8 ms

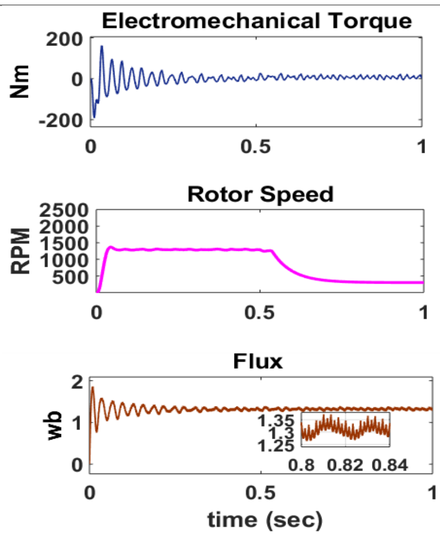
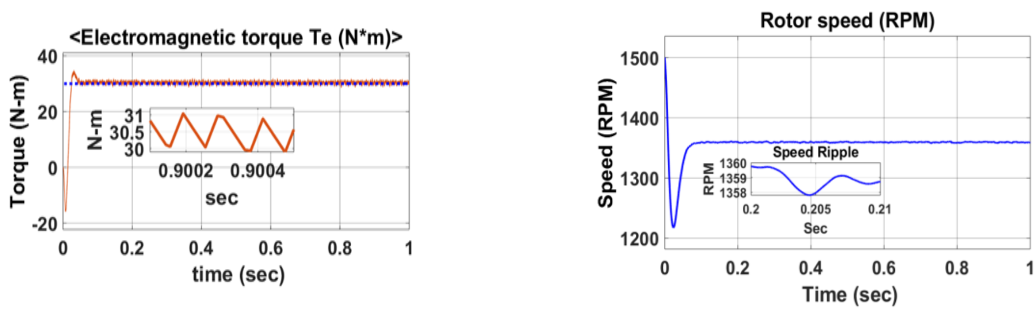


Figure 17. Torque and flux waveforms at 25 % speed using DTC-SVM with single PI.

Fig. 17 shows the torque and flux waveforms at low speeds. It is clear that the controller works effectively at very low speeds. Table 4 shows the comparison of THD for all the three DTC schemes at different reference flux values. Fig.18 shows the speed response and torque response at rated values. Fig. 19 is the simulink model developed in Matlab.



(a) (b)

Figure 18. (a) Torque response along with ripple content at the rated speed, (b) rated speed response versus time.

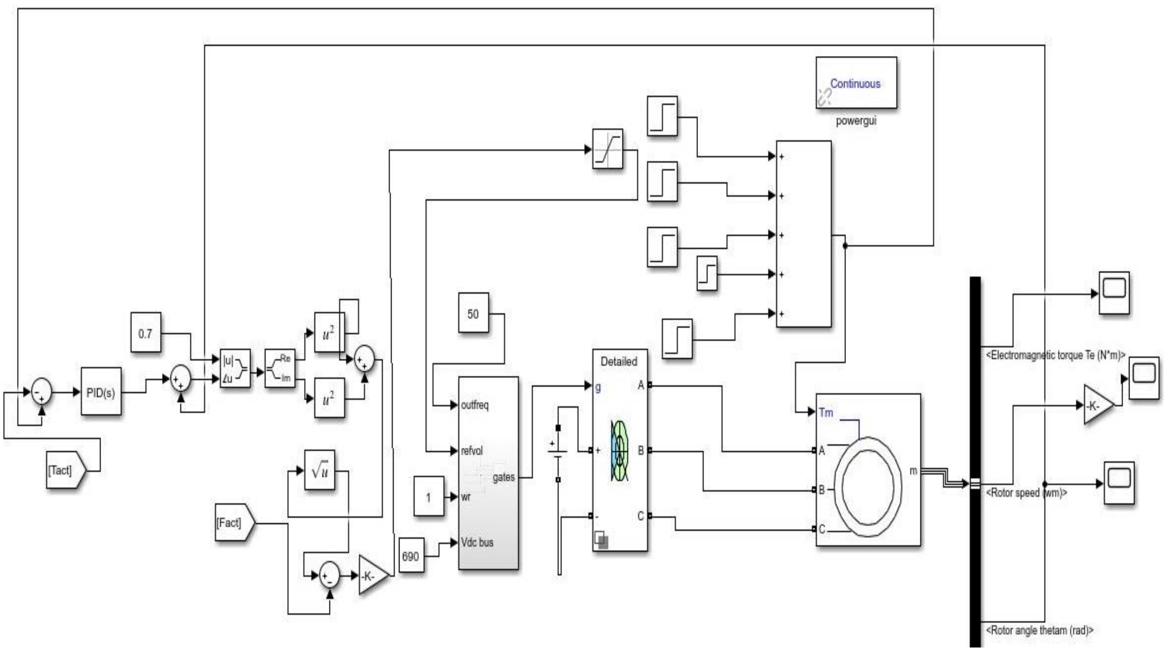


Figure 19. Simulink Matlab model.

Table 4. Total Harmonic Distortion (THD) analyzes.

DTC	Total harmonic distortion (%)					
	Full load			One-Fourth load		
Schemes	Φ_{ref} (wb)			Φ_{ref} (wb)		
	1.0	0.8	0.6	1.0	0.8	0.6
Classical [26]	30.1	30.24	30.31	30.42	30.49	30.51
Two PI	14.47	14.50	14.68	14.72	14.81	14.93
Single PI	13.84	13.92	13.98	13.9	13.94	13.96

6. CONCLUSION

The best control technique to reduce current and torque ripples such that a smooth operation of the drive can be achieved is the need of the hour for an EV. This work investigates the application of DTC-SVM scheme with a single PI controller for IMD used in electric vehicles. Modeling of the induction motor along with electromagnetic torque expression is presented. Torque ripples, flux ripples, stator current THD, settling time, flux trajectories are the chosen parameters to estimate the performance of the proposed control technique. As compared to classical DTC-SVM approach and DTC-SVM with two PI controllers' approach, DTC based on SVM using single PI controller is found to be excellent in obtaining pure sinusoidal stator currents with less THD of 13.72 %, less settling time of 8 ms, less current ripple of 0.16 A and less torque ripple of 0.9 N-m. Simulation results also reveal excellent tracking of torque at varying speeds. In addition, the proposed controller works well at very low speeds which confirm its adaptability to EV application. The work can be extended to study of steady state and dynamic performance under uncertainties incorporating non- linear controllers.

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