

Techniques for Torque Ripple Mitigation in BLDC Motor for Electric Vehicle

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Abstract—Brushless DC Motor has wide-ranging applications in industries with high efficiency, low cost, high torque to mass ratio etc. Especially in Electric Vehicles (EV) it has gained its popularity where it mostly uses BLDC hub motor. But BLDC motor has got some drawbacks, especially during dynamic load conditions it experiences a slight vibration due to torque ripple. Torque ripple can be caused because of commutation torque ripple, mechanical defects, current ripples, imperfect EMF waveform, cogging torque ripple etc. This literally affects the smooth driving experience. This paper relies on the ways to mitigate the torque ripple which is the main incitement for less lifespan of BLDC motor than Induction Motor. It also focus on the mathematical modelling of Brushless_DC_motor and control technique for torque_ripple reduction.

Index Terms— Brushless DC motor, torque ripple, back EMF, mathematical modelling, Pulse Width Modulation, Sliding Mode Controller, Proportional Integral Controller.

I. INTRODUCTION

Brushless DC motor do not have brushed contact which leads to friction loss, heat loss, less life, noisy as in Brushed DC motor. It works on the law of attraction and repulsion. It has got wide range of applications in automotive industry, drones, pumping industry, rolling industry, automation robots, SMPS, toys etc.[1]. The main parts of BLDC motor consists of rotor, stator, electromagnets, upcoming years the use of EV's will be shooting high as it works on electricity rather than internal combustion engine. It is a heavenly solution for the rising air pollution and sky rocketing fuel price. Around 80% to 85% motor used for EV is BLDC hub motors as they are very efficient, high torque to mass ratio, low cost, less noise etc. but on the other hand it experience electromagnetic interference, torque ripple, acoustic noise [4] which deteriorates the performance of the system. Our literature focuses on the ways to abate the torque ripple and improving the efficiency of the BLDC hub motor.

Vibration noise is produced mainly due to the commutation torque ripple [2] in a Brushless DC motor which is operating in a driving mode of six steps. Mechanical defects [3] in the motor is another main reason for torque ripple. In [5] develops a model to reduce ripples in torque based on the phase current PWM model predictive control method and trapezoidal BEMF. But this control strategy suppresses torque ripple only till 1500 rpm. In literature [6], torque ripple reduction using Pulse Amplitude Modulation is mentioned. This method is effective for torque ripple reduction of Brushless DC motor at low speed. A hybrid Cuk DC-DC converter to mitigate the torque ripple

and to improve the voltage rating of the BLDC motor [7]. But by the use of a hybrid Cuk DC-DC converter along with three-phase inverter increases the complexity as well as cost of the circuit. PWM based method is proposed in [5] for a low inductance BLDC motor for commutation torque ripple reduction upto 27.6% and for minimizing the commutation time period to three times the time period. But the drawback of this method is it is not versatile and exclusively used for slotless BLDC motor drive applications like partial prosthetic hand systems. A hybrid switched reluctance motor of 3kW, 60V for electric vehicle (EV) is demonstrated in [15] by improving its performance and reducing torque ripple but it is demonstrated only for no load condition. The electric vehicle (EV) experiences torque ripple under dynamic load condition. Literature [16] proposes a commutation torque optimization using a hybrid pulse width modulation (PWM) technique which consist of a voltage source inverter (VSI) that helps to eliminate the pulse width modulation (PWM) update delay. It investigates on hall signal errors which contributes to torque ripple and regenerative balanced hall signal that eliminates the misaligned and uneven hall signals in the BLDC motor but implementing this system is very tedious and complex.

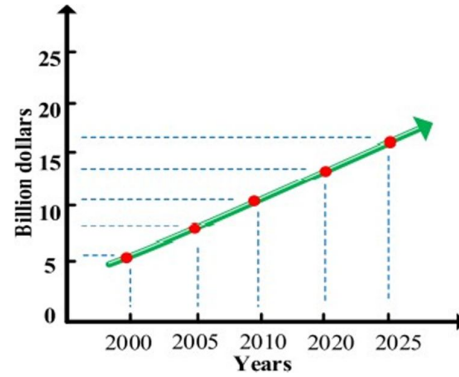


Fig. 1: Market report of BLDC motor

II. MATHEMATICAL MODELLING OF BLDC

Fig. 2 depicts the analogous circuit of a three-phase_inverter-driven BLDCM. A Brushless DC drive's basic components are two-level three-phase_inverter, permanent magnets, electromagnets and DC supply.

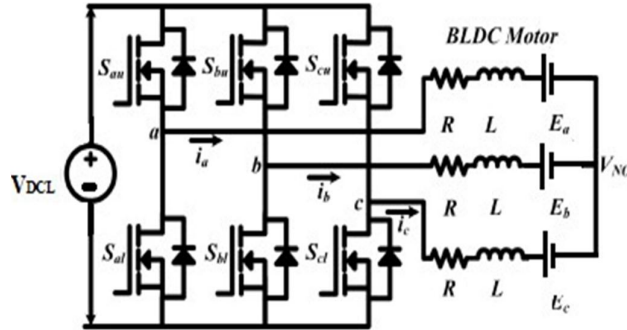


Fig. 2: Equivalent circuit for a three-phase_inverter driven Brushless DC Motor

The 3-phase stator winding of a BLDCM's per phase voltage equations can be expressed as

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} L & 0 & 0 \\ 0 & L & 0 \\ 0 & 0 & L \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} V_{NO} \\ V_{NO} \\ V_{NO} \end{bmatrix} + \begin{bmatrix} E_a \\ E_b \\ E_c \end{bmatrix} \quad (1)$$

where the phase voltages are V_a , V_b , and V_c . The BLDCM's symmetrical 3-phase winding is made up of equal values for resistance, inductance, and electromagnetic field (EMF) at the neutral back E_b , E_c , and E_a . Phase currents i_a , i_b , and i_c are present. Neutral voltage is represented as V_{NO} . The equation for the instantaneous electromagnetic torque is

$$T_{em} = \frac{E_a \cdot i_a + E_b \cdot i_b + E_c \cdot i_c}{\omega_m} \quad (2)$$

where ω_m is the BLDCM's angular speed measured in radians per second.

The optimum waveforms of BEMF and 3-phase current for a BLDCM are depicted in Fig. 3. The two level inverter's DC-link voltage is designated as V_{DCL} . Only two phases are active during the non-commutation period, as can be illustrated in Fig. 4. The comparable circuit diagram displays this (see Fig 5). The current will flow through the phase windings a and c at a specific moment in time when $E = E_a = E_b = E_c$, as shown in Fig. 3. Phases b and c represent the subsequent phase of conduction. The phase c continues to remain in conduction when S_{au} is turned off and S_{bu} is turned on, but the current switches from

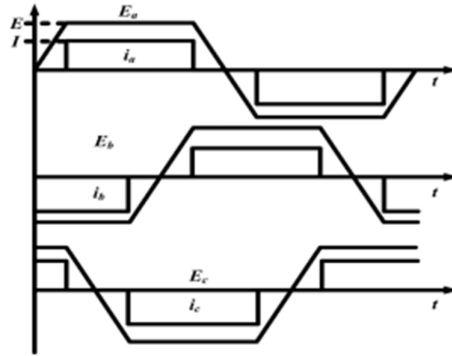


Fig. 3: For a BLDC drive, the back EMF and current waveform [7]

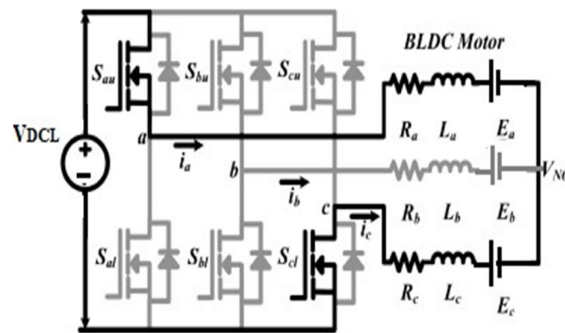


Fig. 4: BLDC drive conduction of phase ac

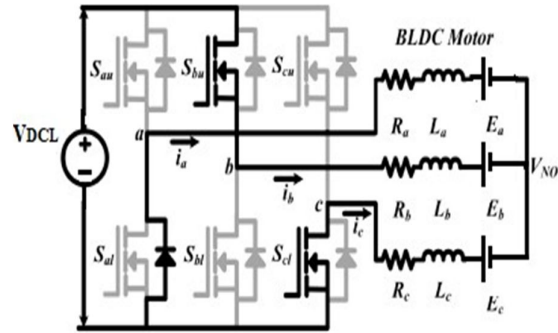


Fig. 5: BLDC drive conduction of phase abc

phase a to phase b. As seen in Fig. 4 and Fig. 5, the energy held in the phase an inductance will now spontaneously freewheel through the bottom switch S_{al} 's body diode.

The phase voltage equation during this commutation interval can be expressed as

$$0 = R \cdot i_a + E_a + L \cdot \frac{di_a}{dt} + V_{NO} \quad (3)$$

$$V_{DCL} = R \cdot i_b + E_b + L \cdot \frac{di_b}{dt} + V_{NO} \quad (4)$$

$$0 = R \cdot i_c + E_c + L \cdot \frac{di_c}{dt} + V_{NO} \quad (5)$$

Since the stator windings are star connected, the neutral point V_{NO} equation is

$$V_{NO} = \frac{V_{DC} - E_a}{3} \quad (6)$$

The rate of change throughout the commutation period can be stated as a function of (3), (4), (5), and (6).

$$\frac{di_a}{dt} = -\frac{V_{DCL} + 2E_a + 3Ri_a}{3L} \approx -\frac{i_a}{t_{comm}} \quad (7)$$

$$\frac{di_b}{dt} = \frac{2V_{DCL} - 3E - E_a - 3Ri_b}{3L} \approx \frac{i_b}{t_{comm}} \quad (8)$$

$$\frac{di_c}{dt} = -\frac{V_{DCL} - 3E - E_a - 3Ri_c}{3L} \approx -\frac{i_c}{t_{comm}} \quad (9)$$

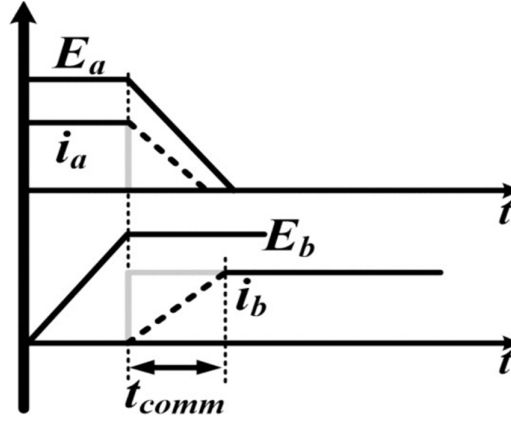


Fig. 6: Phase current as phase a transitions to phase b [7]

where t_{comm} stands for commutation time. The aforementioned (7), (8), and (9) can be used to determine the phase current's rising time and fall time as

$$T_{fall} = \frac{3IL}{V_{DCL} + 2E + 3IR} \quad (10)$$

$$T_{rise} = \frac{3IL}{2V_{DCL} - 2E - 3IR} \quad (11)$$

where T_{rise} is the time it takes for the current in phase b which is i_b to rise from zero to steady state current I and T_{fall} is the amount of time it takes for the current in phase a which is i_a to fall from steady state current I to zero. The electromagnetic torque ripple of the BLDCM is greatly influenced by the phase current's rise and fall times. It is possible to express the electromagnetic torque produced in the BLDCM during the commutation time as

$$T_{em_{com}} = \frac{E_a i_a + E_b i_b - E_c i_c}{\omega_m} \quad (12)$$

Assuming $E_a = E$, the commutation torque in (12) can be obtained from (7), (8), and (9).

$$T_{em_{com}} = \frac{2EI}{\omega_m} - \frac{2E}{\omega_m} \times \frac{V_{DCL} - 4E}{3L} \times t_{comm} \quad (13)$$

It is obvious from the equation above that the second term needs to equal zero so as to diminish the torque ripple. Since the phase resistance is low, the resistive drop is disregarded for the sake of analysis convenience. We get $V_{DCL} = 4E$ when the last term in equation (13) is equated to zero. By substituting this condition in (10) and (11), we can draw the conclusion that the rise time T_{rise} of the incoming phase current should be identical to the fall time T_{fall} of the departing phase current in order to mitigate the torque ripple. In [8] and [9], the impact of changing the dc-link voltage is also illustrated.

The pace of the rotor, which varies depending on the motor's operating conditions, has a direct relationship with the BEMF of the motor. Since the rate of current is zero during the non-commutation period, the torque is equal to $2EI/\omega_m$. However, an alternation in the dc-link voltage is necessary throughout the transition phase to balance the rate of current growth and fall.

III. SLIDING MODE CONTROLLER DESIGN

Sliding Mode Controller (SMC) provide robustness, high stability [10] and reduction in torque ripple. For the design of sliding mode controller we need a plant x_2 , sliding function given by $Sl(\tau)$, controller input $X_i(\tau)$, tracking error $er(\tau)$, state space variables x_1, x_2 and constants like C, η and I_m . Consider the plant as

$$\begin{aligned} I_m \ddot{\theta}(\tau) &= X_i(\tau) - D_d(\tau) \\ \ddot{\theta}(\tau) &= (X_i(\tau) + D_d(\tau))1/I_m \end{aligned} \quad (14)$$

where I_m is the inertial moment, $\theta(\tau)$ is angle signal, $X_i(\tau)$ is the input of the controller and $D_d(\tau)$ is the disturbance.

$$\begin{aligned} x_1 &= \theta \\ \dot{x}_1 = x_2 &= \dot{\theta} \end{aligned} \quad (15)$$

The tracking error is $er(\tau)$ and is given by

$$\begin{aligned} er(\tau) &= \theta(\tau) - \theta_d(\tau) = x_1 - \\ x_1 d \quad e \cdot r(\tau) &= \dot{\theta}(\tau) - \dot{\theta}_d(\tau) = \\ \dot{x}_1 - x_1 \cdot d \end{aligned}$$

The sliding mode function $Sl(\tau)$ is designed as given below where C is a constant and is always greater than zero.

$$\begin{aligned} Sl(\tau) &= C er(\tau) + e \cdot r(\tau) \\) \dot{S}l &= C e \cdot r(\tau) + \\ &\quad e \cdot r(\tau) \\ \dot{S}l &= C e \cdot r(\tau) + \ddot{\theta}(\tau) - \\ \ddot{\theta}_d(\tau) \quad \dot{S}l &= C e \cdot r(\tau) + \\ &\quad \ddot{\theta}(\tau) - x_2 \cdot d \end{aligned}$$

Substituting for equation (14) in $\ddot{\theta}(\tau)$

$$\begin{aligned} 2Sl &= 2(C e \cdot r(\tau) + (X_i(\tau) + D_d(\tau))1/I_m - \ddot{\theta}_d(\tau)) \\ 2 \cdot \dot{S}l &= C e \cdot r(\tau) + (X_i(\tau) + D_d(\tau))1/I_m - x_2 \cdot d \end{aligned}$$

For, $\dot{S}l < 0$, the design of sliding mode controller is

$$X_i(\tau) = I_m(-C e \cdot r(\tau) + \ddot{\theta}_d(\tau) - 1/I_m(k_2 Sl + 1/2 d_m(2l)))$$

$Sgn(Sl)$ is sign function which is defined as 1 if Sl is less than zero and is equal to -1 if Sl is greater than zero.

$$Sgn(Sl) = \begin{cases} -1 & \text{if } Sl < 0; \\ 1 & \text{if } Sl > 0; \end{cases}$$

IV. PROPOSED METHODOLOGY FOR TORQUE RIPPLE MITIGATION

The illustration of the proposed methodology is depicted in Fig. 7. Ref. speed and the actual speed is compared and fed to the Sliding Mode Controller. The controller regulates the speed in order to reach the set point. The output of sliding mode controller is given to the two level three phase inverter having three phases namely a, b and c with a phase shift of 120° . The output voltage V_a, V_b, V_c is fed to drive the BLDC motor which rotates with a speed which is given to the controller as actual speed. Torque ripple T is measured in percentage where T_{max} is upper limit and T_{min} is lower limit in torque ripple waveform and T_{avg} is the average torque ripple between T_{max} and T_{min} respectively.

$$T = \frac{T_{max} - T_{min}}{T_{avg}} \cdot 100 \quad (16)$$

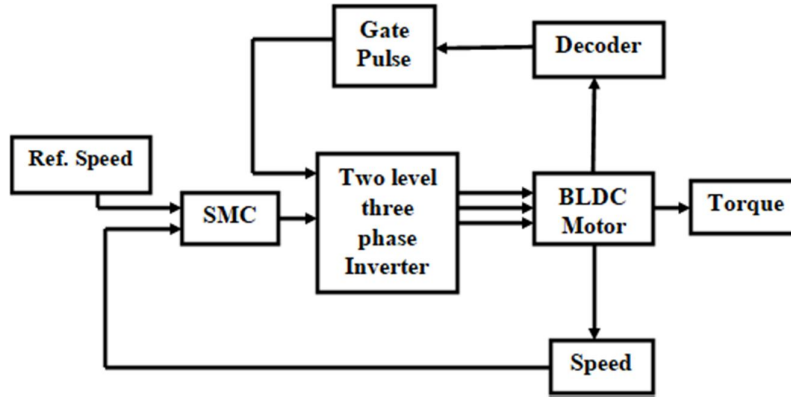


Fig. 7: Block diagram of the proposed method

The hall sensor's in the BLDC motor produces hall signals H_a , H_b and H_c which are realized by the truth table, the simulation of the decoder is shown in Fig. 8. Fig. 9 illustrates the hall signal pulses of phase a, b and c. Fig. 10 depicts the output of the decoder for three phases a, b and c.

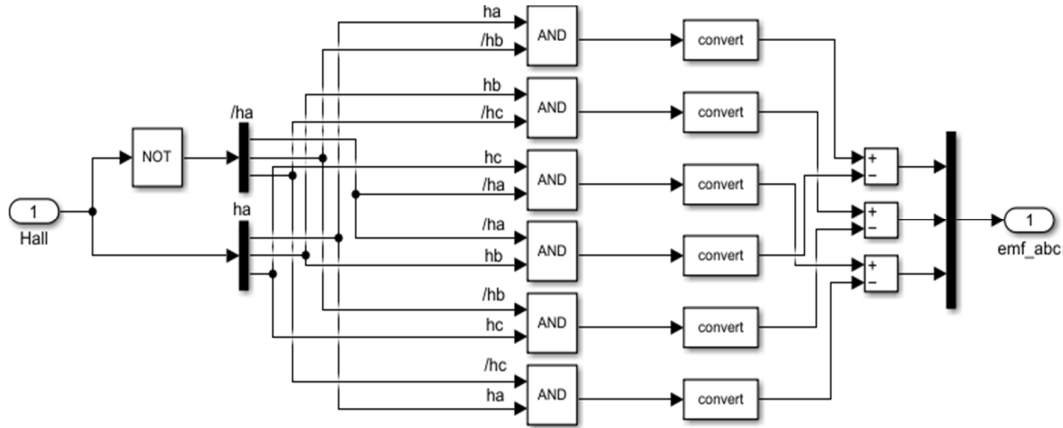


Fig. 8: Simulation of Decoder

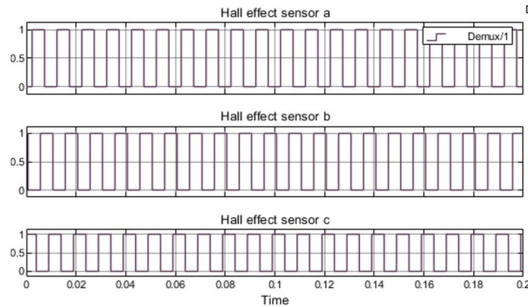


Fig. 9: Hall signals of phase a, b and c

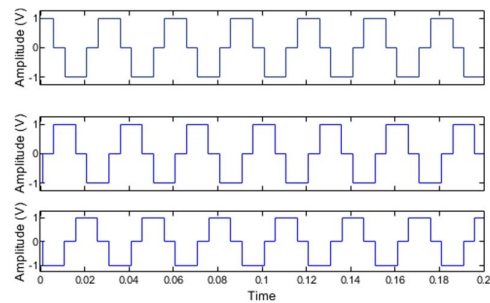


Fig. 10: Output of Decoder for phase a, b and c

The two level three-phase inverter uses 6 switches which we can use either IGBT or MOSFET. The gate need to be triggered by the gate pulses. The gate pulse required for the 6 switches are shown in Fig. 11. Dynamic load is applied to the motor at 1s 3.125kg, 2s 6.25kg, 3s 9.375kg, 4s 12.5kg and 5s 0kg is applied which is depicted in Fig. 14.



Fig. 11: Gate pulses for the inverter

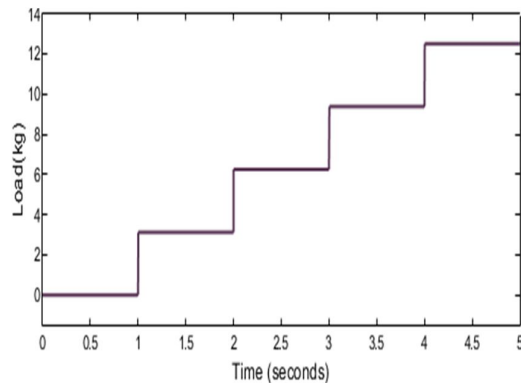


Fig. 12: Dynamic load waveform

V. RESULTS AND ANALYSIS

The stator current and BEMF waveforms for BLDCM using PI controller and SMC is shown in Fig. 12 and Fig. 13. The expected trapizoidal waveform is obtained in both cases with voltage range from -100V to 100V and stator current ranges between -2mA to 2mA.

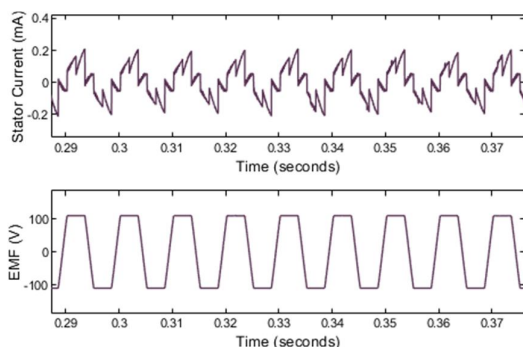


Fig. 13: Stator Current and BEMF waveform in BLDCM with PI controller

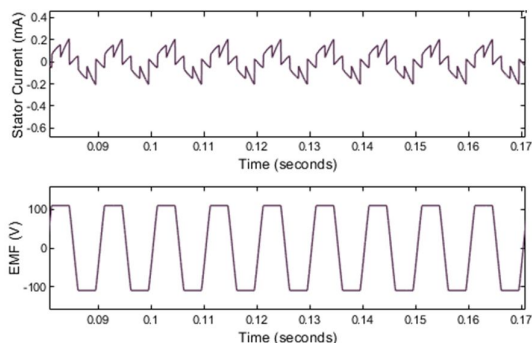


Fig. 14: Stator Current and BEMF waveform in BLDCM with SMC

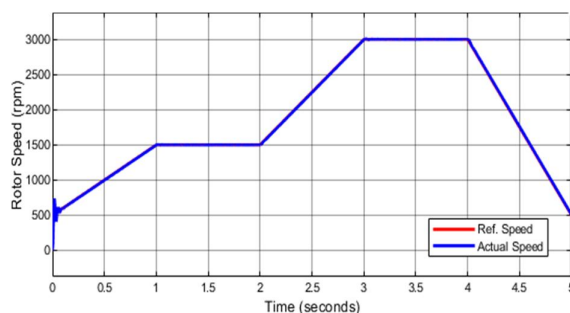


Fig. 15: Speed of BLDC motor using PI controller in no load condition at set points 500rpm, 1500rpm and 3000rpm under acceleration, deceleration and constant speed

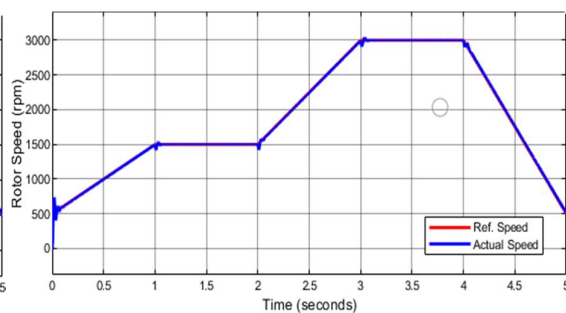


Fig. 16: Speed of BLDC motor using PI controller in dynamic load condition at set points 500rpm, 1500rpm and 3000rpm under acceleration, deceleration and constant speed

Fig. 15 and Fig.16 shows the speed of Brushless DC motor using PI controller under no load and dynamic load conditions. At 0s, actual speed indicated by blue color is 500rpm where small spikes can be observed in the beginning to reach the set point. Then accelerates to 1500rpm and remains in constant speed for 1s. Again

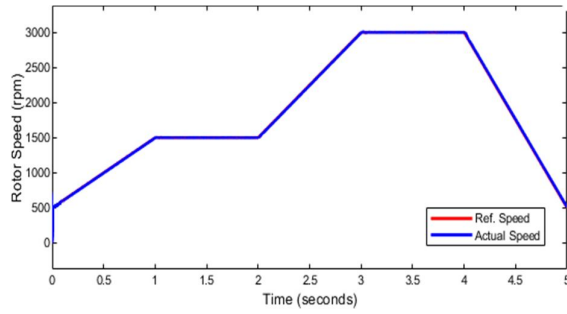


Fig. 17: Speed of BLDC motor using SMC in no load condition at set points 500rpm, 1500rpm and 3000rpm under acceleration, deceleration and constant speed

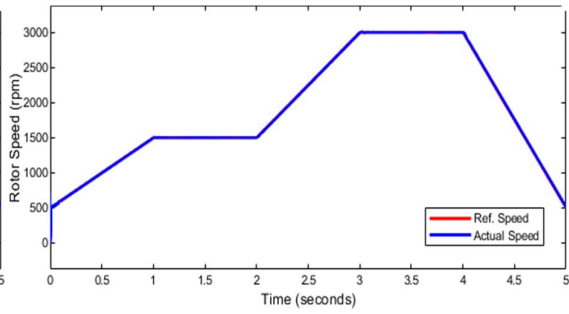


Fig. 18: Speed of BLDC motor using SMC in dynamic load condition at set points 500rpm, 1500rpm and 3000rpm under acceleration, deceleration and constant speed

accelerates to 3000rpm and remain constant for 1s. From 4s, it decelerates from 3000rpm to 500rpm. In dynamic load condition small spikes can be observed to reach the desired set point. Fig. 17 and Fig. 18 shows the speed of Brushless DC motor using SMC under no load and dynamic load conditions. The actual and reference speed indicated by blue and red color respectively coincides with each other and smooth transitions can be observed. At 0s, speed is 500rpm where no spikes is observed in the beginning to reach the set point. Then accelerates to 1500rpm and remains in constant speed for 1s. Again accelerates to 3000rpm and remain constant for 1s. From 4s, it decelerates from 3000rpm to 500rpm.

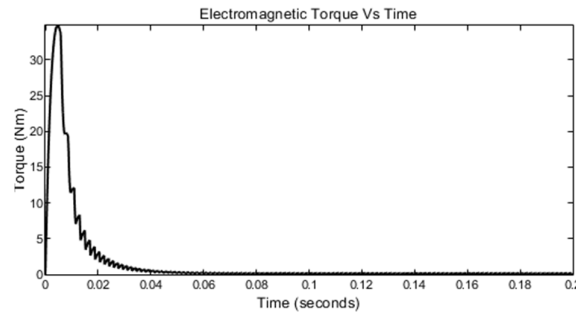


Fig. 19: Electromagnetic Torque in BLDC motor using SMC

The torque ripple for SMC which is shown in Fig. 19 have only one spike above 30Nm, then it gradually decreases and reduce to zero at 0.06 seconds and it has only very small torque ripple compared to PI which has an average ripple with $T_{min}=10.5\text{Nm}$ and $T_{max}=15.2\text{Nm}$, therefore torque ripple being 18.18% Fig. 20 shows the torque ripple waveform for BLDCM using PI controller where $T_{min}=10.505$ and $T_{max}=15.185$ so we get torque ripple of 36.43%.

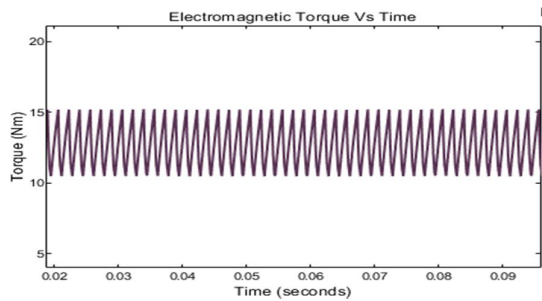


Fig. 20: Electromagnetic Torque in BLDC motor using PI at 1500 rpm and torque of 5 Nm per division

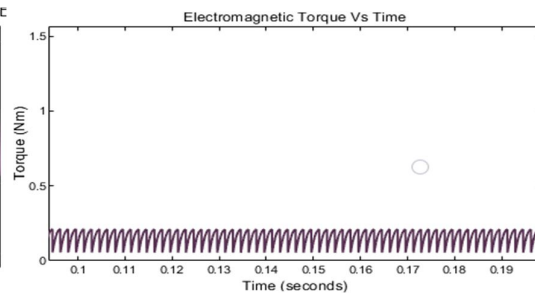


Fig. 21: Expanded view of Electromagnetic Torque in BLDC motor using SMC with torque 0.5 Nm per division

VI. CONCLUSION

The proposed method using Sliding Mode Controller has very low torque ripple compared to PI controller. This means the efficiency of Brushless DC motor is improved by using Sliding Mode Controller (SMC) ensuring smooth driving experience under dynamic load conditions to the driver in electric vehicles (EV). Even though 90% of the controller used for industrial application is PI controller it does not ensure better efficiency for electric vehicles with increased torque ripple causing vibrations and deteriorating the performance of the system. The torque ripple is reduced to 18.18% in this literature.

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