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# Analysis of Commutation Torque Ripple Minimization for Brushless DC Motor Based on SEPIC Converter

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## ABSTRACT
Brushless DC Motors (BLDCM) are widely used in automated industrial applications like Computer Numerical Control (CNC) machinery, aerospace applications and in the field of robotics.But it still suffers from commutation torque which mainly depends on speed and transient line commutation interval. BLDC MOTOR torque ripple causes increased acoustic noise and undesirable speed fluctuation. This paper presents a new circuit topology and dc link voltage current in the control strategy to keep incoming and outgoing phase currents changing at the same rate during commutation. In this paper dc-dc single ended primary inductor converter (SEPIC) a switch selection circuit are employed in front of inverter. In order to obtain the desired commutation voltage resulting in reduced commutation torque ripple. Compared with simulation result conventional system and proposed method can obtain desired voltage much faster and minimize commutation torque ripple more efficiently.
***Keywords:*** Brushless DC Motor(BLDCM),DC link voltage, Commutation, Single ended primary inductor converter(SEPIC).

## I. INTRODUCTION

**B**rushless dc motor (BLDCM) has been widely used in industrial fields that require high reliability and precise control due to its simple structure. Brushless dc motor offer many attractive features like low maintenance, fast response, high efficiency, high power density, good reliability and compact construction.

Brushless dc motor is increasingly being used in military, industrial and commercial applications. But these motors still suffer from commutation torque ripple. The primary disadvantage of brushless dc motor is higher torque ripples compared with conventional machines. So far many research studies have been performed to reduce commutation torque ripple. An original analytical study on commutation torque ripple is presented in from which a conclusion has been drawn that relative torque ripple is independent of current and varies with speed. A similar analysis is presented in and the strategy of changing the input voltage to reduce commutation torque ripple in BLDCM some necessary assumptions such as ideal trapezoidal back electromotive force (EMF), very small current hysteresis or pulse width modulation (PWM) cycle, constant back EMF during commutation no implementation of voltage adjustment is demonstrated in them It is proposed in that a single dc current sensor and a current deadbeat control scheme should be used to keep incoming and outgoing phase currents changing at the same rate during commutation hence effectively suppressing commutation torque ripple.

It is an effective method to introduce some special topology of a circuit to BLDCM drives to control its input voltage buck converter is used, and commutation torque ripple is then greatly reduced at low speed. In a super lift Luo converter is placed at the entrance of the inverter to produce desired dc link voltage and the structure is more competent under the high-speed work condition, compared with the method proposed in A developed structure of the inverter is proposed in which avoids the effect of the fly-wheeling process and acquires more exact estimated torque with sampling current. All of the above methods suffer from slow voltage adjustment, and therefore, they can only achieve satisfactory torque pulsation suppression in low- or high-speed regions.

In this paper a new circuit is proposed an appropriate dc link voltage is used to drive phase currents to increase and decrease in the identical slope resulting in the great reduction of pulsated commutation torque. To get the desired dc link voltage a single-ended primary inductor converter (SEPIC) circuit is used to control the input of the inverter. The adjustment of dc voltage can be completed during non-commutation conduction period and switched immediately at the beginning of commutation by the switch selection circuit. Simulation results are compared with common dc–dc converter the proposed method when applied in a steady state can reduce commutation torque ripple both at high and low speeds with much faster dc voltage regulation.

## II. MATHEMATICAL MODEL OF BLDC MOTOR DRIVE SYSTEM

A 3 phases, 4 poles, Y connected trapezoidal back-EMF type BLDC is modeled. Trapezoidal back-EMF is referring that mutual inductance between stator and rotor has trapezoidal shape. Therefore a b c phase variable model is more applicable than d-q axis. With the intention of simplifying equations and overall model the following.

Assumptions are made:

- Magnetic circuit saturation is ignored.
- Stator resistance, self and mutual inductance of all phases are equal and constant.
- Hysteresis and eddy current losses are eliminated.
- All semiconductor switches are ideal.

The electrical and mechanical mathematical equations of BLDC are:

Phase voltage equations of BLDC motor

$$V_a = Ri_a + (L-M)\frac{di_a}{dt} + E_a \quad (2.1)$$

$$V_b = Ri_b + (L-M)\frac{di_b}{dt} + E_b \quad (2.2)$$

$$V_c = Ri_c + (L-M)\frac{di_c}{dt} + E_c \quad (2.3)$$

Back emf equations of BLDC motor

$$E_a = K_e\omega_m F(\theta_e) \quad (2.4)$$

$$E_b = K_e\omega_m F\left(\theta_e - \frac{2\pi}{3}\right) \quad (2.5)$$

$$E_c = K_e\omega_m F\left(\theta_e - \frac{4\pi}{3}\right) \quad (2.6)$$

Torque equations are each phase of BLDC motor

$$T_a = K_t i_a F(\theta_e) \quad (2.7)$$

$$T_b = K_t i_b F\left(\theta_e - \frac{2\pi}{3}\right) \quad (2.8)$$

$$T_c = K_t i_c F\left(\theta_e - \frac{4\pi}{3}\right) \quad (2.9)$$

Electromagentic torque equation BLDC motor

$$T_e = T_a + T_a + T_c \quad (2.10)$$

$$T_e - T_l = J\frac{d^2\theta_m}{dt^2} + \beta\frac{d\theta_m}{dt} \quad (2.11)$$

$$\theta_e = \frac{p}{2}\theta_m \quad (2.12)$$

$$\omega_m = \frac{d\theta_m}{dt} \quad (2.13)$$

## III. ANALYSIS OF TORQUE DURING COMMUTATION INTERVAL

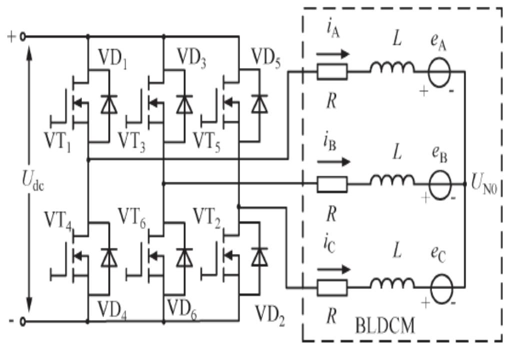


**Fig3.1:** Block diagram BLDCM drive system

The commonly used commutation in 3 phase BLDC motor is the six-step, in which each phase voltage is energized for interval of 120 degree electrical according to therotor electrical position. At any sector, only one phase is energized as positive and one of the other phases is energized as negative in order to maintain a current path. For control the BLDC motor a typical 3 phase full bridge will be used to drive the motor.

For the analysis of commutation time, the commutations of the current through two phases are to be considered. Phase A will be switched off, and the phase B will replace the A phase and the third phase C will remain conducting.

In this analysis the commutation from phase A to phase B will be considered. The current transfer happens during the six-step, since A phase switch is ON while B phase switch will be OFF, and the third phase switch will remain conducting. In this analysis the transition of conduction from Phase A(+)/C(−) to B(+)/C(−) will be considered as shown in figure 3.1. In this case the phase A is the de-energized phase and phase B will be the incoming energized phase and phase C is the conducting phase.

The BLDCM has three stator windings and permanent magnets on the rotor. Its voltage equation of three windings with phase variables is

$$\begin{bmatrix} u_A \\ u_B \\ u_C \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix}\begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} + \begin{bmatrix} L & 0 & 0 \\ 0 & L & 0 \\ 0 & 0 & L \end{bmatrix}\frac{d}{dt}\begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} + \begin{bmatrix} e_A \\ e_B \\ e_C \end{bmatrix} + \begin{bmatrix} U_{N0} \\ U_{N0} \\ U_{N0} \end{bmatrix} \quad (3.1)$$

the electromagnetic torque is

$$T_e = \frac{e_A i_A + e_B i_B + e_C i_C}{\Omega} \quad (3.2)$$

Where $U_{NO}$ is the neutral point-to-ground voltage, $u_A, u_B$ and $u_C$ are the terminal phase voltages with respect to the power ground, $i_A, i_B$ and $i_C$ are phase currents, $e_A, e_B$ and $e_C$ are trapezoidal back EMFs, $L = L_s - M$ is the equivalent inductance of phase windings, *L*s and *M* are self-inductance and mutual inductance, respectively, *R* is the resistance of the phase windings, and Ω is the speed of the rotor.

According to (3.2), to produce a steady electromagnetic torque, the sum of $, e_A i_A, e_B i_B$ ,and $e_C i_C$ has to be constant as far as a certain speed is concerned. It implies that rectangular phase currents are needed, which should be in phase with the corresponding back EMF. phase windings, the actual phase currents, instead of the desired rectangular form, are in a trapezoidal form with a finite rise time. In fact, the different slopes of incoming and outgoing phases have a direct influence on the commutation torque, which can be illustrated using the following analysis. For this analysis, the commutation of the current from phase A to phase B is considered. this current transfer is done by switching off $VT_1$ and switching on $VT_3$, with $VT_2$ remaining on. With only a very small period of PWM, the current through the winding of the motor between commutations is regarded to be constant and equal to $I_m$. It implies that the initial Due to the nonzero inductance of the stator values of $i_A = -i_C = I_m$ and $i_B = 0$ are known at the beginning of commutation.

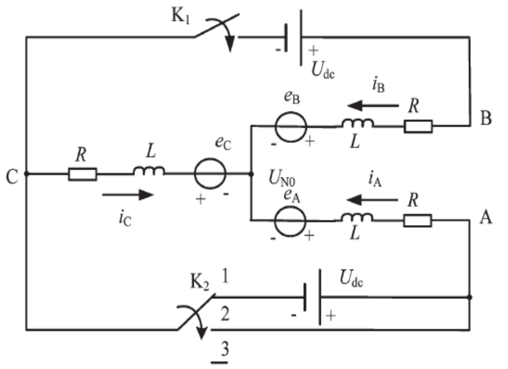


**Fig3.2:** Equivalent circuit during commutation interval

The equivalent circuit during commutation is shown in Fig.3.1. According to Fig. 3.2, switch $K_1$ is off and $K_2$ is on at point 1 before commutation begins. During commutation, $K_1$ is switched on. Because $i_A$ flows through the freewheeling diode $VD_4$, $K_2$ is switched on at point 2, and when the commutation is over, $K_1$ is on and $K_2$ is switched on at point 3 (suspended). $K_1$ and $K_2$ stand for the MOSFETs carrying on PWM modulation when turned on.

Considering very short duration of commutation, back EMFs are supposed to be constant during commutation. Then, the voltage initial values at the beginning of commutation can be drawn as follows $u_A = 0; u_B = U_{dc}; u_C = 0;$

$e_A = E_m; e_B = E_m;$ and $e_C = -E_m$ Then, the voltage equation (3.1) can be rewritten as

$$\begin{cases} 0 = Ri_A + L\frac{di_A}{dt} + e_A + U_{NO} \\ U_{dc} = Ri_B + L\frac{di_B}{dt} + e_B + U_{NO} \\ 0 = Ri_C + L\frac{di_C}{dt} + e_C + U_{NO} \end{cases} \qquad (3.3)$$

The neutral point voltage can be solved as follows:

$$U_{NO} = \frac{1}{3}(U_{dc} - E_m) \qquad (3.4)$$

The electromagnetic torque before commutation is

$$T_{e-pre} = \frac{e_A i_A + e_B i_B + e_C i_C}{\Omega} = \frac{2 I_m E_m}{\Omega} \qquad (3.5)$$

When the frequency of PWM is high and the PWM period is much shorter than the electrical time constant *L/R*, the effect of *R* can be neglected. Then, the slopes of phase currents are approximately drawn by

$$\begin{cases} \frac{di_A}{dt} = -\frac{U_{dc} + 2E_m}{3L} \\ \frac{di_B}{dt} = \frac{2(U_{dc} - E_m)}{3L} \\ \frac{di_C}{dt} = -\frac{U_{dc} - 4E_m}{3L} \end{cases} \qquad (3.6)$$

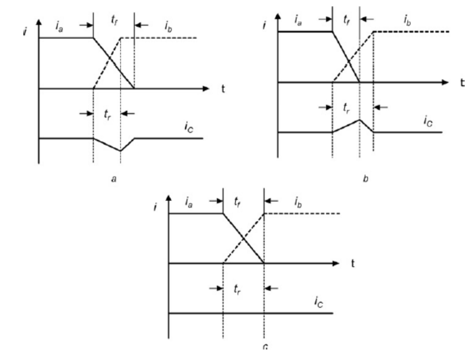


**Fig. 3.3** Current behavior during commutation

a) $U_{dc} > 4E_m, t_f > t_r$

b) $U_{dc} < 4E_m, t_f < t_r$

c) $U_{dc} = 4E_m, t_f = t_r$

The time taken for $i_A$ to vanish from the initial value $I_m$ is

$$t_f = \frac{3LI_m}{U_{dc} + 2E_m} \qquad (3.7)$$

The time taken for $i_B$ to increase from 0 to $I_m$ is

$$t_r = \frac{3LI_m}{2(U_{dc} - E_m)} \qquad (3.8)$$

According to (3.2), (3.6), and $i_A + i_B + i_C = 0$ during commutation, the electromagnetic torque can be calculated as

$$T_{e-com} = \frac{2E_m}{\Omega}\left(I_m + \frac{U_{dc} - 4E_m}{3L}t\right) \qquad (3.9)$$

The relative torque ripple is given by

$$\Delta T_e = T_{e-com} - T_{e-pre} = \frac{U_{dc} - 4E_m}{3L}t \qquad (3.10)$$

According to (3.2) and (3.6)–(3.10), the following conclusions can be drawn.

1) If $U_{dc} > 4E_m, t_f > t_r$ and the torque keeps increasing during commutation.
2) If $U_{dc} < 4E_m, t_f < t_r$, and the torque keeps decreasing during commutation.
3) If $U_{dc} = 4E_m, t_f = t_r$ and the torque is constant during commutation.

The current behaviors with different speeds are shown in Fig.3.3

As can be seen in (3.6), the slopes of the currents during commutation depend on the dc link voltage $U_{dc}$ and the maximum value of back EMF $E_m$. $E_m$ is proportional to speed and considered constant during commutation. $U_{dc}$ is generally invariable due to uncontrollable rectification. Consequently, $U_{dc} = 4E_m$ cannot always be satisfied during speed adjustment, which leads to significant torque pulsation. In (3.10), the torque rippleduring commutation is proportional to $|U_{dc} - 4E_m|$and the closer $U_{dc}$ is to $4E_m$ at the commutation interval, the little the torque ripple becomes. In this paper, a new circuit topology is proposed, which can reduce commutation torque pulsation bykeeping $U_{dc}$ close to $4E_m$ during commutation.

## IV. PROPOSED METHODS FOR TORQUE RIPPLE MINIMIZATION

An adjustable dc link voltage is required tomaintain $U_{dc} = 4E_m$ to avoid the commutation torque pulsation. In this paper, a SEPIC converter with a switchover MOSFET is used to implement the dc link voltage adjustment, as can be seen in Fig.4.1

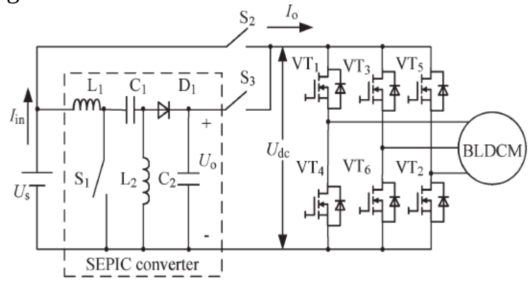


**Fig4.1:** Configuration of BLDCM driving system with a SEPIC converter

In Fig.4.1, $S_1$, $S_2$, and $S_3$ are all power MOSFETs. By operating $S_1$ appropriately, the energy storage components (i.e., $L_1$, $L_2$, $C_1$, and $C_2$) of the SEPIC converter can be adjusted to get the desired output voltage $S_2$ and $S_3$ are switchover power MOSFETs used for choosing between the input of inverter $U_S$ and the output voltage of the SEPIC converter $U_0$, which can be calculated as

SEPIC converter design parameters are

$$L_1 = \frac{U_0(1-D)}{2I_{in}f} = \frac{DU_s}{1-D} \bullet \frac{(1-D)}{2I_{in}f} = \frac{DU_s}{2I_{in}f} \qquad (4.1)$$

$$L_2 = \frac{U_0(1-D)}{2I_o f} \qquad (4.2)$$

$$U_0 = \frac{D}{1-D}U_s \qquad (4.3)$$

Where $D$ is the duty ratio under the operation of $S_1$.

When the iron losses are not taken into account, $E_m$ is proportional to speed, i.e.,

$$E_m = K_e\Omega \qquad (4.4)$$

where $K_e$ is the back EMF coefficient

Then, the duty ratio of $S_1$ for satisfying $U_0 = 4E_m$ can be calculated by

$$D = \frac{4K_e\Omega}{U_s + 4K_e\Omega} \qquad (4.5)$$

According to (4.3), the duty ratio of $S_1$ corresponding to the desired dc link voltage can be estimated by measuring the motor speed. To achieve an immediate change of the input voltage of inverter, $S_2$ and $S_3$ are required to be complementary to each other. At the beginning of every commutation, $S_2$ is switched off, and $S_3$ is on. The SEPIC converter stops adjusting, and the output voltage remains constant. Once commutation is over, $S_2$ is switched on and $S_3$ is off. The SEPIC converter begins regulating again, and its output voltage will reach the expected value before the next commutation. It should be noted that theoretically, the SEPIC converter can finish adjusting during 1/6 electrical cycle with enough energy storage, even if the speed is very high in the steady state. However, as far as the speed step is concerned, the converter generally fails to respond fast enough due to its significant inertia. As a result, when the speed varies significantly, the system needs some time to get the steady state.

BLDC Motor has the following constants and ratings

Pole=4,V=30,R=0.7Ω,L=2.72mH,M=1.5mH, $K_e$=0.5128,$K_t$=0.049,J=0.0002

SEPIC Converter Parameters

$L_1$=0.9375mH,$L_2$=32μH,$C_1$=32μF,$C_2$=32μF

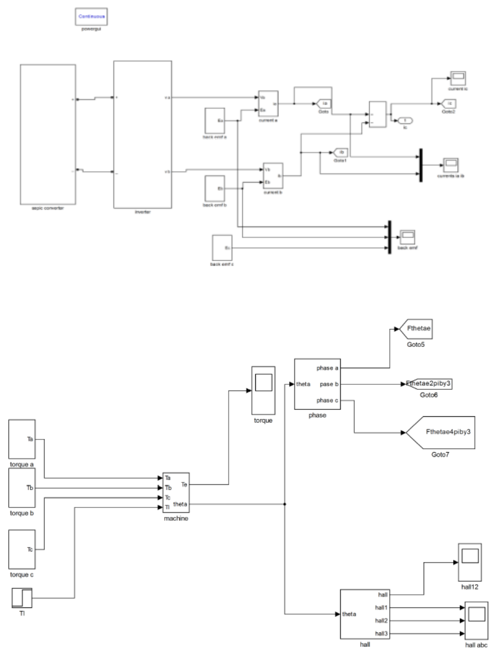

**Fig: 4.2** MATLAB Simulation circuit for Mathematical model BLDC motor with SEPIC converter

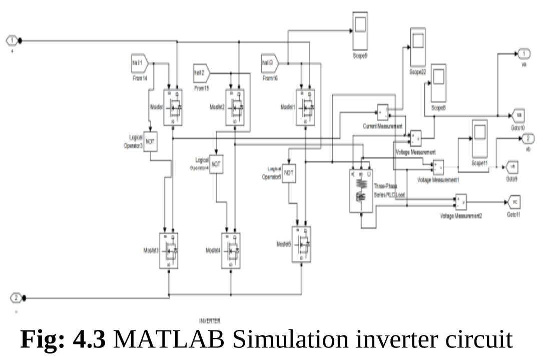

**Fig: 4.3** MATLAB Simulation inverter circuit

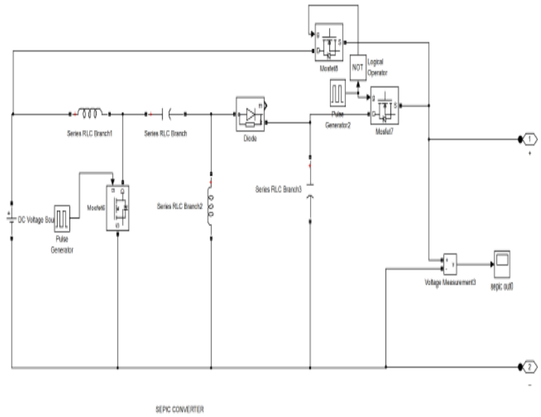

**Fig: 4.4** MATLAB Simulation SEPIC converter

## V. SIMULATION RESULTS

To verify the results of the proposed strategy in simulations. Three phase BLDC motor during transient state without SEPIC converter at an input voltage 30 V (DC)

Torque waveform of three phase BLDC without SEPIC converter at an input voltage 30 V (DC), the DC link output voltage of the BLDC motor, when normal condition input voltage 30V is given to the motor, during the commutation the output voltage of the SEPIC converter will be applied to motor; hence the torque ripple is greatly reduced.

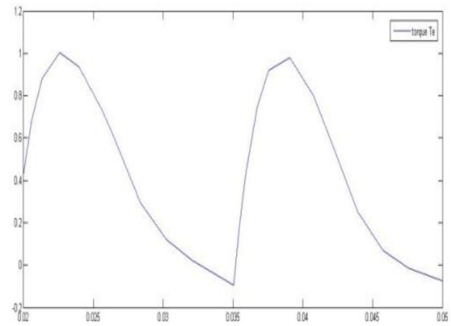

**Fig: 5.1** Electromagnetic torque during commutation interval without SEPIC converter

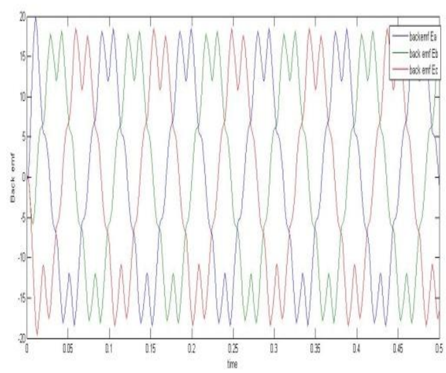

**Fig 5.2** Back emf

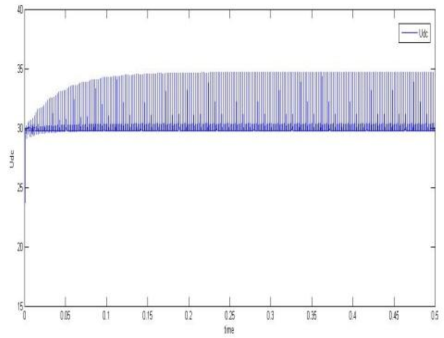

**Fig: 5.3** Dc link voltage $U_{dc}$

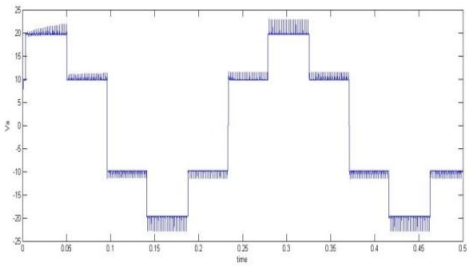

**Fig: 5.4** Inverter output voltage with SEPIC Converter

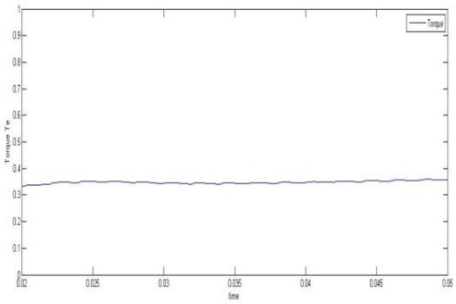

**Fig 5.5** Electromagnetic torque during commutation interval with SEPIC Converter

## VI. CONCLUSION

A circuit topology and control strategy has been proposed to suppress commutation torque ripple of BLDCM in this work. A SEPIC converter is placed at the input of the inverter, and the desired DC link voltage can be achieved by appropriate voltage switch control. No exact value of the commutation interval *T* is required, and the proposed method can reduce commutation torque ripple effectively within a wide speed range and load. The simulated results show the improved performance of reduction of torque ripple.

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