A novel technique for torque ripple suppression in BLDC motor drive using switched capacitor based SEPIC converter

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ABSTRACT

This article reports a strategy for suppressing commutation torque ripple has been proposed by modifying a SEPIC converter using switched capacitor. The torque ripple generated during the commutation period is one of the main disadvantages of a brushless DC (BLDC) motor. The cause for the torque ripple in brushless DC motor has been mathematically analyzed in this work. Henceforth, a modified switched-capacitor based DC-DC converter has been proposed for integration with BLDC drive. Moreover, a theoretical analysis of the relationship has been established between the duty ratio of the DC-DC converter with commutation time and torque ripple. A low cost and simple method to control the dc link voltage of BLDC drive has been proposed and a comparative analysis of the proposed converter with previously existing similar converters has been shown. This work aims at reducing ripple in electromagnetic torque of BLDC motor from the view point of duty ratio of the DC-DC converter and commutation time of the drive. The feasibility of the drive has been evaluated experimentally and through simulation. It has been observed that the integration of the proposed converter with BLDC drive help in torque ripple suppression to 16.5% as compared to BLDC drive without any DC-DC converter.

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1. INTRODUCTION

The brushless DC (BLDC) motor has excellent speed regulation capability enabling it to be widely applicable in industry and domestic applications [1], [2]. The primary factor limiting the use of BLDC motors in many industries is the commutation torque ripple they create [2], [3]. The torque ripple may even reach up to 50% of the value of the average electromagnetic torque. Therefore, reduction of torque ripple is important for improving the performance of the BLDC motor.

The research on reducing torque ripple in BLDC motor has attracted a lot of attention since last decade [4]–[12]. Through literature survey it is observed that commutation torque ripple can be reduced by controlling the rise time and fall time of phase current during commutation [6]. Different modulated duty ratio has been applied for controlling the slopes of the incoming and outgoing phase currents as described in [7]. The torque ripple can be minimized by applying modulated duty ratio to each phase. Hu *et al.* and Li *et al.* [8], [9] presented a different modulation technique for torque ripple minimization using field-programmable gate array (FPGA) algorithm and coordinate transformation theory for both low speed and high-speed operation. The simplest method for torque ripple minimization is application of power modulator along with inverter. The reason for terming the method simplest is that it offers a solution with less complicated circuitry. As a result, different converter topologies have been proposed and studied that offers better reduction of torque ripple [10]–[16]. A bidirectional buck boost converter has been used for torque ripple reduction in BLDC drive, however, the mathematical evaluation of torque ripple reduction has not been elaborated as can be seen [11]. The bidirectional buck boost converter is integrated with inverter through common three switch leg for BLDC drive which increases the complexity of the control circuitry required for the said drive. A torque ripple minimization scheme for BLDC drive has been introduced based on a newly proposed single-inductor multiple output (SIMO) DC-DC converter using FPGA as illustrated in [12]. However, the relation between the converter and torque ripple has not been elaborated. A comparative analysis on torque ripple reduction techniques using four converter topologies has been shown for different operating speed as explained in [13]. Moreover, in recent years, it has been observed that hybrid converters also gained popularity for torque ripple suppression in BLDC drive [14]–[19].

Thus, all these studies [11]–[15] proves that the inclusion of a power modulator in BLDC drive circuitry reduces the unwanted torque ripple but none of them reveals any mathematical relationship of torque ripple reduction with the duty ratio of DC-DC converter. In order to understand the introduction of converter for torque ripple suppression, we have established the mathematical relationship between the duty ratio of the converter along with the electromagnetic torque in BLDC drive. The major contribution of this article is this numerical analysis, which will enable the future studies to incorporate the appropriate DC-DC converter for BLDC drive. In this context, switched-capacitor based SEPIC converter has been introduced in this paper that shows a higher voltage boost ratio compared to other converters presented in [20]–[23]. The switched capacitor plays a vital role here as it helps to reduce the voltage stress across switches used in converters.

In this paper, the work is introduced in: i) Section 2 presents the mathematical analysis of the torque ripple at the time of commutation and its relation with DC link voltage; ii) The proposed scheme of brushless DC motor drive is put forward in section 3 along with the relation between the duty ratio of converter and torque ripple and a modified switched capacitor-based converter is proposed; iii) The method to perform the experiment, results, and discussions are presented in section 4; and iv) The concluding remark has been described in section 5.

2. MATHEMATICAL ANALYSIS OF TORQUE RIPPLE DURING COMMUTATION

An equivalent circuit representation of the brushless DC motor drive has been shown in Figure 1. The voltage equation for the three phases in BLDC motor can be represented as (1). The equation for electromagnetic torque is given by (2).

$$\begin{bmatrix} V_r \\ V_y \\ V_b \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_r \\ i_y \\ i_b \end{bmatrix} + \begin{bmatrix} L & 0 & 0 \\ 0 & L & 0 \\ 0 & 0 & L \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_r \\ i_y \\ i_b \end{bmatrix} + \begin{bmatrix} e_r \\ e_y \\ e_b \end{bmatrix} + \begin{bmatrix} V_{no} \\ V_{no} \\ V_{no} \end{bmatrix} \quad (1)$$

$$T_e = \frac{e_r i_r + e_y i_y + e_b i_b}{\omega_m} \quad (2)$$

Where, V_{no} is the neutral to ground voltage, V_r, V_y, and V_z are the terminal voltages of the three phases. The three phase currents are given by i_r, i_y, and i_b. The trapezoidal back emf are given by e_r, e_y, and e_b. R is the resistance of the phase winding. Assuming all three phases have same resistance and L is the equivalent inductance of the phase winding.

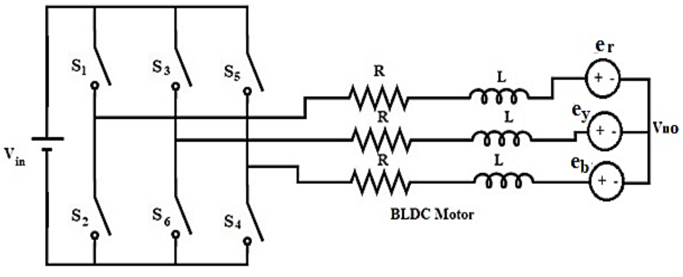

Figure 1. Equivalent circuit representation of BLDC motor

The desired waveform of current is rectangular in shape but practically it is not the same. The actual phase current is trapezoidal in shape comprising of finite rise time and fall time due to the presence of stator inductance [23]–[27]. The actual shape of phase current obtained is presented in Figure 2. The slope of phase current has a direct impact on the torque ripple of the brushless DC motor.

Assuming very short duration of commutation, we can consider the back emf to be constant during commutation. Then the initial values of voltage at the start of the commutation can be considered as $V_r = 0$, $V_y = V_{dc}$, $V_b = 0$, $e_r = E_c$, $e_y = E_c$, and $e_b = -E_c$. Rewriting (1), using the values of initial condition, we get (3).

$$\left.\begin{aligned} Ri_r + L\frac{di_r}{dt} + e_r + V_{no} &= 0 \\ Ri_y + L\frac{di_y}{dt} + e_y + V_{no} &= V_{dc} \\ Ri_b + L\frac{di_b}{dt} + e_b + V_{no} &= 0 \end{aligned}\right\} \tag{3}$$

The neutral point voltage drop can be written as (4). Substituting the initial values of emf and current in the (2), the torque equation before commutation is given by (5).

$$V_{no} = \frac{1}{3}(V_{dc} - E_c) \tag{4}$$

$$T_{e\_start} = \frac{2I_cE_c}{\omega_m} \tag{5}$$

Considering high switching frequency of the pulse width modulation and shorter time period for commutation. The effect of resistance can be neglected. The slope of the phase current obtained using the above assumption has been shown in (6). The time taken for the current (i_r) to decay and reduce to initial value as shown in Figure 3 can be obtained using (6) and has been expressed as (7).

$$\left.\begin{aligned} \frac{di_r}{dt} &= -\frac{V_{dc}+2E_c}{3L} \\ \frac{di_y}{dt} &= \frac{2(V_{dc}-E_c)}{3L} \\ \frac{di_b}{dt} &= -\frac{V_{dc}-4E_c}{3L} \end{aligned}\right\} \tag{6}$$

$$t_{decay} = \frac{3LI_c}{V_{dc}+2E_c} \tag{7}$$

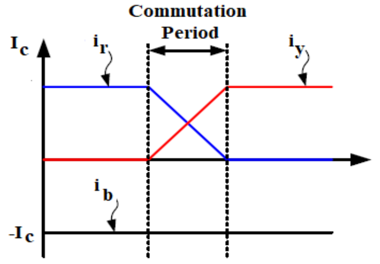

Figure 2. Phase current of three phases during commutation

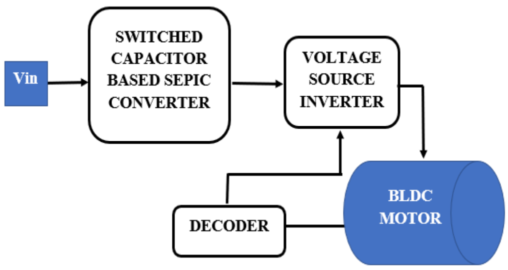

Figure 3. Proposed BLDC drive circuit

The time taken for the current (i_y) to rise from 0 to Ic as shown in Figure 3 can be obtained using (6) and can be expressed as (8).

$$t_{rise} = \frac{3LI_c}{2(V_{dc}-E_c)} \tag{8}$$

Using (2), (6), and the initial conditions, the equation of torque during commutation can be obtained. The expression for electromagnetic torque during commutation is given by (9).

$$T_{e\_end} = \frac{2E_c}{\omega_m}\left[I_c + \frac{V_{dc}-4E_c}{3L}t\right] \tag{9}$$

The torque ripple is the difference between the maximum and minimum electromagnetic torque of the BLDC motor [27-28]. Therefore, the torque ripple is expressed as (10). The relationship between DC link voltage and torque ripple can be described using (10).

$$\Delta T = \frac{2E_c}{\omega_m}\left[\frac{V_{dc}-4E_c}{3L}t\right] \tag{10}$$

3. PROPOSED SCHEME FOR BLDC DRIVE

The schematic diagram of the proposed brushless DC motor drive has been presented in Figure 3. The proposed BLDC drive comprises of SEPIC derived topology integrated with inverter. The proposed DC-DC converter is derived from the conventional SEPIC by connecting switched capacitor cell with it. Unlike classical switched-capacitor based SEPIC converter presented in [22], the proposed converter comprises of one switch, which is required to be controlled.

3.1. Switched-capacitor based SEPIC

The circuit diagram of the newly proposed switched capacitor based SEPIC converter has been presented in Figure 4. The mode of operation of the circuit can be divided into two types: i) continuous conduction mode and ii) discontinuous conduction mode. For brushless DC motor drive operation, we have considered only the continuous conduction mode. The continuous conduction mode of operation can be divided into two more modes based upon the switch on and off state of the switch. The circuit operation during switch on and off mode has been shown in the Figures 5 and 6 respectively.

The relationship between the input and output voltage of the proposed converter is given in (11). In (11), D is the duty ratio, that is equal to the ratio of time the switch is on to the total time period. By changing the operating time of the switch S_1 of the converter, the output voltage obtained from the converter can be changed. This V_o is fed to the inverter of BLDC drive and acts as the DC link voltage.

$$V_o = \frac{2-D}{(1-D)}V_i \tag{11}$$

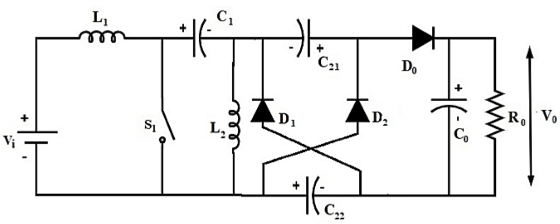

Figure 4. Switched capacitor-based DC-DC converter

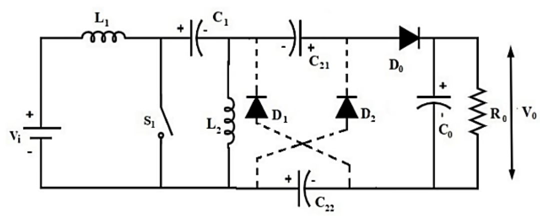

Figure 5. Mode 1 of switched capacitor-based DC-DC converter

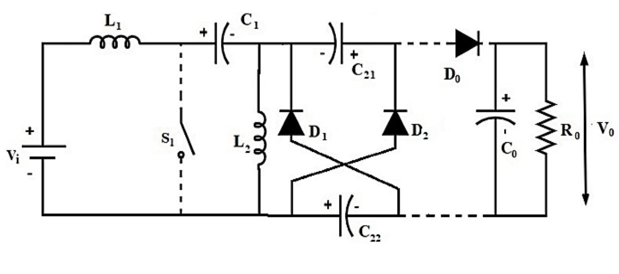

Figure 6. Mode 2 of switched capacitor-based DC-DC converter

3.2. Estimation of torque ripple in the proposed BLDC drive

The proposed DC-DC converter is integrated with inverter to run the BLDC drive. Substituting V_{dc} from (11) in (10), we get (12).

$$\Delta T = \frac{2E_c}{\omega_m}\left[\frac{\frac{(2-D)V_{in}}{(1-D)}-4E_c}{3L}t\right] \tag{12}$$

The equation for torque ripple after the integration of the modified DC-DC converter has been presented in (12). The proposed brushless DC motor drive is operated at different duty ratio of the DC-DC converter. The commutation torque ripple obtained can be calculated using (12). It has been observed that with the change in duty ratio the commutation torque ripple changes. The (10) shows that with change of DC-DC converter, the DC link voltage will change and so does the torque ripple. Therefore, the choice of converter for BLDC drive will become easier for future studies.

4. RESULTS AND DISCUSSION

The proposed DC-DC converter shown in Figure 4, has been designed for an operating frequency of 50 kHz, taking L_1 as 500 µH, C_1 as 5 µF, C_{21} and C_{22} as 5 µF and C_0 as 1 µF. In order to analyze the performance of the proposed converter, a comparative analysis has been performed between single-ended primary-inductor converter (SEPIC) [20], ZETA [21], and SC based ZETA [22]. Table 1 shows the comparative analysis of the output voltage of the proposed converter with the above-mentioned converters. The input voltage has been varied from 5 to 30 volt, keeping the duty ratio constant at 65%. The obtained outcome has been presented in Table 1. The total harmonic distortion of the output voltage for all the converters has also been observed for different duty ratio. Table 2 represents the comparative analysis for the mentioned converters at 50 kHz frequency.

Table 1. A comparative analysis of output voltages of converters presented in [20]–[23] and the proposed converter for D = 65%

Vin (Volt)	SEPIC Vout (Volt) [20]	ZETA Vout (Volt) [21]	SC based ZETA Vout (Volt) [22]	Proposed Converter Vout (Volt)
5	11.16	9.45	15.85	16.21
10	17.87	19.31	33.19	34.75
15	27.16	29.15	50.53	53.29
20	36.45	39	67.88	71.82
25	45.73	48.85	85.22	90.36
30	55.02	58.7	102.6	108.9

Table 2. Comparison of converter topologies

Parameters	SEPIC [20]	ZETA [21]	SC based ZETA [22]	Modified SC based SEPIC
Active switches	1	1	1	1
Vo/Vi at D = 0.65	1.8	1.95	3.39	3.6
THD% at Vo for Vin = 20 volt	22.37	14.79	14.79	11.92

The comparative analysis presented in Table 2 has been done for an input of 20 volt at a duty ratio of 65%. The output voltage obtained using the proposed converter for an input of 20 voltage is 72 volts with total harmonic distortion of 11.92%, which is a much better output as compared to the previously existing converters presented in [20]–[22]. The simulation of the proposed drive is presented in Figure 7. An experimental setup has been developed for verifying the effectiveness of the proposed drive. The experimental test setup for the BLDC drive has been presented in Figure 8. The inverter has been supplied with the output from the DC-DC converter. The V_{dc} applied to the inverter is varied from 12 to 15 volt. The switches used in the inverter circuit are controlled with the help of signals generated by Arduino-UNO. The designed proposed DC-DC converter is applied to generate the V_{dc} voltage. The stator back EMF of the BLDC motor is been observed in the oscilloscope. The obtained stator back EMF waveform for one of the three phases in the proposed drive with 15-volt V_{dc} has been presented in the Figure 9.

As mentioned above, the (12) shows that by varying the duty ratio, the DC link voltage can be controlled, which in turn helps in controlling the ripple in electromagnetic torque of BLDC drive. The Table 3 presents the variation of torque ripple and commutation time with respect to the change in duty ratio of the proposed converter. Moreover, the torque ripple is defined as (14). It can be observed from Table 3 that, with the increase of duty ratio, the commutation time decreases. The torque ripple can be reduced to 16.5% using the proposed simple BLDC drive.

$$\Delta T = T_{MAX} - T_{MIN} \quad (13)$$

$$T_{ripple} = \frac{\Delta T}{T_{avg}} \quad (14)$$

Figure 10(a) illustrates the output current waveform and electromagnetic torque of the proposed drive at a duty ratio of 65%. The BLDC drive has also been operated without using DC-DC converter and the waveform of phase currents and torque is presented in Figure 10(b). The torque ripple obtained in BLDC drive, when operated without using DC-DC converter is 44.9%. It is observed from Table 3 that with the integration of the proposed converter, torque ripple percentage has been reduced down to 16.5% at a duty ratio of 85% which is much less as compared to the BLDC drive without any DC-DC converter.

Table 3. Analysis of commutation time and ripple for proposed drive

Duty ratio	Commutation time (μsec)	Change in torque (ΔT)	Average torque (Nm)	Torque ripple (%)
0.55	637.926	0.8318	2.983	27.88468
0.6	602.33	0.799	2.976	26.84812
0.65	685.7	0.7604	3.055	24.89034
0.7	544.41	0.8554	3.155	27.11252
0.75	400.59	0.7354	3.288	22.36618
0.8	372.3	0.7213	3.475	20.75683
0.85	272.39	0.5863	3.55	16.51549

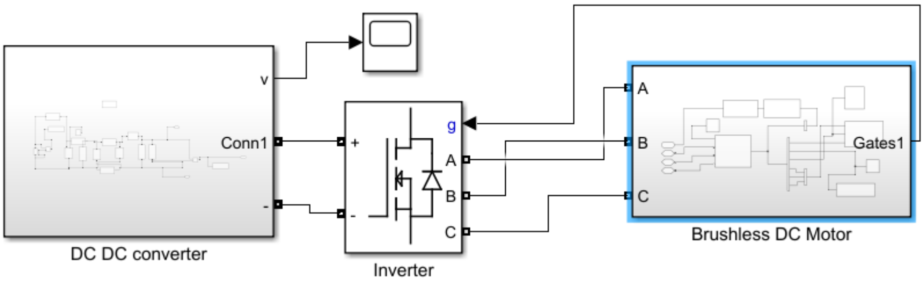

Figure 7. Simulation of the proposed drive

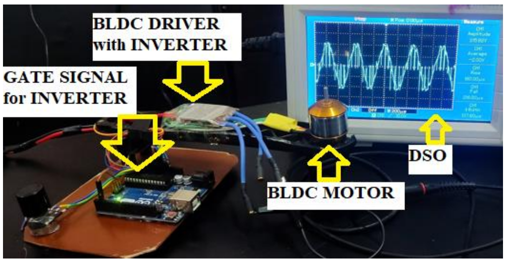

Figure 8. Experimental test setup

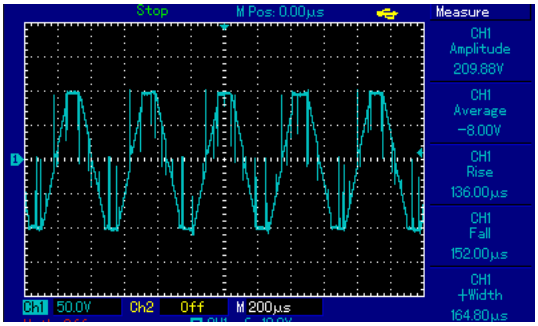

Figure 9. Stator back EMF Waveforms

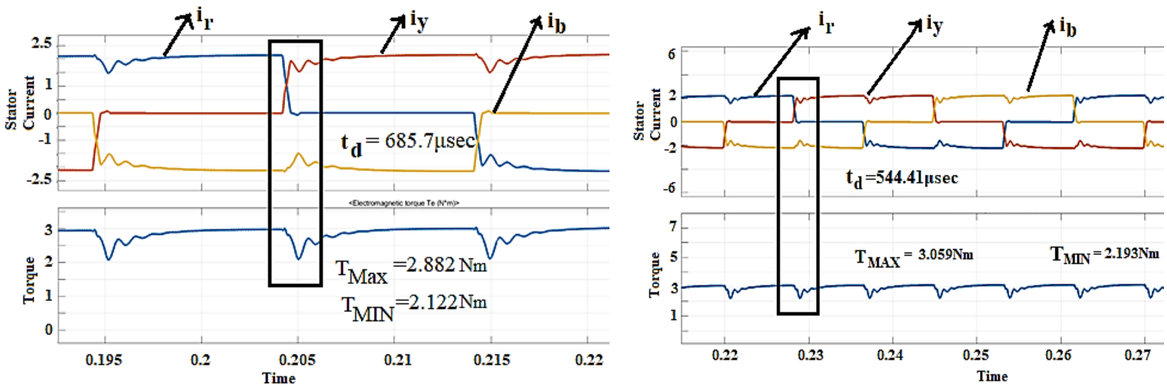

Figure 10. Waveforms of BLDC drive with (a) proposed converter obtained at duty ratio 65% and (b) without DC-DC converter

From the results we may say that, the proposed DC-DC converter offers higher gain of about 7 times the input at a lower duty ratio of 65%. To maintain a lower torque ripple in BLDC, drive high gain converter is a simple solution. Thus, the proposed converter which offers lower THD helps maintain high voltage gain with lower voltage stress across the switch and in turn helps to minimize torque ripple. The proposed drive offers better solution to torque ripple suppression as compared to the complicated modulation technique presented in [8] and complex circuit analysis presented in [26].

5. CONCLUSION

In this study, a modified switched capacitor-based DC-DC converter has been presented to suppress the commutation torque ripple of BLDC motor drive and in previous section it was compared with other such converter fed drives. The main contribution of this paper lies with the mathematical analysis of the cause of torque ripple and the condition for refraining torque ripple. The detailed analysis of the proposed converter fed BLDC drive is presented and in section 4 experimental results are provided. The results obtained shows that the ripple obtained in the electromagnetic torque of the BLDC drive can be minimized with the application of proposed DC-DC converter without using any complicated control techniques. It can be seen that at duty ratio of 55% the torque ripple is 27.88% and with increase in duty ratio to 85%, the torque ripple reduces to 16.27%. The torque ripple in electromagnetic torque can be minimized by simply modulating the converter duty ratio.

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