

# Torque Ripple Minimization of a BLDC Motor Drive by Using Electronic Commutation and Speed, Current Controllers

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**Abstract**— Brushless DC motors are having a major problem with harmonics in torque. The variations in speed and production of noise should be minimized by using proper topologies. BLDC motors have been gaining attention from different Industrial and domestic appliance manufacturers, because of their high efficiency, high power density and easy maintenance and low cost. This paper presents a three phase BLDC motor with low cost drive to be driven without DC link capacitor. The proposed technique uses an electronic commutation and operates the machine exclusive of the intermediate DC link capacitor. The designing of Brushless DC motor drive system along with control system for torque ripple minimization, speed controller and current controllers are presented using MATLAB / SIMULINK and results are evaluated.

**Keywords**— Brushless machines, Torque ripple compensation, six-phase voltage source inverter (VSI), harmonics suppression, pulse width modulation (PWM).

## I. INTRODUCTION

Permanent Magnet Synchronous (PMS) motors and Brushless DC (BLDC) motors are becoming more useful in industrial applications and home appliance because of their high reliability, efficiency and low cost and maintenance compared to other motors. By using rotor position BLDC motors are commutated electronically and the rotor position information can be obtained by using position sensors. BLDC and PMS motors are now designed with high power densities, these causes the increasing their popularity in applications such as airspace applications and mobile coolers.

PMS motors needs continuous rotor position information for their operation and a significant computational time is

required to improve the motor performance by controlling the rotor.

Hall Effect sensors or back emf sensing technique is used to obtain the rotor position of BLDC motor for every 60 electrical degrees. Therefore, BLDC motors have becoming more popular for industrial applications where efficiency, compact and cost effective factors are considered.

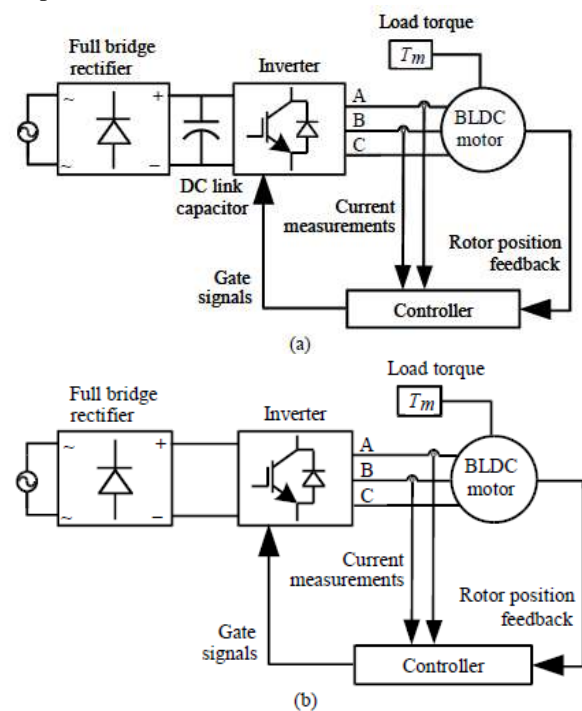


Fig. 1. (a) A typical BLDC motor drive; and (b) a BLDC motor drive without a DC link capacitor.

The motor drive consists of a diode bridge rectifier and a large electrolytic capacitor with a converter fed rotor for rotor position information. The main function includes, bus voltage stabilization, ripple current conduction due to switching events, etc. In automotive applications, one of the

major problems is the exuberant and barbarous temperatures they have to withstand, under hood, which during the summer months would reduce their life.

The intermediate DC link capacitor used in indirect conversion topologies, requires a large space for its installation which results in increasing its weight and occupying place. Usually, a large electrolytic capacitor is employed to support the intermediate DC link voltage. The lifetime and properties associated with the capacitor are affected by the ambient temperature. Furthermore, the type of dielectric material, the ambient temperature and the storage temperature are the most significant aging factors for an electrolytic capacitor mainly in hot or cold environments viz. heating, ventilation and air conditioning applications. So the inclusion of the capacitor in the circuit decreases the overall converter reliability, as it is the most vulnerable component amongst the other in the circuit.

Without the DC link capacitor, the rectified mains supply is directly applied to the drive. The absence of DC link capacitor causes to reduce the overall cost of the motor drive but at the expense of harmonics in torque, which are inevitable and expected to be around zero crossing points of the supply.

## II. MATHEMATICAL MODEL

In three-phase BLDC motor drives trapezoidal back emf can be obtained by energizing only two phases and the third one remains in off state at any instant of time. As such, only two switches of the inverter are in conduction at any instant. Usually, these two switches are controlled using PWM or a micro controller is used to generate the hysteretic control signals, either in torque control or speed control mode. This switching approach is not suitable for motor drives with no DC link capacitor because there is no continuation path for the phase current when the controlled switches are in off state. In the projected BLDC motor drive, a switching algorithm, which is based on solitary switch control while keeping the other switch in ON state for the complete switching interval, is employed. The switch that remains in ON state provides a freewheeling path to the inductive current whereas the controlled switch in OFF state.

In a position sensor less BLDC motor drive, the commutation points of the inverter can be obtained by knowing the back EMF zero-cross-points (ZCP) and a period of time delay of speed dependent. The phase back-EMF is trapezoidal which is induced in the stator windings of a BLDC motor, so that the Zero Crossing Point of the back-EMF can be detected by monitoring the terminal voltage waveform of a silent phase.

The case in point when the terminal voltage of the silent phase equivalent with the half dc link voltage, during which point switching devices are turned ON is the zero crossing point of the back-EMF. The estimation processes of commutated points are shown in fig.

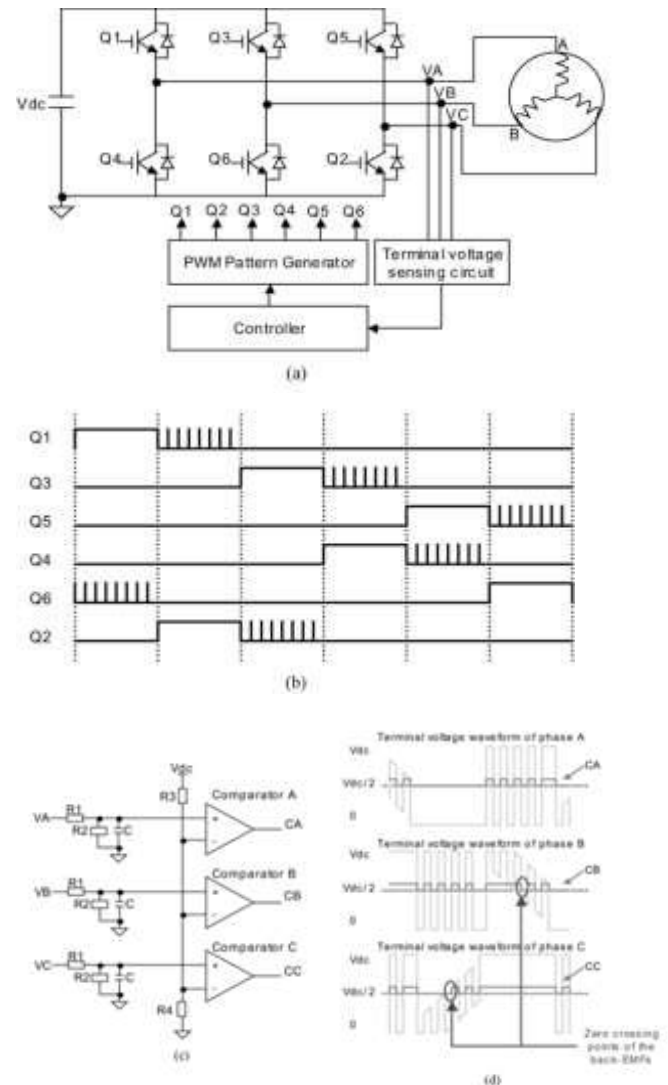


Fig.2

Two different methods for reducing the commutation torque ripple when a single current sensor is used in the dc link of the inverter to regulate the current flowing through two phases in series. These methods are inappropriate to apply to various trapezoidal BLDC motors, because they are open loop in nature.

The introduction of independent current sensors in the motor phases provides a great approach for reducing commutation torque ripple, because the current regulation of each phase is possible during commutation periods. The commutation

torque ripple can be minimized during low speed by the introduction of direct current sensing with hysteresis current controller.

The commutation torque ripple can be reduced by the introduction of feed-forward term in current controller to compensate for the average voltage variation of the non-commutated phase due to commutation in bipolar pulse width modulation (PWM) inverter-fed BLDC motor drives. However, this method cannot be applied to unipolar PWM which is an appropriate low cost application, because the voltage between the neutral point of the inverter and the neutral point of the machine varies with the ON-OFF position of the switching device of the inverter.

**COMMUTATION TORQUE RIPPLE REDUCTION STRATEGY**

*A. Analysis of commutation Torque Ripple*

Average voltage  $V_{m1}$  applied to a non-commutated phase before commutation is

$$V_{m1} = \frac{V_{dc}}{2} D_a \quad \dots\dots (1)$$

$$V_{m2} = \frac{V_{dc}(2D_b - 1)}{3} - \frac{e_a + e_b + e_c}{3} \dots (2)$$

*B. Voltage Disturbance Rejection Method*

In order to minimize the pulsating current, The PWM duty ratio during commutation must be modified in order that the average voltage of the non commutated phase maintains constant value, that is  $V_{m2} = V_m$

$$D_b = \frac{1}{2} + \frac{3}{4} D_a + \frac{e_a + e_b + e_c}{2V_{dc}} \quad \dots\dots(3)$$

$$D'_b = D_b \times \frac{t_c}{T} \quad \dots\dots(4)$$

In the voltage disturbance rejection method, the input for compensation should be applied to the inverter only during the commutation. So that the voltage disturbance rejection method uses a commutation interval that can be measured or estimated from phase current. However, using current sensors increases the cost of a motor driver.

Table.1: Switching Algorithm

Step	Hall sensor output			Switch is on state	Controlled switch
	Ha	Hb	Hc		
1	1	0	0	A1	C2
2	1	1	0	C2	B1
3	0	1	0	B1	A2
4	0	1	1	A2	C1
5	0	0	1	C1	B2
6	1	0	1	B2	A1

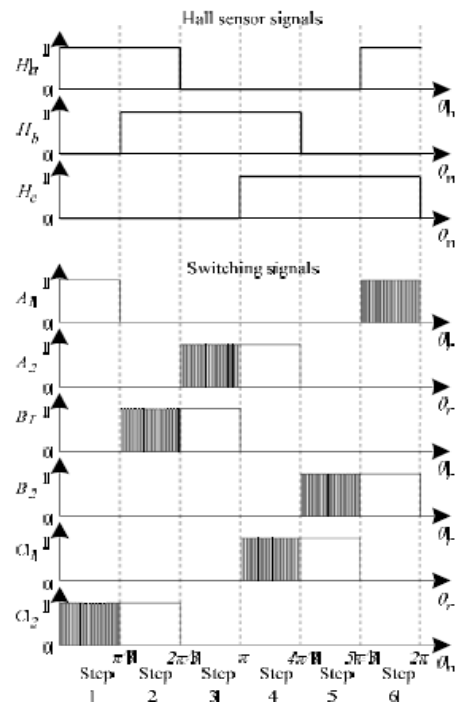
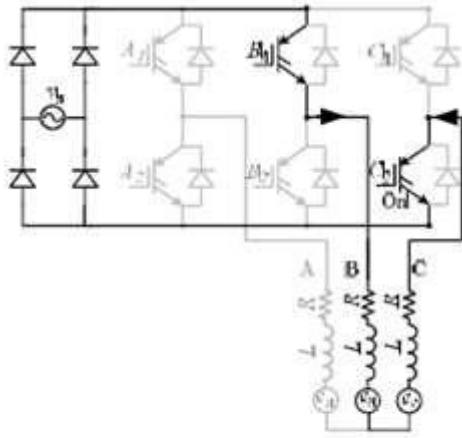
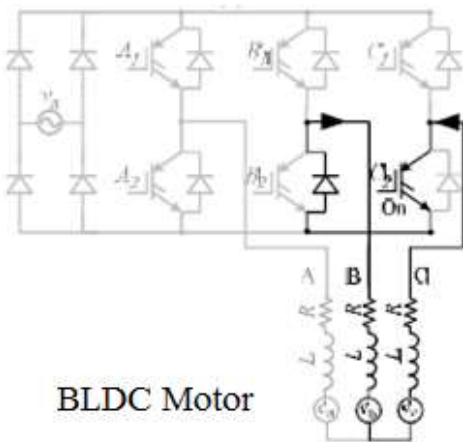


Fig.3: Hall Sensor signals and Switching Signals

**(C) MEASUREMENT OF COMMUTATION INTERVAL**



(a) BLDC Motor



BLDC Motor

(b)

Fig.4: Step 2 of the switching algorithm: (a) B1 is on; (b) B1 is off.

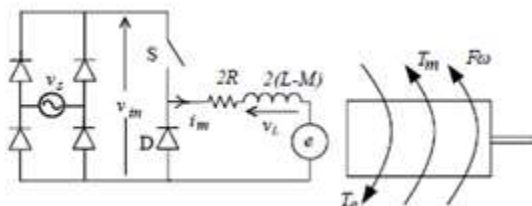


Fig.5: A buck converter based model of the motor drive

If R is assumed to be small.

$$V_{in}(t) = 2(L - M) \frac{di_m}{dt} + e(t) \quad (5)$$

$$0 = 2(L - M) \frac{di_m}{dt} + e(t) \quad (6)$$

Let the speed of the rotor is  $\omega$  in  $\text{rads}^{-1}$ . Then the torque produced by the motor  $T_e$  (Nm), is given as

$$T_e = \frac{e(t)i_m(t)}{\omega} \quad (7)$$

$$T_e - T_m = J \frac{d\omega(t)}{dt} + F\omega(t) \quad (8)$$

Where J is the combined inertia ( $\text{kgm}^2$ ) of the rotor and load and F is the mechanical speed of the motor related by

$$P\omega = \frac{d\theta_r}{dt} \quad (9)$$

Where P is the number of pole pairs of the BLDC motor

Time T is the interval for  $V_{in}(t)$  to reach E from 0V and  $T_m$  is the period of the input mains voltage.

$$T = \frac{1}{2\pi f} \sin^{-1} \left( \frac{E}{V_m} \right) \quad (10)$$

Where  $V_m$  is the peak value (V) and f is the frequency (Hz) of the supply.

$$t_1 = t - \left( \frac{T_m}{2} - T \right) \quad (11)$$

$$t_2 = t - \left( \frac{T_m}{2} \right) \quad (12)$$

$$t_3 = t - \left( \frac{T_m}{2} + T \right) \quad (13)$$

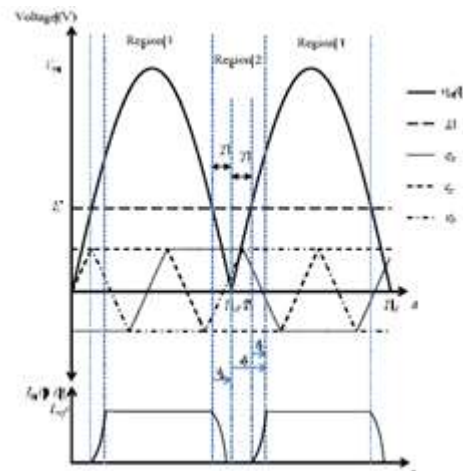


Fig.6: Controllable and uncontrollable regions of the motor drive at steady state.

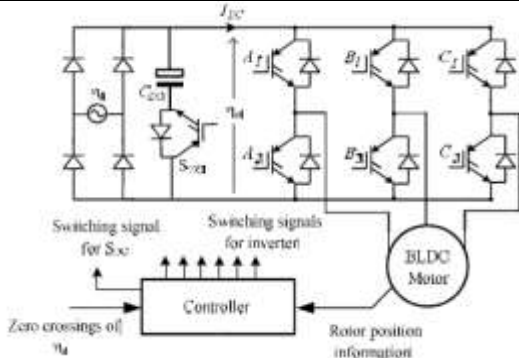


Fig.7: Proposed technique for torque ripple compensation

IV. IMPLEMENTATION

$$C_{DC} \frac{dV_m(t)}{dt} = I_{avg} \quad (14)$$

By approximating the derivative, the minimum value of  $C_{DC}$  that is required to provide  $I_{avg}$  from the DC link is given by

$$C_{DC} = \frac{2T I_{avg}}{V_{in} - E} \quad (15)$$

To apply the voltage disturbance signal to the system, the commutation duration must be known. To know the commutation duration current sensors have been used. The position senseless controller already uses the terminal voltages for obtaining the ZCP of phase back-EMF. For voltage disturbance signal, if the terminal voltage gives the information related to commutation interval, then the current sensors are not required. When using the out-going phase unipolar PWM scheme, the silent phase terminal voltages remains positive(or zero) dc bus voltage during commutation and has a different (lower or higher) value than half the dc bus voltage until silent phase back EMF reaches to zero. By measuring the comparator output transition time after starting the commutation,, the commutation duration can be known.

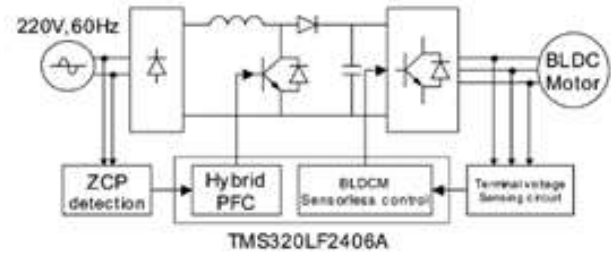
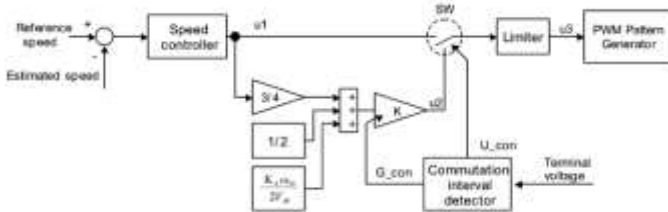


Fig.8: Configuration of the experimental BLDC motor drive

TABLE I  
 MOTOR PARAMETERS

Rated power	1.5 [kW]
Pole number	4
Line-to-line resistance	0.82 [ $\Omega$ ]
Line-to-line inductance	6 [mH]
Back-EMF constant	0.0162 [V/rpm]

Torque ripple, defined as the difference between the least and highest torque divided by the greatest torque, consists of two components: the electromagnetic torque fluctuation and the reluctance torque. Torque ripple in brushless dc motors is mostly due to the fluctuations of the field distribution and the armature MMF which depends on the motor structure and feed current waveform. At high speeds, torque ripple is usually filtered by system inertia. On the other hand at small speeds torque ripple produces noticeable effects that may not be tolerable in applications such as positioning and robotics. An idealized brushless DC motor has a trapezoidal back electromotive force (EMF) waveform. Zero torque ripples is produced for this waveform when the motor is fed by rectangular current. However for practical reasons, non-uniformity of magnetic material and design tradeoffs it is hard to produce the trapezoidal wave shape it a desired manner. Therefore torque ripple appears even though rectangular current is fed in conventional control. In addition, since the motor windings are inductive, the current controller has often no ability to produce the required di/dt in the commutation period due to finite DC bus supply voltage, the resulting torque ripple is called commutation torque ripple. Torque ripple can create undesirable noise and vibration in speed applications, and can cause inaccuracies in motion control.

V. SIMULATION RESULTS

This paper proposes a method of minimization of torque ripple of the BLDC motor with un-ideal back EMF waveforms. The duty cycle of the pulses used to operate the inverter gates is calculated in the torque controller in normal conduction period and commutation period. Simulation results show that compared with conventional control; there is an apparent reduction in ripple.

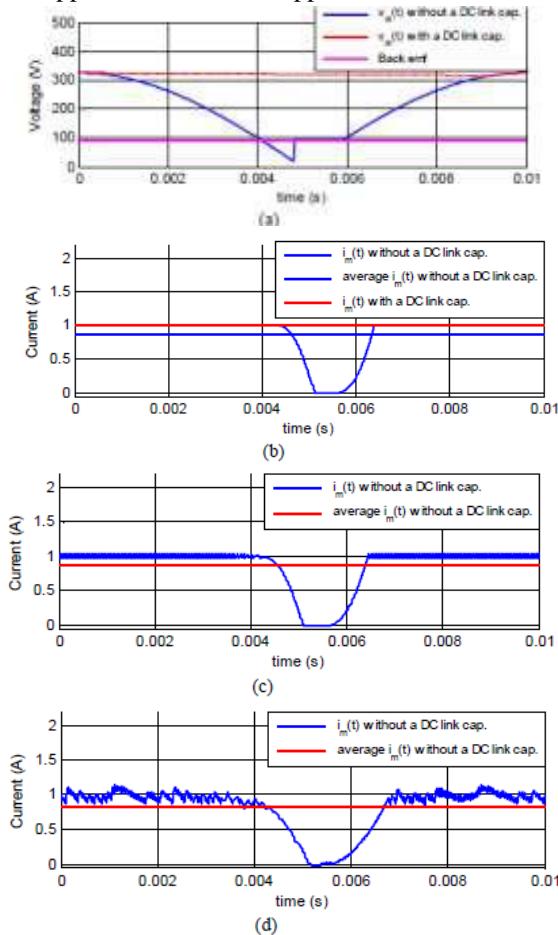


Fig.10: Case 3 with M1 for  $E=65V$ , (a)  $V_m(t)$  and  $E$ ; (b)  $I_m(t)$  by theoretical analysis; (c)  $I_m(t)$  by simulation; and (d)  $I_m(t)$  by experiment

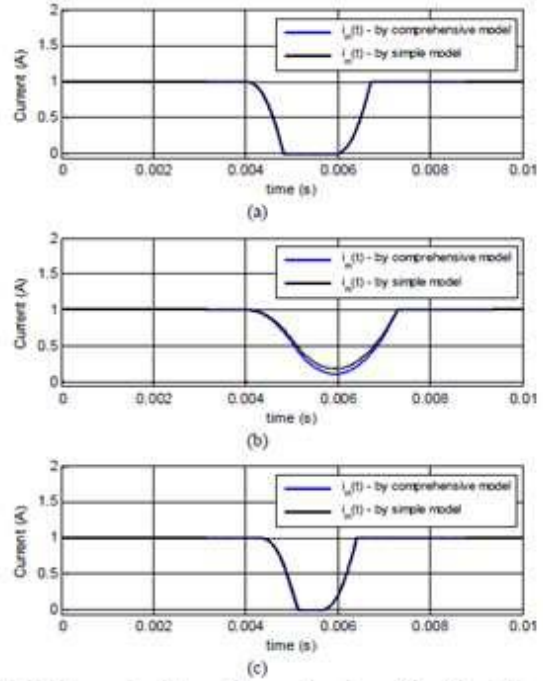


Fig.11: A comparison between the comprehensive model and the simple model; (a) case 1 with M1; (b) case 2 with M2; and (c) case 3 with M1

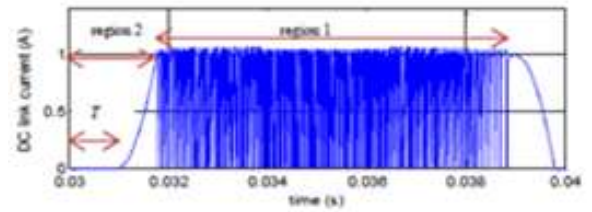


Fig.12: Current drawn from the DC link for case 1

TABLE II  
 COST COMPARISON BETWEEN THE CONVENTIONAL CONVERTER AND THE PROPOSED COMPENSATION TECHNIQUE

	Conventional converter (USD)	Proposed technique (USD)
Electrolytic DC link capacitor 150 $\mu$ F/400 V	3.8	0
4.7 $\mu$ F/400 V capacitor	0	0.29
IGBT 600 V / 10 A	0	0.51
Isolated gate driver 5.3 kVrms /2.5 A	0	1.12
Sub total	3.8	1.92
Saving due to compensation	N/A	1.88
Percentage saving from the total BOM cost	N/A	6%

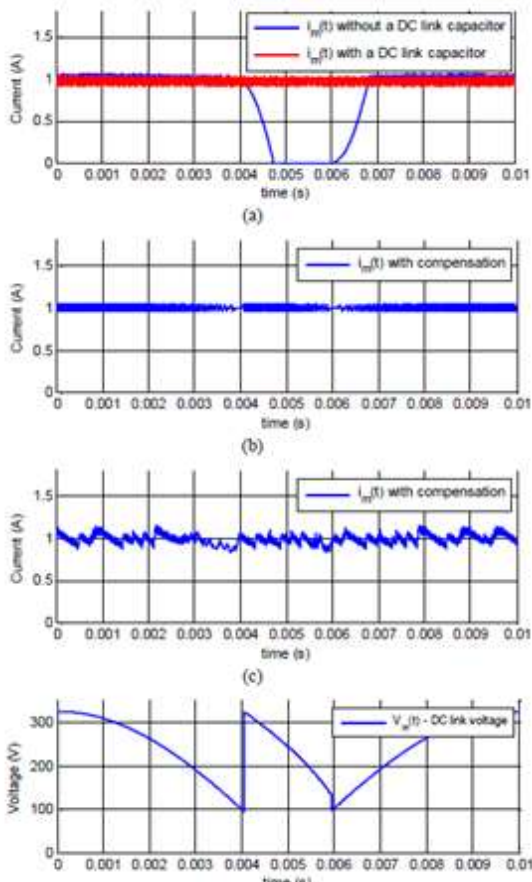


Fig.13: Proposed compensation for case 1: (a) simulated  $i_m(t)$  without a capacitor and with a  $150 \mu F$  capacitor, (b) simulated  $i_m(t)$  with proposed compensation; (c) experimental  $i_m(t)$  and (d) DC link voltage with proposed commutation

The motor drive reliability expected to be improved by the removal of DC link capacitor. The periodic torque ripples are predictable by removing the DC link capacitor and the motor drive applicability can be reduced. The compensation capacitor is approximately around 3% of the innovative capacitor.

The switching loss of the additional switch is not dominant due to lower switching frequency and current in comparison to the IGBTs in the inverter. So that the total harmonic distortions are reduced and the overall performance of the device is improved due to the absence of the DC link capacitor. As the torque ripple compensation capacitance is low the magnitudes of the capacitor charging currents and transient problems associated are low and hence this method is preferred for compensation and to improve the performance of the drive.

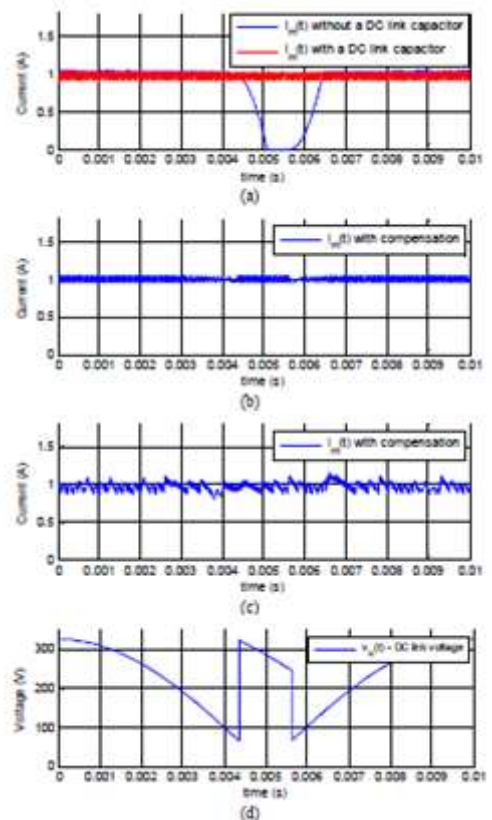


Fig.14: Proposed commutation for case 3: (a) simulated  $i_m(t)$  without a capacitor and with  $150 \mu F$  capacitor; (b) simulated  $i_m(t)$  with proposed compensation; (c) experimental  $i_m(t)$ ; and (d) DC link voltage with proposed compensation.

However, the major disadvantage of this proposed method is that the overall motor drive becomes complex. An additional IGBT and driving stage is needed in terms of hardware components.

$$T = \frac{\sin^{-1}\left(\frac{95}{325}\right)}{2 \times \pi \times 50} = 0.94ms \quad (16)$$

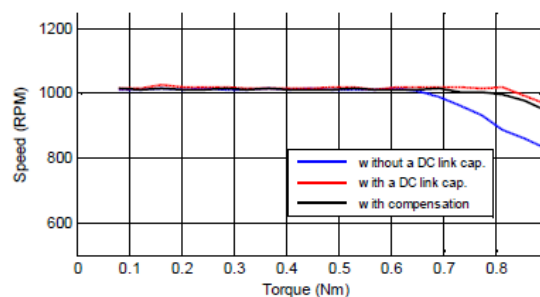


Fig.15: Torque speed characteristic curve with a  $150 \mu F$  DC link capacitor

The current in IGBT is measured to estimate the loss introduced by the additional IGBT, which is used in compensation circuit.

$$P_C = I^2 R_{ON} \quad (17)$$

TABLE III  
INPUT THD, TORQUE RIPPLE AND EFFICIENCY

	Conventional converter with stiff DC link	Converter without compensation	Converter with compensation
THD of the input current	203.4 %	114.3 %	105.6 %
Torque ripple due to the absence of the DC link capacitor	0 %	100 %	8 %
Efficiency of the converter	82.3 %	81.6 %	81.4 %

Turn ON and turn OFF losses can be found by using turn on and turn off switching energy parameters in the datasheet. The sum of turn on and turn off energies gives the total switching energy.

Switching loss can be calculated by  $P_S = E_S f_s$  (18)

Where  $f_s$  is the switching frequency. For the additional switch the switching frequency is 100Hz for a main supply.

## VI. CONCLUSION

A simple mathematical model and a reparation technique for inherent torque ripples of a BLDC motor drive, operated without a DC link capacitor, have been proposed. The simplicity of the model permits the controller to be implemented on inexpensive microcontroller platforms with very low resources. With the proposed technique for compensating torque ripples, comparable performance to a conventional BLDC motor drive with a large DC link capacitor can be achieved. However, with the torque ripple compensation technique, the overall complexity of the motor drive has been increased, which is a major disadvantage. Based on the application, major augmentations in both hardware and firmware may be required. The good agreement between the theoretical results, simulated results and experimental results demonstrate the accuracy of the simple buck model and the effectiveness of the proposed compensation technique. The proposed compensation technique is expected to be useful for manufacturing low cost BLDC motor drives with comparable performance.

APPENDIX  
PARAMETERS OF THE MOTORS

Parameter	Motor M1	Motor M2
$R$	3 $\Omega$	7.5 $\Omega$
$L - M$	15 mH	54 mH
$J$	0.0024 kgm <sup>2</sup>	0.0024 kgm <sup>2</sup>
$F$	0.001 Nms	0.001 Nms
$P$	3	3
Back emf	Trapezoidal	Trapezoidal
Torque constant	0.8 NmA <sup>-1</sup>	1.4 NmA <sup>-1</sup>
Rated power	250 W	250 W

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