A mitigation technique for torque ripple in a brushless DC motor by controlled switching of small DC link capacitor

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ABSTRACT

High performance applications are now days utilizing the brushless DC motor (BLDC) drives due to its ruggedness, compactness, high torque to weight ratio, high dynamic response etc. the feature of square-wave current excitation waveforms in BLDC motor drives allows some major system simplifications for trapezoidal BLDC motors. The developed torque is constant in ideal conditions in this motor when its back emf waveform is of trapezoidal type. Despite this, due to the physical construction of the motor and its settings, torque ripple exists in the output torque and is an undesired phenomenon in the BLDC motor drives and are also linked to the motor's control and driver sides. This paper provides a new way for reducing torque ripple and is simple, compact and cost effective. To prove the correctness of the compensation technique, circuit is modelled and simulations are carried to examine the theoretical performance of the BLDC motor drive. Experiments on a prototype drive were conducted to further validate the theoretical analysis as well as the utility of the proposed technique.

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1. INTRODUCTION

Brushless direct current (BLDC) motors are commonly employed in low and medium power applications like computer peripherals, electric powered vehicles, servos, fans, electric-bikes, electric-cars, sewing machines, variable speed drive systems of aerospace, domestic appliances, and robots [1]-[3]. This motor offers numerous benefits, including high torque, a simple structural design, very high-power density, good speed controlling performance, higher power to weight ratio, minimal maintenance, good power factor, higher efficiency, dependable reliability, low noise, compact size, longer life and simple control schemes. A brushless DC motor is a permanent magnet synchronous motor that controls the currents in its static armature with position detectors and an electronic commutator. It has magnets on the rotating rotor, and its operating characteristics are similar to those of a separately excited DC motor [4], [5]. Based on commutation methods, two main types of BLDC motors that are common are: a) trapezoidal type BLDC and b) sinusoidal type BLDC (PMAC). Because of its simple construction, low cost, and higher efficiency, the trapezoidal type motor is a more striking choice for most applications [6]. A smooth instantaneous torque waveform is generated in ideal conditions in these two types of BLDC drives. Any source with non-ideal qualities that causes the phase currents or back-EMF waveforms to depart from their fully sinusoidal shapes will produce unwanted pulsing torque components [7]. Due to time harmonics in the current waveforms and time-varying delays involving the commanded and real currents, the inverter contributes to torque ripples in general.

Trapezoidal permanent magnet motors have some noticeable differences from PMAC motors and for BLDC motors, current excitation waveforms are square-wave waveforms.

The reduction of the torque ripples and the improvement of control performance of BLDC motor have been the major research hotspot in recent years [8]-[12]. The perfect BLDC motor, in theory, should have the correct trapezoidal back EMF waveform to provide to the controller as feedback to control the three phase currents. In the square-wave waveforms of current excitation, when the current changes levels, the commutation torque takes the form of spikes or dips at each discrete time instantresulting in the ripple torque.

Torque ripples must be practically non-existent or very minimal in some precise motion control applications. Commutation torque ripples can cause noise and vibrations, posing serious challenges that limit the BLDC motor's high-performance operation. They also create speed oscillations, which cause motor performance to deteriorate. In addition to the above-mentioned issues, torque ripples can cause resonances in the mechanical parts of the system, resulting in acoustic noise, and they can cause undesirable patterns on machined surfaces in some machine tool applications [13]-[18].

The torque ripples can be eliminated with the use of large electrolytic capacitor in the DC link of motor drive. But large capacitors are typically rated for a short duration of time. Electrolytic capacitors costs about 5-15% of motor drive cost. Bulky capacitors require 5-20% of space in the motor drive PCB. These are first to fail due to electrolyte presence. Maintenance and repair will be costly. Its lifetime is affected by the operating temperature, heating and ventilation issues which amounts to reduction of reliability of the drive. Researchers sought to overcome the issue of torque ripples in BLDC motors in a number of studies [19]-[24], and many approaches for reducing the generation of pulsating torque components were proposed. Despite the growing number of strategies for minimising pulsing torque production in BLDC motor drives that have been described so far, practical and cost-effective solutions are scarce and have yet to materialise for applications. This proposed study presents a compensatory technique for lowering commutation torque ripple in high-performance BLDC motor drives using a very small DC link capacitor [25]. The controller algorithm for this proposed project has been created to develop signal pulses to control the drive for effectively minimising ripples of the developed torque so that the system may be stabilised fast with fewer torque ripples [26]-[30]. A compensation method is proposed for a brush less DC motor to reduce torque ripple with minimum components and less cost is presented in this paper. In this method, instead of a large value capacitor as used in conventional drives, a very less value of capacitor is used. The necessary model, simulations and results aregiven in the following pages.

2. TORQUE RIPPLE ANALYSIS IN BRUSH LESS DC MOTOR

The voltage obtained from the inverter will be applied to three stator phase windings of brush less DC motor. At the input side of a brushless DC motor, a hex-connected bridge inverter is used to generate the appropriate switched pulses to the stator windings as needed. Normally during speed control or torque control, at any point of time the switches which are connected to any two phases will be controlled. But here only one switch is controlled and the second switch will be in OFF state during the whole interval as shown in the above figure. During the "OFF" position of the controlled switch, freewheeling path for the inductive current is provided by the power switch in the "ON" position. P, Q, and R are phases and P_1 and P_2, Q_1 and Q_2, R_1 and R_2 are the inverter switches. 1 and 2 subscripts are used to distinguish upper and lower switches of each phase. From Figures 1(a) and 1(b), the equations during ON and OFF states of switch Q_1 of the brush less DC motor drive will be expressed by following equations:

$$V_{in}(t) = 2i_m(t)R + 2(L-M)\frac{di_m(t)}{dt} + e(t) \tag{1}$$

$$0 = 2i_m(t)R + 2(L-M)\frac{di_m(t)}{dt} + e(t) \tag{2}$$

By taking the assumptions that the resistance R is very minimal and can be neglected, it become:

$$V_{in}(t) = 2(L-M)\frac{di_m(t)}{dt} + e(t) \tag{3}$$

$$0 = 2(L-M)\frac{di_m(t)}{dt} + e(t) \tag{4}$$

The motor's mechanical and electrical speeds are intertwined by:

$$P\omega = \frac{d\theta_r}{dt} \tag{5}$$

Where θr is the position of rotor in radians, P denotes the number of pole pairs on the rotor of brush less DC motor.

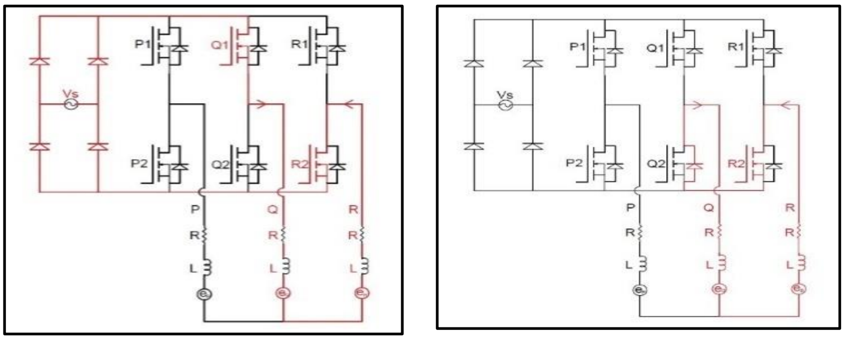


Figure 1. Current path when (a) Q1 is ON and (b) when Q1 OFF

Figure 2 illustrates therectifiedsupply voltage and the phase current builded up based on rectified supply voltage. Here E denotes average value of back-EMF appearing across DC line. It is observed from the figure that the phase current isnot maintained at the reference value at the time of zero crossings of supply voltage. The entire voltage area is divided into two different regions based on the motor phase current.

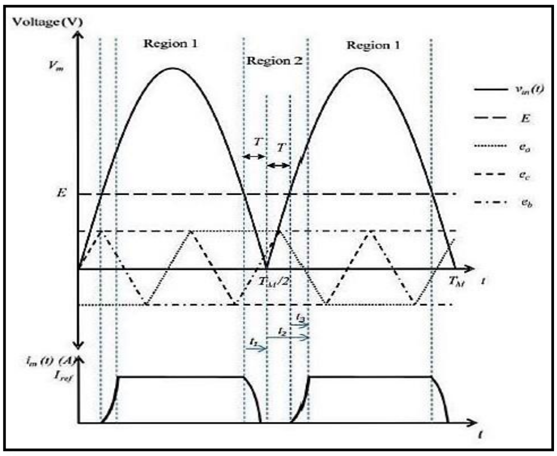


Figure 2. Supply voltage and phase current of brush less DC motor with no capacitor showing controllable and uncontrollable regions

During region-2, the motor phase current is nonlinear and uncontrolled as shown by (3) and (4). As a result, the torque in region-2 will be uncontrollable as well. Apart from that, the region-2 time duration is determined by the Back EMF as it grows. Therefore, it becomes necessary to analyse the effect of uncontrollable current on the developed torque. It is observed that the phase current becomes uncontrollable whenever the Back-EMF value becomes more than the value of supply voltage V_{in}(t). And how much duration that the phase current will be uncontrollable will be calculated in the following lines considering the derived equations and parameters of brush less DC motor.

T and T_M are the time intervals for V_{in}(t) to rise from 0 V to E and the supply voltage period, respectively. Thus, T can be given as:

$$T = \frac{1}{2\pi f}\sin^{-1}\left(\frac{E}{V_m}\right) \tag{6}$$

where V_m is the supply voltage's peak value and f is the frequency [8].

During region-2, current I_m(t) can be calculated in time intervals such that I_m(t) can be expressed as a piecewise function, minimising the complexity of formulations:

$$t_1 = t - \left(\frac{T_m}{2} - T\right) \tag{7}$$

$$t_2 = t - \left(\frac{T_m}{2}\right) \tag{8}$$

$$t_3 = t - \left(\frac{T_m}{2} + T\right) \tag{9}$$

To clarify, phas**e** current and voltage across the inductance in region-2 are denoted by I_m(t1) and $V_L(t_1)$ respectively, where the time 't' fulfils (T_M /2-T) ⩽ t⩽ T_M/2. To simplify the mathematical analysis, the input source voltage $V_{in}(t)$ to the motor is considered to be a piecewise linear function in region-2. From Figure 2, voltage across the inductance during 't_1' $V_L(t_1)$ canbe given by approximationas:

$$V_L(t_1) = -\frac{E}{T}t_1 \tag{10}$$

However, $V_L(t)$ can be given as:

$$V_L(t) = 2(L - M)\frac{dI_m(t)}{dt} \tag{11}$$

By (10) and (11) we get:

$$2(L - M)\frac{dI_m(t_1)}{dt_1} = -\frac{E}{T}t_1 \tag{12}$$

The general solution of (12) in time-domain is given as:

$$I_m(t_1) = -\frac{Et_1^2}{4(L-M)T} + C \tag{13}$$

The complete solution of $I_m(t_1)$ in time domain after substituting initial conditionI_m=I_{ref} at t_1=0 is

$$I_m(t_1) = -\frac{Et_1^2}{4(L-M)T} + I_{ref} \tag{14}$$

The condition for $I_m(t_1)$ to become discontinuous before the zero crossing of supply voltage $V_{in}(t)$ can be represented quantitatively using (15) as:

$$(L - M) < \frac{ET}{4I_{ref}} \tag{15}$$

Similar to derivation of $I_m(t_1)$, the solution for $I_m(t_2)$ and $I_m(t_3)$ can be found and given by:

$$I_m(t_2) = \frac{Et_2^2}{4(L-M)T} - \frac{Et_2}{2(L-M)} - \frac{ET}{4(L-M)} + I_{ref} \tag{16}$$

$$I_m(t_3) = \frac{Et_3^2}{4(L-M)T} \tag{17}$$

$I_m(t)$, following the zero crossing of $V_{in}(t)$ is represented by (16). Furthermore, evaluating the polarity of (16) at t_2=T allows us to deduce the essential condition for $I_m(t)$ to be continuous during region-2 and offers:

$$L - M > \frac{ET}{2I_{ref}}. \tag{18}$$

2.1. Method to reduce torque ripples

As observed in the previous pages when there is no capacitor there will be current discontinuities which leads to ripples in torque produced. Furthermore, in case of without capacitor the average value of torque generated from the motor drive is less compared to a case where large capacitor is used. As we observed in the earlier, the current discontinuities are occurring at the zero crossings of $V_{in}(t)$ which is to be avoided to improve current continuity and thereby reducing the torque ripple. To do so a small capacitor in series with a controlled switch S_{dc} is connected in the DC link of motor drive. By controlling the switching of a tiny dc link capacitor, a compensation method is offered as a remedy to the above-mentioned problem of motor drives with no big capacitor.

During region 1 capacitor is chargedthroughtheantiparallelfreewheelingdiode of controlled switch S_{DC}. Here the discharge of capacitor to supply current to motor drive during region-2 will be controlled by the switching signals given to S_{DC}.To eliminate torque ripples, the energy stored in the capacitor during region-1 must be sufficiently enough to keep $I_m(t)$ to be at Iref during region-2. The motor controller is designed so that the S_{DC} switching signal is calculated by comparing the difference between $V_{in}(t)$ and E.

The back EMF 'E' will be calculated using the speed of the motor and speed can be calculated using the rotor position in (5). Because the suggested technique only gives energy to the drive during region-2 i.e., when E > $V_{in}(t)$, the size of the capacitor required is less [10] than the capacitor in a typical brushless DC motor drive. As a result, a low-cost capacitor and a regulated switch are sufficient to efficiently eliminate torque ripple. The capacitor value has to be chosen so that it can keep the DC link voltage during region-2 when E>$V_{in}(t)$ so as to keep $I_m(t)$ at I_{ref}, and it is provided by the following equation after taking necessary approximation

$$C_{DC} = \frac{2TI_{avg}}{V_m - E} \tag{19}$$

Where I_{avg} is the average current drawn from the DC link to keep $I_m(t)$ constant at I_{ref}.

Despite the fact that the proposed approach includes a switch and a capacitor, the total cost and space required for the motor drive are projected to be minimal. For quick switching, no additional component is necessary because the switch control is simple. In contrast to semiconductor switches, large capacitors are typically rated for a short duration of time and by removing the huge DC link capacitor, the drive's reliability will improve. The compensation capacitor required is usually 3% to 5% of the value of the big electrolytic capacitor. Furthermore, even if the proposed compensating approach fails, the motor drive may be able to run with a torque ripple. As a result, the additional components will have no effect on the motor drive's reliability. Because the additional switch has a lower switching rate and carries less current than the MOSFET/IGBT switches in the inverter, the switching power loss is not as great. Because there is no big DC connection capacitor, the input current's total harmonic distortion (THD) will be reduced. Also, as the magnitudes of charging currents of capacitors are reduced due to the existence of small capacitance to lessen torque ripple, the proposed compensating method's transient difficulties are minimal.

2.2. Implementation

To create switching pulses for the control switch and for the inverter switches, the controller circuit reads the rotor position and speed as the information inputs. The back-EMF (E) is calculated by plotting it as a function of the rotor position (as determined by hall sensor output). The back-EMF (E) thus computed is added with ΔE and is then compared with the supply voltage. The controlled switch S_{DC} receives the switching signal based on the difference received by the controller as per the algorithm. Therefore, the charging and discharging of capacitor will be done basedon the switching signal of controlled switch S_{DC} to eliminate the torque ripple.

Whenever the calculated back-EMF exceeds the supply voltage ($V_{in}(t)$), the phase current $I_m(t)$ enters region-2 and becomes uncontrollable, as well as the torque, which produces ripples. The difference ΔE can be positive or negative depending upon the changes in load torque to motor drive. To eliminate torque ripple, the capacitor must discharge the energy stored in it to keep $I_m(t)$ at I_{ref}. To accomplish so, the capacitor must be sufficiently charged during region-1 of the charging phase to supply energy during the discharging phase.

Based on the switching pulses the duty cycle of switch S_{DC} varies. Depending on the position of the rotor, PWM signals to the inverter switches are created in the controller. The algorithm in the proposed innovative controller to generate output signals that serve as switching signals for the capacitor in the dc link and for the inverter switches is given in the Figure 3.

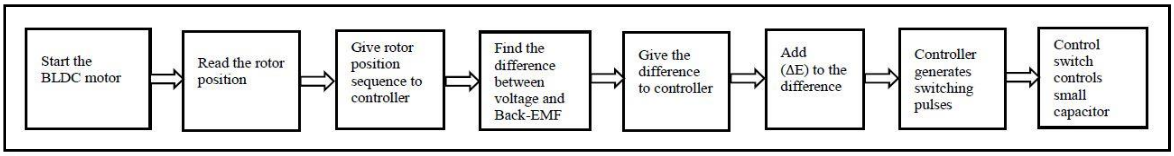


Figure 3. Sequential flow of the proposed work

To achieve the average value, the equations derived theoretically for $I_m(t)$ are solved using recommended motor parameters. The continuity of $I_m(t)$ can also be classified based on the value obtained. The theoretical solutions produced by solving the mathematical equations are compared with simulation results obtained using MATLAB/Simulink and with experimental findings to demonstrate the accuracy of the suggested technique. The complete simulation model of the proposed compensation is presented in the Figure 4. The acquired findings are also compared to those of a brushless DC drive connected with a big DC link capacitor [13].

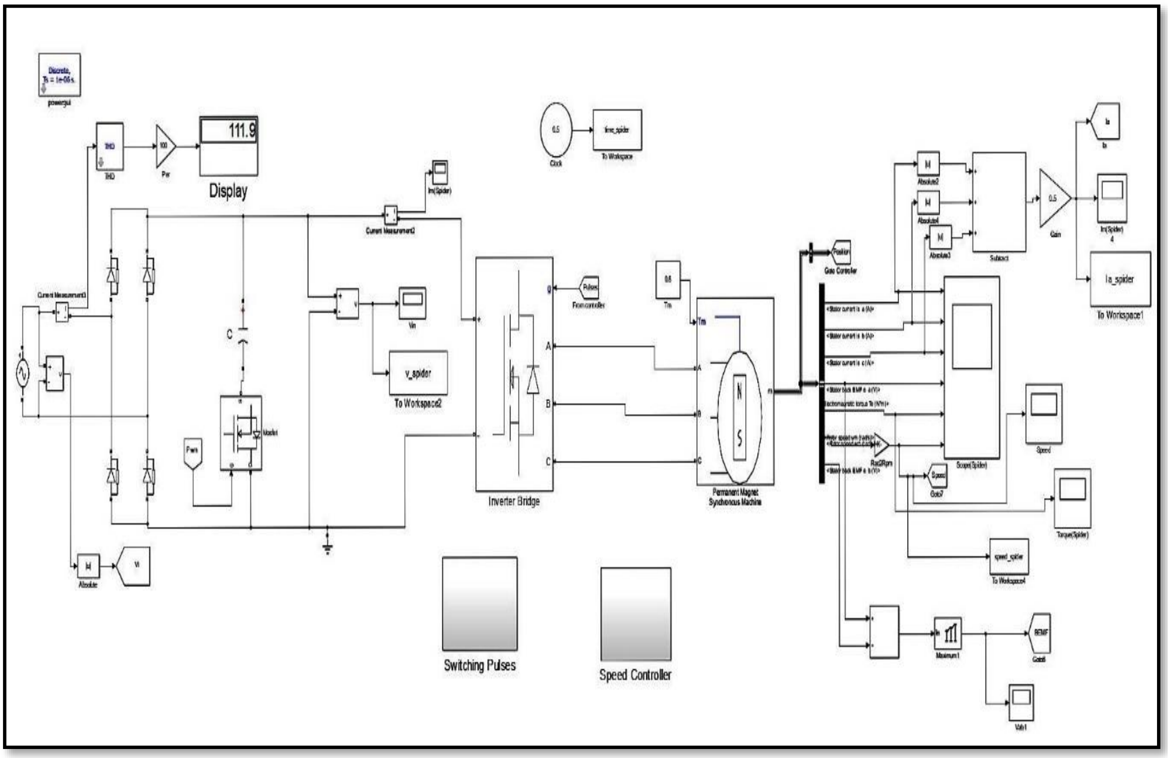
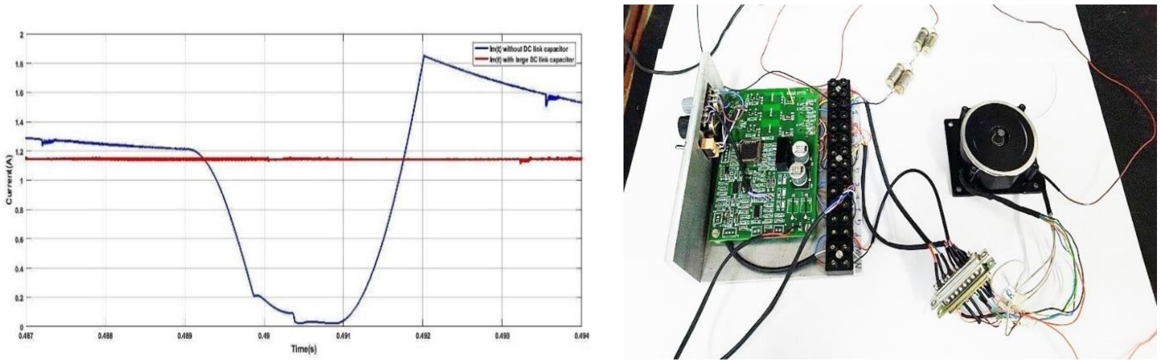


Figure 4. Diagram of complete simulation model

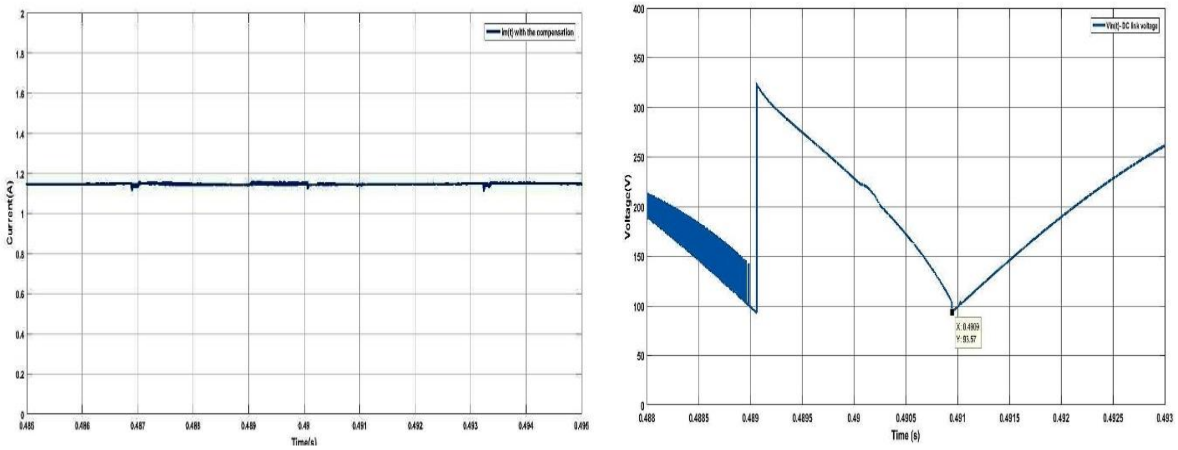
Figure 5(a) shows the simulation results for current $I_m(t)$ where it becomes discontinuous before zero crossings of $V_{in}(t)$ using the proposed motor shown in Figure 5(b). Figure 5(b) depicts the hardware unit that was tested. In region-2, (15) shows the decrease in phase current until it reaches a discontinuous point. The increase in phase current is given by (18) until I_{ref}. The phase current is becoming discontinuous for a longer duration, as shown by the results. As a result, there is a long period of time when there is no torque in the motor output. As a result, there are ripples in the generated torque and also resulting in the average value of generated torque to be smaller.



(a) (b)

Figure 5. Simulation result of current and hardware unit, (a) simulation result of current $I_m(t)$ with and without a big DC link capacitor and (b) hardware prototype of the model

Numerical methods can be used to calculate the average value of current extracted from the DC link capacitor. The required Iavg is found to be 0.46 A using the numerical method, and the capacitor should deliver this current when the back-EMF E > $V_{in}(t)$ during region-2 to eliminate torque ripple. From (20), the minimum capacitor required to compensate torque ripple after substitutingthe values is found to be 3% of large DC link capacitor value. The cost of such a smallcapacitoris very less incomparison to large DC link capacitor which is used in conventional drives. The simulation results of phase current and DC link voltage with the proposed approach for the case of current discontinuity before zero crossings of $V_{in}(t)$ are presented in the Figure 6(a) and 6(b) respectively.



(a) (b)

Figure 6. Simulations results using proposed compensation method (a) simulation result of $I_m(t)$ and (b) simulation result of DC link voltage

3. RESULTS AND DISCUSSION

The topology and algorithm were built in MATLAB/Simulink to analyse and verify the suggested controller algorithm. For the configuration, a feasible hardware prototype discrete controller was constructed and the proposed control algorithm was implemented using a DSP-based controller. The performance of the suggested approach was evaluated and compared using three different DC link capacitors: a) without any DC link capacitor, b) with a big DC link capacitor, and c) with a small DC link capacitor.

Table 1 shows the parameters of the brushless DC motor that was used. The control algorithm for the controlled switch S_{DC} and the MOSFETs (inverter switches) was loaded into the DSP controller. As can be seen from the findings, the proposed compensation technique greatly reduces total harmonic distortion (THD) as compared to a typical brushless DC motor drive. Ripples in the generated motor torque induced by the absence of the capacitor are reduced using the proposed compensation technique, leaving just a 9% ripple, which is extremely small. The torque ripple is found to be 93.6 percent without the DC link capacitor. The obtained comparison of mathematical answers, simulation results, and experimental results, on the other hand, verifies and confirms the proposed compensating method's accuracy. The results of this compensatory technique can be utilised to create a brushless DC motor drive with less components and improved performance at a low cost. The results are presented in Table 2. Waveforms of the Electromagnetic torque and phase current for each condition are presented in Figurse 7 and 8 respectively. The effect of load change on torque ripple is presented in the Table 3 and last two colums show the reduction in torque ripple due to tuning of back emf fet to comparator. Figures 7(a) to (d) shows electromagnetic torque comparison. Figures 8(a) to (d) shows phase current comparison.

Table 1. Motor parameters

Parameter	Value
Resistance per phase (R)	3 Ω
Inductance per phase (L-M)	0.015 H
Total inertia (J)	0.0024 kg.m^2
Viscous friction (B)	0.001 Nm. s
Pole pairs (P)	3
Type of back-EMF	Trapezoidal waveform
Motor torque constant (k_t)	0.8 Nm/A

Table 2. Torque ripple and THD

Condition	Voltage ripple (%)	Torque ripple (%)	Current ripple (%)	THD (%)
Without capacitor	55.5	93.6	60.8	127
With large capacitor	2.3	1.8	1.6	215
With only small capacitor	52.4	87.9	57.5	124
With proposed compensation	35.6	9	8.9	114

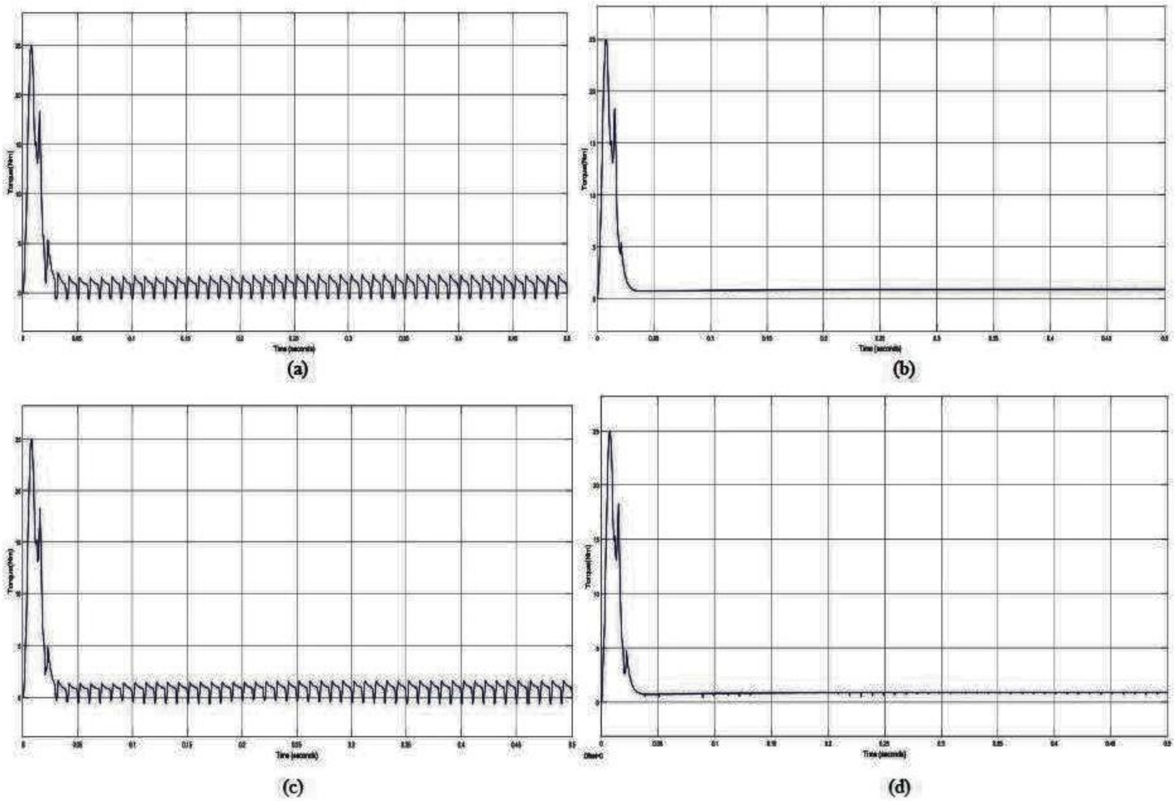


Figure 7. Electromagnetic torque comparison for; (a) without a DC link capacitor, (b) with a big DC link capacitor, (c) with a small DC link capacitor, and (d) with proposed compensation in each case

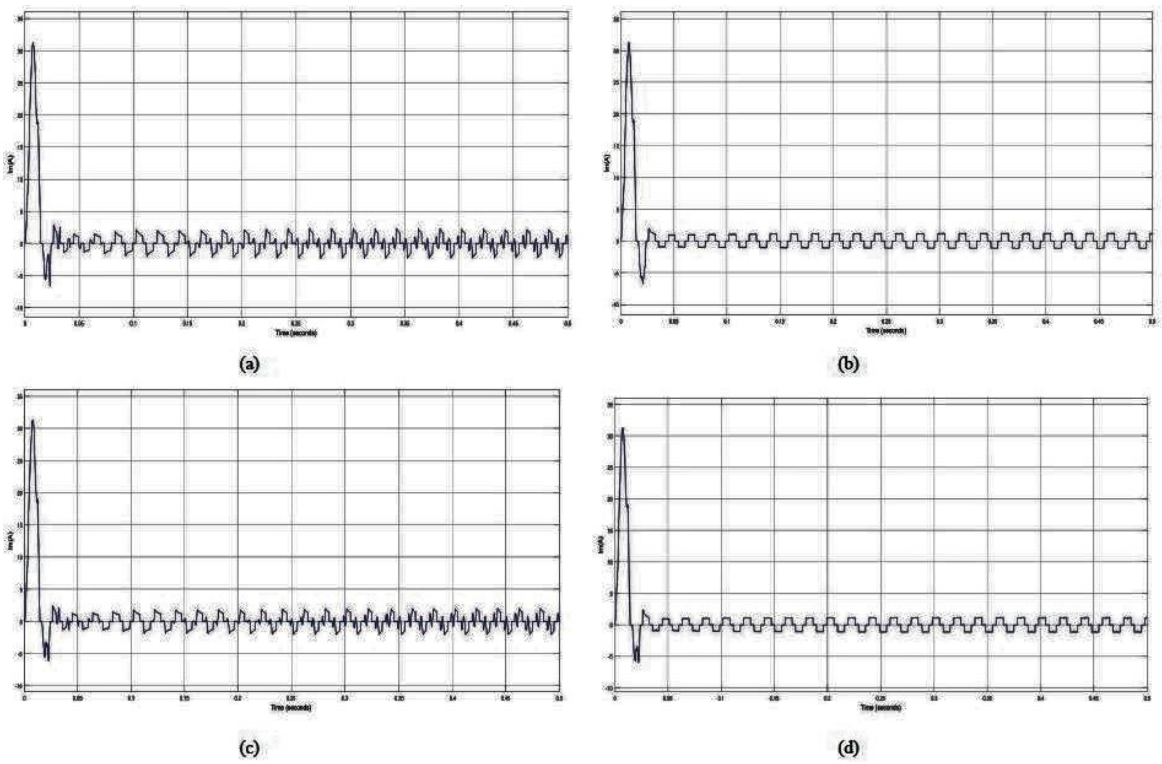


Figure 8. Phase current comparison for; (a) without a DC link capacitor, (b) with a big DC link capacitor, (c) with a small DC link capacitor, and (d) with proposed compensation in each case

Table 3. Torque ripple with different loads

S.NO	Load torque T_L (Nm)	Torque ripple (%) With large capacitor at E=95 V	Torque ripple (%) With proposed compensation at E=95 V	Back-EMF E+ΔE (V)	Torque ripple (%)
1	0.6	2.57	8.75	105	8.39
2	0.8	1.74	14.64	90	14.35
3	1.0	1.72	22.04	78	19.42
4	1.2	1.43	33.33	70	25.28

4. CONCLUSION

Brushless DC's torque ripple affects performance and produces inaccurate characteristics, thus it's critical to limit it. The work described here is a torque ripple minimization strategy using a Novel controller drive system to eliminate torque ripples while meeting other motor control objectives. A small capacitor in series with a controlled switch is used to decrease the torque ripple that occurs due to current discontinuity in brushless DC motor. The needed capacitor value is calculated using a brushless DC motor drive system mathematical analysis. In this study, MATLAB/Simulink is utilised to validate the results by simulating motor settings. An additional algorithm is included in the controller apart from commutation procedure of normal brushless DC drive to generate switching pulses to small DC link capacitor. Despite the fact that the compensating technique employs a small DC link capacitor and an extra semiconductor switch, the overall cost and footprint of the motor drive are greatly reduced. Additionally, the controller circuit design is not much complex. The motor reliability is increased by using small DC capacitor instead of large DC capacitors which are rated for short period of time. Also, the results obtained from simulation are verified by designing hardware unit. The results are promising and show that the proposed method to remove the torque ripples in brushless DC motors is successful. The motor drive with the proposed technique also works well when the load changes, whether it be speed or torque.

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