A Single Switch Controlled Capacitor Based Compensation Technique in a BLDC Motor Drive

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***Abstract*— The torque ripple reduction in a BLDC motor is a very crucial factor to determine the stable behaviour of BLDC drive. Torque ripples may arise in the controller and driver side of BLDC motor, due to mutual coupling torque, which arises in the motor due to interaction of rotor magnetic field coupling with stator winding current. A step down converter or buck converter model analysis of BLDC motor is proposed in order to relate the torque to the phase currents of motor. A single switch controlled capacitor is proposed, which is replacing the traditional DC link capacitor model, and is found to be efficient as it reduces the speed ripple and also helps in bringing down the total harmonic distortion and also reduces the torque ripples. A MATLAB/ SIMULINK model is simulated and presented as the compensation technique, to analysis its efficiency. Results can be used to design a BLDC drive with reduced torque ripples, speed ripples, and total harmonic distortion**.

***Keywords*— Brushless DC motor, torque ripple, speed ripple, total harmonic distortion, buck converter model, single switch controlled capacitor.**

I. INTRODUCTION

The permanent magnet brushless DC machines, have simple control and have certain advantages of high reliability, high efficiency, and long operating life making them a good choice for industrial use. They are having six individually separate and distinct positions of operation. Hall Effect sensors are displaced by 120 electrical degree and installed in the stator. These sensors utilises the position of rotor and sends signals, which helps in the electronic commutation of BLDC motor. This rotor position feedback technique is utilised, hence inverter acts as electronic commutator, receiving feedback from position sensors. The ripples are due to the coupling torque due to rotor magnetic field interacting with stator currents. The BLDC motor drives comprises of a single phase diode bridge rectifier, a small electrolytic capacitor controlled by a switch, an inverter fed with rotor position information.

A major disadvantage of BLDC motor is the presence of torque ripple. Many attempts has been made to reduce it, a three phase feeding system , that utilises selective harmonic to reduce torque ripples is presented in [1], a Fourier analysis of torque model of BLDC motor is studied , then a suitable current harmonic weights method is used to reduce torque ripples in [2]. In some cases the design of the BLDC motor i.e., its stator and rotor designing is modified to reduce torque ripples as in [3], while in some other cases the design of the controller used to generate pulses to inverter switches is modified as in [4]. A buck converter analysis can be used to analyse the torque but the absence of the capacitor shows the presence of the torque ripples [5]. The commutation torque ripples can be reduced by using a CUK converter, whose output modes are varied during normal conduction and commutation periods as given in [6]. Hence the disadvantages of these works are that torque ripples cannot be reduced in entire speed range of operation using only PWM chopping method. Usually PAM method may also be used. Also the presence of complicated designing and presence of increased number of components can lead to increasing of losses in the system.

II. PROPOSED METHODOLOGY

Here the work comprises of a single switch controlled capacitor used, and rotor feedback position sensing is used. The complicated Laplace or Fourier analysis is avoided instead the duty cycle of the switch controlling the capacitor has been the main concern. The capacitor used is only 3% the size of bulky DC link capacitor, and simpler design makes it suitable for analysis as well as the torque ripple , speed ripple and total harmonic distortion has been compared with the other cases (i.e., without capacitor and with large capacitor), and found to be much improved . A study of three different cases using MATLAB/SIMULINK environment has been done to compare the values of torque ripple, speed ripple and total harmonic distortion.

The block diagram of the proposed methodology is given in Fig. 1 where we can see that a single phase diode bridge rectifier operates and converts AC to DC, then the single switch controlled capacitor is placed that is operated by varying duty cycle of IGBT as required, the DC supply is converted to AC by inverter and given to BLDC motor terminals. A rotor position feedback is used to produce switching pulses for inverter at the controller and this gate pulses are fed to inverter terminals for operation.

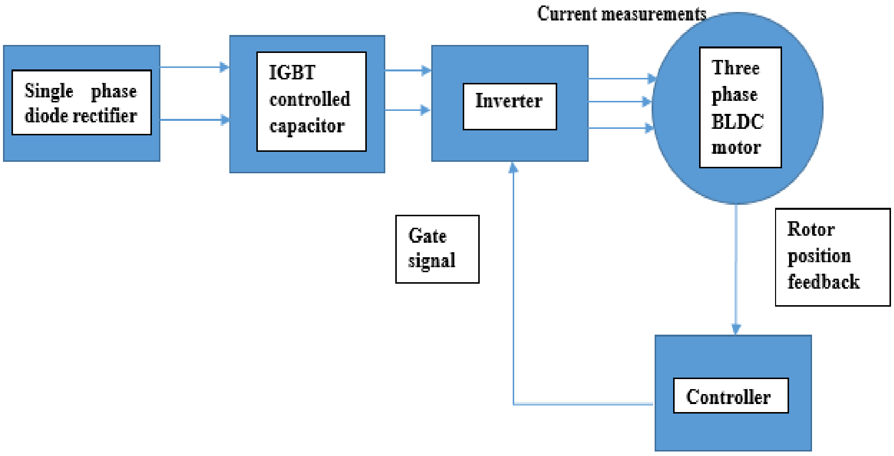

Fig1: Block diagram of proposed method

III. BUCK CONVERTER MODEL TORQUE ANALYSIS OF BLDC MOTOR

Let us consider the modelling of a three phase star connected BLDC motor which has symmetrical and concentrated stator windings, with no hysteresis and eddy current losses, and no armature reaction is considered. The PWM voltage and current control mode operation is considered. Here only two phases are energized at a given conducting period. Here a switch is kept on throughout while, the other is chopped at regular frequency. The switching algorithm of BLDC motor using hall sensor outputs H1, H2 and H3 are given in table I [5]. At any step of operation the switch kept on provides path for motor current to continue flowing while another switch is being controlled and chopped.

TABLE I
SWITCHING PATTERN OF INVERTER SWITCHES

Discrete step position	**Hall sensor output**			**Switch kept ON**	**Switch being chopped and controlled**
	H1	**H2**	**H3**		
1	1	0	0	A	F
2	1	1	0	F	B
3	0	1	0	B	D
4	0	1	1	D	C
5	0	0	1	C	E
6	1	0	1	E	A

Considering any step of operation of the BLDC motor, a switch remains on throughout while the other chops depending on hall sensor outputs. Taking any step for analysis, we find similar conclusion and that the operation is similar to that of a buck converter model. This is because of the symmetry of inverter and windings of the motor. Fig. 2 illustrates the buck equivalent model [5] of the operation of BLDC motor at any step chosen from the table I.

Here let $V_{in}(t)$ be the input voltage to the buck converter (V), i_m is the phase current (A), S and D represent the controlled switch and freewheeling diode, and V_L be the voltage across inductance. Assuming an ideal full wave rectifier with no DC capacitance, the input to the buck converter $V_{in}(t)$ be which can be given as [7],

$$V_{in}(t) = V_m \sin\omega t \qquad (1)$$

Where V_m is the peak voltage and ω is the angular velocity (rads^{-1}) and t is the time in seconds. Fig. 3 illustrates the rectified supply voltage for a given reference current is divided into region 1 and region 2 depending upon phase current maintained at reference current or not [5]. Since we know phase current is non-linear and is uncontrollable in region 2. From (2) we know since torque proportional to phase current even torque becomes uncontrollable in region 2.

$$T_e = \frac{1}{\omega(t)} e(t)\, i_m(t) \qquad (2)$$

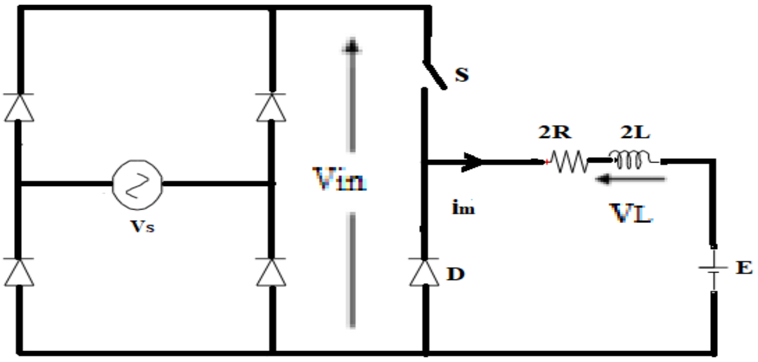

Fig 2 : Buck model of BLDC motor

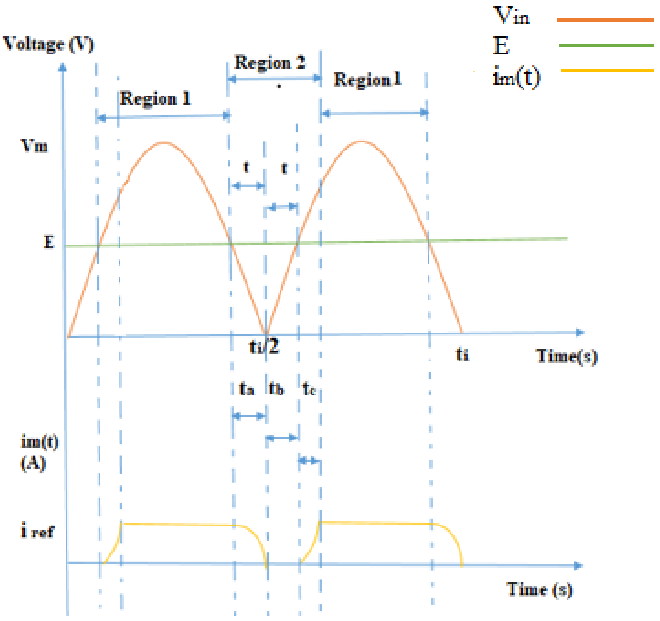

Fig.3: Region 1 and 2 of operation of rectified output

To find the duty cycle applicable to the switch at both regions, we consider that the supply voltage is less than the back emf value at region 2, hence largest possible duty cycle is applied to switch at this period. Let t be the time required for $V_{in}(t)$ to reach back-emf E from 0V. Let t_i be the time taken by input voltage supply to complete a cycle [5].

$$t = \frac{1}{2\pi f} sin^{-1}\left(\frac{E}{V_m}\right) \qquad (3)$$

Where f is the frequency (Hz) of the input supply. We obtain piecewise function of time of currents from which nature of torque is also determined for region 2 [5].

$$t_a = t - \left[\frac{t_i}{2} - t\right] \quad (4)$$

$$t_b = t - \left[\frac{t_i}{2}\right] \quad (5)$$

$$t_c = t - \left[\frac{t_i}{2} + t\right] \quad (6)$$

From Fig. 4, $V_L(t_a)$ can be obtained as:

$$V_L(t_a) = -\frac{E}{t} t_a \quad (7)$$

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

$$V_L(t) = 2(L)\frac{di_m(t)}{dt} \quad (8)$$

Equating (7) and (8) we get,

$$2(L)\frac{di_m(t_a)}{dt_a} = -\frac{E}{t} t_a \quad (9)$$

The general time domain solution of (9) is,

$$i_m(t_a) = -\frac{Et_a^2}{4(L)t} + c \quad (10)$$

Substitute initial conditions, $i_m = i_{ref}$, $t_a = 0$ gives,

$$c = i_{ref} \quad (11)$$

The complete solution for $i_m(t_a)$ will be,

$$i_m(t_a) = -\frac{Et_a^2}{4(L)t} + i_{ref} \quad (12)$$

The value of $i_m(t)$ at zero crossing defined as i'_m will be given as,

$$i'_m = -\frac{Et}{4(L)} + i_{ref} \quad (13)$$

From Fig. 4, $V_L(t_b)$ can be obtained as:

$$V_L(t_b) = -\frac{E}{t} t_b - E \quad (14)$$

From (14) substituting to (8) and hence finding value for $i_m(t_b)$ as,

$$i_m(t_b) = \frac{Et_b^2}{4(L)t} - \frac{Et_b}{2(L)t} + c \quad (15)$$

Apply initial conditions (13) to (15) we get,

$$i_m(t_b) = \frac{Et_b^2}{4(L)t} - \frac{Et_b}{2(L)t} + -\frac{Et}{4(L)} + i_{ref} \quad (16)$$

Equation (16) represents $i_m(t)$after the zero crossing of $V_{in}(t)$. Moreover, it is possible to derive the necessary and sufficient condition for $i_m(t)$ to be continuous during region 2 by inspecting the sign of (16) at, i.e.,

$$L > \frac{Et}{2i_{ref}} \quad (17)$$

Depending upon the above condition if satisfied then it is in continuous region else its discontinuous current. Similarly we get the current piecewise function for t_c period as,

$$i_m(t_c) = \frac{Et_c^2}{4(L)t} \quad (18)$$

Equation (12), (16) and (18) used to obtain the values of instantaneous torque during region 2. The equation (12) represents $i_m(t)$ until $V_{in}(t) = 0$. If $i_m(t)$ is continuous in region 2, (16) represents the dynamics after$V_{in}(t) = 0$. If $i_m(t)$ is discontinuous in region 2 after $V_{in}(t) = 0$ then (16) provides the dynamics of $i_m(t)$ until to the point where$i_m(t) = 0$. Then, $i_m(t)$starts to build up during t_c and is governed by (18).

IV. DESIGN OF CAPACITANCE AND DUTY CYCLE OF SWITCH FOR COMPENSATING TORQUE RIPPLES

The charging and discharging of capacitor is based on duty cycle provided to the switch S1 at both the regions 1 and 2. During the region 1, capacitor *C*1 is charged by the antiparallel diode across the switch S1. At this time the $V_{in}(t) > E$. During region 2 the $V_{in}(t) < E$ hence the capacitor has to store enough charge in order to keep the $i_m(t)$ at i_{ref} in region 2 to eliminate torque ripple [8]. Since no natural discharging path present for capacitor at region 2, so the S1 given appropriate gate signals to control that.

$$C1\frac{dV_{in}(t)}{dt} = I_{avg} \qquad (19)$$

Where I_{avg} represents current taken from DC link to maintain $i_m(t)$ at i_{ref}. By approximating the derivative, value of $C1$ will be,

$$C1 = \frac{2tI_{avg}}{V_m - E} \qquad (20)$$

The duty cycle needed to be provided for switch S1 is found from the ON-time period of switch as [8],

$$t_{ON} = \frac{1}{2\pi f}\sin^{-1}\left(\frac{E}{V_m}\right) \qquad (21)$$

The duty cycle D to be applied to the switch controlling the charging and discharging of capacitor is obtained as,

$$D = \frac{t_{ON}}{t_{ON}+t_{OFF}} \qquad (22)$$

V. SIMULATION RESULTS AND DISCUSSION

Here considering three cases for analysis where with a large capacitor, without a capacitor and with a small capacitor controlled by a switch, the ripple values are analysed. The above topologies and algorithms are implemented using MATLAB. The BLDC motor parameters used to study the cases are given in table II along with their values and units.

TABLE II.
PARAMETERS OF THE BLDC MOTOR USED.

SL.No.	**Name of the parameters with notations**	**Value**	**Unit**
1	Resistance(R)	.36	Ω
2	Inductance(L)	1.67	mH
3	Number of Poles(P)	4	-
4	Rated Power(P)	350	Watts
5	Torque Constant(T)	0.9	NmA^{-1}
6	Rotor Inertia(J)	0.003	kgm^2
7	Force(F)	0.002	Nms

Table III shows the inputs applied to the system during simulation in the three cases of observation. Here the input V_s of 325V is rectified using a single phase diode bridge rectifier, then the output is fed to an inverter. The load torque is given at time 1second. The values of capacitor used in all the cases are being mentioned.

Table III.
VALUES OF INPUT VOLTAGES AND CAPACITORS USED.

SL.No.	**Cases**	**Input Voltage Vs (V)**	**Capacitor (µF)**
1	With capacitor	325	180
2	Without capacitor	325	0
3	With small capacitor and switch	325	6

In the first case where we consider a large capacitor has been used to reduce the torque ripples, speed ripples, and THD of the system. The value of the large capacitance is taken as 180 µF. Fig. 4 shows the rotor speed (RPM), torque obtained from the motor (Nm), and stator current(A) of the motor when a large DC link capacitor is placed in the circuit. The value of the ripples [6] can be calculated using the following formulas,

$$N_{ripple} = \frac{N_{high}-N_{low}}{N_{high}+N_{low}} * 100\% \qquad (23)$$

$$T_{ripple} = \frac{T_{high}-T_{low}}{T_{high}+T_{low}} * 100\% \qquad (24)$$

$$I_{ripple} = \frac{I_{high}-I_{low}}{I_{high}+I_{low}} * 100\% \qquad (25)$$

Where N_{high} and N_{low} are the maximum and minimum speed over a period of time respectively, T_{high} and T_{low} are the maximum and minimum torque over a period of time respectively, and lastly I_{high} and I_{low} are the maximum and minimum current over a period of time respectively. Since a large capacitor is placed maximum reduction of ripples is seen, with the disadvantage that the component sizing is large. Let us consider that a load torque is applied at 0.2s, hence we see an increment in the value of torque produced after 0.2s.Here Fig.4a) shows the speed of rotor when a large capacitance is used. The speed seems to be having less ripples, similarly Fig. 4b) and Fig. 4c) also shows that the stator current and torque produced will also have reduced value of ripples at the cost of a large capacitor.

The major disadvantages of using a large capacitor is that, at high temperature, or fluctuating climate, the value of capacitance varies severely and the lifespan of such capacitors are very less compared to a smaller capacitor. Other than these a large capacitor makes the hardware designing and implementation complicated. The chance of damage to hardware increases, and also the weight of all whole system increases by a large extent. Using (23), (24) and (25) the values of the ripples are calculated.

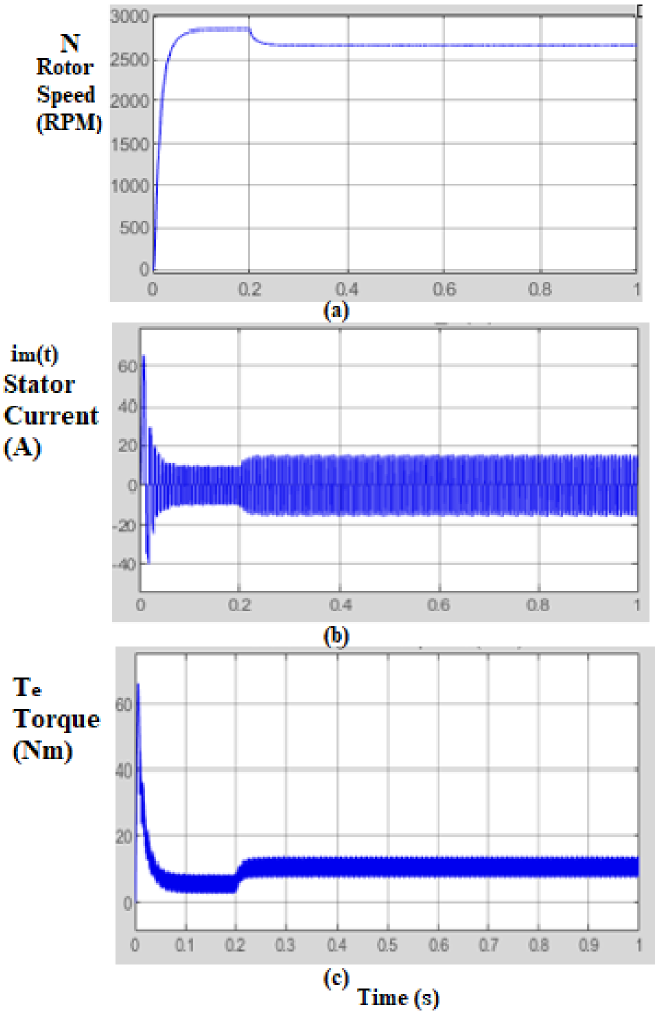

Fig.4 a) The output rotor speed waveforms of BLDC motor with a large capacitor 180 µF. b) The output stator current waveforms of BLDC motor with a large capacitor 180 µF. c) The output torque waveforms of BLDC motor with a large capacitor 180 µF.

Fig. 5 shows the second case of analysis where the rotor speed (RPM), torque obtained from the motor (Nm), and stator current (A) of the motor when no DC link capacitor is placed in the circuit. Here we can see that when a capacitor is removed from the system, the ripples are maximum at this point. There is no compensation of ripples provided. The values of ripples can be calculated using (23), (24), and (25), similar as in previous case. Here no compensation technique is used hence from here originally the amount of ripples present the system can be calculated. The maximum amount of ripples occur hence the system is the most unstable in this case. Here also at 0.2s a load torque is applied to the system which can be seen in the waveforms. Finally the third case is being considered in Fig. 6 where the compensation technique introduced in this paper is being analysed. Here an IGBT switch is used, to control the charging and discharging of the capacitor in both regions. Here a small capacitor is used as it operates only in region 2 for eliminating the ripples. Using (20) the capacitance value is calculated to be 6 µF. Also (22) gives the duty cycle of switch to control the capacitor. Compared to both the above cases this is the most efficient technique used.

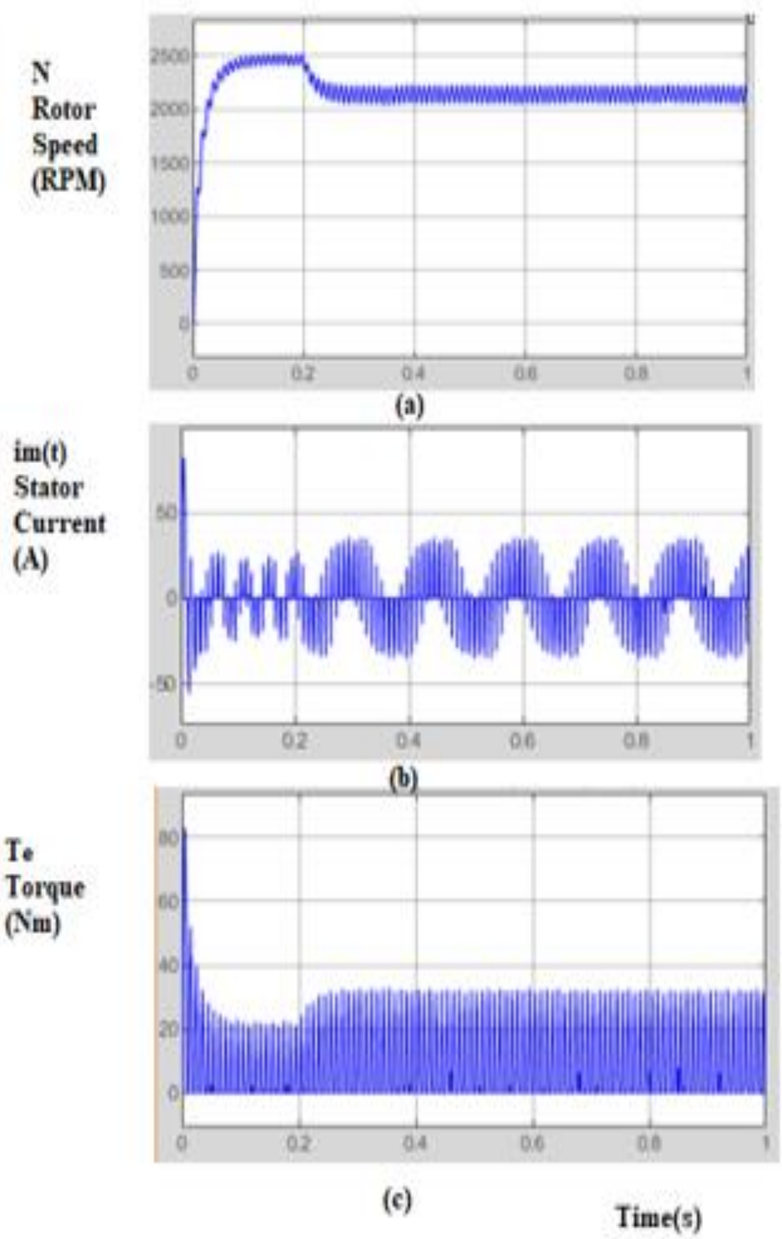

Fig.5: a) The output rotor speed waveforms of BLDC motor without a capacitor. b) The output stator current waveforms of BLDC motor without a capacitor c) The output torque waveforms of BLDC motor without a capacitor.

Fig. 6 shows the third case of analysis where the rotor speed (RPM), torque obtained from the motor (Nm), and stator current (A) of the motor when a small DC link capacitor used along with a switch to control it, is placed in the circuit. Here we can see the least amount of ripples are presented. The speed is linearly varying with less amount of ripples with respect to time. This strategy can be used since the circuit is not heavy and bulky. Also the reliability is increased since the small capacitor can operate for longer period of time. Switching frequency of the switch is taken as 200Hz. The switching losses associated with the switch is also calculated to be 0.05W, hence it is negligible.

A comparison of all the values of ripples obtained in all the three cases has been tabulated in table IV, which shows the THD (total harmonic distortions) , torque ripples, speed ripples, and current ripples obtained. From the table it is clear that maximum ripples obtained in case 2 while minimum ripples obtained in case 3. From the analysis it is clear that this method of compensation is suitable to reduce the ripples occurring in the BLDC motor operation.

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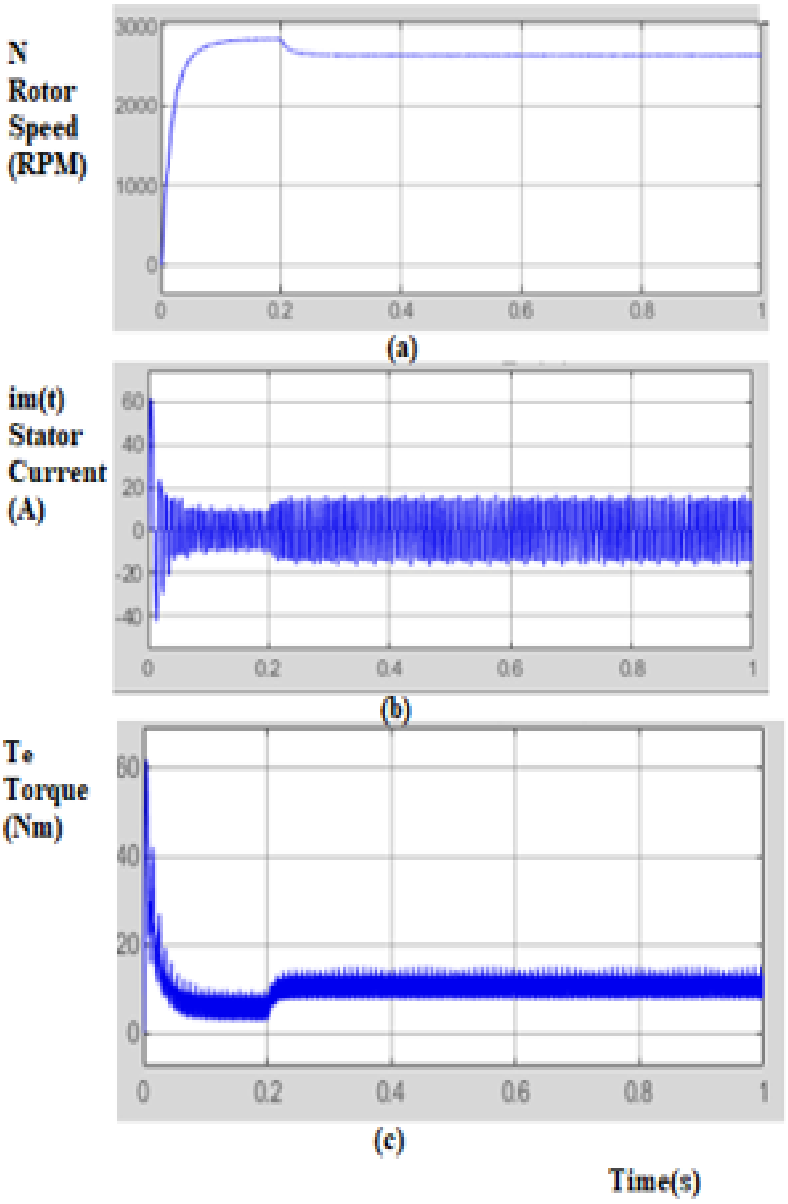

Fig.6: a)The output rotor speed waveforms of BLDC motor with a small capacitor 6 µF. b) The output stator current waveforms of BLDC motor with a small capacitor 6 µF. c) The output torque waveforms of BLDC motor with a small capacitor 6µF.

TABLE IV
COMPARISON OF VALUES OF OUTPUTS

CASES	With capacitor	Without capacitor	With small capacitor and switch
THD	481.58%	385.08%	299.86%
Speed ripple	0.199%	5.26%	.05%
Torque ripple	20%	100%	15%
Current ripple	29%	35%	20%

The total harmonic distortion (THD) of the input current to the inverter is measured with a DC link capacitor, without a capacitor and with a small capacitor and switch, and these values are tabulated in table IV. From the observation it is clear that the THD is improved for case 3 hence the efficiency will be maximum for this case. THD is measured using the FFT analysis in MATLAB. Fig. 7 shows the different THD of input currents obtained during simulation of all three cases.

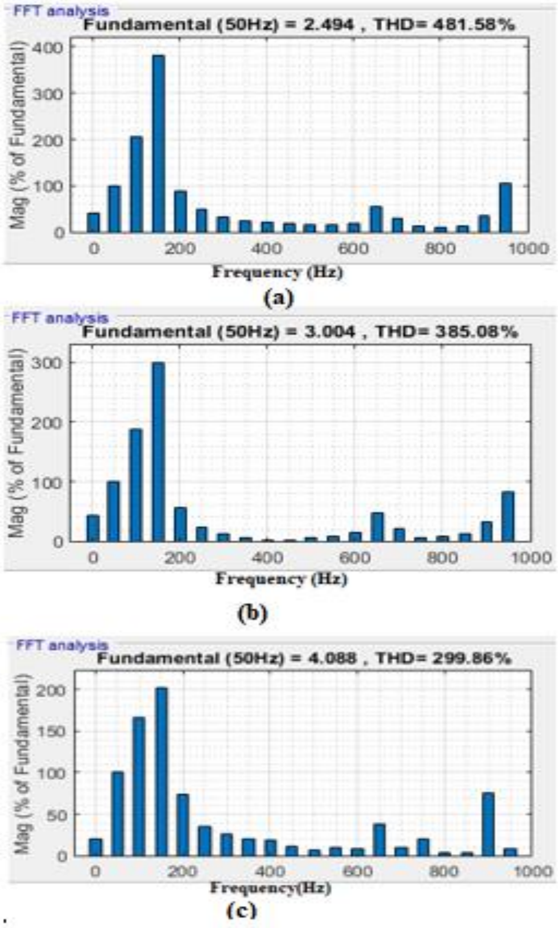

Fig.7: a) THD of case 1 when a large DC capacitance is used. b) THD of case 2 when no DC capacitance is used. c) THD of case 3 when a small DC capacitance is used along with a switch to control it.

VI. CONCLUSION

A simple compensation technique to reduce torque ripple, speed ripple and current ripple along with the THD of input currents is proposed for a BLDC motor drive, operated with a small capacitor along with a switch. This technique can be used in inexpensive hardware implementation. In the control segment no extra components have been used. The reliability is increased compared to large capacitance circuit, as this scheme can operate for longer period of time .Comparison of various cases gives a detailed study of this compensation technique and shows how it is more efficient than other techniques.

As a future scope of this work the hardware implementation can be considered. Any microcontroller can be taken which will produce pulses for the switches for the operation of BLDC motor drive.

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