# NOVEL LOW COST CONVERTER TOPOLOGIES TO DRIVE SPINDLE MOTOR AT HIGH SPEED WITH HIGH STARTING TORQUE

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*Abstract-This paper presents two low cost inverter topologies to drive a spindle motor at high speed with high starting torque with the help of bipolar starting and unipolar running algorithm. These two topologies have been realized with only eight switches, which are far less count as compared to other available topologies for driving a spindle motor. Apart from eight switches, three resistors ($R_s$) are connected in series with the freewheeling diodes present in lower part of the inverter circuit to minimize the negative torque because of unexcited phases of motor during unipolar mode of operation. Both the topologies are used to achieve high starting torque with high speed with simple control. The operation of the brushless DC motor drive using the proposed novel topologies are presented discussed and compared. The influence of choice of $R_s$ on drive performance is analyzed. In this algorithm the changeover speed is estimated at which smooth changeover is possible from bipolar to unipolar. The proposed topologies have been simulated using MATLAB/Simulink and the results are presented. The proposed inverter topologies are best suited for low power drives.*

*Index Terms: Bipolar Starting and Unipolar Running Drive, HDD Spindle Motor, Unipolar Drive*

## I INTRODUCTION

Brushless DC (BLDC) Motors are used in various drive applications because of its high efficiency and power density. The speed requirement for the Spindle Motor especially those used in computer hard disks is increasing day by day, to facilitate faster data access [1, 5, 7]. Such high speed operation could be achieved by three methods. The first method is to design the machine with low back EMF constant which offers high speed for a given system voltage. But the disadvantage is that a low back EMF constant results in low starting torque. The second method is to use a higher DC bus voltage [6, 8, 13-16]. With this method high starting torque and high speed operation can be obtained. But the disadvantage is that the switch voltage rating is increased which requires a current protection to limit the current during low speeds. This also adds cost and safety hazard to the system. The third method is to use a converter which can provide high speed with high starting torque [11, 17].

To get high torque BLDC motor needs to be operated in bipolar mode and to get high speed BLDC motor should be operated in unipolar mode [2 - 4]. In [2], a new converter is proposed which can achieve high starting torque with high speed by using 14 switches (8 FETs of the inverter plus 6 FETs for controlling freewheeling current) of same rating. Drawback of this circuit is, using more gate drives and more switches. This adds extra cost and space to the system. In this paper two new inverter topologies are

proposed which uses bipolar operation to achieve high torque during starting and unipolar operation to achieve high speed. In these topologies only 8 switches and three resistors ($R_s$) are connected in series with the freewheeling diodes present in lower part of the inverter circuit. The proposed inverter topologies are similar to conventional 3-leg inverter with one additional leg, to which neutral point of BLDC motor is connected.

## II BIPOLAR STARTING AND UNIPOLAR RUNNING OPERATION

In conventional BLDC motor during bipolar operation, at any time across DC bus, two phases come in series [9-12]. So only half of the DC bus voltage is applied to each phase, which adds torque constant on both phases there by achieving high starting torque. But speed will be limited due to the application of half the DC bus voltage per phase. In linear region of operation, torque, speed, current relations can be explained by the following equations.

$$Torque \quad T = \frac{K_t V_s}{R} - \frac{2 K_t^2}{R} \varpi_m \qquad (1)$$

$$Stalling \quad Torque \quad T_{Stalling} = \frac{K_t V_s}{R} \qquad (2)$$

$$No \ Load \quad Speed \quad \varpi_{nl} = \frac{V_s}{2 K_t} \qquad (3)$$

$$Stalling \quad current \quad I_{Stalling} = \frac{V_s}{2 R} \qquad (4)$$

The final speed attained by the motor for a particular load torque is given by

$$\varpi_{m1} = \frac{T_{Stall} - T_L}{B + \frac{2 K_t^2}{R}} \qquad (5)$$

where $K_t$ , $V_s$, R, $\omega_m$ , $T_L$, J,B, are torque constant, supply voltage, resistance of one phase winding, rotational speed, load torque, moment of inertia and friction constant respectively. The torque constant is identical to back EMF constant in SI units.

Current regulator is provided in DC line such that the line current is not exceeding the specified limit based on the current rating of motor and device current ratings. The theoretical torque-speed characteristic with hysteresis current regulator in DC line is given in Fig. 1. The no load speed is $\omega_{m1}$ and starting torque is T1. This mode of operation is preferred to get high torque and low speed.
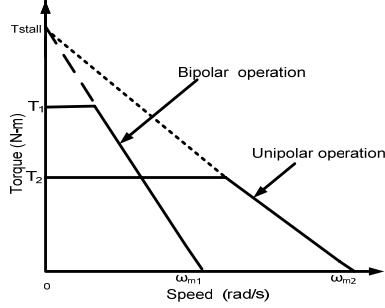
Fig. 1. Torque Speed Characteristics of BLDC Motor

Application of full DC bus voltage to each phase will achieve higher speed [7].This can be achieved in unipolar operation where each phase conducts only in one direction. The torque constant of unipolar drive is half of that of bipolar drive. This makes unipolar drive to operate at high speed due to less voltage drop because of back EMF than that of bipolar at the same speed. If the motor is supplied by the same voltage and operates in linear range, the same starting torque is generated in both modes of operation because the phase resistance of a unipolar drive is half of that of bipolar and is shown in Fig. 1. However, during starting large input current causes the magnetic saturation, which reduces the torque constant .This magnetic saturation produces non-linear speed torque characteristic. A unipolar drive has large reduction in torque constant as compared to bipolar drive. But due to the presence of current regulator placed in DC line, the effect of saturation is not observed in both modes of operation. The torque, speed and current relations and final speed attained for a particular load in unipolar drive in linear region can be expressed by the following equations. The unipolar mode is preferred to get low starting torque and high speed.

$$Torque\ T = \frac{K_t V_s}{R} - \frac{K_t^2}{R}\varpi_m \tag{6}$$

$$Stalling\ Torque\ T_{Stalling} = \frac{K_t V_s}{R} \tag{7}$$

$$No\ Load\ Speed\ \ \varpi_{nl} = \frac{V_s}{K_t} \tag{8}$$

$$Stalling\ current\ I_{Stalling} = \frac{V_s}{R} \tag{9}$$

$$\varpi_{m1} = \frac{T_{Stall} - T_L}{B + \frac{K_t^2}{R}} \tag{10}$$

In order to get high torque motor should be operated in bipolar mode and to get high speed motor should be operated in unipolar mode. Shifting of modes between bipolar and unipolar is achieved based on the speed requirement [11].The torque-speed characteristic of BLDC motor with bipolar starting and unipolar running is shown in Fig.2.It is possible to change the mode from bipolar to unipolar at any desired speed such that this value should be less than the final speed attained in continuous bipolar running for a particular load. However, if speed is selected as the speed at which the bipolar and unipolar characteristics intersect, which is defined as 'critical speed $N_C$, as shown in Fig. 2, the torque will not possesses any jump at changeover. If changeover speed is other than critical speed, either greater or smaller, the drive will experience jump in torque at change over speed. The value of critical changeover speed is estimated in linear region of operation by using equation 1 and upper limit value in the current controller and is expressed as

$$\varpi_c = \frac{V - I_u R}{2K_t} \tag{11}$$

Here $I_u$ indicates upper limit value in hysteresis current regulator placed in the DC line. The critical speed of a BLDC drive is dependent on supply voltage, $I_u$, resistance of phase winding and torque constant. It is independent of load torque. The critical changeover from bipolar to unipolar can also be described in terms of DC line current. The speed of the drive will become critical when the DC line current falls to half of the upper limit value of current limiter in bipolar mode of operation. In this paper, the two proposed topologies for inverter are making use of this mode of operation. The models were verified with an inverter motor model developed using MATLAB/SIMULINK.
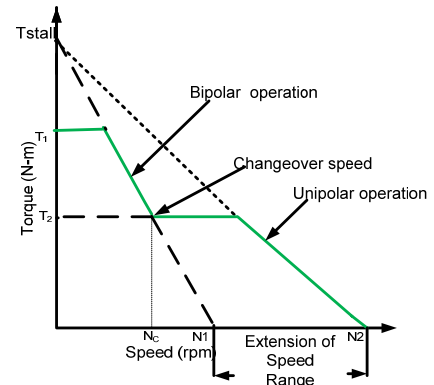


Fig. 2. Torque – Speed Characteristics in Bipolar Starting Unipolar Running Mode

## III PROPOSED INVERTER OPERATION TOPOLOGY-I

The first novel proposed inverter topology is given in Fig. 3.It consists of 4 legs and can be operated as a bipolar drive, unipolar drive or bipolar starting and unipolar running drive. The 3 phases of the BLDC motor are connected to first 3 legs and neutral point is connected to the fourth leg. As compared with the converter circuit proposed in [2] , with 14 switching devices including 6 transistors present in freewheeling path, this circuit has only 8 switches with additional 3 resistors. The resistor Rs is connected in series with the freewheeling diode present across each switch on the lower part of the inverter.

In order to operate the drive in bipolar mode, the switches Q7 and Q8 are off so that the inverter circuit is as in Fig.4. In this mode, first 3 legs are active and the 4th leg is inactive [20, 22].

With reference to rotor position $0^0$-$60^0$, by switching on Q1, Q4 and switching off Q5, phase A conducts in positive direction and phase B conducts in negative direction. The current in phase C is freewheeling through phase B, diode D6 and $R_s$. In the next interval of rotor position i.e., $60^0$-$120^0$, by switching off Q4 and switching on Q6, a freewheeling path is established through phase B, diode D3, switch Q1 and phase A as shown in Fig.5. This mode of operation is described by the following equations.

$$V_s = R(i_a - i_c) + L\frac{d}{dt}(i_a - i_c) + e_a - e_c \qquad (12)$$

$$0 = R(i_a - i_b) + L\frac{d}{dt}(i_a - i_b) + e_a - e_b \qquad (13)$$

Here R, L are the winding parameters of each phase, $e_a$, $e_b$ and $e_c$ are back EMFs of each phase and $i_a$, $i_b$, $i_c$ are the phase currents and $V_{dc}$ is the DC supply voltage. Equation 13 is valid till the current $i_b = 0$, as diode D3 can carry only the forward current. It can be observed that while freewheeling energy stored in negative conducting phase B is converted into useful torque
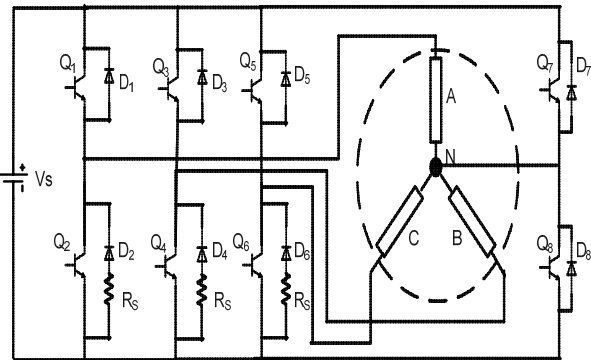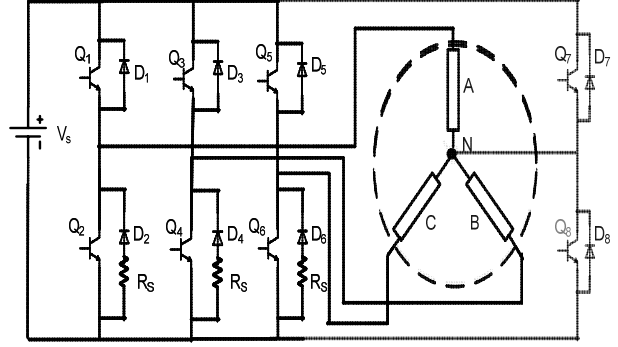


Fig. 3. Proposed Inverter First Topology



Fig. 4. Proposed First Topology in Bipolar Operation

After further advancement of rotor position by $60^0$, by switching on Q3 and switching off Q1, freewheeling of phase A current $i_a$ flows through phase A, phase C , switch Q6, and through D2 and Rs and is given in Fig 6. This mode of operation is described by the following equations.

$$V_s = R(i_b - i_c) + L\frac{d}{dt}(i_b - i_c) + e_b - e_c \qquad (14)$$

$$0 = R(i_a - i_c) + L\frac{d}{dt}(i_a - i_c) + e_a - e_c + R_s i_a \qquad (15)$$

Equation 15 is valid till $i_c$=0, due to the presence of diode D2.While freewheeling, energy in phase A is partially converted into useful torque and the rest of energy is dissipated as heat in resistor $R_s$.
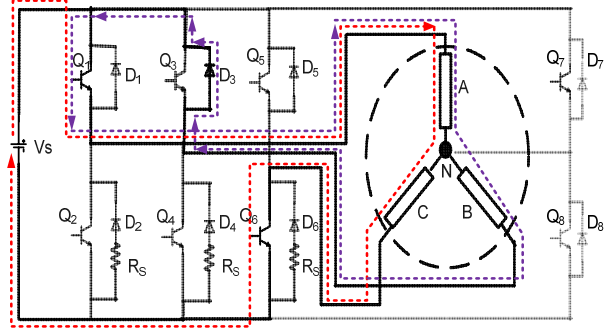


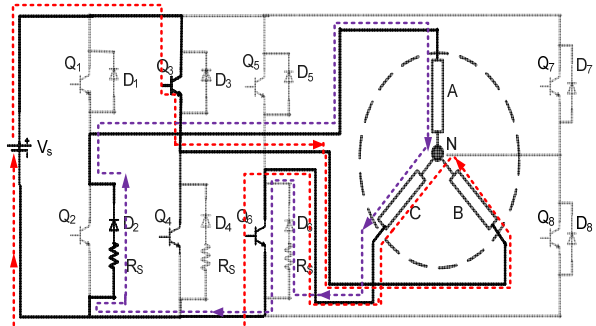Fig.5. Freewheeling of Negative Conducting Phase B



Fig. 6. Freewheeling of Positive Conducting Phase A

It can be observed that the freewheeling energy from negative conducting phase is completely converted into useful torque, whereas the freewheeling energy from positive conducting phase is partially converted into useful torque in bipolar mode of operation.

The details of commutation sequence of bipolar mode of operation with respect to rotor position are given in Table I. The bipolar mode of operation continues till the motor reaches to a specified changeover speed, where changeover will take place from bipolar to unipolar mode in order to attain high speed.

During unipolar operation switch Q8 in Fig.1 is permanently closed so that Q2, Q4 and Q6 are bypassed as shown in Fig. 7. With reference to rotor position $0^0$-$60^0$, by switching on Q1, Phase A conducts in positive direction, phase B has negative back EMF and carrying positive current, which free-wheels through diode D4 which in turn produces negative torque as shown in Fig.8 and phase C commutates. Due to this net torque decreases and drive will not attain the expected speed. This problem has been overcome in [2] by using 6 additional switches in series along with the freewheeling diodes. In this proposed converter the above problem is overcome by adding a high value resistor $R_s$ in series along with the freewheeling diode. The presence of $R_s$ in freewheeling path reduces the magnitude of negative torque as most part of freewheeling energy is dissipated in the form of heat in resistor $R_s$. Due to this the drive will reaches to expected speed.

Unopolar mode of operation is described by the following equations with reference to the rotor position $0^0$-$60^0$

$$V_s = Ri_a + L\frac{d}{dt}i_a + e_a \qquad (16)$$

$$0 = Ri_b + L\frac{d}{dt}i_b + e_b + R_s i_b \qquad (17)$$

### TABLE I
### Commutation Sequence in Bipolar Operations

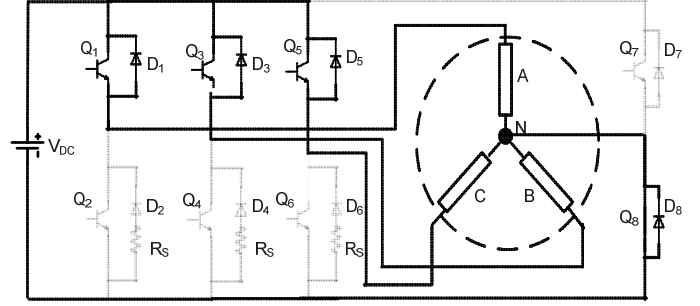| Rotor Position | $0^0$-$60^0$ | $60^0$-$120^0$ | $120^0$-$180^0$ | $180^0$ $240^0$ | $240^0$ $300^0$ | $300^0$ $360^0$ |
|---|---|---|---|---|---|---|
| Energized Phases | A,B | A, C | B, C | B, A | C, A | C, B |
| Switches Closed | Q1, Q4 | Q1, Q6 | Q3, Q6 | Q3, Q2 | Q5, Q2 | Q5, Q4 |
| Commutating Phase | C | B | A | C | B | A |
| Switch Opened | Q5 | Q4 | Q1 | Q6 | Q3 | Q2 |
| Free - wheeling through | D6, $R_s$ | D3 | D2, $R_s$ | D5 | D4, $R_s$ | D1 |



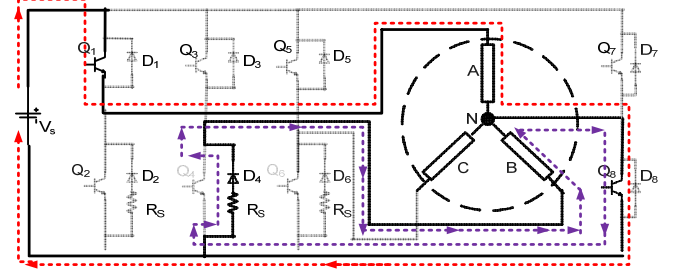Fig. 7. Proposed Inverter Circuit in Unipolar Mode



Fig. 8. Conduction in Phase A and Freewheeling of Phase B in Unipolar Operation

The details of switching sequence, commutation sequence in unipolar operation is given in Table II. Each phase is energized for $120^0$ and during this period in other two phases one phase freewheels and the other phase commutates for a period of $60^0$ causing less negative torque due to presence of $R_s$. Hence in comparison with [2] almost the same performance is achieved with lower number of switches and gate drives with minimum complexity in control.

### TABLE II
### Commutation Sequence in Unipolar Operation

| Rotor Position | $0^0$- $120^0$ | $120^0$-$240^0$ | $240^0$-$360^0$ |
|---|---|---|---|
| Energized Phase | A | B | C |
| Switch Closed | Q1 | Q3 | Q5 |
| Commutating Phases | $0^0$-$60^0$ C | $120^0$-$180^0$ A | $240^0$-$300^0$ B |
| | $60^0$-$120^0$ B | $180^0$-$240^0$ C | $300^0$-$360^0$ A |
| Switch Opened | Q5 | Q1 | Q3 |
| Free - wheeling through | $0^0$-$60^0$ Phase B, D4,Rs | $120^0$-$180^0$ Phase C, D6,Rs | $240^0$-$300^0$ Phase A, D2, Rs |
| | $60^0$-$120^0$ Phase C, D6,Rs | $180^0$-$240^0$ Phase A, D2, Rs | $300^0$-$360^0$, Phase B, D4, Rs |

This inverter topology is economical as number of switches is reduced to only 8 as compared to 14 switches in [2]. But in the proposed first topology inverter in bipolar operation, during freewheeling mode of positive conducting phase, some energy is wasted in the resistor $R_s$. This problem is addressed in the proposed modified inverter topology described in the next section

## IV PROPOSED MODIFIED INVERTER OPERATION-TOPOLOGY-II

The proposed modified inverter novel topology is as given in Fig. 9. Here a transistor Q7 is placed between negative terminal of DC source and the common terminal of three resistors placed along with freewheeling diodes in negative conducting phases. This topology is also realized by using 8 switches [21].

The 3 phases of the BLDC motor are connected to 3 legs and neutral point is connected to switch Q8. In bipolar operation switch Q7 is closed and switch Q8 is as shown in Fig. 10. Closing Q7 makes applying a short across resistor $R_s$. That is, there is no influence of $R_s$ in freewheeling. No wastage of freewheeling energy due to positive conducting phases in bipolar operation as in the case of first topology.

With reference to rotor position $0^0$-$60^0$, by switching on Q1 and Q4, phase A conducts in positive direction and phase B conducts in negative direction. By switching off Q4 and switching on Q6, a free-wheeling path is established through phase B, diode D3, switch Q1 and Phase A as in the case of first proposed inverter, as shown in Fig.11. The equations 12 and 13 are governing the operation in this mode.

After $60^0$ of rotor advancement, by switching off Q1 and switching on Q3, the free-wheeling energy in positive conducting phase A flows through D2, phase A, phase C, and Q6, avoiding the resistor $R_s$ as in Fig.12 and is described by the following equations..

$$V_s = R(i_b - i_c) + L\frac{d}{dt}(i_b - i_c) + e_b - e_c \qquad (18)$$

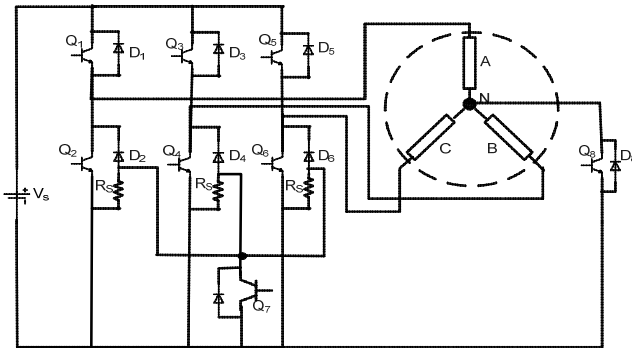$$0 = R(i_a - i_c) + L\frac{d}{dt}(i_a - i_c) + e_a - e_c \qquad (19)$$



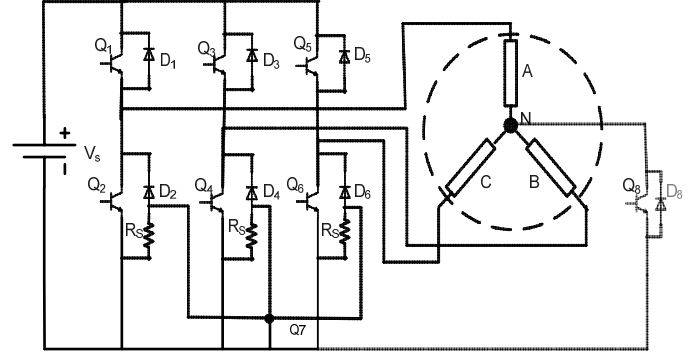Fig. 9. Proposed Inverter Second Topology Circuit



Fig. 10. Inverter Topology in Bipolar Operation

The advantage of the modified proposed second inverter topology is that, a part of freewheeling energy in phase A appearing as heat in resistor $R_s$ is eliminated as current is not passing through the $R_s$. Entire freewheeling energy is converted into positive torque .The commutation sequence of this inverter in bipolar operation is given in Table III
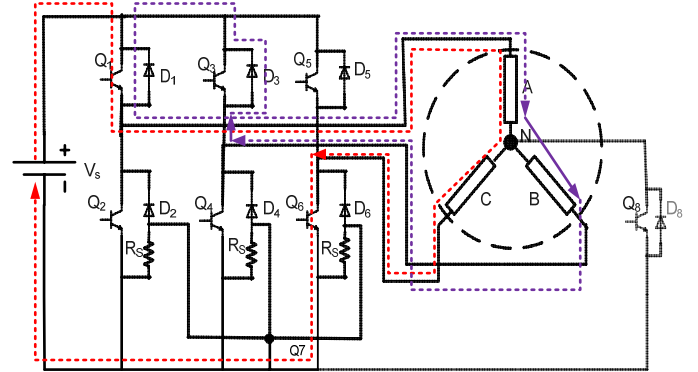


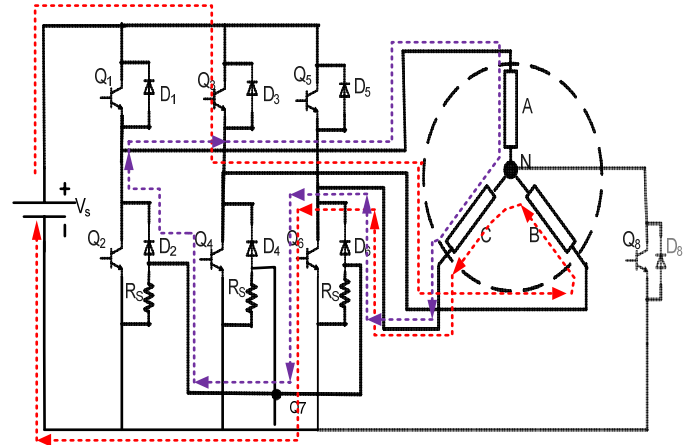Fig. 11. Freewheeling of Negative Conducting Phase B



Fig. 12. Freewheeling of Positive Conducting Phase A

**TABLE III**
**Commutation Sequence in Bipolar Operation of**
**Modified Inverter Topology**

| Rotor Position | $0^0$-$60^0$ | $60^0$-$120^0$ | $120^0$-$180^0$ | $180^0$ $240^0$ | $240^0$ $300^0$ | $300^0$ $360^0$ |
|---|---|---|---|---|---|---|
| Energized Phases | A,B | A,C | B,C | B,A | C,A | C,B |
| Switches Closed | Q1, Q4 | Q1, Q6 | Q3, Q6 | Q3, Q2 | Q5, Q2 | Q5, Q4 |
| Commutating Phase | C | B | A | C | B | A |
| Switch Opened | Q5 | Q4 | Q1 | Q6 | Q3 | Q2 |
| Free - wheeling through | D6 | D3 | D2 | D5 | D4, | D1 |

The switch Q8 is made on and Q7 is made off for unipolar mode of operation and is as given in Fig. 13. The neutral of the load is connected to negative DC bus. As the switch Q7 is open, the resistor $R_s$ is not short circuited. The resistor $R_s$ limits the current there by the influence of negative torque due to the non-energized phases. The operation in this mode is exactly same as that of first topology and the commutation sequence given in Table II is applicable here also.

## V SIMULATION RESULTS

The mathematical model of BLDC is given in Appendix I. Maxon EC6 215550, a 6 volts 1.2W motor [23] was considered for validating the proposed converter. The ratings of this motor are given in Appendix II.
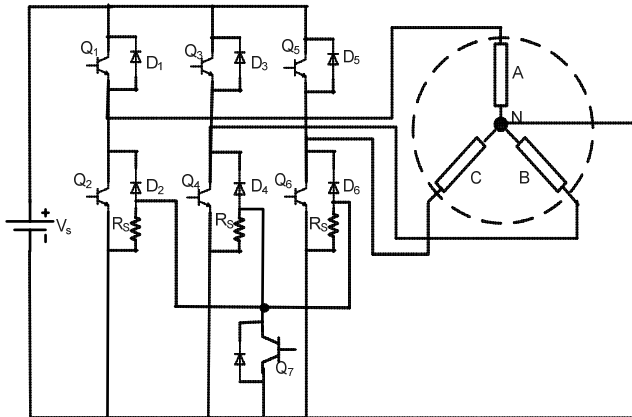


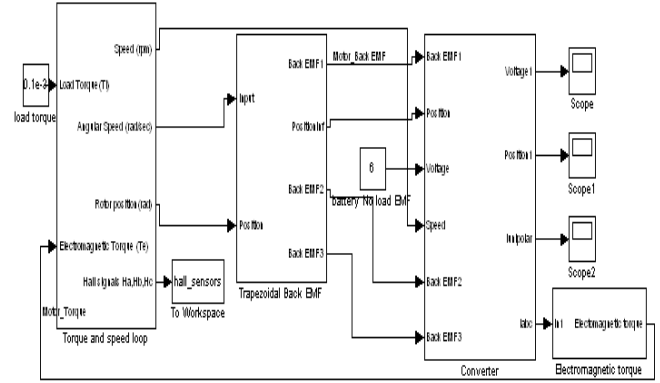Fig. 13. Proposed Modified Inverter Circuit in Unipolar Mode



Fig. 14. MATLAB/Simulink Model of BLDC Motor Mode

As the function of resistor $R_s$ is majorly to limit the current in freewheeling mode in unipolar operation in order to reduce the negative torque, it should be selected as high as possible. It is taken as 100 ohms which is high as compared to phase resistance of 6.25 ohms of BLDC motor. MATLAB/Simulink based model was developed for the motor and the Inverter. Fig. 14 shows the Simulink model of BLDC motor. It consists of 4 main blocks. The first one is torque speed block. In this block electromagnetic torque and load torque is compared, rotor speed and its position are taken as output. Second block is trapezoidal back EMF block, in this block based on rotor position information trapezoidal back EMFs are generated. Third block is converter block. Back EMF, voltage and position information are inputs for converter block and current is output.

Based on changeover speed value the converter block selects bipolar switching logic or unipolar switching logic. Fourth block is electromagnetic torque generator block. From the current and position information torque block generates electromagnetic torque.

Based on motor parameters the critical change over speed for the motor is selected as 14493 rpm. For a case study, the changeover speed is taken as 20000 rpm, which is higher than critical speed. This value should be less than the final speed attainable by drive if it is continuously running in bipolar mode for a particular load value. The load on the motor is 0.1mN-m. For this load, the final speed in bipolar mode of operation is 23651 rpm. Fig. 15 shows the speed vs. time plot of the motor in bipolar starting and unipolar running. It clearly indicates higher speed is achieved as soon as the system is switched from bipolar mode to unipolar. The changeover is taking place at 20000 rpm. Fig. 16 show one phase back EMF and corresponding phase current. Fig. 17 shows the torque vs. speed characteristic of drive.
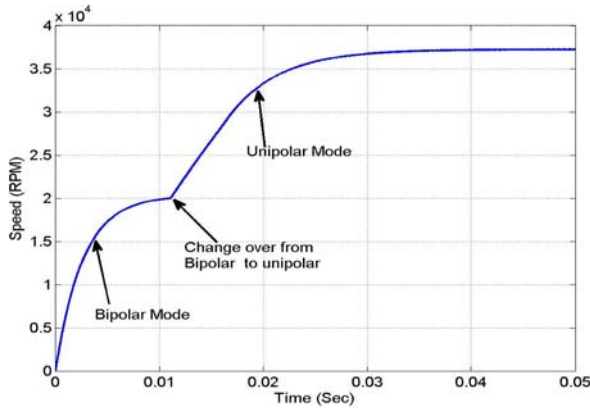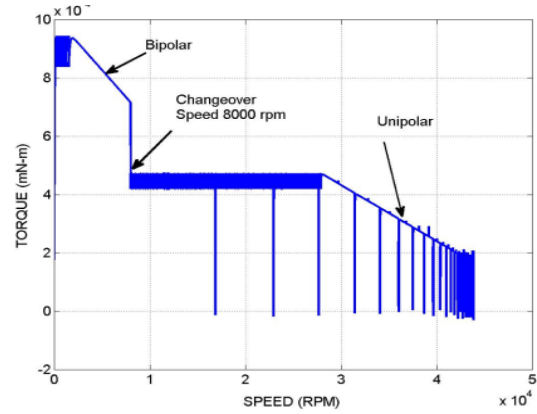
Fig. 15. Speed vs. Time of Motor



Fig. 16. Back EMF and Phase Current



Fig. 17.Torque Speed Characteristics with $T_L$=0.1mN-m



Fig. 18. Torque Speed Characteristics with Changeover Speed as 8000 rpm



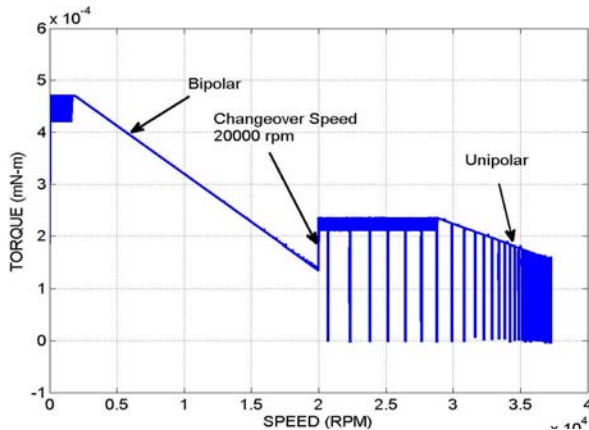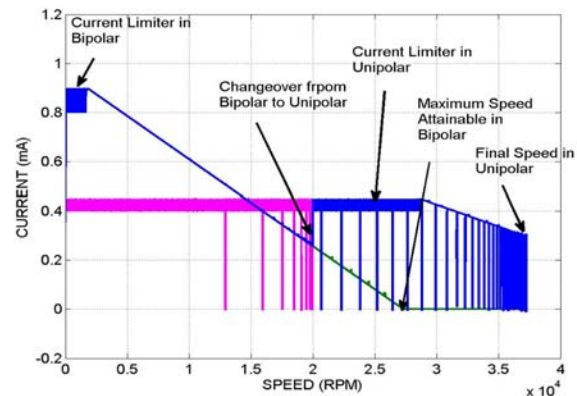Fig 19. Torque –Speed Characteristics with Changeover Speed as 15000



Fig. 20. Current - Speed Characteristics with Bipolar Starting and Unipolar Running

The speed torque characteristics of spindle motor at changeover speeds less than and nearly equal to critical speeds, i.e., at 8000 rpm, 15000 rpm are shown in Fig.18 and Fig19 The observation is that at change over speed, torque possesses jumps at speeds other than critical speed. The line current drawn from DC supply with respect to

speed is given in Fig. 20.  It is observed that, the drive is operating in bipolar only for few milliseconds and so the freewheeling effect during commutation is having negligible influence in this mode. This is the reason for possessing same characteristics to drive for both the proposed topologies. The drive mode is changed to unipolar with in
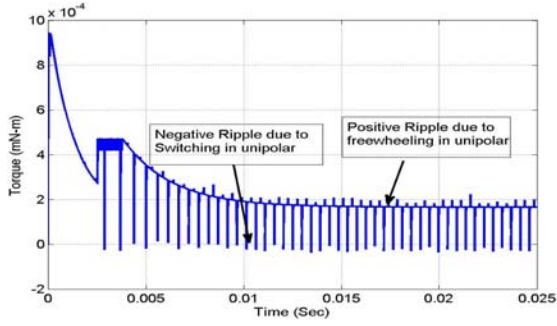
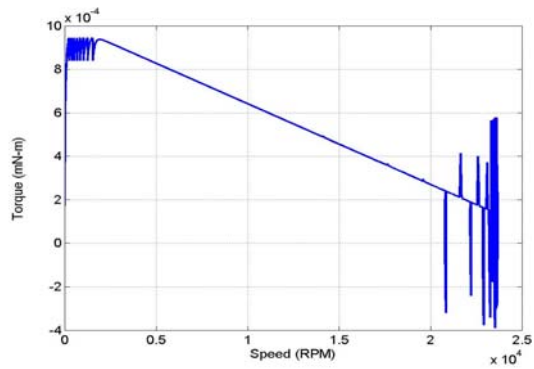Fig. 21. Influence of Freewheeling on Unipolar Operation



Fig. 22. Speed Torque Characteristics with Negative Torque
during Freewheeling in Unipolar Mode

few milliseconds of starting and the minimized negative
torque due to freewheeling of unexcited phases is as shown
in Fig. 21. If the negative torque is not minimized by
introducing the resistor $R_s$ in freewheeling path, the drive is
settling at a low speed of 23593 rpm with more ripples in
torque and is shown in Fig. 22. The influence of selection
of Rs is studied for a load torque of 0.1mN-m and results
are tabulated in Table IV. For higher values of $R_s$, torque
developed and final steady speed are increasing

**TABLE IV**
**Influence of selection of $R_s$ on Torque and Speed**

| Resistance Rs (Ohms) | Steady State Speed (RPM) | Torque (mN-m) |
| --- | --- | --- |
| 0 | 23593 | 0.1368 |
| 20 | 37220 | 0.1532 |
| 100 | 43089 | 0.1656 |
| 200 | 44212 | 0.1670 |
| 500 | 44939 | 0.1684 |

## VI CONCLUSIONS

The proposed cost effective inverter topologies can
be utilized to drive a BLDC motor at high speeds with high
starting torque using bipolar-starting and unipolar-running
algorithm. This is possible using the same rating devices in
both modes of operation and placing a current regulator in
the DC line. Both topologies differ only with the bipolar
mode of operation and possess same unipolar operation. The
characteristics of the drive with the two topologies will not
differ much because of less period of bipolar mode
operation. Due to this only one set of characteristics are
presented for discussion. These topologies are realized by
using only 8 switches and best suited for low power drives.
The resistance $R_s$ in freewheeling path should be selected as
higher value in order to limit the current to as minimum as
possible thereby reducing the influence of negative torque.
If Rs is taken as low value, the drive will run at relatively
low speed. If Rs is made zero, the drive will run at very low
speed. These topologies can be operated in any one of three
modes unipolar mode, bipolar mode and bipolar starting and
unipolar running mode depending upon the requirement of
speed and torque.

Since a high power drive would require a high
powered resistor $R_s$, these topologies are best suitable for
low power applications.

## VII APPENDIX -I

The three phase star connected BLDC motor can be
described by the following four equations in bipolar mode
of operation [9, 10, 18- 19]

$$v_{ab} = R(i_a - i_b) + L\frac{d}{dt}(i_a - i_b) + e_a - e_b \qquad (20)$$

$$v_{bc} = R(i_b - i_c) + L\frac{d}{dt}(i_b - i_c) + e_b - e_c \qquad (21)$$

$$v_{ca} = R(i_c - i_a) + L\frac{d}{dt}(i_c - i_a) + e_c - e_a \qquad (22)$$

The developed torque and speed are estimated by
using the following equations.

$$T_e = \frac{1}{\omega_m}\left[e_a i_a + e_b i_b + e_c i_c\right] \qquad (23)$$

$$T_e = B\omega_m + j\frac{d\omega_m}{dt} + T_L \qquad (24)$$

The symbol $v$, i and e denote the phase to phase voltages,
phase currents and phase back EMF's respectively, in three
phases a, b and c. The resistance R and the inductance L are
per phase values and $T_e$ and $T_L$ are the electrical torque and
the load torque. J is the rotor inertia; B is a friction constant
and $\omega_m$ is the rotor speed.

The back EMF's and the electrical torque developed can be
expressed as

$$e_a = \frac{K_e}{2}\omega_m F(\theta_e) \qquad (25)$$

$$e_b = \frac{K_e}{2}\omega_m F(\theta_e - \frac{2\pi}{3}) \qquad (26)$$

$$e_c = \frac{K_e}{2}\omega_m F(\theta_e - \frac{4\pi}{3}) \qquad (27)$$

$$T_e = \frac{K_t}{2}\left[F(\theta_e)i_a + F(\theta_e - \frac{2\pi}{3})i_b + F(\theta_e - \frac{4\pi}{3})i_c\right] \qquad (28)$$

Where $K_e$ and $K_t$ are the back EMF and torque constants and $\theta_e$ is the electrical angle of rotor position.

The function $F(\theta_e)$ gives the trapezoidal waveform of the back EMF. One period of this waveform can be written as

$$
\begin{aligned}
F(\theta_e) &= 1 & 0 \le \theta_e < \frac{2\pi}{3} \\
&= 1 - \frac{6}{\pi}\left(\theta_e - \frac{2\pi}{3}\right) & \frac{2\pi}{3} \le \theta_e < \pi \\
&= -1 & \pi \le \theta_e < \frac{5\pi}{3} \qquad (29) \\
&= -1 + \frac{6\pi}{3}\left(\theta_e - \frac{5\pi}{3}\right) & \frac{5\pi}{3} \le \theta_e < 2\pi
\end{aligned}
$$

As phase currents are balanced,

$$i_a + i_b + i_c = 0 \qquad (30)$$

By eliminating one phase current variable, the two independent voltage equations can be written as

$$v_{ab} = R(i_a - i_b) + L\frac{d}{dt}(i_a - i_b) + e_a - e_b \qquad (31)$$

$$v_{bc} = R(i_a + 2i_b) + L\frac{d}{dt}(i_a + 2i_b) + e_b - e_c \qquad (32)$$

For implementation in Matlab/Simulink, above equations are used for bipolar operation.

In unipolar mode of operation, the BLDC motor can be described by the following equations.

$$v_{an} = Ri_a + L\frac{d}{dt}i_a + e_a \qquad (33)$$

$$v_{bn} = Ri_b + L\frac{d}{dt}i_b + e_b \qquad (34)$$

$$v_{cn} = Ri_c + L\frac{d}{dt}i_c + e_c \qquad (35)$$

$$T_e = B\omega_m + j\frac{d\omega_m}{dt} + T_L \qquad (36)$$

Here $v_{an}$, $v_{bn}$ and $v_{cn}$ are the voltages applied across each phase winding. For implementation in Matlab/Simulink, above equations are used.

## APPENDIX –II
## BLDC MOTOR PARAMETERS [23]
## Motor Model:   Maxon EC 6 215550

| | |
|---|---|
| Number of poles | 2 |
| Power rating | 1.2 Watt |
| Nominal Voltage | 6 Volts |
| No load speed | 47130 rpm |
| Stall torque | 0.5 mN-m |
| No load current | 60 mA |
| Resistance per phase | 6.25 Ohms |
| Inductance per phase | 0.0455 mH |
| Torque Constant | 1.05 mN-m/AS |
| Rotor inertia | 0.005 g-cm$^2$ |
| Friction constant | 1.38* $10^{-8}$ N-m/(rad/s) |
| Windings connection | Star |

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