A Novel H- Bridge Topology to Drive Spindle Motor at High Speed with High Starting Torque

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Abstract: **A Hard Disc Drive (HDD) spindle motor is, a brushless DC (BLDC) motor, widely used for high speed applications due to its high efficiency and controllability. This paper presents a novel H-bridge circuit topology to drive a spindle motor at high speed with high starting torque. The proposed scheme is simple in its control logic, easy to implement and offers better dynamic response. Each phase of the spindle motor is excited by one H – Bridge and the entire topology requires 12 switches in total for excitation of three phase BLDC motor. The proposed scheme has been simulated on MATLAB/SIMULINK platform, the results are presented and discussed. To compare the results of this topology with other methods, this proposed topology uses same rating devices as in bipolar, unipolar, bipolar start unipolar run operations [8-10]. This scheme is well suited for low and medium power drives.**

Index Terms: H - Bridge, HDD Spindle Motor, BLDC Drive, High Speed with High Starting Torque

I INTRODUCTION

In order to facilitate faster data access, the speed requirement for the spindle motor used in Hard Disc Drives is increasing day by day [1-3]. Such high speed operation can be achieved by using any of the four methods. The first method is to design the machine with low back EMF constant, which gives a high speed with a given system voltage. However it suffers from low starting torque and consequently a longer transient period. It is one of the drawbacks in high speed applications of low and medium power drives.

The second method is to use higher DC bus voltage. With this method high starting torque and high speed operation can be obtained. But the disadvantage is that the switch voltage rating is to be increased which requires a current protection to limit current in the circuit during low speeds. The third method is winding method where in windings connected in series to get high starting torque and in parallel to obtain high speed. This requires additional switching devices and more complex control logic.

Fourth method is developed comprising the merits of the bipolar and unipolar drives and the scheme uses bipolar starting and unipolar running [4-7]. In this method, a high starting torque is developed during start by running the drive in bipolar mode and after reaching to a specified speed, the drive is converted into unipolar to get high speed. The negative torque developed by the freewheeling current of non excited windings in unipolar mode is addressed in [4, 8-10] and various topologies were proposed to minimize it.

In this paper a novel inverter topology is proposed by using H – bridge configuration for low and medium power drives to improve the dynamic response and to achieve high speed. Current regulator is provided in DC line to ensure that line current does not exceed a specified limit decided based on the current rating of motor and device ratings. In realizing this topology, same rating devices are used as in bipolar starting unipolar running method [8-10] in order to compare this drive in contrast to other topologies. The details of this method are presented in the next section.

II PROPOSED H - BRIDGE CONFIGURATION

The proposed H-bridge inverter topology is given in Fig 1. It consists of three H-bridges exciting three phases of the spindle motor independently. Each H bridge is possessing 4 switches with freewheeling diodes connected in anti parallel across them. Each phase winding is equivalent to a series circuit of resistance, inductance and back EMF of that phase. The back EMF value is dependent on speed of rotor and its position and on electromagnetic design of motor. The variation of back EMFs of three phases with respect to its rotor position is given in Fig 2. The fundamental task for a motor drive is to develop constant ripple free torque for smooth mechanical motion. It is difficult to produce it due to cogging and the developed torque is not unidirectional unless the phase currents changes sign whenever back EMF does.

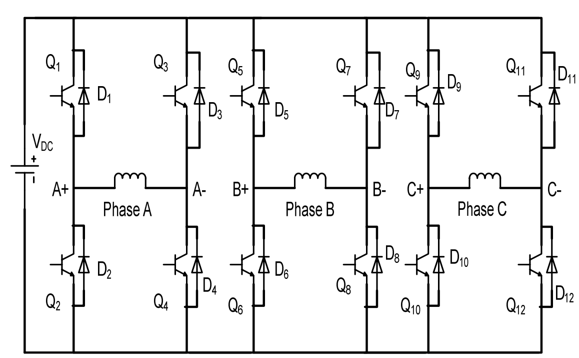


Fig. 1 Proposed H- Bridge Configuration

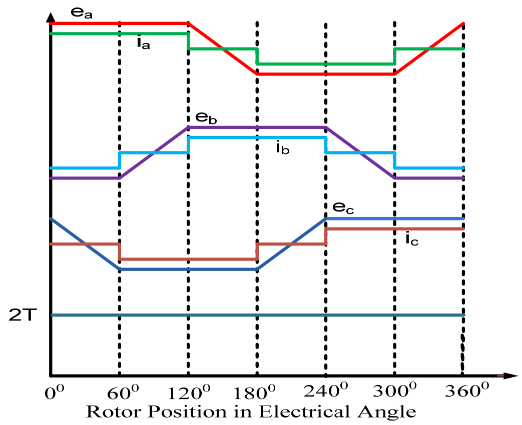
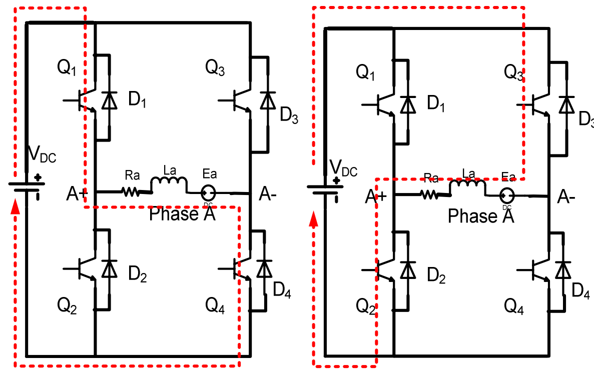


Fig. 2 Back EMFs, Currents and Torque for ideal BLDC Drive



(a) (b)

Fig 4 Direction of (a) Positive and (b) Negative Current Flow

In an ideal case, the torque will be unidirectional as shown in Fig 2. In practice, phase current does not change sign exactly at the point that the back EMF does, resulting in torque ripple. Hall sensors are used to identify which phases are to be excited based on rotor position and by controlling these currents the torque is controlled.

In the proposed inverter topology each phase winding of the spindle motor is excited by one H – bridge [15], requiring totally 12 switches as against 8 in [8-10] and 14 in [4]. Each phase acts independently to produce torque and independent phase current control is possible. Initially the operation of the circuit is analyzed on the basis of per phase and then analysis is made on three phase basis. The circuit topology with only one phase excitation is shown in Fig 3. This circuit can be turned on by two ways. Fig 4(a) and Fig 4 (b) describe the positive and negative direction current flow respectively. The turn off behavior is guided by the fundamental behavior of inductors i.e., the current can't change instantaneously but must be continuous and higher the voltage across the inductor the faster the change in current through it. When Q1 and Q4 are turned off, the freewheeling current flow the through diodes D2 and D3. During this period, the voltage across inductor is

$$L\frac{di_a}{dt} = -V_{dc} - Ri_a - e_a \qquad (1)$$

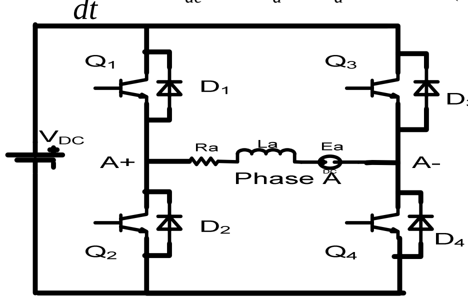


Fig. 3 H Bridge Acoss Phase A

which is negative when $i_a > 0$, $V_{dc} > 0$ and $e_a > 0$. Here L and R are phase inductance and resistance, V_{dc} , i_a and e_a are supply voltage , current and back EMF of phase A respectively .

With time the phase current decreases exponentially and at zero current the diodes will turn off. The energy in the inductor is returned to the supply and the circuit rests. Similar conditions prevail for opening the switch pair Q2 and Q3. At no time vertical pairs of switches Q1and Q2 or Q3 and Q4 are closed simultaneously to avoid a shoot through fault.

The analysis of three phase drive differs from that of single phase drive operation due to the effect of freewheeling of one phase for every 60^0 of rotor advancement.

From Fig 2, it is observed that when the rotor position is 0^0 - 60^0, phase A induced EMF is positive and Phase B induced EMF is negative and phase C induced EMF changes sign from positive to negative. So phase A has to be excited in positive direction by switching on Q_1 and Q_4 and phase B is to be excited in negative direction by switching on Q_6 and Q_7 and phase C will freewheels through D_{10} and D_{11} till the energy stored in phase C is fed back to DC supply as shown in Fig. 5

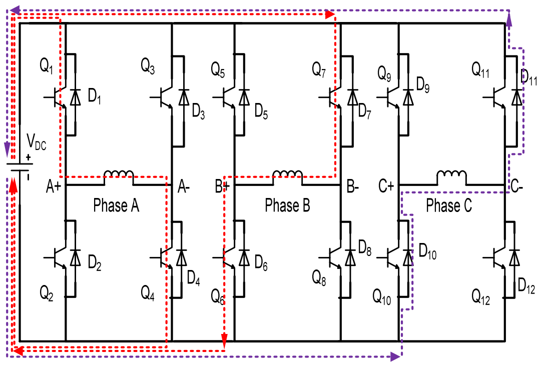
The following equations are written based on KVL, for the phases A, B and C respectively in this interval.

$$Ri_a + L\frac{di_a}{dt} + e_a = V_{dc} \qquad (2)$$

$$Ri_b + L\frac{di_b}{dt} + e_b = -V_{dc} \qquad (3)$$

$$Ri_c + L\frac{di_c}{dt} + e_c = -V_{dc} \qquad (4)$$

Here equation 4 is valid till $i_c = 0$



. Fig. 5 Drive Operation for Rotor Position 0^0-60^0

It is observed that even though the phases A and B are connected in parallel across the supply experiencing full system voltage, the current drawn by them is limited by the current limiter placed in the DC line which will limit the current based on device current and rated value of motor current. In turn, it is equivalent to applying a low voltage across the windings during starting. However, torque developed in phase A and phase B aid each other to give high starting torque,

After advancement of rotor by an angle 60^0, that is in interval 60^0-120^0, induced EMF in phase A is still positive and induced EMF is negative in phase C and Induced EMF in phase B changes sign from negative to positive. So the switches Q1 and Q4 are still to be in closed state and switches Q10 and Q11 are to be closed and phase B freewheels through diodes D5 and D8 as shown in Fig 6

The following equations are written based on application of KVL to the phases A, B, and C respectively in this interval.

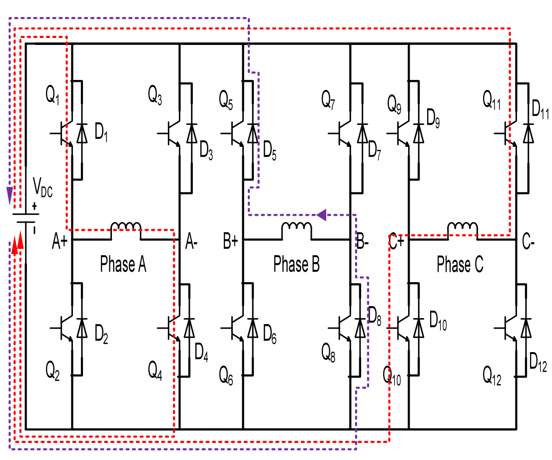


Fig. 6 Drive Operation for Rotor Position 60^0- 120^0

$$Ri_a + L\frac{di_a}{dt} + e_a = V_{dc} \qquad (5)$$

$$Ri_b + L\frac{di_b}{dt} + e_b = -V_{dc} \qquad (6)$$

$$Ri_c + L\frac{di_c}{dt} + e_c = -V_{dc} \qquad (7)$$

Here equation 6 is valid till $I_b = 0$

In subsequent intervals of rotor position, the details of the energized phases, switches closed and opened and diodes participating in freewheeling are described in Table I.

At any instant of time, two phases are always connected in parallel across the supply and third phase is freewheeling in this proposed inverter.

III COMPARISION OF PROPOSED TOPOLOGY WITH EXISTING METHODS

In general a BLDC drive is operated in bipolar mode to get high starting torque and low speed and in unipolar mode to get low starting torque and high speed [11-15]. In spindle motor drive, to get high torque with high speed bipolar starting and unipolar running algorithm is proposed and implemented [4, 7]. This algorithm is implemented in different methods. In [4], it is implemented by using 14 switches where as in [8, 10] it is implemented by using only 8 switches. In these methods, the drive is started in bipolar mode to get high torque and after reaching to a specified speed, the drive is made to operate in unipolar mode to get high speed.

In conventional bipolar mode of operation at any instant of time two phases are connected in series. Each phase experience half the supply voltage $V_{dc}/2$ and carries same starting current. Torque due to current in each winding aid each other to give high starting torque. However, steady state speed is reduced due to reduced voltage to each winding.

In unipolar mode of operation, only one phase is excited at a time and so full supply voltage V_{dc} is applied across winding resulting in high speed and low starting torque due to current limiter in DC line. Based on this bipolar mode of operation is preferred for high torque and low speed applications whereas unipolar mode of operation is preferred to get low torque and high speed applications. In the bipolar start unipolar run method, each phase winding experience half the supply voltage during starting and full supply voltage during running thereby offering high starting torque and high speed under running conditions.

TABLE I
Details of Switching Sequences With Respect to Rotor Position

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
Commutating Phase	C	B	A	C	B	A
Switches closed	Q1 Q4 Q6 Q7	Q1 Q4 Q10 Q11	Q5 Q8 Q10 Q11	Q5 Q8 Q2 Q3	Q9 Q12 Q2 Q3	Q9 Q12 Q6 Q7
Switches Opened	Q9 Q12	Q6 Q7	Q1 Q4	Q10 Q11	Q5 Q8	Q2 Q3
Freewheeling through	D10 D11	D5 D8	D2 D3	D9 D12	D6 D7	D1 D4

In the proposed topology, the drive is operating always in bipolar mode allowing current to flow in both directions in every phase. Here the phases are connected in parallel across the supply experiencing full supply voltage (V_{dc}). During starting, the net voltage applied to the winding is reduced due to the presence of current limiter. Since the device rating is same in proposed topology as that topologies in [4, 8-10], the current in excited windings of present topology is same as that in bipolar operation. Due to this the starting torque developed in this method is same in magnitude as in bipolar mode of operation. As motor speed increases, the current drawn from supply reduces but still reduced voltage is applied across the phases till the current in each phase falls to below upper limit of current limiter. Once the current fall below upper limit of current limiter, then each phase experiences full DC supply and there by high speed is achieved. As the drive in this mode is operating continuously in bipolar the developed torque is high and so the dynamic response is much superior to that of other methods proposed in [4, 8 and 10]. As this topology have open windings, the power rating of drive increases.

Table II gives a comparison of this topology with the other existing methods. This comparison is made by considering the effect of DC line current limiter. It is observed that the stalling torque in all cases is same, with a better dynamic response for H-bridge as compared to other topologies.

TABLE II
Comparison of H- Bridge with Existing Topologies

Topology → / Based On ↓	Topology-1 [4]	Topology-2 [8,10]	H Bridge
Number of Devices	14	8	12
Starting Mode	Bipolar	Bipolar	Bipolar
Running Mode	Unipolar	Unipolar	Bipolar
Maximum Voltage Across Each Phase	$V_{DC}/2$, at starting; V_{DC}, during running	$V_{DC}/2$, at starting; V_{DC}, during running	V_{DC}, at starting and running
Current Rating of Devices	I^*	I^*	I^*
Stalling Torque	T	T	T
Transient Response	High	High	Very High

I^* is the current rating of devices

IV SIMULATION RESULTS

The mathematical model of the BLDC drive is given in Appendix I. Maxon EC6 215550, a 6 volts 1.2W motor [17] is considered for validating the proposed converter. The ratings of this motor are given in Appendix II MATLAB/Simulink based model is developed for the motor and the inverter. Fig. 7 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 are compared, rotor speed and its position, Hall sensors signals are taken as output. Second block is trapezoidal back EMF block, in this block based on rotor position, trapezoidal back EMF's are generated. Third block is a converter block. This block uses the equations which describe the operation of inverter for every 60^0 of rotor advancement in one revolution. Phase currents and DC line current are calculated. The DC line current limiter placed in this block decides the amount of supply voltage to be applied to the inverter without exceeding the device rating and motor rated current during starting as well as in running conditions of the drive. Back EMFs, voltage and position information are inputs for converter block and phase current and DC line current are the output. Fourth block is electromagnetic torque generator block. From the phase currents information, torque block generates electromagnetic torque.

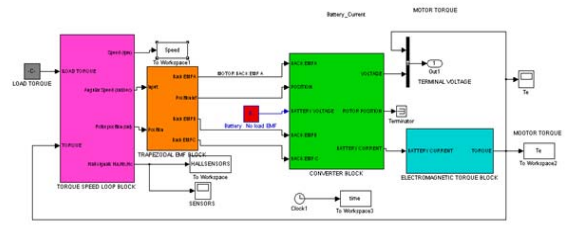


Fig. 7 Simulink Model of BLDC Drive

The load torque is taken as 0.23 m N-m. The Back EMF and enlarged phase current of phase A are shown in Fig 8.

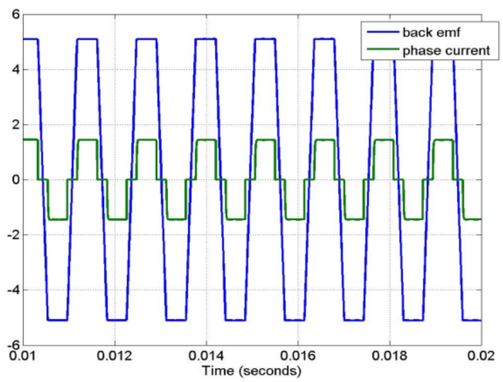


Fig. 8 Back EMF and Enlarged Current in Phase A

It is observed that the current and back EMF are not in phase which is the cause for generating the ripples in torque. Both quantities are possessing six steps in a cycle period. The phase currents are shown in Fig. 9.

It is observed that at any instant of time, the sum of phase currents is zero. The current drawn from the DC mains is given in Fig. 10. The speed time characteristics of the drive are given in Fig. 11. The final speed attained by the drive for this load is 46, 411 rpm. This is achieved in a time of 0.013 seconds. The torque – speed characteristic of the drive is given in Fig 12. The torque remains constant till the speed reaches to a value of 29889 rpm where current in each phase reduced to upper current limit value of 0.45A. For speed up to 29889 rpm, reduced supply voltage is applied across every phase and above this speed rated voltage of 6 V is applied across every phase. Under steady state condition, torque developed is 0.293 m N-m for a load torque of 0.23mN-m. The difference in the two values is due to friction constant.

For a comparison purpose simulation study is carried out on the same drive with same device ratings in bipolar mode, unipolar mode and bipolar starting and unipolar running mode with a load torque of 0.23mN-m.

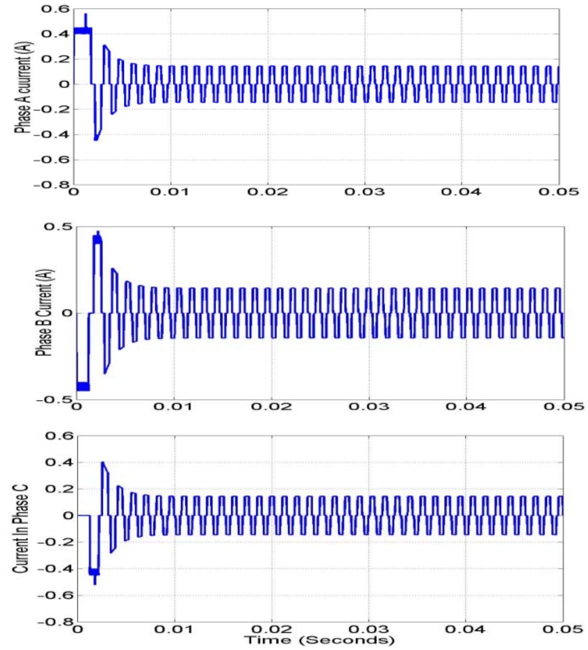


Fig. 9 Currents in Three Phases

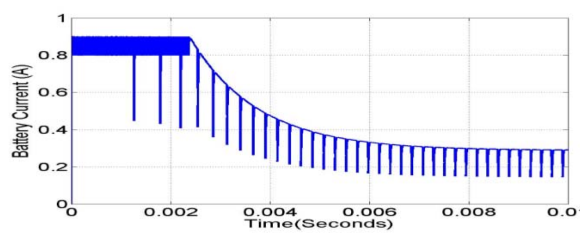


Fig. 10 Battery Current

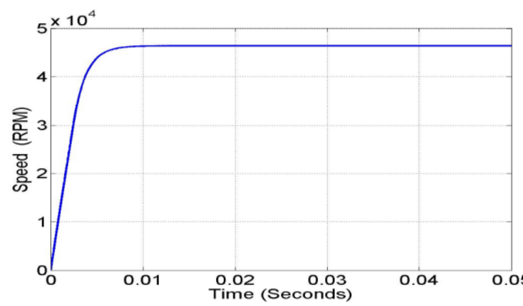


Fig. 11 Speed – Time Characteristic

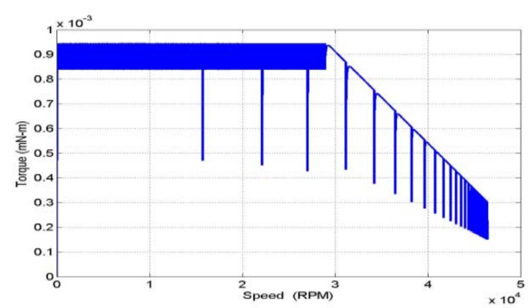


Fig. 12 Torque- Speed Characteristic

TABLE III
Comparison of Results of H-bridge with other methods

Toplogy → / Based on ↓	Bipolar	Unipolar	Bipolar Starting Unipolar Running	H - bridge
Number of devices	6	3	8	12
Torque (mN-m)	0. 2612	0.2904	0.2904	0.293
Steady State Speed	20226	38863	38864	46411
Stalling Torque (without current limitation)	1.008	1.008	1.008	2.016
Stalling Torque (with current limitation)	0.945	0.4725	0.945	0.945

From the Table III, it is observed that H Bridge is giving better performance as compared to all other methods.

For a load torque of 0.3 m N-m, speed vs. time characteristics is plotted for all methods and is shown in Fig. 13. It is observed from the Fig. 13 that the dynamic response of bipolar mode is better than that of unipolar mode of operation and its final speed is 18398 rpm. The final speed in unipolar is higher and is 35313 rpm. In bipolar start unipolar run method, initially the dynamic response coincides with that of bipolar and final speed is same as in unipolar method i.e., 35313 rpm with a better dynamic response as compared to unipolar mode of operation.

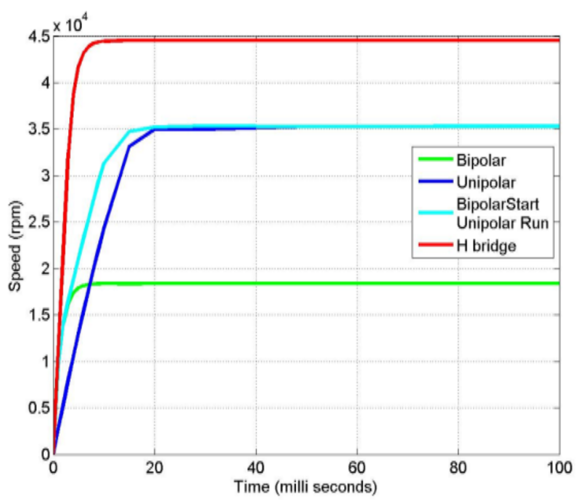


Fig. 13 Dynamic Response of BLDC Drive in Different Modes of Operation

In the case of H- bridge configuration, due to continuous operation in bipolar, torque is high and so the dynamic response is very high as compared to all other methods with more speed. The final speed attained is 44548 rpm.

V CONCLUSIONS

The proposed novel H bridge based inverter topology to drive the BLDC motor at high speed with high starting torque is presented. At any instant of time, one phase of the motor winding carries positive current, one phase carries negative current and the third phase freewheels into supply. The drive always operates in bipolar mode during starting and running condition. High torque and high speed is achieved in this proposed topology with rated current during starting and rated voltage during running. This scheme offers high speed and high torque as compared to the present existing systems with simple control circuit. It delivers more output due to open winding converter topology of inverter. Due to this, the dynamic response of this scheme is much better as compared to the other existing methods. This drive is most suitable in applications like spindle motors, automobiles where high speed with high starting torque is desirable.

VII APPENDIX –I

The three phase star connected BLDC motor can be described by the following equations in bipolar mode of operation [11-16]

$$v_{ab} = R(i_a - i_b) + L\frac{d}{dt}(i_a - i_b) + e_a - e_b \qquad (A.1)$$

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

$$v_{ca} = R(i_c - i_a) + L\frac{d}{dt}(i_c - i_a) + e_c - e_a \qquad (A.3)$$

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

$$T_e = \frac{1}{\omega_m}\left[e_a i_a + e_b i_b + e_c i_c\right] \qquad (A.4)$$

$$T_e = B\omega_m + j\frac{d\omega_m}{dt} + T_L \qquad (A.5)$$

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 ω_m is the rotor speed.

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

$$e_a = \frac{K_e}{2}\omega_m F(\theta_e) \qquad (A6)$$

$$e_b = \frac{K_e}{2}\omega_m F(\theta_e - \frac{2\pi}{3}) \qquad (A7)$$

$$e_c = \frac{K_e}{2}\omega_m F(\theta_e - \frac{4\pi}{3}) \qquad (A8)$$

$$T_e = \frac{K_t}{2}\left[F(\theta_e)i_a + F(\theta_e - \frac{2\pi}{3})i_b + F(\theta_e - \frac{4\pi}{3})i_c\right] \qquad (A9)$$

Where K_e and K_t are the back EMF and torque constants and θ_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

$$\begin{aligned} F(\theta_e) &= 1 & 0 \le \theta_e < \frac{2\pi}{3} \\ &= 1 - \frac{6}{\pi}\left(\theta_e - \frac{2\pi}{3}\right) & \frac{2\pi}{3} \le \theta_e < \pi \\ &= -1 & \pi \le \theta_e < \frac{5\pi}{3} \qquad (A10) \\ &= -1 + \frac{6\pi}{3}\left(\theta_e - \frac{5\pi}{3}\right) & \frac{5\pi}{3} \le \theta_e < 2\pi \end{aligned}$$

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

APPENDIX –II

BLDC MOTOR PARAMETERS [17]

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*s
Windings connection	Star

VIII REFERENCES

[1] R. Civilian, D. Stupak, "*Disk drive employing multi mode spindle drive system*", US Patent 5471353, Oct 3, 1995.

[2] E. Grochowski, R.F. Hyatt, "*Future trends in hard disk drive*", IEEE Trans. on Magnetics, Vol. 32, No 3, Pages : 1850-1854, May 1996

[3] J.D.Ede, Z.Q.Zhu, D.Howe, "*Optimal split ratio control for high speed permanent magnet brushless DC motors*", Proc. 5th Int. Conf. Electrical Machines and Systems, Vol. 2, Aug 2001, Pages: 909-912

[4] G.H. Jang ,M.G. Kim, "*A Bipolar-Starting and Unipolar - Running Method to Drive an HDD Spindle Motor at High Speed with Large Starting Torque*", IEEE *Transactions on Magnetics*, Vol. 41, No.2, Pages: 750-755, Feb. 2005.

[5] Jang, G.H., Kim, M.G., Kim, H.Y., "*A bipolar-starting and unipolar-running method to drive a brushless DC motor in high speed with large starting torque*", International Conference on Magnetics, INTERMAG 2003, Pages: HB-07

[6] Jang, G.H., Kim, M.G., "*A bipolar-starting and unipolar-running method to drive an HDD spindle motor at high speed with large starting torque*", Asia-Pacific Magnetic Recording Conference, Pages:36–37,2004

[7] S.W.Cameron. "*Method and apparatus for starting a sensor less polyphone DC motors in dual coil mode and switching to single coil mode at speed*", U.S.Patent 5455885, Nov.28,1995

[8] PVRL Narasimham, M.Neelima,, M Maruthi Krishna and V Naresh, " *A Novel Low Cost Inverter for Extended Torque-Speed Characteristics of Spindle Motor*" , SPEEADAM 2010, June 14-16, Pisa, Italy (EMD 0509)

[9] PVRL Narasimham, AVRS Sarma, D.Srinivasarao, "*A Novel Low Cost Bipolar –Starting and Unipolar –Running Converter to Drive Spindle Motor*", INDUSCON 2010,Nov 8-10 ,Sao Paulo, Brazil (paper ID 65)

[10] PVRL Narasimham, AVRS Sarma, E Vargil Kumar, "*A Novel Low Cost Bipolar-Starting and Unipolar Running Converter for Extended Torque-Speed Characteristics of Spindle Motor*" , PECON 2010, Kaulalumpur, Malaysia

[11] T.Kenzo , S. Nagamori, "*Permanent Magnets and Brushless DC Motors"*, Tokyo, Japan, Sogo Electronics, 1984.

[12] J.R.Hendershot, T.J.E.Miller, "*Design of Brushless Permanent Magnet Motors"*, Oxford Univ. Press, 1994

[13] R. Krishnan, "*Permanent Magnet Synchronous and Brushless DC Motor Drives",* CRC press, 2010

[14] R Krishnan, "*Electric Motor Drives Modeling, Analysis and Control*", Prentice Hall, 2001

[15] Duane C. Hanselman," *Brushless Permanent-Magnet Motor Design*", McGraw Hill, Inc, 1994

[16] Baldursson , Stefan, "*BLDC Motor Modelling and Control – A MATLAB/SIMULINK implementation* ", Master Thesis , Gothenburg, 2005

[17] Maxon Precision Motors Inc., http://www.maxonmotor.com