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Research paper

Impact of Converter Topologies on the Performance of Permanent Magnet Brushless DC Motor

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Abstract

Comparative merits over AC motors leads to replacing of other electrical motors by DC motors in applications stretching from high-speed automation to electric motorbikes. However, brushed DC motors are popular for applications where speed needs to be varied or torque needs to be controlled precisely. Because of higher performance and/or reliability, Brushless DC motors are preferred rather than brushed one. Moreover typical brushed DC motor is exposed to sparking during commutation. Electronic commutation via power converters in BLDC motors replaces the mechanical commutation of typical DC motor. It is essential to understand the impact of these converters on the performance of BLDC motors. Hence this paper presents a comparative analysis of various power converters fed Brush Less DC motor. The simulation results show that the impact of power converters on the enactment of BLDC motor.

Keywords: *VSI, ZSI, MLI, ZSMLI, BLDC and transient behavior*.

1. Introduction

An electric motor is an electro mechanical device which transforms electrical energy into mechanical energy. This principle makes electric motors to be an integral part of the industry. More than half of all the electrical energy in the world is utilized by various applications which are employed with electric motors. Henceforth it is very much advisable to select a kind of motor which has inbuilt nature of energy savings. The BLDC motor is extensively employed in appliances, automotive, aerospace, consumer, medical, automated industrial equipment and instrumentation. The brushless D.C. motor is essentially an inside out electronically commutated D.C. motor and can therefore be controlled in the same way as a conventional D.C. motor. Compared with a brushed DC motor or an Induction motor, the BLDC motor is characterized by higher efficiency and reliability, lower acoustic noise, smaller and lighter, greater dynamic response, better speed versus torque characteristics, higher speed range and longer life. Replacing the inefficient motors with more efficient BLDC motors will result in substantial energy savings. Electronic commutation is the major advantage of BLDC and it can be accomplished via various power converters. It is necessary to have a competitive power converter for BLDC drive. Basically BLDC motor is fed by a power converter called inverter circuit made up of different combination of switches. Typically the efficiency of BLDC motor also depends on power converter circuits. There exist two traditional power converter or inverter circuits, namely Voltage Source Inverter (VSI) and Current Source Inverters (CSI). VSI topology is used as it produces effective, low harmonic level output voltage. However, its usage towards an AC drive system is choice able as it bucks the output voltage.

Hence an Adjustable Speed Drive system suffers from following limitations[4].

- Inverter cannot yield a voltage greater than the DC bus voltage
- Increased complexity and cost.
- Requires boost converter.
- CSI is next to VSI from which a drive system can be fed.

Limitations of CSI are as follows

- Obtainable output voltage is greater than the DC input voltage.
- Vulnerable to EMI noise in terms of reliability.

To overcome the classic V-source and I-source inverters limitations, impedance (Z) source inverter which is a buck boost inverter can be engaged for any drive system[6]. On the way to different inverter topologies, predominant features of Multilevel inverter (MLI) also attract the drives. An overview of MLIs shows that they can generate output voltages with very low distortion and dv/dt, produce smaller common-mode voltage and operate with lower switching frequency compared to the more conventional two-level inverters[7]. They also include an array of power semiconductors and capacitor voltage sources, the output of which generate voltages with stepped waveforms. By increasing the number of levels in the inverter, the output voltages have more steps generating a staircase waveform which has a reduced harmonic distortion results in reduction of filter requirements. Great efforts are put towards reduction of Total Harmonic Distortion (THD) in MLI. It leads to proposing a Z- Source Multilevel Inverter (ZSMLI) topology for the BLDC drive system. ZS-MLI consists of active states and shoot through the states. By properly adjusting the shoot through the time period of pulses in ZSMLI, the DC voltage can be bucked or boosted. Moreover the proper selection of firing pulses can limit the THD in the output voltage.

A detailed evaluation of impedance source inverter, multi-level inverter and impedance based multilevel inverter fed BLDC motor

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is presented in the following sections with MATLAB/SIMULINK simulation assessment [12].

2. VSI fed BLDC Motor

The most common BLDC motor topology makes use of a stator structure consisting of three phases. BLDC motor drives necessitate a variable-frequency, variable-amplitude excitation that is typically delivered by a three-phase, full-bridge inverter which is shown in Figure. It is also identified as Voltage Source Inverter. The inverter is customarily responsible for both the electronic commutation and current regulation. The current in each coil surrogates from positive to negative during each electrical cycle. The stator is classically a salient pole structure which is designed to create a trapezoidal back-EMF wave shape.

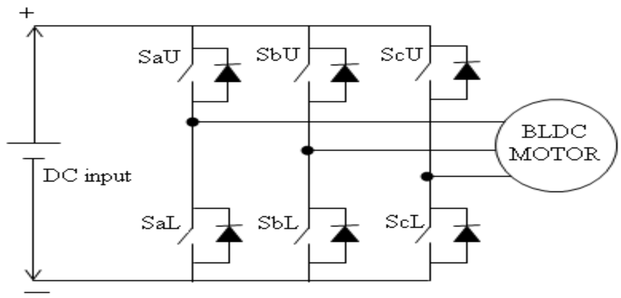

Fig. 1: VSI fed BLDC motor

In the 120˚ mode of operation, two phases are conducting current and the other is always floating without producing any torque during each and every conduction interval. All three phases of 180˚ commutation are expected to conduct current in all sectors, which results in more power delivered from the inverter side to the motor side of the same power supply voltage rather than the foremost mode. Based on the above switching sequences a BLDC motor can be operated under either 120 ˚ mode or 180˚ mode. By neglecting mutual inductance three phase BLDC motor equations can be written as [5]

$$\left.\begin{aligned} V_a &= I_aR + L\frac{dI_a}{dt} + ea \\ V_b &= I_bR + L\frac{dI_b}{dt} + eb \\ V_c &= I_cR + L\frac{dI_c}{dt} + ec \end{aligned}\right\} \quad (1)$$

Where V_a, V_b and V_c are the respective phase voltages of the winding. Ia, Ib and Ic are the respective phase currents of the winding

Stator self-inductances are $La = Lb = Lc = L$

Stator phase resistances are $Ra = Rb = Rc = R$

Generated back emf of 3 phases are ea, eb and ec

An emf known as back or counter emf is produced in each winding, when a BLDC rotates, which is responsible for producing constant torque. Depending on the erection of the rotor structure generated emf may be of sinusoidal or trapezoidal in nature.

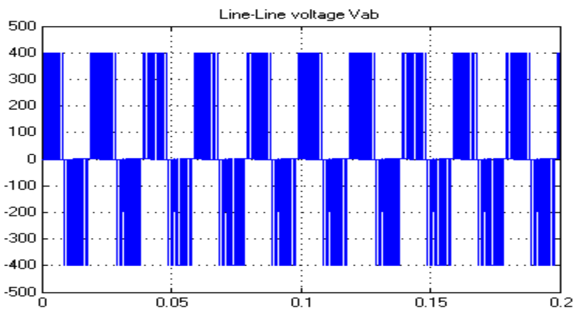

Fig. 2: Single phase output Voltage from VSI

The back emf is a function of rotor position (θ) and has the amplitude.

$$E = Ke\ \omega \quad (2)$$

Where ω is the rotor mechanical speed.

The equation of motion for simple system is,

$$J\frac{d\omega}{dt} + B\omega = T_e - T_l \quad (3)$$

Where, T_l is the load torque, B is damping constant, J is motor inertia.

Generated electromagnetic torque is given by

$$Te = \frac{eaIa + ebIb + ecIc}{\omega} \quad (4)$$

MATLAB Simulink Modeling of VSI fed BLDC motor is given as follows.

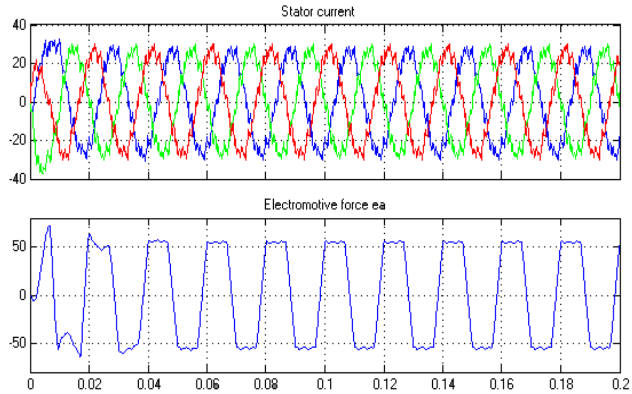

Fig. 3: Three phase stator current and Back EMF

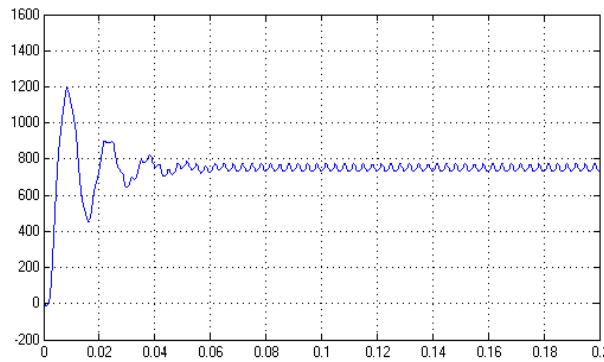

Fig. 4: Speed response of VSI fed BLDC Motor

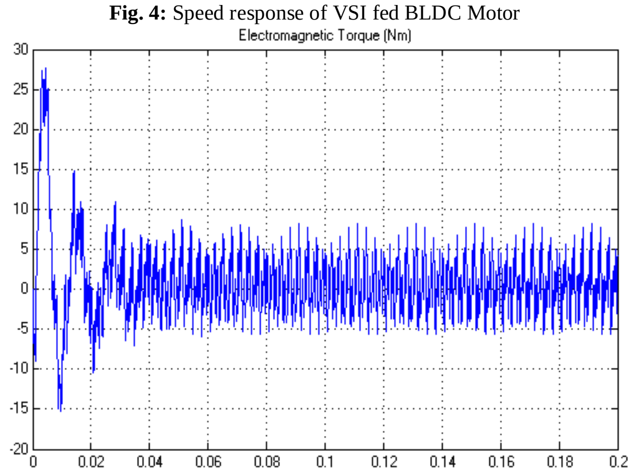

Fig. 5: Torque of VSI fed BLDC Motor

The above figures from 2 to 5 are the typical waveforms of output voltage of VSI, three hase BLDC motor stator current, torque and speed curves of VSI fed BLDC motor.

3. ZSI Fed BLDC Motor

ZSI is assembled with a unique impedance network, coupled between a power source and the inverter circuit, to provide both boost and buck-boost inverters properties, thereby overcomes the conceptual hurdles and limitations of the traditional voltage source and current source inverters. With the unique LC network, a shoot through the state is deliberately added to boost up the output voltage. The ZSI is an alternative to the existing topologies with many innate advantages. It composes of split inductors and capacitors connected in the X shape LC network between the input DC source and the traditional power converter topology. A diode is allied in series with the power source to block the reverse flow of current. A voltage type Z-source inverter can assume all active and null switching states of VSI. Unlike conventional VSI, a Z-source inverter has a distinctive feature of allowing both power switches of a phase leg to be turned ON concurrently (shoot-through state) without damaging the inverter. As a result, the new Z-source inverter by self-boosting transports the output voltage higher value as in a six-switches standard three-phase inverter. Therefore, it magnifies the motor operating speed range and condenses its torque ripple.
Normally traditional inverters have 8 vector states (6 active states and 2 zero or open states). But ZSI along with these 8 normal vectors has a supplementary state known as shoot through state, during which the 11switches of one leg are short circuited. In this state, the stored energy in the impedance network when the inverter is in its active state is transferred to the load, thus providing boost operation. Whereas, this shoot through state is banned in VSI [4].

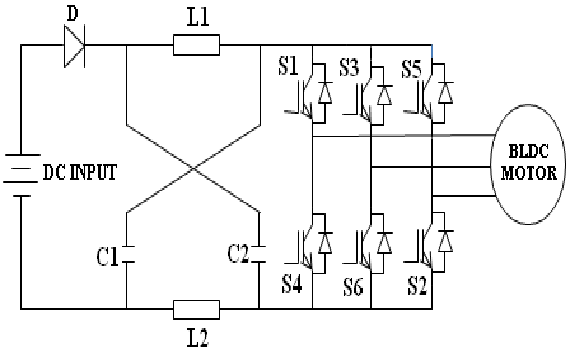

Fig. 6: ZSI fed BLDC motor

The ZSI can be operated under three following modes[4 and 10].

Mode I

The inverter bridge is operating in one of the six traditional active vectors; the equivalent circuit is as shown in following figure 7.

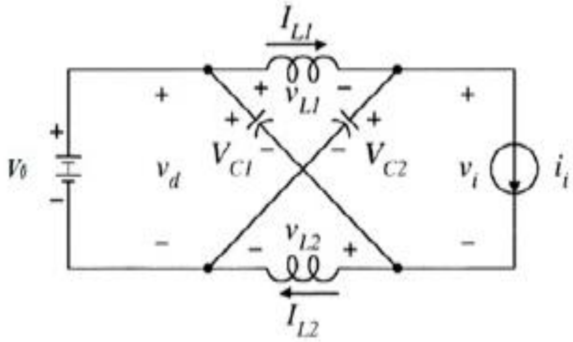

Fig. 7: ZSI in Active state

Mode II

The inverter bridge is operating in one of the two traditional zero vectors and shorting through either the upper or lower three devices, thus acting as an open circuit viewed from the Z-source circuit. Again, under this mode, the inductor carries current, which contributes to the line current's harmonic reduction as shown below.

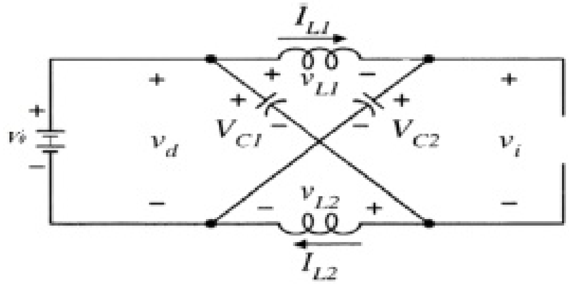

Fig. 8: ZSI in Null state

Mode III

The inverter bridge is operating in one of the seven shoot-through states. This shoot-through mode is used in every switching cycle during the traditional zero vector period generated
by the PWM control. Depending on how much a voltage boost is needed, the shoot-through interval (T0) or its duty cycle (T0/T) is determined. It can be seen that the shoot-through interval is only a fraction of the switching cycle.

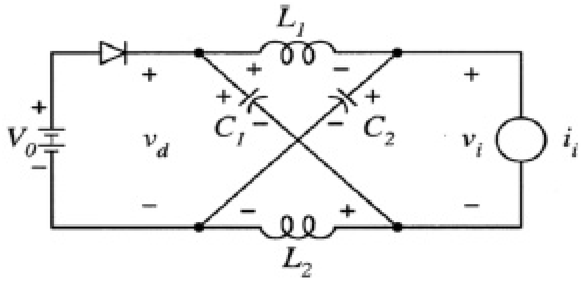

Fig. 9: ZSI in shoot through state

There are a number of control methods available to control Z-source inverter. It includes three types of PWM control algorithms: simple boost control (SBC), maximum boost control (MBC), constant boost control (CBC) [9 and 10]. SBC actually employs two polarity DC signal along with the conventional sinusoidal PWM technique carrier and reference signals. Pulses are generated when the reference signal has higher amplitude than the carrier. When the carrier signal has higher amplitude than the reference, then the carrier will be compared with either the positive DC or negative DC line. If the carrier amplitude is higher than the DC line, then the pulse will be generated.

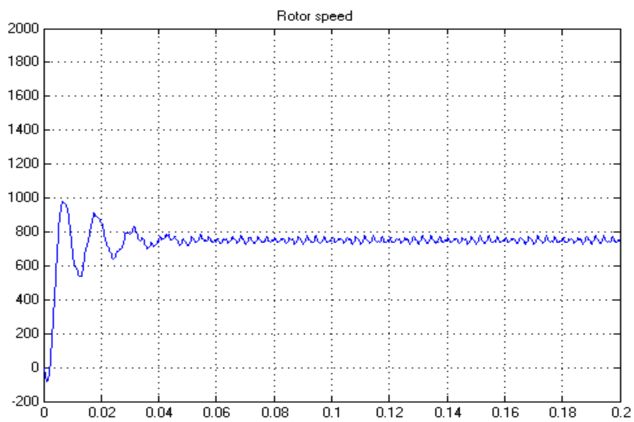

Fig. 10: Speed response of ZSI fed BLDC Motor

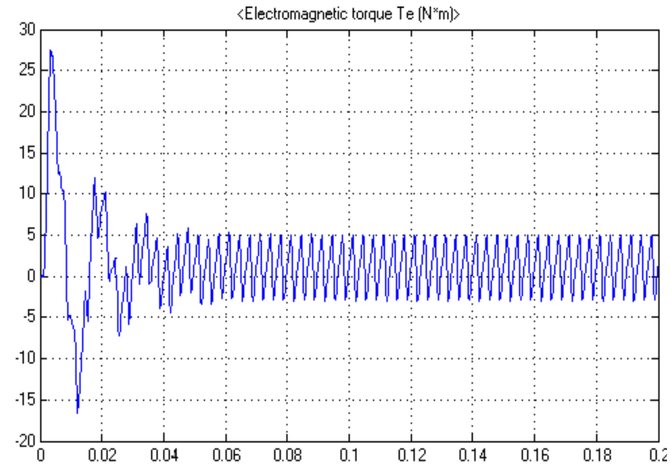

Fig. 11: Torque of ZSI fed BLDC Motor

MATLAB/SIMULINK Model of the ZSI fed BLDC motor and performance curves are presented above with the SBC pulse generation

4. Multilevel Inverter FED BLDC Motor

Conventional inverter is utilized mostly to generate AC voltage from DC voltage. This two level inverter can only produce two different output stages of $Vdc/2$ or $-Vdc/2$. However, it creates an output square wave whereas AC sinusoidal voltage is attained only via PWM switching techniques. Even though it suffers from harmonics, EMI and high dv/dt stress, these limitations pave a path for evaluation of Multi level inverter(MLI). A MLI does create an AC voltage with several voltage levels rather than only two levels[8]. The addition of several levels achieves a smoother stepped waveform with lower harmonic distortions and dv/dt stress. There are three most dynamically developed multilevel inverter topologies. Among them Cascaded inverter is proposed for BLDC drive which has less THD compared with other topologies [1]. The general structure of a single phase cascaded multilevel inverter circuit is shown in Figure 12. A special H-bridge circuit is incorporated with each separate voltage source $Vdc1, Vdc2, Vdc3$ in cascade. Four active switching elements constitute a single H-bridge. It ensures positive or negative polarity of output voltage or also can be simply zero volts which depend on the switching condition of switches in the circuit.

This multilevel inverter topology employs three voltage sources of equal magnitudes. It is fairly easy to generalize the number of distinct levels [3].

Table 1: Switching sequences for Single phase with 50 Hz output (for seven level output)

Switch	Duration (ms)							
	t1	t2	t3	t4	t5	t6	t7	t8
Sa1	1	0	0	1	1	0	0	1
Sa2	0	0	1	1	0	0	1	1
Sa3	1	1	0	0	0	0	1	1
Sa4	0	1	1	0	0	1	1	0
Sa5	0	0	1	1	0	0	1	1
Sa6	1	0	0	1	1	0	0	1
Sa7	1	0	0	1	1	0	0	1
Sa8	0	0	1	1	0	0	1	1
Sa9	1	1	0	0	0	0	1	1
Sa10	0	1	1	0	0	1	1	0
Sa11	0	0	1	1	0	0	1	1
Sa12	1	0	0	1	1	0	0	1

t1 to t2 = milli seconds

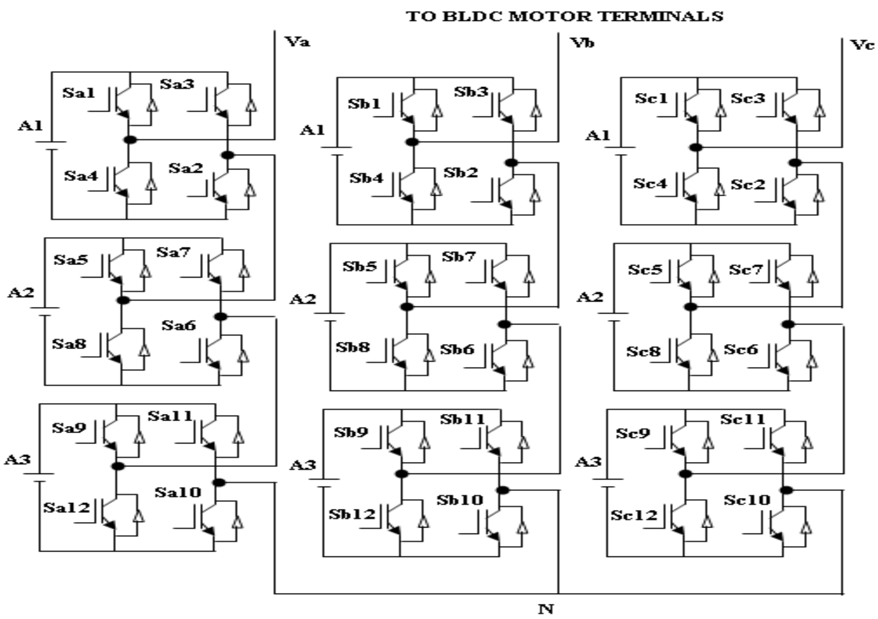

Fig. 12: Cascaded Multilevel inverter for BLDC motor

For an S number of sources or stages, the resulting number of output level will be

$$N_L = 2S + 1 \quad (10)$$

For three number of sources, the output waveform will have seven levels ($\pm 3Vdc, \pm 2Vdc, \pm 1Vdc$ and 0). The voltage amplitude level at each stage can be obtained by the equation,

$$A_L = LVdc \quad (11)$$

Where L is stage number

The number of controlled switches used in this topology is expressed as,

$$N_S = 4S \quad (12)$$

The output voltage of the multilevel inverter is given as,

$$V_{out} = A1 + A2 + A3 \quad (13)$$

Where A1, A2 and A3 are DC voltage sources [2].

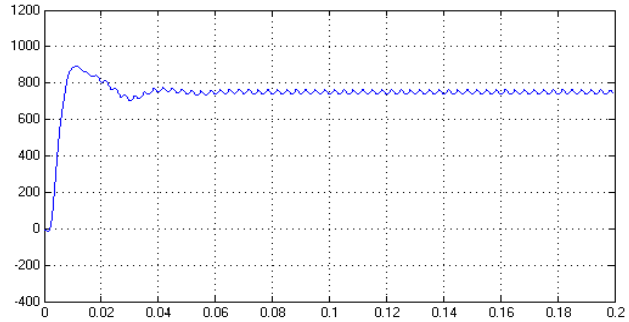

Fig. 13: Speed response curve of MLI fed BLDC motor

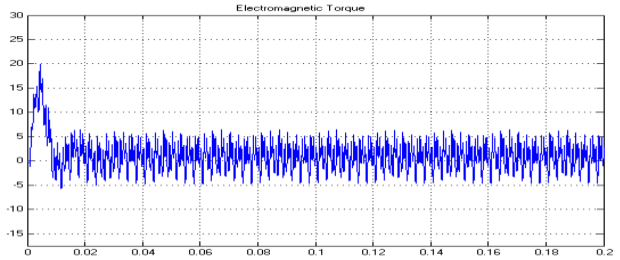

Fig. 14: Torque curve of MLI fed BLDC motor

Advantages of cascaded multilevel inverters are modularized layout and packaging. This enables the manufacturing process to be done more quickly and cheaply [2,13]. Figures from 12 to 14 presents the implementation of MLI fed BLDC motor and its performance analysis.

5. Z Source based Multilevel Inverter FED BLDC Motor

Advantages of MLIs include lower voltage stress, improved harmonic performance, low EMI and reduction in switching losses. Regardless of these rewards, multilevel inverters output voltage amplitude is suffering from multi DC sources. In certain circumstances, it is restricted to have numerous isolated DC buses; or in some industrial applications, economic considerations make the power system to be designed with just one DC bus.

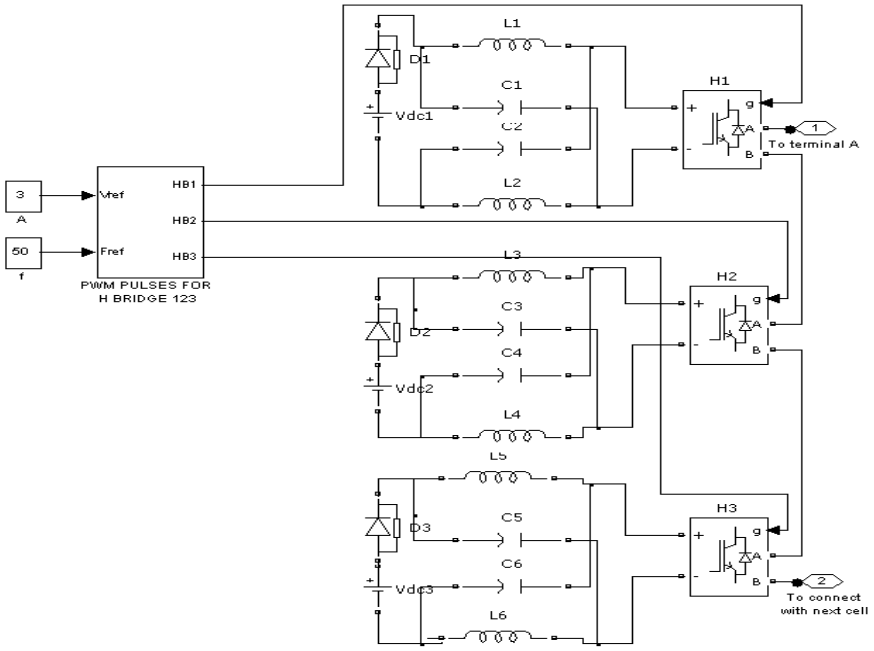

Fig. 15: Z source based MLI fed BLDC Motor

It demands a provision for buck or boost operation of MLI output voltage with the available DC bus. To resolve the mentioned limitations, Z-source based multilevel inverter is proposed for the BLDC drive [11].

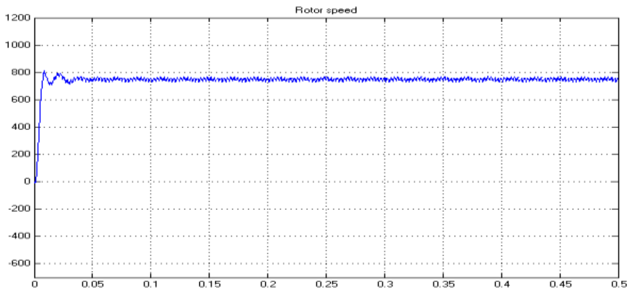

Fig. 16: Speed response curve of ZSMLI fed BLDC motor

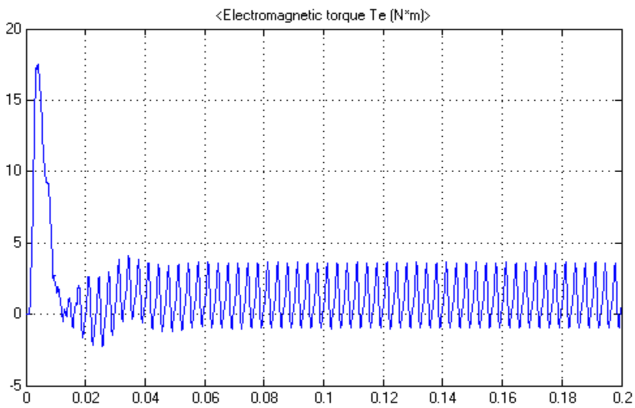

Fig. 17: Torque curve of ZSMLI fed BLDC motor

6. Results and Discussion

A motor drive must have adequate performance with regard to both dynamic and steady state operation response. Steady state response is concerned with the accuracy of control methods. A further consideration is the speed response of the system to rapid changes of control signal or load [12].

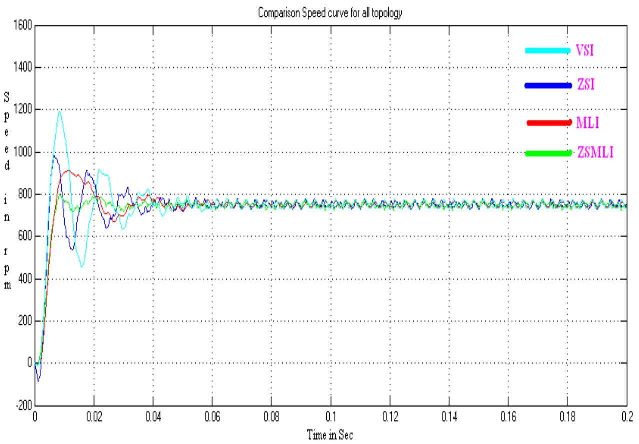

Fig. 18: Speed response curve of different topology fed BLDC motor

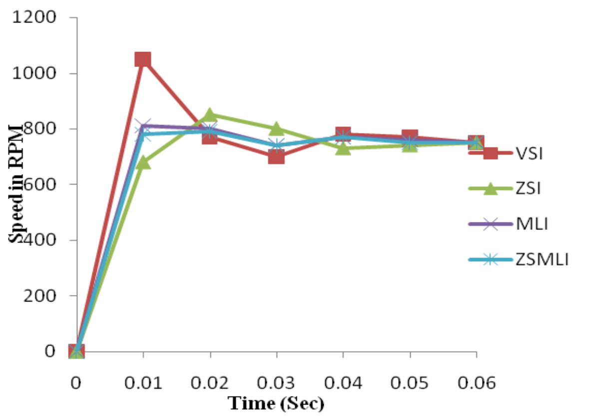

Fig. 19: Comparison of transient behavior between different topology fed BLDC motor

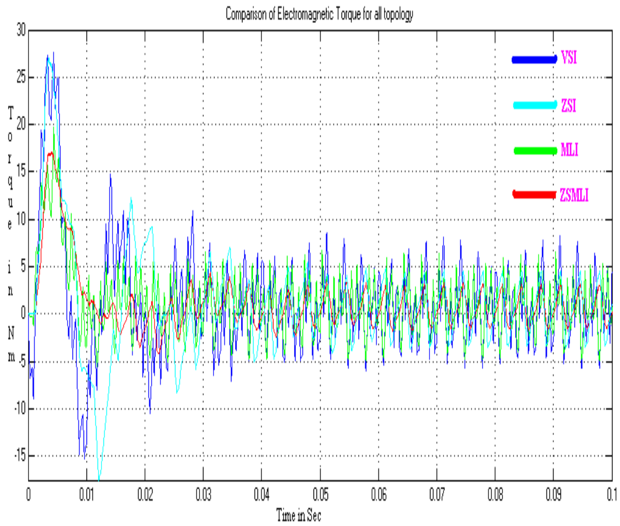

Fig. 20: Torque response curve of different topology fed BLDC motor

The above study on the impact of topologies shows that the dynamic response of ZSMLI fed BLDC is appreciable. It gives less overshoot and acceptable settling time compared to all other topologies. Moreover the same topology leads to reduction in torque ripple as the Figure 20 shows.

7. Conclusions

This paper aims to convey the impact of power converter topologies on the performance of BLDC drive. One of the typical inverter topology leads to restricted level of output, whereas insertion of impedance source inverter excludes the restriction by shoot through state. Usage of Multilevel inverter with the available range of DC voltage sources produces required amplitude. Addition of impedance network with the cascaded multilevel inverter results in a very competitive topology which improves the output voltage amplitude even with the available DC source. Thus Impedance Source based Multilevel Inverter becomes an encouraging topology for Brushless DC drive. Both dynamic and steady state operation of ZSMLI fed BLDC drive is evaluated by SIMULINK simulation results.

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