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Control Strategy for Symmetrical Multi Level Inverter Fed Modular BLDC Motor Drive using Low Frequency modulation Technique

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ABSTRACT: This paper presents a new design and implementation of a three-phase multilevel inverter (MLI) for modular brushless dc motor drive using low frequency modulation. The proposed MLI is also a modular type and it can be extended for extra number of output voltage levels by adding additional modular stages. The impact of the proposed topology is its proficiency to maximize the number of voltage levels using a reduced number of isolated dc voltage sources and electronic switches. . In this design, each permanent magnet BLDC motor is powered by a MLI and number of motors and MLI sets are stacked together in order to give the required power rating and to have good reliability The four quadrant operation of this design is also done in this paper to operate the motor clockwise and counter clockwise i.e., in motoring mode and regenerative braking mode. This is essential in saving the power as in the regenerative braking mode of operation; the power is fed back to the supply mains. The speed control of the drive system using Hall Effect sensor signals is also studied in this paper. moreover, the results are compared for both the cases i.e., MLI fed modular BLDC motor and single inverter fed BLDC motor, which shows there is a certain improvement in the emf and current waveforms.

KEYWORDS: modular BLDC motor drives, Modular Multilevel inverters, Hall Effect sensor signals, Low frequency modulation, sinusoidal pulse-width modulation (SPWM)

I. INTRODUCTION

Almost all the adjustable speed drives require three phase induction motors for their operation. If there is any fault in the machine under operation, or there is a need to extend or decrease the rating of the machine in terms of its operating voltage or power to be handled, the existing machine cannot be operated and the machine has to be replaced by a new machine with the required ratings. To overcome this, a new modular design construction is proposed which is the interconnection or group of such machines where the machines can be added or disconnected depending upon the rating of the loads. A four quadrant operation is necessary in utilizing the electricity effectively during regenerative braking mode of operation of a machine.

The motor modules are mounted on a common shaft and inverter modules are used to power each motor separately, thus independent drive units are formed with the combination of the motor and inverter. There are number of advantages achieved by modular design for both inverter and motor such as reducing the occurrence of faults, power rating scalability i.e., to increase or decrease the rating of the drive system simply adding or removing the inverter and motor modules which reduces the cost of the redesign and repairs can also be done easily by replacing the faulted module, without disturbing the unfaulted modules. Each set of stator coils are driven by each inverter separately and the permanent magnet motor id normally operated in Brushless DC motor mode.

Recently, multi-level inverters have obtained great attention as a single stage inverter. Although, they need high number of components, but due to their advantages such as generating output voltage with extremely low distortion factor, low dv/dt, small output filter size, low electromagnetic interface, and low total harmonic distortion, still have great attention. Practically, all of these advantages appear strongly as the number of dc-power sources increased as in the case of renewable energy systems. The general concept of is to utilize isolated dc sources or a bank of series capacitors to produce ac voltage waveforms with higher amplitude and near sinusoidal waveform. There are three conventional types of named as neutral point diode clamped [3], flying capacitor [5], and cascaded H-Bridge [6]. Almost all of them are suffering from increased components number per level, and complex control architecture [6].

Among the different topologies for MLIs, they can be classified into two main categories: 1) single dc-source inverter such as FC, and NPC inverters; 2) multi-dc sources inverters such as CHB inverter [7]. While, multi-dc sources inverter is divided into symmetrical and nonsymmetrical topologies.

If we integrate the concept of MLI for driving the modular BLDC motors instead of a single stage inverter, the above said advantages can be achieved. The MLIs can also be used in modular i.e., number of MLIs can be used in parallel, so that the harmonic content in each waveform can be reduced and the performance of the motor drives can be improved.

Section II describes about the configuration and design of Symmetrical Multi Level Inverter for BLDC Motor Drive. Section III explains about the Modulation Techniques for the Proposed MLI. Section IV is about the controller in which Hall Effect sensors, PWM Module and PI controller are briefly explained. Section V deals with the design of the proposed system using MATLAB/ SIMULINK and the results obtained from this designed circuit. Section VI gives the conclusion of the project and some of applications of this project.

II. SYMMETRICAL MULTI LEVEL INVERTER FOR BLDC MOTOR DRIVE

A true modular design with axial gap permanent magnet motors can be realized although a single rotor and multiple sets of stator windings can form a modular motor drive. In this design, a common shaft is used for all motor modules and every motor module has separate stator and rotor, as shown in the Fig 1. Separate MLIs are used to power each motor module, so that independent drive unit is formed. The common DC power can be shared by the MLI modules so that the cost reduces or the fault tolerance level can be increased by having a separate DC source. Required number of the stack of the inverter and motor modules can be used depending on the power requirement of the specific applications which leads to considerable savings in redesigning of the module for different applications. Even if there is any failure in any unit, the drive system is continue in operation but at reduced power. The information about the position of the rotor gives the controlling a PM motor properly and this information can be known by using Hall Effect sensors or optical encoders. Position sensorless schemes can also be employed in certain applications where the starting of the motor doesn't require the MLIs. If each drive unit is employed with its own position sensor, the reliability will be increased and if only one set of position sensors are used, the system is formed with less cost [4].

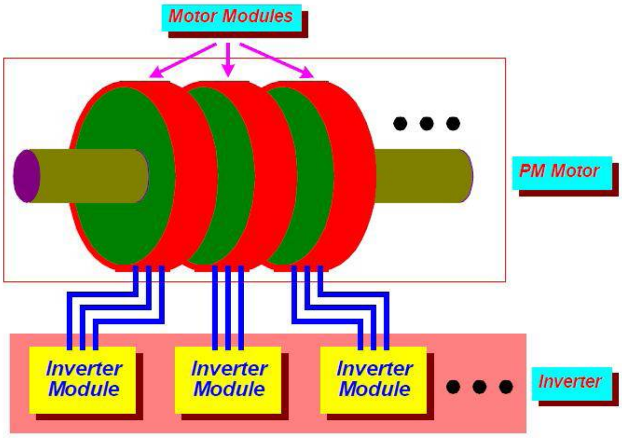

Fig 1: Modular MLI and modular motor drive system configuration

The permanent magnet motors are excited mainly two ways. First, the motor is given sinusoidal current which has a sinusoidal back emf, which is called driving the motor in synchronous ac mode. Second, the BLDC motors, which is very attractive for high power drive systems and is thus the choice for the traction motor drive. Three phase Permanent magnet motor with a trapezoidal back EMF excited by quasi square current waveforms is used for this purpose, which is given by three phase fully controlled converter. Inverter phase commutation is the simplicity of this approach. A voltage source inverter produces quasi square wave current waveform which is well matched to the flat top of the trapezoidal back EMF waveform, so that the cost of the drive system is going to be less. Requirement for accurate stator current commutation control is the disadvantage of the trapezoidal back EMF waveform. The torque developed in a PM motor with a trapezoidal back EMF is very sensitive to the relative phase of the quasi square wave currents imposed by the inverter with respect to the back EMFs. Pulsating torque can be developed in these drives because of a small phase error in commutation. Thus the information of the back emf should be accurate for proper commutation of stator currents with an inverter [6].

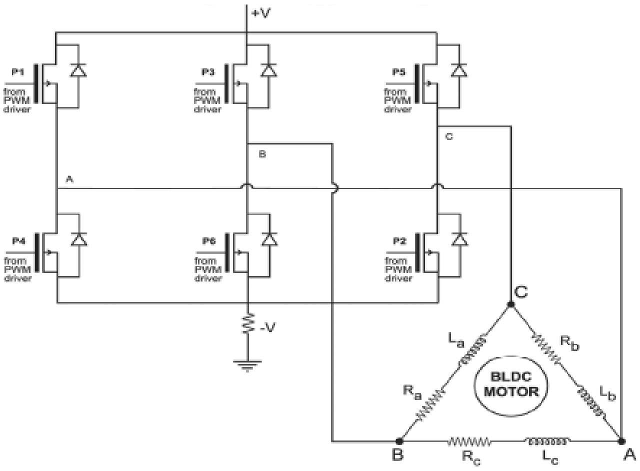

Fig 2: Equivalent Circuit of power stage of BLDC motor.

A new modular three phase MLI with reduced components count is proposed for driving the modular brushless DC motor drive system. The suggested three phase symmetrical inverter is shown in Fig3 (a). Each arm consists of series connection of DC battery with a series connected switch, for example arm A is consisting of one DC battery connected in series with switch Q_1. Adding the common dc voltage source (E) in to each arm forms the pole, creating the pole voltages (V_{A0}, V_{B0}, V_{C0}). In order to obtain the zero state pole voltage another switch Q_2 is added to the pole, similarly Q_4 and Q_6 for pole (B) and (C). Fig 3(b) shows the primary basic cell, where each cell consists of two switches S_1, S_2 and single dc voltage source. The two switches operate in a complementary fashion. Therefore, each cell can produce two voltage levels (0, E): when S_1 in ON-STATE, zero voltage is produced across the cell terminals, and when S_2 in ON-STATE, E volt is applied across the cell terminals. Furthermore, using only one cell per each pole and applying suitable control signals to the S_1 , S_2,Q_1 and Q_2 , three voltage levels per pole (i.e.,0,E ,2E) are produced. The output pole voltage for n cells connected in series configuration is shown in Fig.3(c).

TABLE I:
DIFFERENT SWITCHING STATES AND THE CORRESPONDING OUTPUT VOLTAGES

Switching States	Switch				Basic Unit Output Voltage	Pole Voltage(V_{A0})
	S_1	S_2	Q_1	Q_2		
1	ON	OFF	ON	OFF	0	E
2	OFF	ON	ON	OFF	E	2E
3	OFF	OFF	OFF	ON	-	0

Table I summarizes the different switching states and the corresponding output voltages for both the basic cell and the pole voltage (V_{A0}) of the proposed MLI topology.

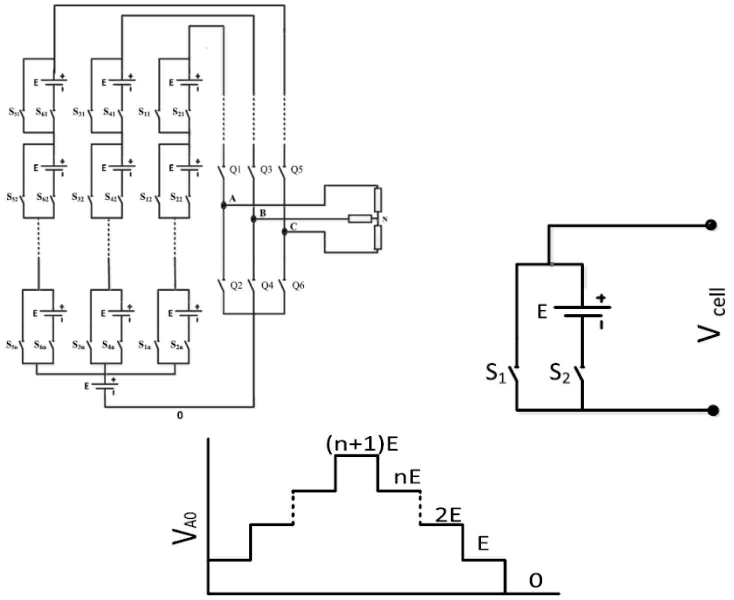

Fig 3(a) Generalized power circuit of the suggested three-phase symmetrical MLI (b) Basic cell (c) Pole voltage waveform V_{A0} for n--cell.

The proposed topology is a modular type therefore it can be extended to any levels. Equations (1)–(4) provide the relations of the proposed topology as

$N_{Pole} = N_{Cell} + 2$ (1)
$M_{Level} = 2N_{Cell} + 3$ (2)
$N_{SW} = 3(2N_{Cell} + 2)$ (3)
$N_{PS} = 3N_{Cell} + 1$ (4)

Then for the example of $N_{Cell} = 1$, $N_{Pole} = 3$ [based on (1)] which is the pole voltage levels and $M_{Level} = 5$ [based on (2)] which is the output line-to-line voltage levels. Note that the number of output phase voltage levels N_{ph} will be derived to be seven levels in low frequency modulation and nine levels for high frequency modulation.

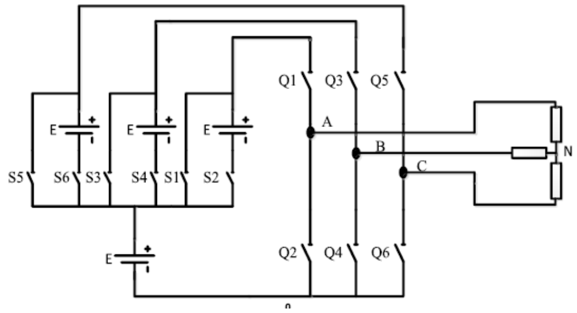

Fig 4: Proposed three-phase MLI topology.

III. MODULATION TECHNIQUES FOR THE PROPOSED MLI

The MLI modulation techniques are classified into two main groups according to the switching frequency used to drive inverter switches: 1) low frequency modulation technique, 2) pulse-width modulation (PWM) techniques that cover conventional PWM techniques, sinusoidal pulse-width modulation(SPWM) , space vector pulse-width modulation(SVPWM), sub-harmonic pulse-width modulation(SHPWM), and switching frequency optimal pulse-width modulation(SFO-PWM) [9]. In this paper, one modulation technique is investigated to achieve sinusoidal output voltages waveforms as described in the following.

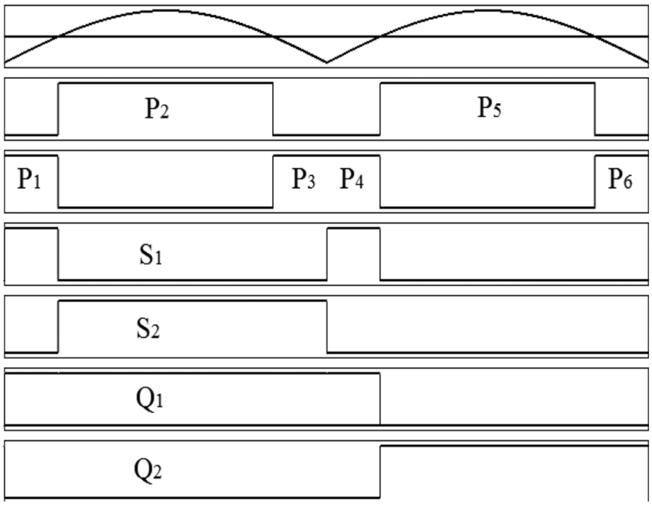

Fig5: Switching patterns for low frequency modulation technique.

Low Frequency Modulation Technique

The low frequency modulation is considered as the basic modulation technique due to its lower switching frequency than the other modulation methods. It causes the switching loses reduced dramatically [8]. In order to investigate the performance of the proposed MLI, three levels per pole by using single basic cell in each pole is used as shown in Fig. 2. It is simulated via PSIM and MATLAB/SIMULINK software packages. In order to generate the required switching signals for the proposed MLI , a rectified sine waveform has a frequency equals to the output voltage frequency (=50 Hz) is compared with a dc voltage signal has an amplitude equal to half of the sine wave amplitude as shown in Fig. 3. The intersection points between them identify six periods (P1 to P_6)[1].

Four switching signals are constructed from these periods combination in order to generate a sinusoidal output voltage. The control equations for the (S_1, S_2, Q1 and Q_2) are given in (6)–(9), respectively. The same scenario is applied to inverter poles (V_{B0}) and (V_{C0}) after shifting the basic sinusoidal voltage with -120^0, 120^0 respectively.
Therefore, the required switching signals for the overall three poles can be generated

$S_1 = P_1 + P_4$ (5)
$S_2 = P_2 + P_3$ (6)
$Q_1 = P_1 + P_2 + P_3 + P_4$ (7)
$Q_2 = P_5 + P_6$ (8)

Where (+) stands to logic OR.
Balancing three phase output voltage can be achieved by Operating the MLI according to switching states shown in Table III. The suggested MLI has 12 modes of operation per one cycle. It is essentially to note that: when switches Q_1, Q_3 , Q_5 and are in OFF-STATE, switches S_1 to S_6 have two possibilities for operation. Switches S_1 to S_6 may be in ON-STATE or at OFF-STATE. Both of them will not affect the output waveforms. However, keeping switches S_1 to S_6 in the OFF-STATE will reduce the overall voltage stresses on Q_1, Q_3 and Q_5[1].

TABLE II:
SWITCHING STATES OF THE PROPOSED TOPOLOGY (SWITCH ON: 1, S WITCH OFF: 0)

V_{AB}	V_{BC}	V_{CA}	S_1	S_2	Q_1	Q_2	S_3	S_4	Q_3	Q_4	S_5	S_6	Q_5	Q_6
E	-2E	E	1	0	1	0	0	0	0	1	0	1	1	0
2E	-2E	0	0	1	1	0	0	0	0	1	0	1	1	0
2E	-E	-E	0	1	1	0	0	0	0	1	1	0	1	0
2E	0	-2E	0	1	1	0	0	0	0	1	0	0	0	1
E	E	-2E	0	1	1	0	1	0	1	0	0	0	0	1
0	2E	-2E	0	1	1	0	0	1	1	0	0	0	0	1
-E	2E	-E	1	0	1	0	0	1	1	0	0	0	0	1
-2E	2E	0	0	0	0	1	0	1	1	0	0	0	0	1
-2E	E	E	0	0	0	1	0	1	1	0	1	0	1	0
-2E	0	2E	0	0	0	1	0	1	1	0	0	1	1	0
-E	-E	2E	0	0	0	1	1	0	1	0	0	1	1	0

IV. CONTROLLER FOR BLDC MOTOR DRIVE

Modeling of a controller is depicted in the Fig 5. The controller consists the Proportional and Integral (PI) controller, Hall Effect sensor signals, and the PWM module for the generation of the Gate signals to drive the controlled converter. The Hall Effect sensor signals are first decoded by the decoder and then the PWM module is used for the generation of the Gate pulses [2].

A. PI CONTROLLER

The regulation of speed is accomplished with PI Controller. By increasing the proportional gain of the speed controller, the controller's sensitivity is increased to have faster reaction for small speed regulation errors. This allows a better initial tracking of the speed reference by a faster reaction of the current reference issued by the speed controller. This increased sensitivity also reduces the speed overshooting. The armature current reduces faster, once the desired speed is achieved. An increase of the integral gain will allow the motor speed to catch up with the speed reference ramp a lot faster during sampling periods. This will indeed allow a faster reaction to small speed error integral terms that occur when a signal is regulated following a ramp. The controller will react in order to diminish the speed error integral a lot faster by producing a slightly higher accelerating torque when following an accelerating ramp. On the other hand, too high increase of the proportional and integral gains can cause instability, and the controller becoming insensitive. Too high gains may also result in saturation [2].

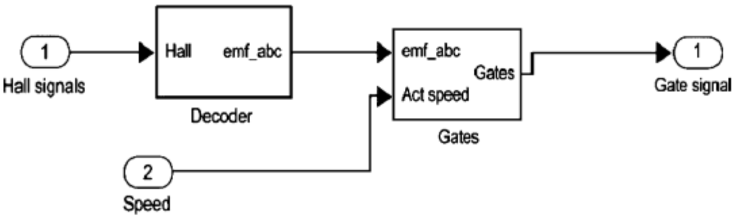

Fig 6: Modelling of Controller.

B. PWM MODULE

The PWM module simplifies the task of generating multiple synchronized Pulse Width Modulated (PWM) outputs. It has six PWM I/O pins with three duty cycle generators. The three PWM duty cycle registers are double buffered to allow glitchless updates of the PWM outputs. For each duty cycle, there is a duty cycle register that will be accessible by the user while the second duty cycle registers holds the actual compared value used in the present PWM period [2].

C. Hall Effect sensors

A Hall Effect sensor is a transducer that varies its output voltage in response to a magnetic field. Hall Effect sensors are used for proximity switching, positioning, speed detection, and current sensing applications.

In its simplest form, the sensor operates as an analog transducer, directly returning a voltage. With a known magnetic field, its distance from the Hall plate can be determined. Using groups of sensors, the relative position of the magnet can be deduced.

Frequently, a Hall sensor is combined with circuitry that allows the device to act in a digital (on/off) mode, and may be called a switch in this configuration. Commonly seen in industrial applications such as the pictured pneumatic cylinder, they are also used in consumer equipment; for example some computer printers use them to detect missing paper and open covers. When high reliability is required, they are used in keyboards.

Hall sensors are commonly used to time the speed of wheels and shafts, such as for internal combustion engine ignition timing, tachometers and anti-lock braking systems. They are used in brushless DC electric motors to detect the position of the permanent magnet. In the pictured wheel with two equally spaced magnets, the voltage from the sensor will peak twice for each revolution. This arrangement is commonly used to regulate the speed of disk drives [2].

V. SIMULATION AND RESULTS

Simulink Model of BLDC motor control using single inverter is shown in Fig 7 and the Simulink Model of BLDC motor control using MLI - low frequency modulation technique is shown in Fig 8.

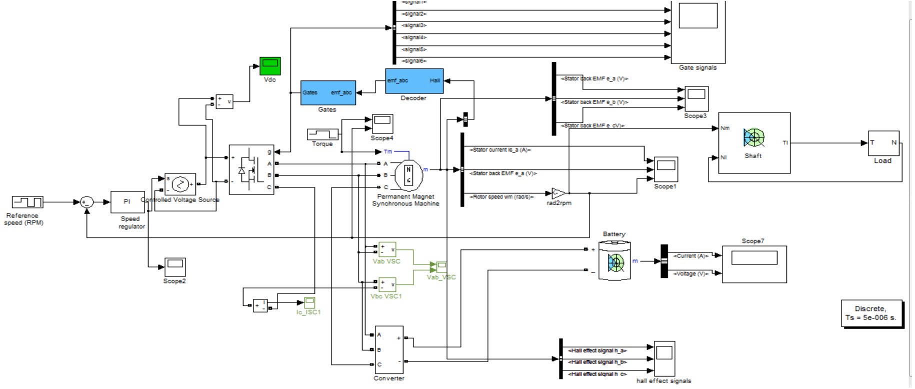

Fig 7: Simulink Model of BLDC motor control using single inverter

The main difference in the both is the number of inverters used in the first is only one where as in the proposed technology is two along with a pulse transformer which is going to give reduced harmonics in the input of the BLDC motor. The former uses the hall effect sensor controlling technique where as the later uses the low frequency modulation technique.

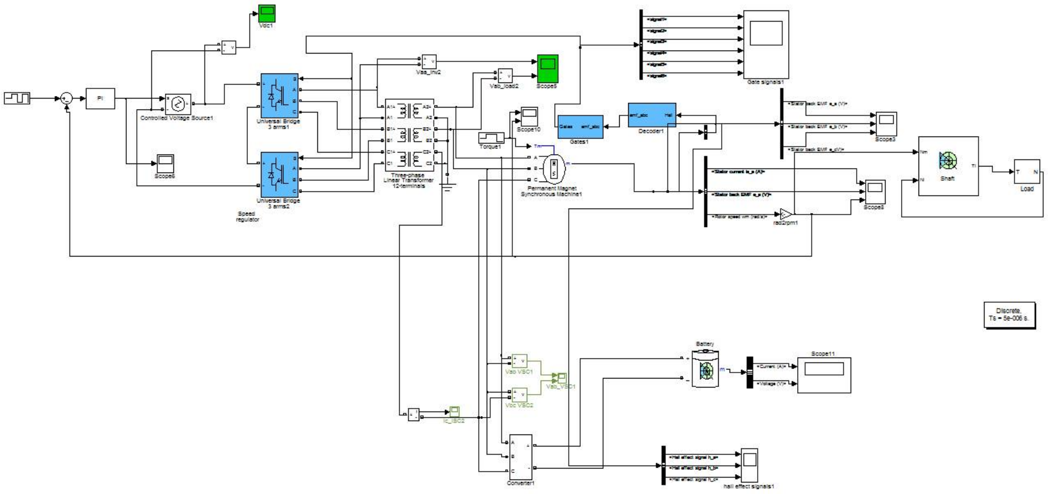

Fig 8: Simulink Model of BLDC motor control using MLI - low frequency modulation technique

The phase voltages of the two topologies are shown in the Fig 9 and Fig 10. The waveform with the MLI shows there is an improved phase voltage over the phase voltage with the single inverter.

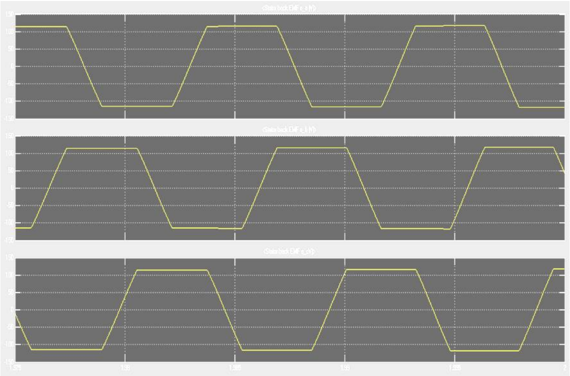

Fig 9: Phase voltages (V_{A0}, V_{B0}, V_{C0}) with single inverter

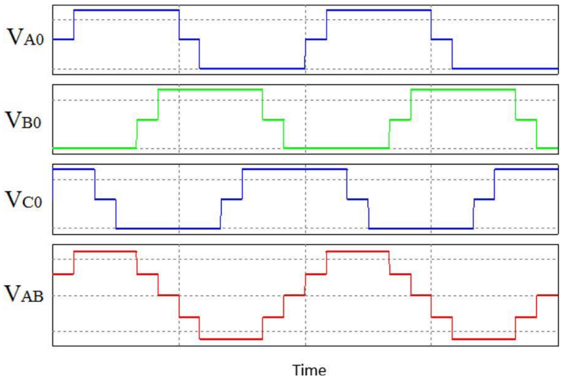

Fig 10: Phase voltages (V_{A0}, V_{B0}, V_{C0}) and line-to-line voltage (VAB) with MLI-low frequency modulation technique

The Fig 11 and Fig 12 shows the line voltages of the two topologies. We see that, there is an improved line voltage waveform with the MLI compared with the line voltage with the single inverter.

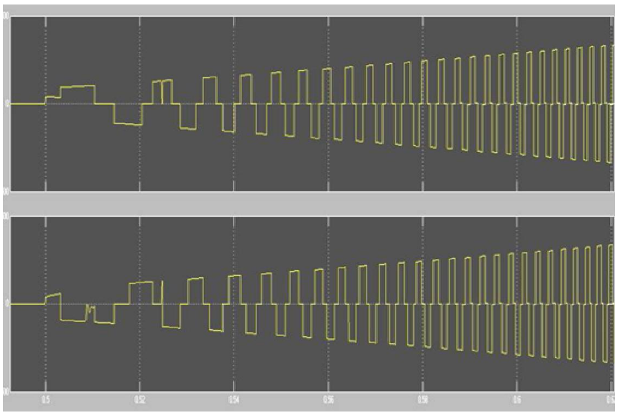

Fig 11: line-to-line voltage (V_{AB} and V_{BC}) with single inverter

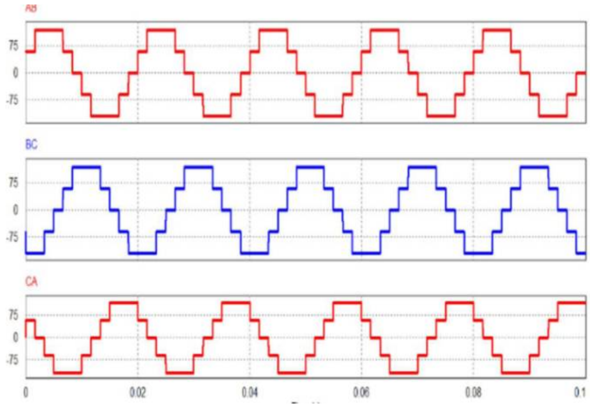

Fig 12: Output line-to-line voltages (V_{AB} , V_{BC} and V_{CA}) with MLI- low frequency (50 Hz) modulation technique.

VI. CONCLUSION

In this paper, we overcome the drawbacks of the BLDC motor supplied by single inverter to some extent and we have improved the performance of the motor with the BLDC motor supplied by a MLI. Although MLI technology have many components in its design, but presents an efficient control methodology over the former. We have attained the improvement in the electronic commutation with the MLI topology. The overall functioning of BLDC motor is thus improved and achieved the desired level. This is proved by the obtained results through MATLAB / SIMULINK.

The advantages of this proposed project is reliability of controlling techniques, superior performance in speed control, efficient conservation of energy on load and no load conditions, quicker and smooth transition from braking to motoring and vice-versa. The disadvantage of this model is arcing might occur when a proto type model is designed for higher rating motors, and if the motor rating is small, this is not a serious issue and hence, can be negligible.

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