IJCRT.ORG ISSN : 2320-2882

INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)

An International Open Access, Peer-reviewed, Refereed Journal

A Novel Regenerative Braking Control of BLDC Motor Driven Electric Vehicle

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Abstract: In this paper, a novel regenerative braking control strategy for Brushless DC (BLDC) motors in electric vehicles (EVs) is introduced. The proposed control approach is a fusion of diverse regenerative techniques and is compared across various BLDC motor regenerative braking control methods employing different performance metrics and switching techniques. The findings reveal that the plugging method results in a shorter stopping time, with a significant improvement when employing the proposed technique, along with enhanced energy recovery using different switching methods. Additionally, the study includes the simulation of a bidirectional inverter for multi-input scenarios. The effectiveness of the proposed method is validated using MATLAB/Simulation software.

Index Terms - Hybrid Electric Vehicle (HEV), Regenerative braking, Bidirectional Inverter, BLDC Motor, Electric Breaking.

I. Introduction

The role of automobiles in modern society is of paramount importance, and the Internal Combustion Engine (ICE) has represented a remarkable technological achievement, earning widespread recognition within the industry [1]-[3]. However, the rapid growth of the global automobile sector raises environmental concerns and puts pressure on fossil fuel resources [4]. Therefore, current research within the automotive field is focused on the development of an electric transportation system that can offer a clean, sustainable, and intelligent alternative, in the form of Electric Vehicles (EVs) and Hybrid Electric Vehicles (HEVs) [5]-[8]. EVs come with both advantages and disadvantages. Notably, since electricity is generated from fossil fuels, EVs outperform ICE vehicles in terms of both equivalent miles and the cost of driving per mile [9]-[11]. Nevertheless, electricity generated from renewable sources presents a lower environmental risk and is a more sustainable option [12]-[13]. Despite their benefits, battery-powered vehicles face challenges such as high initial costs, limited driving range, and extended charging times [14]. This has paved the way for HEVs, which utilize both traditional ICE and electric propulsion systems [15]-[17] .

Traditional mechanical braking has been used in vehicles since their inception, but it dissipates the kinetic energy of the wheels. Electric braking, when combined with hydraulic braking, proves to be an efficient strategy for stop-and-go driving in congested areas [18]-[22]. Two key methods plug braking and regenerative braking; have been employed in EVs and HEVs with electric traction motors. While plug braking is effective in terms of deceleration, it fails to recover kinetic energy during braking. Regenerative braking, on the other hand, autonomously stores power in the battery during the braking phase, enhancing energy conversion efficiency [23]-[26]. However, due to certain limitations, regenerative braking does not always deliver the expected braking force [27]. Subsequent sections of this paper provide a description of the proposed method in Section 2, present the results and engage in a discussion in Section 3, and conclude in Section 4.

II. PROPOSED SCHEME AND MODELLING

2.1 SINGLE STAGE ELECTRIC BRAKING METHODS

Utilizing a single-stage bidirectional DC/AC converter to drive the Brushless DC (BLDC) motor, the single-stage electrical braking technology effectively ensures both braking functionality and energy recovery [28]. As illustrated in Figure 1, the BLDC motor is powered by a single-stage bidirectional converter, with back electromotive forces (EMF) and armature currents denoted as Ea, Eb, Ec and Ia, Ib, Ic, respectively. The system includes switches S1-S6, freewheeling diodes D1-D6, and an intermediate circuit capacitor denoted as C. To achieve precise control, the inverter is adjusted based on rotor position data acquired from Hall sensors Ha, Hb, and Hc. Figure 2 further delineates the switching configurations and sequences that can be employed to implement various braking methods, including single switch, multi-switch, and plugging techniques.

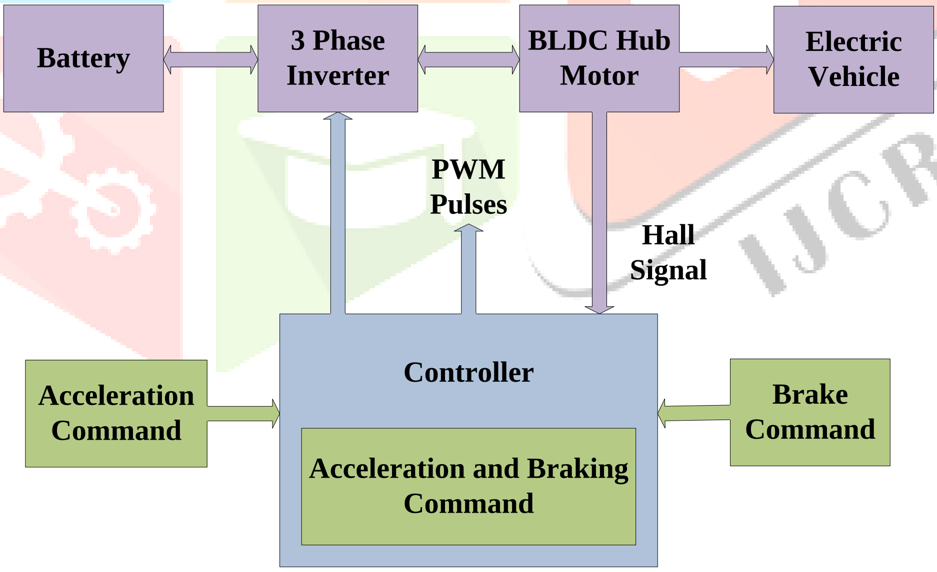

Figure 1. Block diagram for performance evaluation of various electric braking methods

In the commutation state during pulse width modulation (PWM) switching, only a single switch is activated among S2, S4, and S6, and in total, two switches from the set S1-S6 are used. In contrast, the three-switch method involves the simultaneous operation of all three switches, S2, S4, and S6, in PWM switching mode during each commutation state. The plugging switching sequence closely resembles the two-switch method, with the key distinction being the use of a continuous signal in place of PWM pulses.

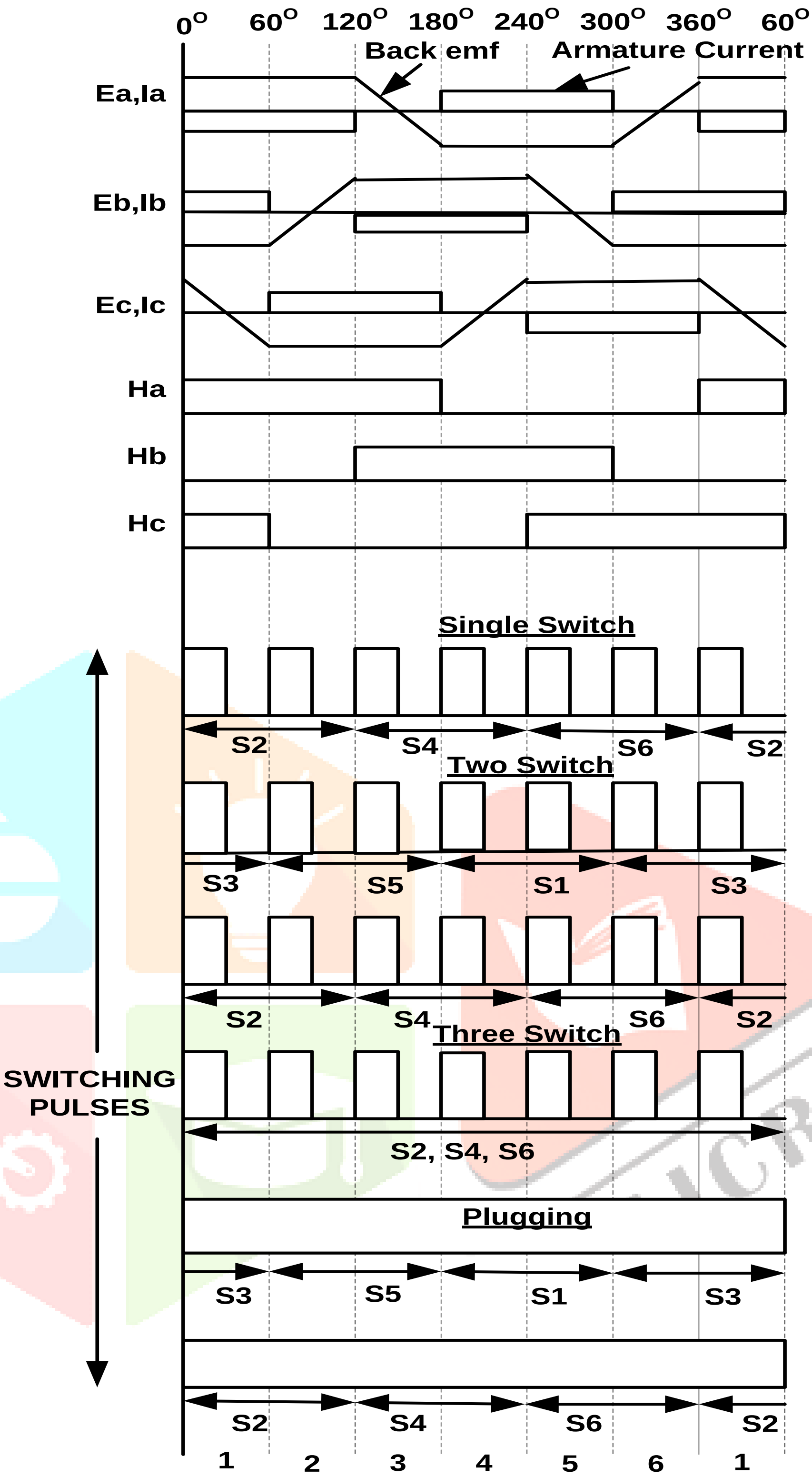

Figure 2. Sequencing of switching in conventional electric braking

2.2 MECHANISM USED

Following the assessment of various braking techniques in terms of their performance, a novel regenerative braking control strategy, emphasizing energy recuperation and deceleration (stopping time), has been introduced. The selection of switches for this braking method is determined by the position of the brake pedal, as illustrated in Figure 3. When the brake pedal is pressed in the range of 0 to 18, it follows a linear curve, resulting in an output voltage that varies between 0.85 V and 4.2 V.

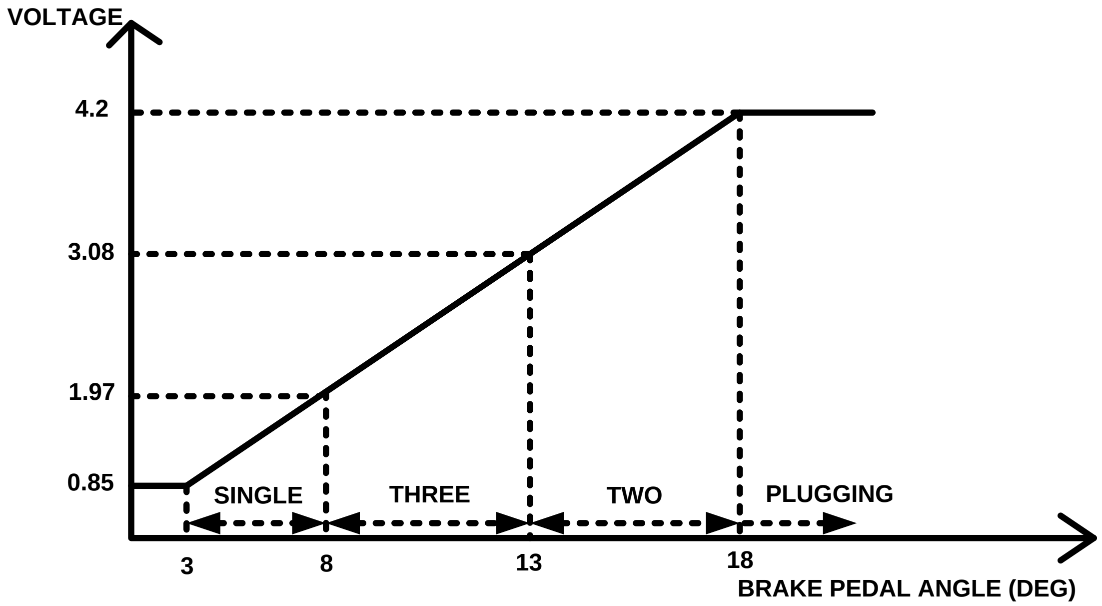

Figure 3. Characterstics of Brake Pedal Angle with respect to Voltage

2.3 ANALYSIS AND CONTROL OF A BIDIRECTIONAL INVERTER

For enabling dynamic regeneration and charging across a wide range of speeds, a bidirectional DC-AC power converter is a crucial component. When an acceleration command is initiated, the electric machine switches to motor mode [29]. To regulate the machine's output torque, a DC to AC converter alters the direction and magnitude of the armature current. During regenerative mode, such as deceleration or continuous charging, the dynamic energy from the vehicle is transferred to the battery or capacitance through the alternator and an AC to DC converter upon detecting the deceleration command. Figure 4 illustrates the circuit of two-stage DC-AC converters, which are commonly found in most Hybrid Electric Vehicles (HEVs) and Electric Vehicles (EVs).

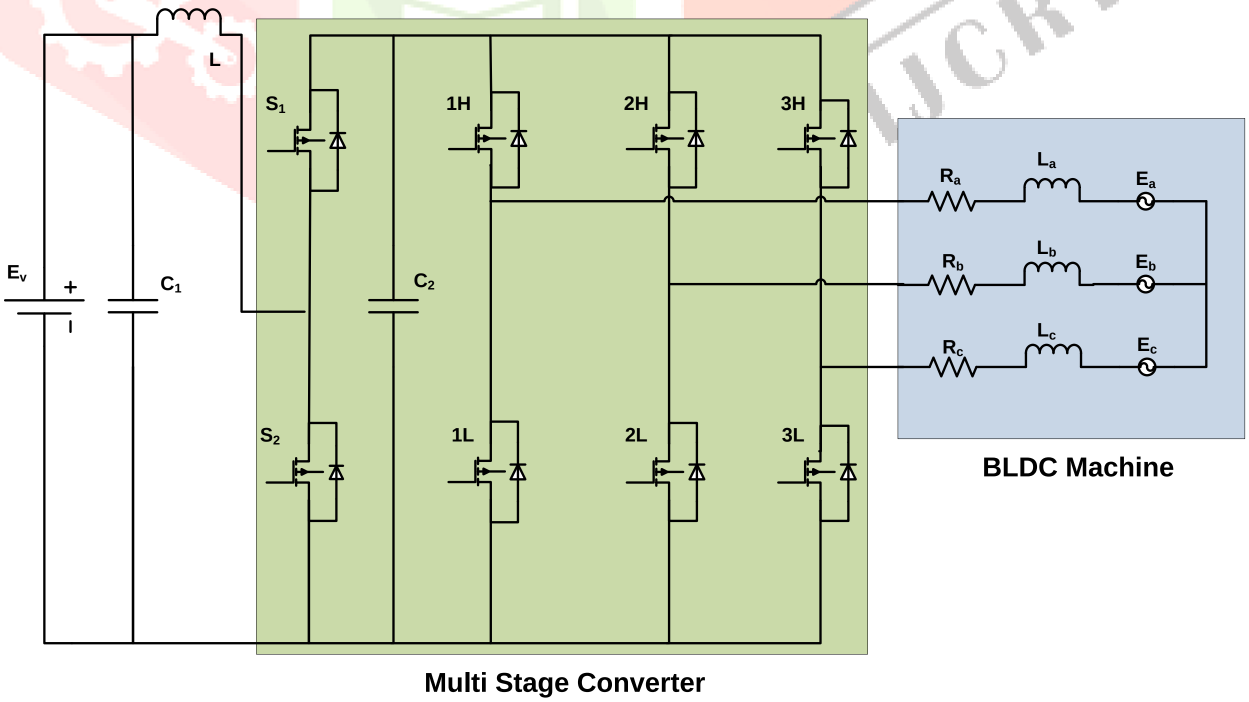

Figure 4. Two Stage Bidirectional Dc/Ac Converter With The Bldc Machine

2.4 SINGLE SWITCH OPERATED REGENERATIVE BRAKING

Figure 5 illustrates the phase relationship between the back electromotive force (EMF), the armature current of the Brushless DC Motor (BLDCM), and the switching signals within the bidirectional DC/AC converter. In this configuration, only one power switch is active during each commutation state. Utilizing the principle of volt-second balancing, it is observed that the net change in the equivalent inductor voltage (VL) over one electrical cycle is zero, as expressed by the equation (1):

$$\int_t^{t+T_s} V_L(\mathrm{t})\mathrm{dt} = \mathrm{DT_s}\left[2v_{emf} - i_a(2R)\right] + D'T_S\left[2v_{emf} - i_a(2R) - V_{dc}\right] = 0 \quad (1)$$

The variable 'T' denotes the switching period, 'Vemf' corresponds to the back EMF, and 'ia' represents the armature current. In a similar vein, by adhering to the concept of capacitor charge balancing, one can maintain equilibrium in capacitor charge.

$$\int_t^{t+T_s} i_{dc}(\mathrm{t})\mathrm{dt} = \mathrm{DT_s}\left(\frac{-V_{dc}}{R_b}\right) + D'T_S\left(i_a - \frac{V_{dc}}{R_b}\right) = 0 \quad (2)$$

$$i_a = 2\,\frac{V_{emf}}{D'^2R_b + 2R} \quad (3)$$

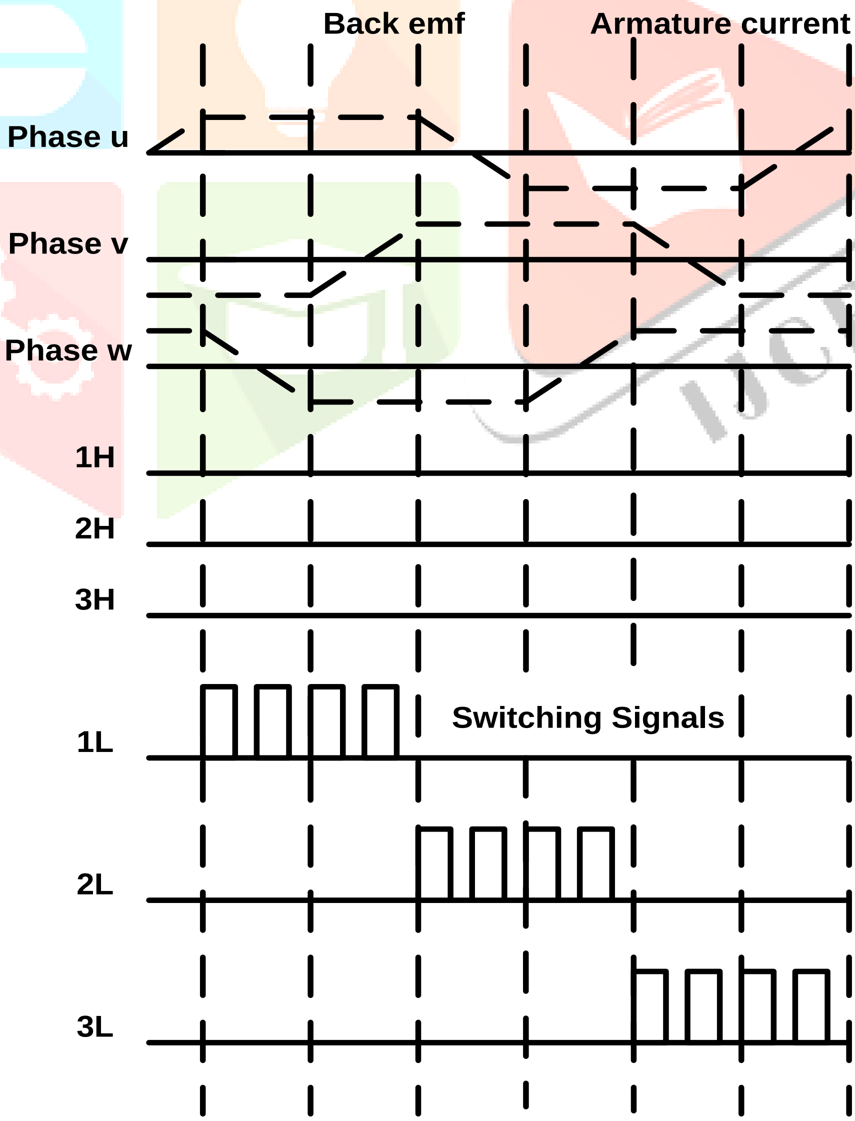

Figure 5. Single Switch Operated regenerative braking

Here, 'D' signifies the duty cycle, and the sum of 'D' and 'D' equals 1. When Equation (1) is substituted with Equation (2), it allows us to represent the charging voltage 'Vdc' in terms of 'D', the internal resistance 'R' of the armature, and the corresponding load resistance 'Rb,' as shown below:

$$\frac{V_{dc}}{V_{emf}} = 2\,\frac{1}{\left(D' + 2\frac{K}{D'}\right)} \tag{4}$$

The ratio of 'R' to 'Rb' is denoted by 'K'. To determine the optimal conversion ratio for the switching strategy, we can differentiate Equation (4) with respect to 'D' and equate the resulting expression to zero, yielding Equations (5) and (6).

$$\frac{dT(D')}{dD'} = 2\,\frac{(2K - D'^2)}{(D'^2 + 2K)} \tag{5}$$

$$T_{\max}\ (D') = \frac{2}{2\sqrt{2K}} = \frac{1}{\sqrt{2K}} \tag{6}$$

2.5 TWO SWITCHES OPERATED REGENERATIVE BRAKING

The recovery of a vehicle's maximum kinetic energy becomes a significant consideration when the vehicle is operating at relatively high speeds. Conversely, for low-speed operations, the issue of braking torque is of utmost importance [30]-[32]. Regenerative braking with two switches proves to be advantageous for low-speed operations. Figure 6 illustrates the phase relationship between the back electromotive force (EMF), the armature current of the BLDC motor, and the switching signals. For each commutation condition, Figure 6 provides an equivalent circuit. The charging voltage, the averaged armature current, and the maximum conversion ratio can be expressed in equations (7) to (8), using the same methodology as described in the preceding section in equation (9).

$$\frac{V_{batt}}{V_{emf}} = \frac{2}{(2D' - 1) + \left(\frac{2K}{2D' - 1}\right)} \tag{7}$$

$$i_a = \frac{2V_{emf}}{(2D' - 1)\ \ ^2R_b + 2R} \tag{8}$$

$$T_{max}(D') = \frac{2}{3\sqrt{K}} \tag{9}$$

Differing from the single-switch switching method, both the back electromotive force (EMF) and the battery voltage can be utilized to generate the armature current, leading to swift development of braking torque. The connection between the energy input (Wi) from the battery and the recovered energy (output energy, Wo) from the vehicle is characterized by Equation (10).

$$\frac{W_i}{W_c} = 1 + \frac{4\,.V_{emf}}{V_{batt} - 2\,V_{emf} - i_a 2\,R} \tag{10}$$

The principles of volt-second balancing, capacitor charge balance, as well as the determination of charging voltage, average armature current, and maximum conversion ratio can all be derived from equations (11) to (13).

$$\frac{V_{dc}}{V_{emf}} = \frac{2}{\left(D' + \frac{7K}{4D'}\right)} \tag{11}$$

$$i_a = \frac{2V_{emf}}{\left(D'^2 R_b + \frac{7R}{4}\right)} \tag{12}$$

Table 1 provides an overview of the primary features of the three regenerative braking switching methods designed for the standard inverter. Given the machine's speed and specific parameters, one can utilize the voltage ratio equation to assess the potential for kinetic energy recovery. Additionally, by considering that the induced torque is directly proportional to the armature current, the braking torque can be computed using the armature current equation.

TBALE 1 COMPARISION OF DIFFERENT SWITCHING TECHNIQUES FOR VARIOUS LIGHT ELECTRIC VEHICLES.

PARAMETERS	SINGLE SWITCH	TWO SWITCHES	THREE SWITCHES
NUMBER OF SWITCHES	1	2	3
INFORMATION OF POSTION	Required	Required	Not Required
BOOST RATIO	$2\frac{1}{\left(D' + 2\frac{K}{D'}\right)}$	$\frac{2}{(2D' - 1) + \left(\frac{2K}{2D' - 1}\right)}$	$\frac{2}{\left(D' + \frac{7K}{4D'}\right)}$
BRAKING TORQUE	$2\frac{V_{emf}K_t}{D'^2R_b + 2R}$	$\frac{2V_{emf}K_t}{(2D' - 1)R_b + 2R}$	$\frac{2V_{emf}K_t}{\left(D'^2R_b + \frac{7R}{4}\right)}$
TMAX =K	0.5	0.44	0.57

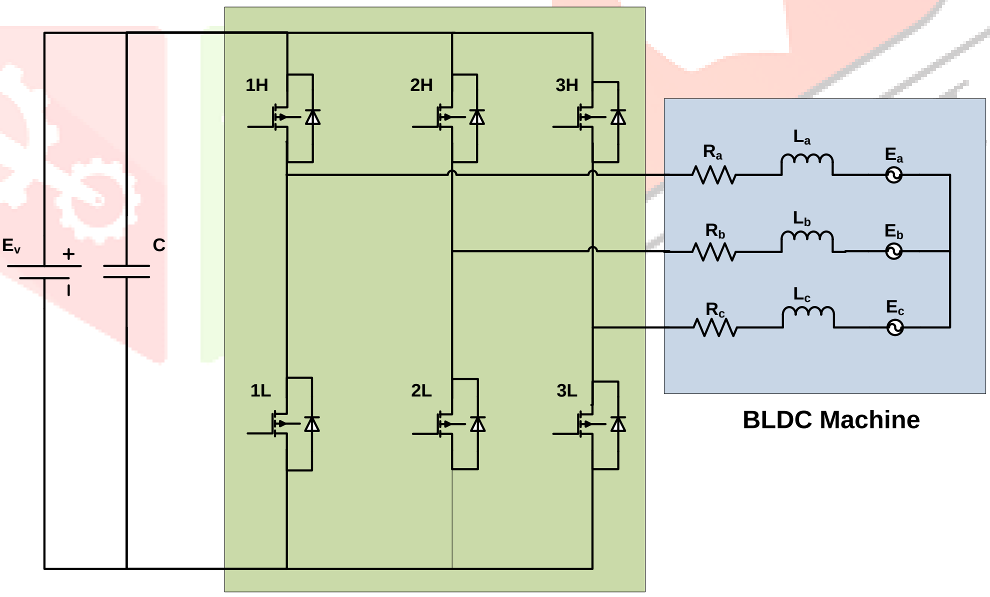

Figure 6. Single Stage Bidirectional Dc/Ac Converter with BLDC Machine

2.6 ANALYSIS AND OPERATING PRINCIPLE OF THE ENERGY-REGENERATION

In this work, Brushless DC (BLDC) motors characterized by sinusoidal back electromotive forces (EMF) have been employed. Figure 7 illustrates the equivalent circuit, in which 'L' and 'R' denote the armature inductance and resistance, respectively. Furthermore, the back EMFs of the armature are denoted as 'ea,' 'eb,' and 'ec,' while the armature current for phases 'a,' 'b,' and 'c' is represented as 'ia,' 'ib,' and 'ic,' respectively. The switching sequences governing the energy-regenerative modes for BLDC motors are depicted in Figure 2. Line-to-line armature back EMFs are characterized as 'eab,' 'ebc,' and 'eca,' and the commutation signals are denoted as 'H1-H3,' while the six power switches are indicated as 'S1-S6.'
During normal mode, the high side switches, namely 'S1,' 'S3,' and 'S5,' operate in pulse width modulation (PWM) switching mode, while the low side switches 'S2,' 'S4,' and 'S6' operate in a standard high or low configuration. In contrast, during the energy-regenerative mode, all of the switches are engaged in PWM switching mode.

III. Results and Discussion

This is the waveform of stator back emf of the BLDC motor used in the diagram in Figure 7. The waveforms come out to be sinusoidal in nature ultimately in steady state. It has transient time of 0.02 seconds.

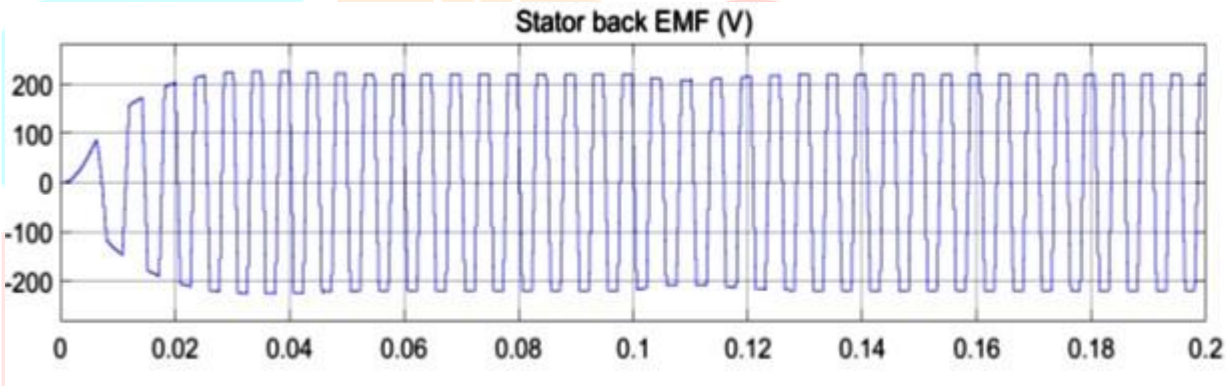

Figure 7. Stator Back Emf of BLDC Motor

This is the waveform of stator current in figure 8. While starting a large amount of current is required and hence the motor operates as shown in the waveform i.e. large current at the starting time. This waveform has a transient duration of 0.1 sec and then this waveform reaches its steady state.

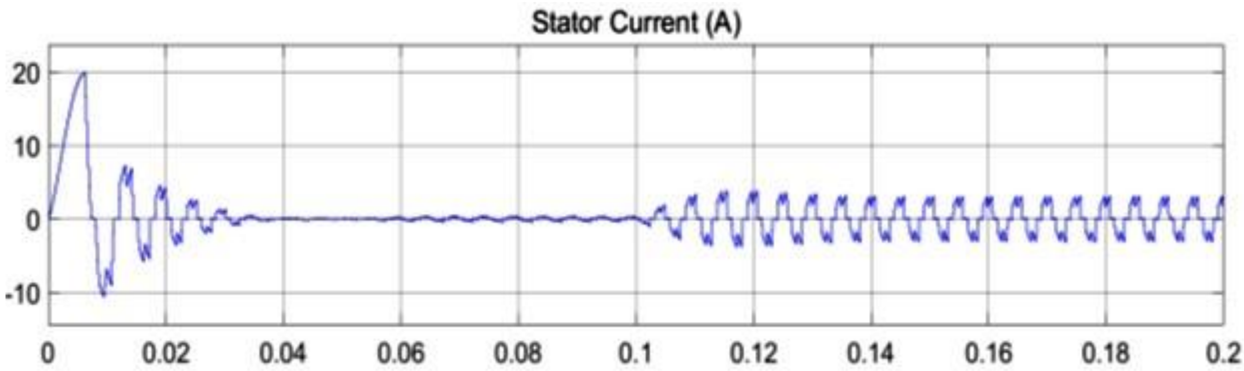

Figure 8. Stator Current of BLDC Motor

This waveform shows the speed of the rotor which has reached 3000 rpm at the steady state as given in figure 9. Since we know that the motor is starting its speed starts increasing from0 rpm and reaches 3000 rpm finally. After being accelerated to a certain point, the motor starts maintaining a high constant speed. At this condition no stress is there on the system as no sudden dynamics is introduced. Here the motor speed is maintained constant at a speed of 3000 rpm. Hence, we see that a high constant speed operation is obtained which is represented in figure 10.

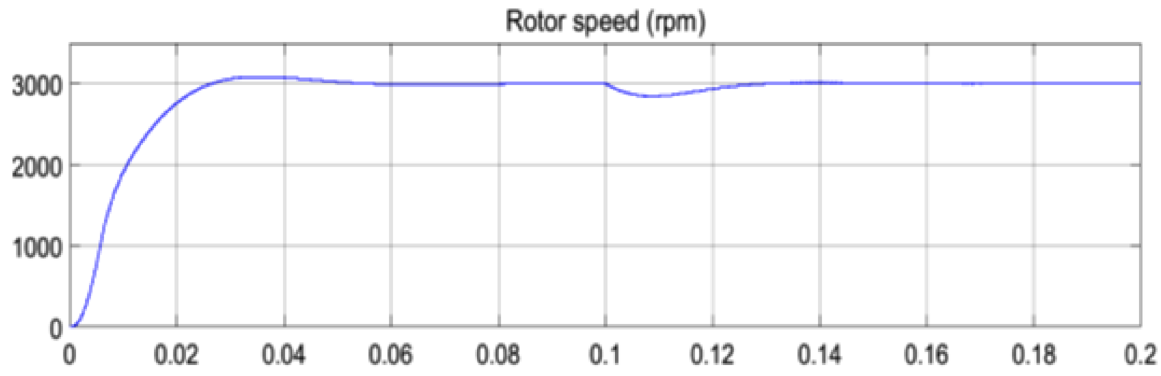

Figure 9. Rotor Speed of BLDC Motor

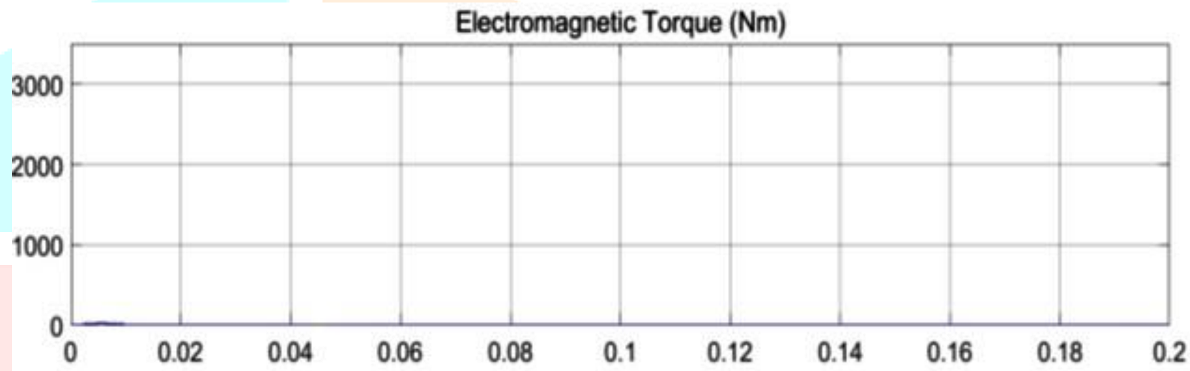

Figure 10. Electromagnetic Torque of BLDC Motor

It is the waveform of output of inverter which is sinusoidal in nature i.e. AC. It has some spikes as it is not pure AC which can be seen in below waveform given in figure 11.

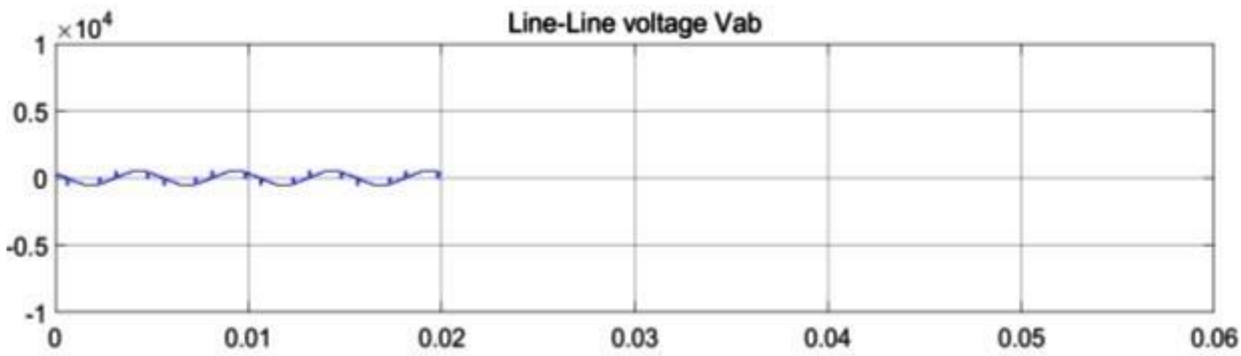

Figure 11. Inverter Line Voltage

This is the input of the inverter which is DC in nature. This is given as the input to the inverter given in figure 12.

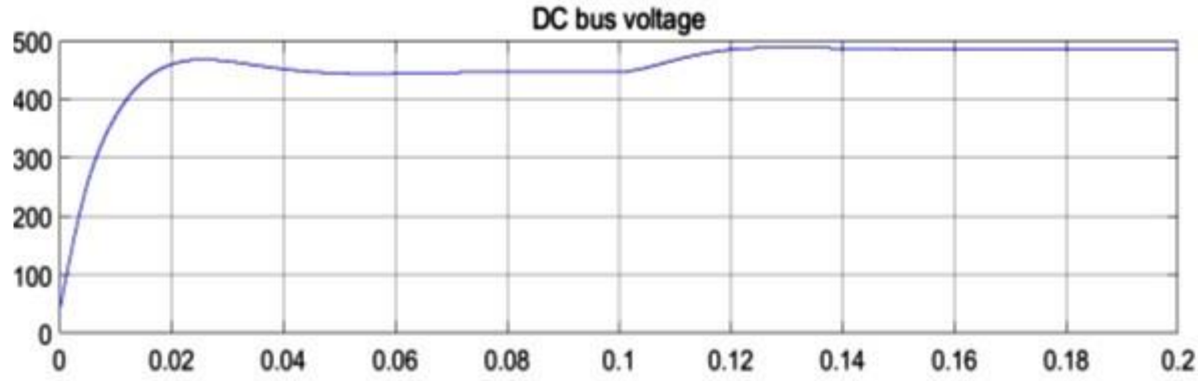

Figure 12. Inverter DC Bus Voltage

IV. Conclusion

The present situation of resources available clearly shows that they will be exhausted quite eventually. As a matter of fact, renewable power resources have been the only option. Electric motors are often used to propel electric vehicles rather than combustion engines. Numerous motors, such as Permanent magnet synchronous motor, SRM, and BLDC motors, can also be used to propel the vehicle, and besides BLDC motors are more commonly used due to some of the advantages including high efficiency, high power density, and massive starting torque, ease of operation, lighter weight, and compact structure.

Mechanical braking on its own wastes' energy, so regenerative braking has been commonly used, that saves a lot of energy while also increasing the range of an electric vehicle. Such a regenerative braking can also be accomplished in a variety of ways, including the use of a dc/dc converter, an electronic gearshift mechanism, and an ultra-capacitor, each of which has advantages and disadvantages. As a result, a single stage converter with controllable switching is often used to obtain regenerative braking in EVs. Alternative techniques of regenerative braking in EVs, such as using one, two, or three switches, are proposed and applied there in model, and also the BLDC motor is controlled.

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