A Modular Converter Topology Fed Brushless DC Motor Drive for Electric Vehicle Applications

Muzeeb Khan Patan, M.Serabanda

***Abstract*— Numerous advantages of a BLDC motor over a brushed DC motor are absence of the mechanical commutators which allows higher speeds, therefore it is easier to dissipate heat in the BLDC and reduce audible and electromagnetic noise. Having individual converters has advantages like more flexible individual control and simpler design but does not encourage functionality merging. The proposed integrated circuit allows the permanent magnet based drive is opted to operate in motor mode or acts as boost inductors of the boost converter, and thereby boosting the output torque coupled to the same transmission system or dc-link voltage of the inverter connected to the output of the integrated circuit. Motor control algorithm for a dual power split system is proposed for hybrid electric vehicles (HEV). The proposed control technique is to use interleaved control to significantly reduce the current ripple and thereby reducing the losses and thermal stress under heavy-load condition. In order to evaluate performance of the control algorithm, HEV simulator is developed using MATLAB/ Simulink. Finally proposed converter fed BLDC drive with closed loop operation is presented. Matlab/Simulink model is developed and simulation results are presented.**

***Index Terms*— BLDC drive, Hybrid Electric Vehicles (HEV), Boost Converter, Electric Vehicles (EV), Internal Combustion Engine (ICE)**

I. INTRODUCTION

Now-a-Days, Brushless DC (BLDC) motors are one of the electrical drives that are rapidly gaining popularity, due to their high efficiency, good dynamic response and low maintenance and are widely used in many motor applications developing high torque with good speed response. BLDC motors finds its applications in numerous fields like Aerospace, home appliances, defense systems, electronic gadgets etc. In order to obtain these power electronics converters have become an indispensable part of many power-management systems. Recently, because of increasing oil prices and environmental concerns, hybrid electric vehicles (HEVs) and electric vehicles (EVs) are gaining increased attention due to their higher efficiencies and lower emissions associated with the development of improved power electronics and motor technologies. High reliability, high efficiency, and power density are key factors for electric propulsion of electric and hybrid electric vehicles. Hybrid Electric Vehicle (HEV) is an emerging technology in the modern world because of the fact that it mitigates environmental pollutions and at the same time increases fuel efficiency of the vehicles. Recently, developments in power electronics and semiconductor technology have lead improvements in power electronic systems. Pulse Width Modulation variable speed drives are increasingly applied in many new industrial applications that require superior performance. Hence, different circuit configurations namely multilevel inverters have become popular and considerable interest by researcher are given on them.

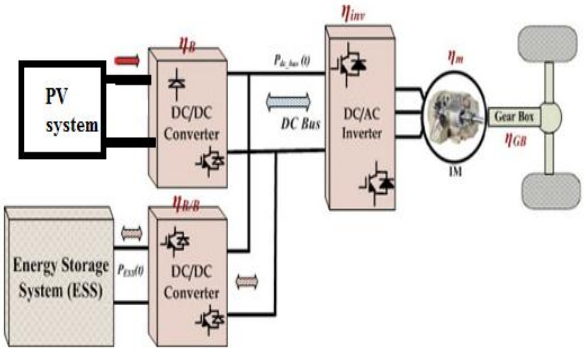

Fig.1 Block diagram of HEV

Variable voltage and frequency supply to A.C drives is invariably obtained from a three-phase voltage source inverter. Hybrid Electric Vehicle (HEV) is an emerging technology in the modern world because of the fact that it mitigates environmental pollutions and at the same time increases fuel efficiency of the vehicles. In vehicular applications, power electronic dc/dc converters require high power bidirectional flow capability with wide input range since the terminal voltage of energy storage devices varies with the state of charge and load variations. Power electronic inverters are widely used in various industrial drive applications.

To overcome the problems of the limited voltage and current ratings of power semiconductors devices, some kinds of series and/or parallel connections are necessary and have several merits such as energy consumption, better system efficiency, improved quality of product, good maintenance, and so on. Many commercial hybrid electric vehicle (HEV) systems use a traditional bidirectional dc-dc converter to interface the battery and the inverter dc bus. There is growing interest in electric vehicle (EV) and hybrid electric vehicle (HEV) technologies because of their reduced fuel usage and greenhouse emissions [1]–[3]. PHEVs have the advantage of a long driving range since fuel provides a secondary resource. Connection to the electric power grid allows opportunities such as ancillary services, reactive power support, tracking the output of renewable energy sources, and load balance. For purposes of this paper, plug-in vehicles will be lumped together with EVs. Most EV charging can take place at home over night in a garage where the EV can be plugged in to a

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convenience outlet for Level 1 (slow) charging. Level 2 charging is typically described as the primary method for both private and public facilities and requires a 240 V outlet.

An electric vehicle is an emission free, environmental friendly vehicle. However, the electric vehicles remain unpopular among the consumers due to their lack of performance and their inability to travel long distances without being recharged. So, vehicle that embraces both the performance characteristics of the conventional automobile and the zero-emission characteristics of the electric vehicles are greatly being anticipated by the general consumers and the environmentalists alike. Technically, the quest for higher fuel economy is shaped by two major factors: how efficiently a power train converts fuel energy into useful power, and how sleek a vehicle is in terms of mass, streamlining, tire resistance, and auxiliary loads. On the other hand, vehicle functionality and comfort are shaped by various other factors, many of which run counter to higher fuel economy. Examples abound, from the way torque converter sacrifices efficiency to provide better shift smoothness and responsiveness to the wide variety of features that add mass to a vehicle.

II. HEV CONFIGURATIONS

A brief description about various HEV configurations available in the market is presented. The three main configurations are the series, parallel and the dual-mode configurations and the explanation of each one of them with their merits and demerits follows.

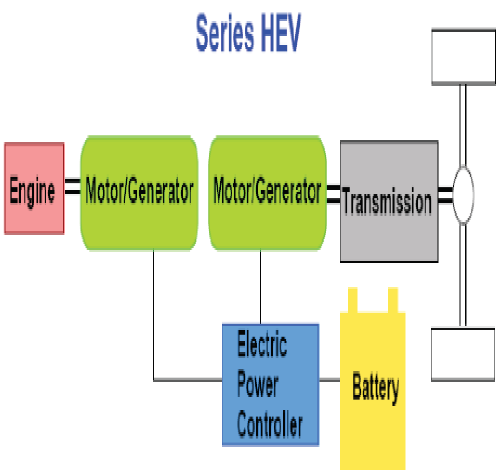

Fig.2 Series HEV drive train

In series HEV configuration, only the electric motor is connected to the drive train and thus the vehicle is entirely driven by the electric motor. The Internal Combustion (IC) engine drives an electric generator (commonly known as alternator), which then supplies the electric power to the motor and battery pack. The IC engine will turn off if the battery is fully charged. In some cases, the electric power supply for the electric motor can come both from the battery and the engine generator set. As only the electric motor is connected to the drive train, the IC engine can run at an optimum speed to run the generator thus greatly reducing the emissions. The batteries can either be charged off-board, by external DC power link from the electric-grid, or on-board, with the help of an alternator and an IC engine. In this setup, it is possible to design the operation such that the IC engine never idles and thus the overall emissions are reduced. The schematics of series HEV is shown in Figure 2.

It can be seen that the IC engine is connected to the alternator (generator) which in turn is connected to the battery pack and electric motor through an electronic control unit. This scheme allows the electric motor to get its power from either battery pack or the alternator or both as per the battery state of charge and vehicle acceleration requirements [4-6].

B. Parallel HEV Configuration

In the parallel HEV configuration there are two power paths for the drive train, while one comes from the engine the other comes from the electric motor. During short trips the electric motor can power the vehicle, while during long drives the IC engine can power the vehicle. The vehicle can thus have engine only, motor only, or a combination of engine and motor mode of operation. The electric motor can also assist the engine during hill climbs and vehicle accelerations, thus the rating of the IC engine can be reduced. This configuration is illustrated in Figure 3.

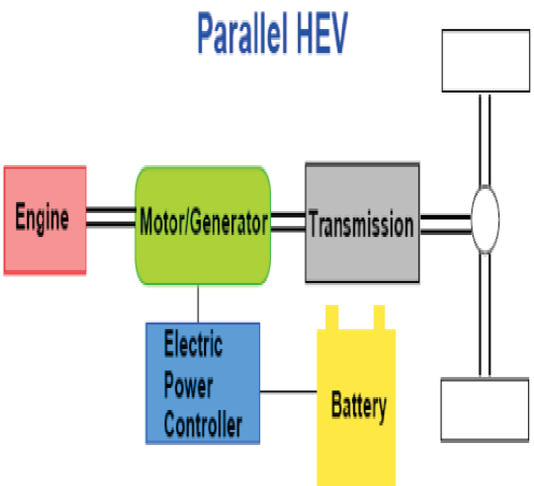

Fig.3 Parallel HEV drive train

In parallel HEV configuration, the drive train is connected to the electric motor and engine through a mechanical coupling or an angle gear. These vehicles do not require a generator (as in the case of series HEV configuration) and they can be connected to an electric grid (off-board) for recharging the batteries. The electric motor can be made to act as generator via a mechanical clutch which can then be used for regenerative braking. Both the gas-powered engine and the electric motor can turn the transmission simultaneously, and the transmission, of course, turns the wheels. The fuel tank and gas engine and the batteries and electric motor connect independently to the transmission—as a result, in a parallel hybrid; both the electric motor and the gas engine can provide power.

III. PROPOSED INTEGRATED CIRCUIT AND CONTROL TECHNIQUE

A. Proposed Integrated Inverter/Converter Circuit

In Fig. 4, *C*in and *C*out can stabilize the voltage when input and output voltages are disturbed by source and load, respectively. Diode (*D*) is used for preventing output voltage impact on the input side. When the integrated circuit is operated in inverter (motor) mode, relay will be turned ON and six power devices are controlled by pulse width modulation (PWM) control signals

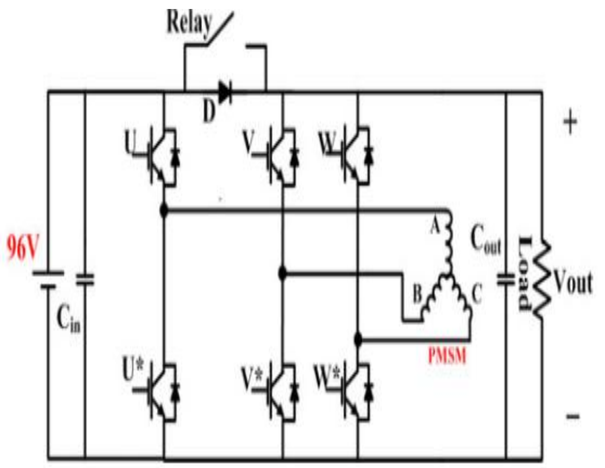

Fig. 4 shows the integrated circuit for dual-mode control

When the proposed integrated circuit is operated in the converter mode, relay is turned OFF. And a single-phase or interleaved control method will be applied to control of the power devices depending upon the load conditions.

B. Modeling and Controller Design under Boost Mode

This section will introduce the model of boost converter and derive the transfer function of the voltage controller. Fig.5 shows the non ideal equivalent circuit of the boost converter, it considers non ideal condition of components: inductor winding resistance *RL*, collector-emitter saturation voltage *V*CE, diode forward voltage drop *VD* , and equivalent series resistance of capacitor *R*esr .

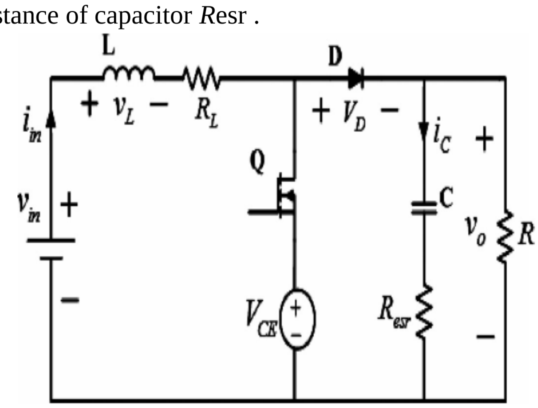

Fig.5 Equivalent circuit of the boost converter

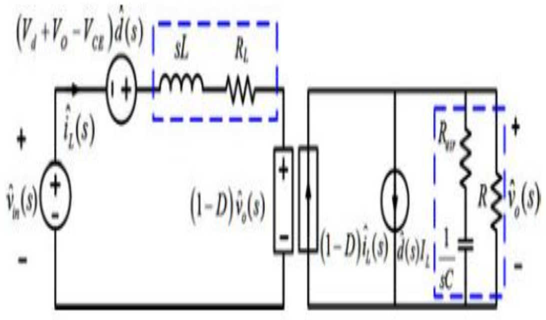

Fig.6 Small-signal equivalent circuit

Analysis of the boost converter by using the state-space averaging method [4], small-signal ac equivalent circuit can be derived, as shown in Fig. 6.

$$G_{vd}(s) = \frac{-6.737 \times 10^{-5} s^2 + 0.06827s + 2498}{2.004 \times 10^{-5} s^2 + 0.00409s + 3.242} \quad (1)$$

Fig. 7 shows the block diagram of voltage loop, using a proportional-integral (PI) controller for the compensator. In this paper, the switching frequency is 20 kHz and voltage loop bandwidth will be less than 2 kHz. And the phase margin should be more than 45◦ to enhance the noise immunity. For the designed controller shown in (2), proposed converter interfaced to induction machine through inverter topology.

$$C(s) = \frac{0.0248387s + 13.073}{s} \quad (2)$$

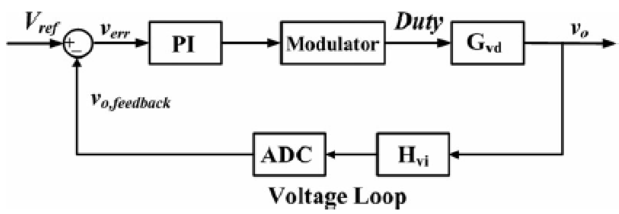

Fig.7 Block diagram of voltage loop

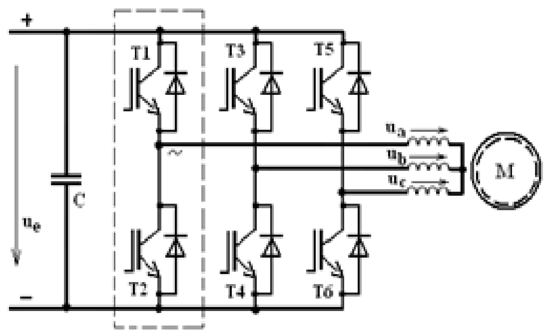

Fig.8 Proposed Converter Applied to BLDC Drive System

The BLDC motor is an AC synchronous motor with permanent magnets on the rotor (moving part) and windings on the stator (fix part). Permanent magnets create the rotor flux. The energized stator windings create electromagnet poles. The rotor (equivalent to a bar magnet) is attracted by the energized stator phase, generating a rotation. By using the appropriate sequence to supply the stator phases, a rotating field on the stator is created and maintained. This action of the rotor - chasing after the electromagnet poles on the stator - is the fundamental action used in synchronous permanent magnet motors. The lead between the rotor and the rotating field must be controlled to produce torque. This synchronization implies knowledge of the rotor position.

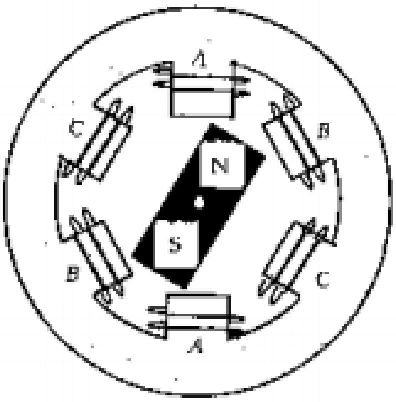

Fig.9: A 3-Phase Synchronous Motor with a Single Permanent Magnet Pair Pole Rotor

On the stator side, three phase motors are the most common. These offer a good compromise between precise control and the number of power electronic devices required to control the stator currents. For the rotor, a greater number of poles usually create a greater torque for the same level of current. On the other hand, by adding more magnets, a point is reached where, because of the space needed between magnets [17], the torque no longer increases. The manufacturing cost also increases with the number of poles. As a consequence, the number of poles is a compromise between cost, torque and volume.

The BLDC Motor Control:

The key to effective torque and speed control of a BLDC motor is based on relatively simple torque and Back EMF equations, which are similar to those of the DC motor [18],[19]. The Back EMF magnitude can be written as:

$$E = 2NlrB\omega$$

And the torque term as

$$T = \left(\frac{1}{2}i^2\frac{dL}{d\theta}\right) - \left(\frac{1}{2}B^2\frac{dR}{d\theta}\right) + \left(\frac{4N}{\pi}Brl\pi i\right)$$

Where N is the number of winding turns per phase, l is the length of the rotor, r is the internal radius of the rotor, B is the rotor magnet flux density, ω is the motor's angular velocity, i is the phase current, L is the phase inductance, θ is the rotor position, R is the phase resistance.

IV. SIMULATION RESULTS

Here the simulation carried by two different cases they are 1) Proposed interleaved boost converter multiplier module 2) Proposed converter with interleaved boost converter Applied to BLDC Drive.

Case-1Proposed interleaved boost converter

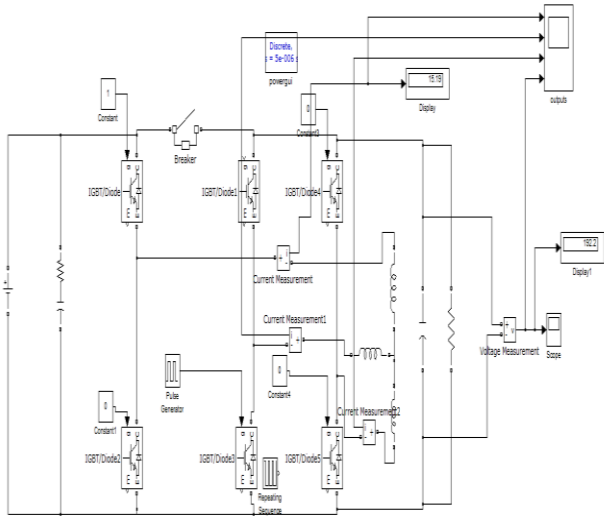

Fig.10 Matlab/simulink model of the integrated circuit and controller

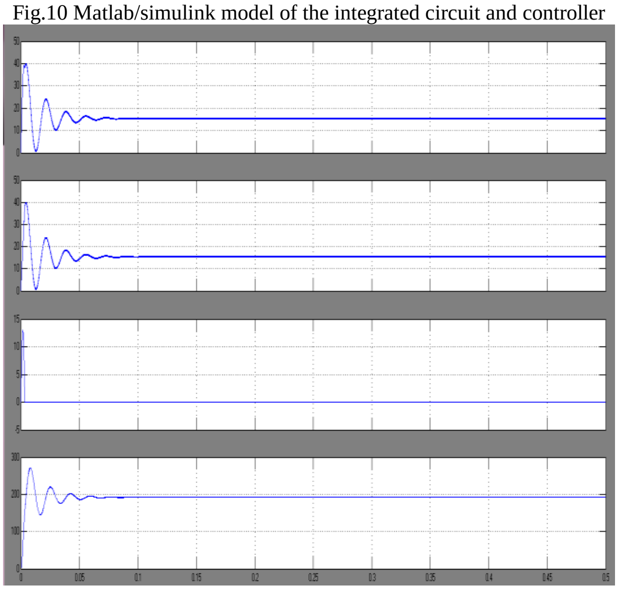

Fig.11 measured current with and without interleaved control, Single-phase interleaved boost converter

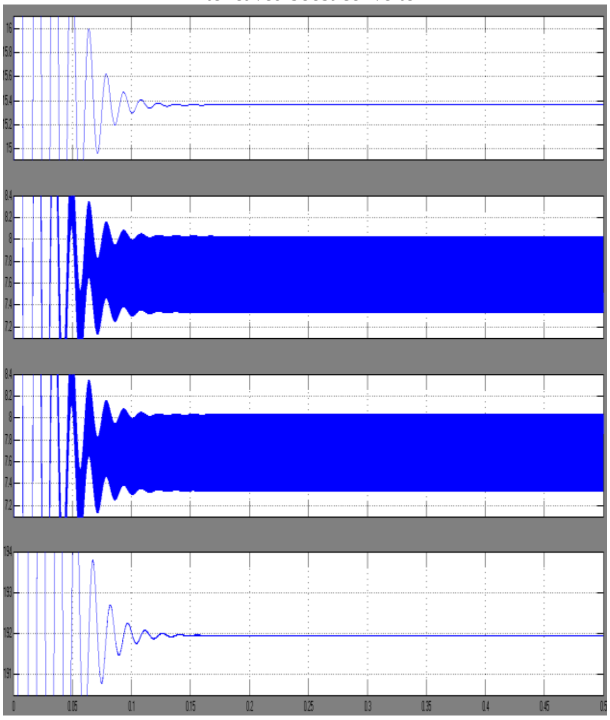

Fig.12 Measured current with and without interleaved control, Two-phase interleaved boost converter

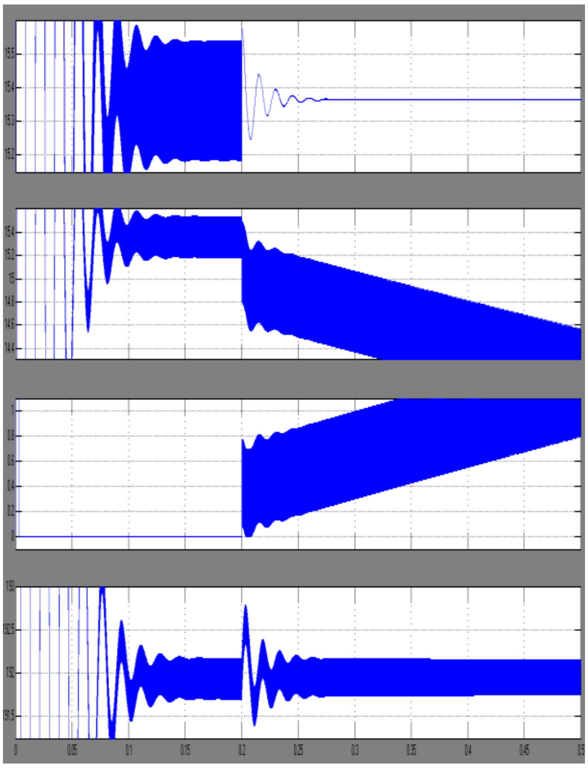

Fig. 13 Simulated waveforms for the transition between single-phase control and two-phase interleaved control from two-phase interleaved to single-phase modes.

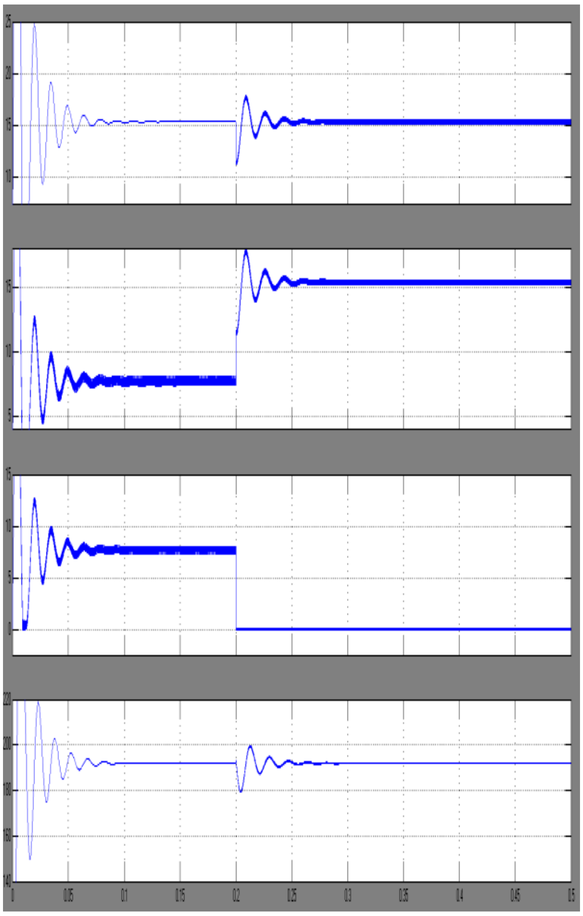

Fig. 14 Simulated waveforms for the transition between single-phase control and two-phase interleaved control single-phase to two-phase interleaved modes

Case 2: Proposed Converter Fed BLDC Drive

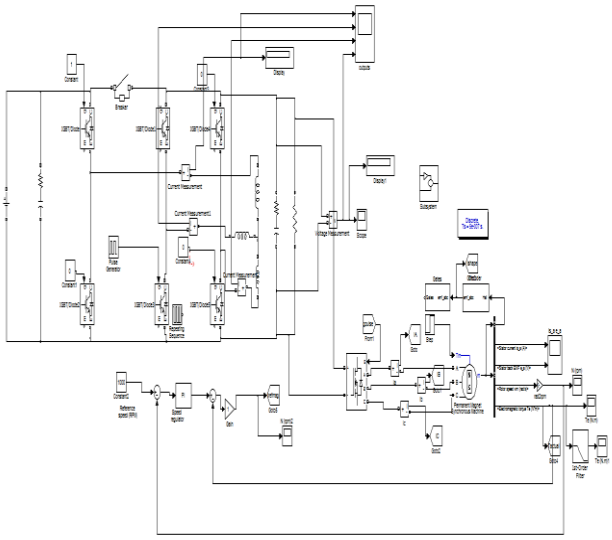

Fig.15 Matlab/Simulink Model of Proposed Converter Fed BLDC Drive

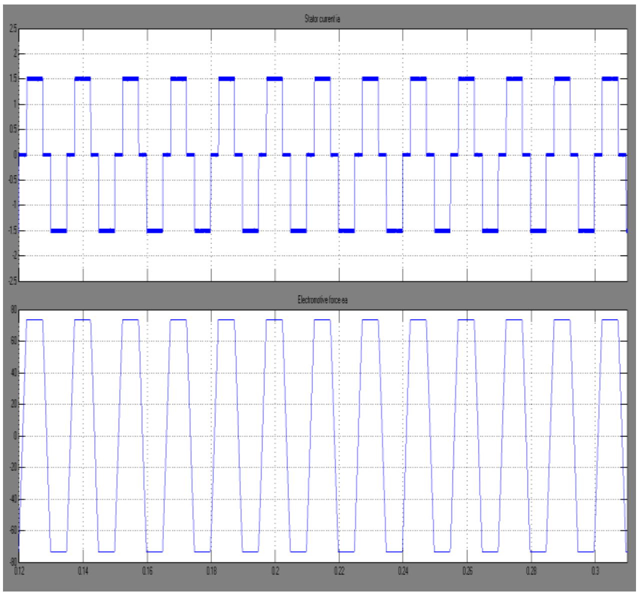

Fig.16 Stator Current, Back EMF

Fig.16 shows the Stator Current, Back EMF of Proposed Converter Fed BLDC Drive.

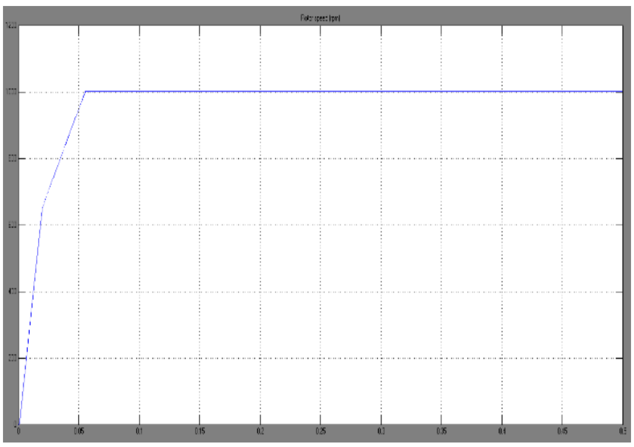

Fig.17 Speed of Proposed Converter Fed BLDC Drive

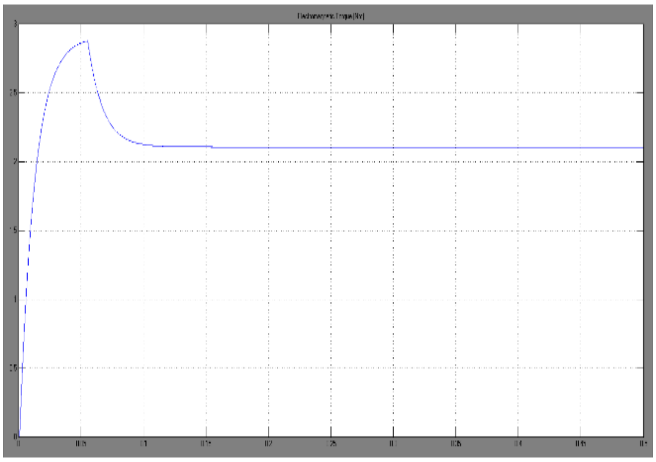

Fig.18 Electromagnetic Torque of Proposed Converter Fed BLDC Drive

V. CONCLUSION

In order to run a BLDC motor, a rotating Electric Field is necessary. As electronic commutation is applied in control of BLDC motor, complexity of Power Electronic circuit is increased. To achieve accurate and better performance from a BLDC motor, it is generally fed from a Voltage Source Inverter (VSI) with proposed DC/DC Converter. In this paper, a new converter topology has been proposed which has superior features over conventional topologies in terms of the required power switches and isolated dc supplies, control requirements, cost, and reliability. Proposal of new integrated inverter/converter circuit of motor drives with dual-mode control for EV/HEV applications to significantly reduce the volume and weight, proposal of a new control method for the integrated inverter/converter circuit operating in boost converter mode to increase the efficiency, verification of the proposed integrated inverter/converter circuit. The above proposed converter tested by adding the BLDC motor and verified the speed torque characteristics.

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