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AN IMPROVED EV/HEV WITH INTEGRATED INVERTER/CONVERTER CIRCUIT

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Abstract: A combined circuit for motor drives with an Impedance Network along with dual mode control for EV/HEV applications is proposed. The integrated circuit allows the permanent magnet synchronous motor 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. In motor mode, the proposed integrated circuit acts as an inverter and it becomes a boost-type boost converter, while using the motor windings as the boost inductors to boost the converter output voltage. The proposed combined Network Eliminates the Shoot through effect produced by the IGBT's are noticeable in single supply gate drivers. On interleaving the boost converter, it improves efficiency, reduce ripple, and shrink capacitor and inductor size.
Index Terms: Boost converter, inverter, and motor drives.

I. INTRODUCTION

Electric transportation is not a new phenomenon in fact; the concept has been around for more than 100 years. However, given growing environmental sensitivities, long-term supply concerns, fossil fuel prices and improved technology, there is a strong motivation to further accelerate this market segment. Government regulations like the 130-g/km (and future planned 95-g/km) CO_2 average emission limits for car manufacturers in Europe are also catalysts behind new electrified transportation alternatives. With the adoption of more electronics, vehicles become safer, exhibit higher performance, and are more efficient. Electric transportation is a key element within the overall renewable energy landscape. Energy for charging is expected to come from renewable sources like wind-, solar- or water powered plants. Home and public charging stations will also become more prevalent and can take advantage of off-peak charging (night-time) and green energy sources such as wind. With a full range of analog and embedded processing products, TI is at the forefront of helping to bring safer, affordable and more efficient electric transportation solutions to market. TI's solutions for this industry range from optimized and dedicated integrated circuits to full system-level solutions to help our customers optimize and accelerate product development. TI's experience in diverse markets such as industrial control, industrial motor drives, digital power supplies, smart metering and grids, wired and wireless communications, consumer electronics, and energy efficiency enables engineers to meet increasing needs for higher speeds, higher precision, lower power and more robust equipment – all while maintaining the high standards of quality and reliability that the automotive and transportation market demands. The hybrid and electric vehicle system is built of several modules to form the drive train and energy storage system. The battery block (typically a Li-ion chemistry in the range of 400 V) is managed and monitored by the battery management system (BMS) and charged via an on-board AC/DC converter module, with voltages ranging from 110-V single-phase to 380-V three-phase systems. The DC/AC inverter uses the high voltage of the battery to drive the electric motor, but also is used for regenerative breaking, storing energy back into the battery. To connect the high-voltage battery to the conventional 12-V board net requires a DC/DC converter. The connection of a high-voltage battery to the inverter also requires a reversible DC/DC converter in most cases. The complete HEV system has to meet specific safety requirements (up to ASIL-D) that are specifically relevant for managing the high-voltage battery pack, as well as the drive train used for breaking. Plug-in hybrid electric vehicles (PHEVs)and battery electric vehicles (BEVs) are two quickly emerging technologies that use powerful electric motors as the propulsion source. In order to power these electric motors, large battery packs are made up of hundreds of cells, totaling 300-400 V installed in the vehicle. Because batteries have a finite energy capacity, PHEVs and BEVs must be recharged on a periodic basis, typically by connecting to the power grid. The charging system for these vehicles consists of an AC/DC rectifier to generate a DC voltage from the AC line, followed by a DC/DC converter to generate the DC voltage required by the battery pack. Additionally, advanced charging systems might also communicate with the power grid using power line communication (PLC) modems to adjust charging based on power grid conditions. The battery pack must also be carefully monitored during operation and charging in order to maximize energy usage and prolong battery life. High-performance analog parts are also available to provide critical system functions and features such as sensor feedback, isolation, chip power supplies and communication transceivers. A converter that increases voltage is called a step-up converter and a converter that decreases voltage is called a step-down converter. In EVs/HEVs step-up and step-down converters are combined into one unit. An application of a step-up converter is converting EV/HEV battery voltage (typically 180-300 volts) to about 650 volts to power the traction motor. An advantage of using a converter to increase voltage from the battery is a smaller and less expensive battery may be used while still utilizing an efficient high voltage motor. An application of a step down inverter would be decreasing the high voltage direct current (DC 180-300 volts) from the HEV/EV battery to low voltage. The integrated circuit allows the permanent magnet synchronous motor 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. In motor mode, the integrated circuit acts as an inverter and it becomes a boost-type boost converter, while using the motor windings as the boost inductors to boost the converter output voltage. Moreover, a new control technique for the proposed integrated circuit under boost converter mode is proposed to increase the efficiency. 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 contrast, single phase control is used for not invoking additional switching and conduction losses under light-load condition. Experimental results derived from digital-controlled 3-kW inverter/converter using digital signal processing show the voltage boost ratio can go up to 600Wto 3 kW. And the efficiency is 93.83% under full-load condition while keeping the motor temperature at the atmosphere level.

II. BOOST CONVERTER

A boost converter (step-up converter) is a power converter with an output DC voltage greater than its input DC voltage. It is a class of switching-mode power supply (SMPS) containing at least two semiconductor switches (a diode and a transistor) and at least one energy storage element. Filters made of capacitors (sometimes in combination with inductors) are normally added to the output of the converter to reduce output voltage ripple. Power can also come from DC sources such as batteries, solar panels, rectifiers and DC generators. A process that changes one DC voltage to a different DC voltage is called DC to DC conversion. A boost converter is a DC to DC converter with an output voltage greater than the source voltage. A boost converter is sometimes called a step-up converter since it “steps up” the source voltage. Since power (P = VI) must be conserved, the output current is lower than the source current. A boost converter may also be referred to as a 'Joule thief'. This term is usually used only with very low power battery applications, and is aimed at the ability of a boost converter to 'steal' the remaining energy in a battery. This energy would otherwise be wasted since the battery's low voltage makes it unusable for a normal load. This energy would otherwise remain untapped because in most low-frequency applications, currents will not flow through a load without a significant difference of potential between the two poles of the source (voltage.)

A. Operating principle

The key principle that drives the boost converter is the tendency of an inductor to resist changes in current. When being charged it acts as a load and absorbs energy (somewhat like a resistor), when being discharged, it acts as an energy source (somewhat like a battery). The voltage it produces during the discharge phase is related to the rate of change of current, and not to the original charging voltage, thus allowing different input and output voltages.

- In the On-state, the switch S is closed, resulting in an increase in the inductor current;
- In the Off-state, the switch is open and the only path offered to inductor current is through the flyback diode D, the capacitor C and the load R. These results in transferring the energy accumulated during the On-state into the capacitor

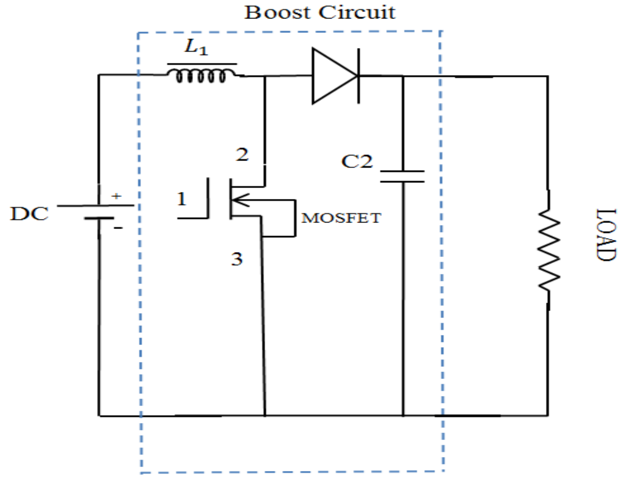

Fig.1. Boost Converter

The input current is the same as the inductor current. So it is not discontinuous as in the buck converter and the requirements on the input filter are relaxed.

B. Converter Interleaving

- This can be thought of as a method of paralleling converters.
- However, it has additional benefits to offer in addition to those obtained from conventional approaches of paralleling converters.
- Widely used in personal computer industry to power central processing units.

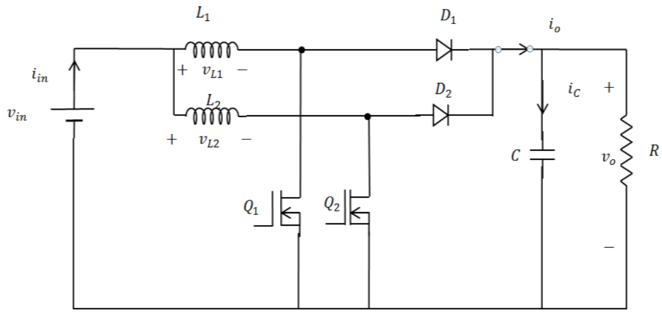

Fig. 2. Interleaved Operation Of Converter

C. Need For Isolated Gate-Control Signals for the Switches

As already mentioned the switches in bridge configurations of inverters need to be provided with isolated gate (or base) drive signals. The individual control signal for the switches needs to be provided across the gate (base) and source (or emitter) terminals of the particular switch. The gate control signals are low voltage signals referred to the source (emitter) terminal of the switch. For n-channel IGBT and MOSFET switches, when gate to source voltage is more than threshold voltage for turn-on, the switch turns on and when it is less than threshold voltage the switch turns off. The threshold voltage is generally of the order of +5 volts but for quicker switching the turn-on gate voltage magnitude is kept around +15 volts whereas turn-off gate voltage is zero or little negative (around –5 volts). It is to be remembered that the two switches of an inverter-leg are controlled in a complementary manner. When the upper switch of any leg is 'on', the corresponding lower switch remains 'off' and vice-versa. When a switch is 'on' its emitter and collector terminals are virtually shorted. Thus with upper switch 'on', the emitter of the upper switch is at positive dc bus potential. Similarly with lower switch 'on', the emitter of upper switch of that leg is virtually at the negative dc bus potential. Emitters of all the lower switches are solidly connected to the negative line of the dc bus. Since gate control signals are applied with respect to the emitter terminals of the switches, the gate voltages of all the upper switches must be floating with respect to the dc bus line potentials. This calls for isolation between the gate control signals of upper switches and between upper and lower switches. Only the emitters of lower switches of all the legs are at the same potential (since all of them are solidly connected to the negative dc bus) and hence the gate control signals of lower switches need not be isolated among themselves. As should be clear from the above discussion, the isolation provided between upper and lower switches must withstand a peak voltage stress equal to dc bus voltage. Gate-signal isolation for inverter switches is generally achieved by means of optical-isolator (opto-isolator) circuits. The circuit makes use of a commercially available opto-coupler IC. Input stage of the IC is a light emitting diode (LED) that emits light when forward biased. The light output of the LED falls on reverse biased junction of an optical diode. The LED and the photo-diode are suitably positioned inside the opto-coupler chip to ensure that the light emitted by the LED falls on the photo-diode junction. The gate control pulses for the switch are applied to the input LED through a current limiting resistor of appropriate magnitude. These gate pulses, generated by the gate logic circuit, are essentially in the digital form. A high level of the gate signal may be taken as 'on' command and a low level (at ground level) may be taken as 'off' command. Under this assumption, the cathode of the LED is connected to the ground point of the gate-logic card and anode is fed with the logic card output. The circuit on the output (photo-diode) side is connected to a floating dc power supply. The control (logic card) supply ground is isolated from the floating-supply ground of the output. The two grounds have been shown by two different symbols. Indicates that the photo-diode is reverse biased. A resistor in series with the diode indicates the magnitude of the reverse leakage current of the diode. When input signal to LED is high, LED conducts and the emitted light falls on the reverse biased p-n junction. Irradiation of light causes generation of significant number of electron-hole pairs in the depletion region of the reverse biased diode. As a result magnitude of reverse leakage current of the diode increases appreciably. The resistor connected in series with the photo-diode now has higher voltage drop due to the increased leakage current. A signal comparator circuit senses this condition and outputs a high level signal, which is amplified before being output. Thus an isolated and amplified gate signal is obtained and may directly be connected to the gate terminal of the switch (often a small series resistor, as suggested by the switch manufacturer, is put between the output signal and the gate terminal of the switch).

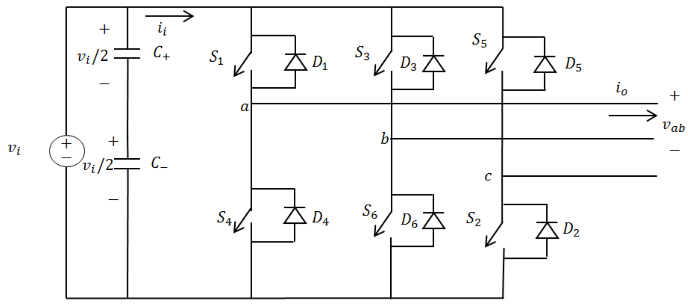

Fig. 3. Three-phase VSI topology

D. Neutral Point Clamped Inverter

NPCI topology that allows for line-to-line waveforms with five voltage levels and line-to-neutral waveforms with three voltages Neutral Point Clamped Inverter topology levels. The phase outputs are the center point of a series connection of four IGBTs, and the DC bus input is connected to the top and bottom row of devices, Al, Bl, CI, and A4, B4, C4, respectively. The center point of the DC bus is shown by a ground symbol 10 and is connected between a pair of series connected diodes in each phase. These six clamping diodes connected to the neutral bus control the voltage distribution among the four IGBTs in each phase leg. A conventional inverter requires the switches to sustain the full voltage drop between the positive and negative DC buses. However, the voltage drop (stress) across each switch of the NPCI is one half of the voltage between the positive and negative bus since the switches on either side of the neutral bus are in series, and an actual neutral point exists. Each IGBT has an individual gate signal that must be referenced between the respective IGBT gate and emitter terminal. The diode shown between the collector and emitter of each IGBT is an internal "body diode" inherent to the IGBT device structure. The DC bus has a positive, negative, and neutral connection with large low frequency filter capacitors and smaller high frequency filter capacitors. The bus structure is discussed in more detail in the physical system section. Operation This specific NPCI topology uses 3-level switching instead of 2-level switching used in conventional 3-phase inverters. The three levels correspond to the positive, negative, and neutral buses. Taking leg A of the phase output A is connected to the positive bus 11 by turning on switches Al and A2. Turning switches A3 and A4 on connect the phase A output to the negative bus, and turning switches A2 and A3 on connects the phase A output to the neutral bus. The other two phases operate in the same manner, but with phase shifted results with respect to phase A. The resulting waveforms for the switches in leg A, where N covers one cycle of the desired output waveform. The control strategy for the NPCI is similar to a conventional converter in that a control voltage signal, a repetitive triangle wave signal, and a comparator function are used to produce the gate signals. The control voltage signal for each phase of the NPCI is the same signal used in the conventional converter, and likewise for the triangle wave.

III. METHODOLOGY

A. Existing Integrated Circuit

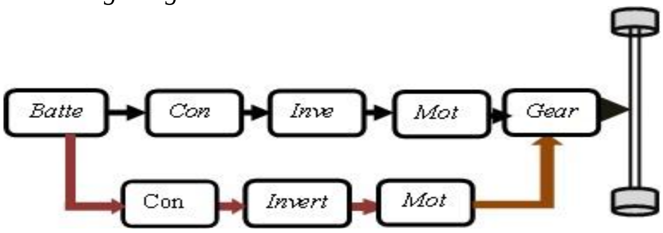

Fig. 4. Conventional multimotor drive system

In Parallel hybrid electric vehicle (HEV) and electric vehicle (EV) system, the converter is used for boosting the battery voltage to rated dc bus for an inverter to drive motor. In the multimotor drive system the system will use two or more motors to boost torque as in Fig. 4, especially under low speed and high-torque region for such applications; two or more inverters/converters are required. Fig. 5 shows the application of the integrated circuit for motor drives with dual-mode control for EV/HEV applications. As shown in Fig. 5, the integrated circuit allows the permanent magnet synchronous motor (PMSM) 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 an inverter connected to the output of the integrated circuit. In motor mode, the integrated circuit acts as an inverter and it becomes a boost-type boost converter, while using the motor windings as the boost inductors to boost the converter output voltage. Therefore, the integrated circuit can significantly reduce the volume and weight of the system.

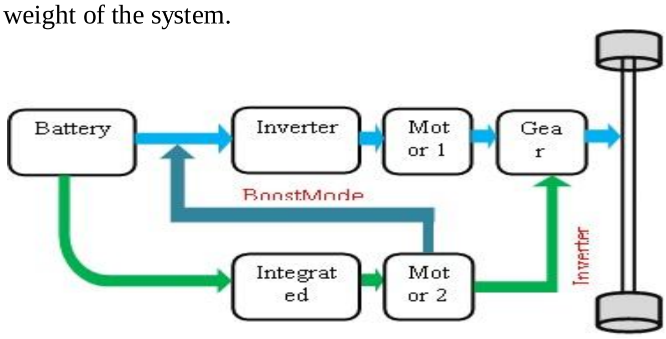

Fig. 5. Integrated Inverter/Converter for the multimotor drive system of EV/HEV

The integrated circuit presented in this paper can act as an inverter and a boost converter depending on the operation mode. For the integrated circuit, it not only can reduce the volume and weight but also boost torque and dc-link voltage for motor/converter modes, respectively. Moreover, a new control technique for the integrated circuit under boost converter mode is proposed to increase the efficiency. For conventional circuit a single phase boost converter has been widely used for boost control due to its simplicity. However, for higher power applications, an interleaved boost converter can reduce the current ripple and components stress and thereby reducing the losses and thermal stress. Based upon the interleaved control idea, a boost-control technique using motor windings as boost inductors for the integrated circuit will be proposed. Under light load, the integrated circuit acts as a single-phase boost converter for not invoking additional switching and conduction losses, and functions as the two-phase interleaved boost converter under heavy load to significantly reduce the current ripple and thereby reducing the losses and thermal stress. Therefore, the control technique for the integrated circuit under boost converter mode can increase the efficiency.

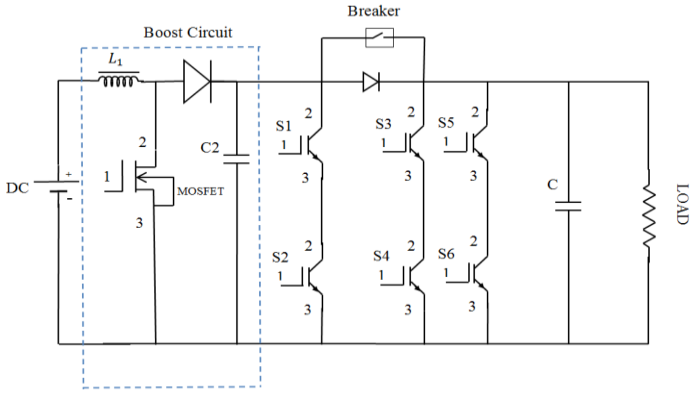

Fig.6. Integrated circuit for dual mode of motor drives and boost converter

Fig. 6 shows the integrated circuit for dual-mode control. 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 (IGBTs in Fig. 6) are controlled by pulse width modulation (PWM) control signals. When the 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. Proposed Integrated Circuit

A new integrated circuit for motor drives with dual mode Control for EV/HEV applications with the permanent magnet synchronous motor is proposed. The permanent magnet synchronous motors (PMSM) operate in motor mode or acts as boost inductors of the boost converter. The integrated circuit is a combination of power IGBT can act as an inverter and a boost converter depending on the operation mode. Under light load, the integrated circuit acts as a single-phase boost converter for not invoking additional switching and conduction losses, and functions as the two-phase interleaved boost converter under heavy load to significantly reduce the current ripple and thereby reducing the losses and thermal stress. The control technique for the integrated circuit under boost converter mode can increase the efficiency. The use of impedance network reduces the shoot-through effect produced by the two IGBT when turned ON at same time.

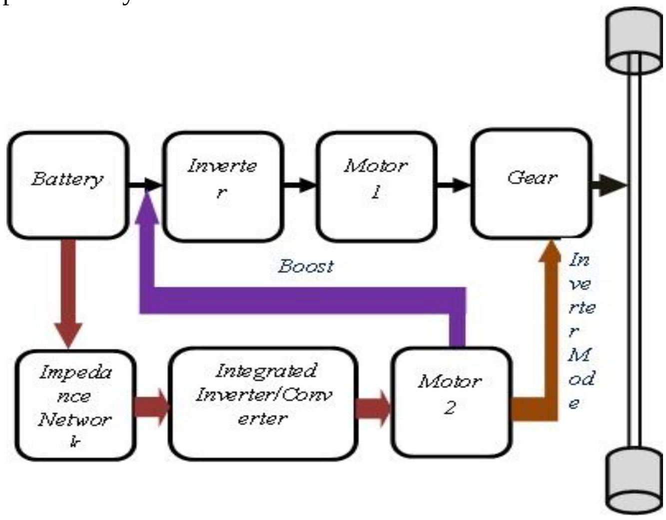

Fig. 7. Proposed Integrated Inverter/Converter for the multimotor drive system of EV/HEV

The efficiency for interleaved control is increased as load goes more as compared to that for single-phase control. Therefore, the boost converter is controlled by the proposed hybrid control method , as load is more than the switching point of power ratio for the given voltage ratio shown in Fig. 12(b), the converter is controlled by interleaved mode to significantly reduce the current ripple and thereby reducing the losses. In contrast, as load is less than the switching point of power ratio for the given voltage the converter is controlled by the single phase control method without invoking additional conduction and switching losses as compared to that for two-phase interleaved control. The transition point is determined by the load condition and implemented in the interrupt service routine (ISR) for the flow chart of the proposed control for the proposed integrated circuit under boost converter mode.

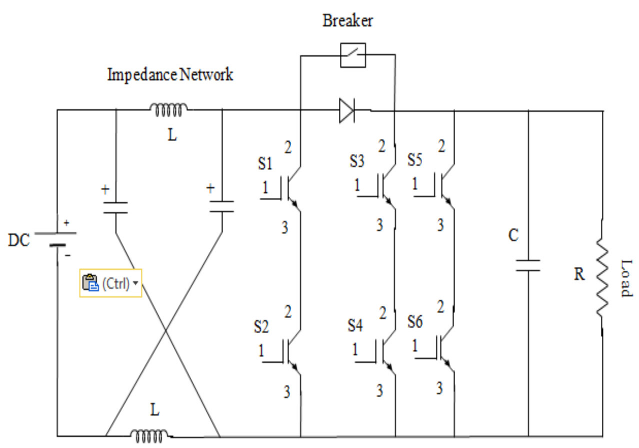

Fig. 8. Circuit diagram of proposed system

It is very common that an IGBT used for motor drive, UPS and someother industrial applications, be selected for 10 micro-second shortcircuitwithstand time (SCWT) if regular de-sat protection driver isused. But this driver generates high turn-off stress to the IGBT duringinverter short circuit or the output becomes faulty. Under these abnormalconditions when the IGBT is turned-off abruptly, failures canoccur if the IGBT is not selected properly. If the smart fault protectionis not used, high turn-off loss will be generated and even short circuit current can ramp-up to a dangerous level destroying the IGBT. Thereare several ways to turn-off the IGBT once fault condition is detected.Gate is discharged through high gate resistance. This discharge pathis activated only during the above said abnormal conditions. This isnot the best solution.Gate voltage is abruptly reduced to zero.Adding some source inductance which is common for both gate dischargepath and load current.Gate de-bias occurs and the shoot through effect produced by IGBT in the Integrated Circuit Fig. 8 is reduced using impedance network.The use of capacitors at both input and output end stabilizes the voltage by distributing the source and load voltage.

C. Modelling Of Boost Converter In Proposed System

This section will introduce the model of boost converter and derive the transfer function of the voltage controller. Fig. 9 shows the non-ideal equivalent circuit of the boost converter, it considers non ideal condition of components: inductor winding resistance R_L, collector-emitter saturation voltage V_{CE}, diode forward voltage drop V_D, and equivalent series resistance of capacitor R_{esr} .Analysis of the boost converter by using the state-space averaging method, small-signal ac equivalent circuit can be derived, as shown in Fig. 10. By Fig. 10, the transfer function of the voltage controller can be derived.

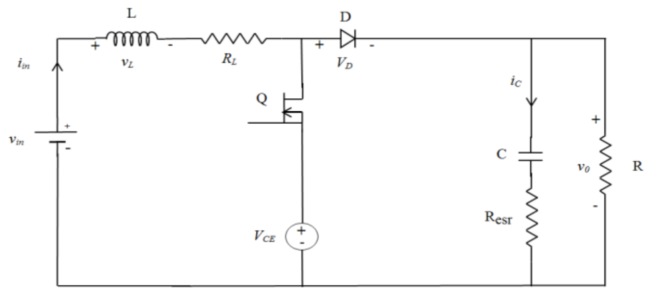

Fig. 9. Equivalent circuit of boost converter

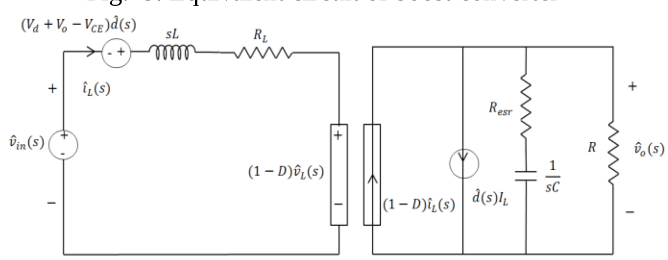

Fig. 10. small signal equivalent circuit

G(s=)

$$\frac{s^2 \cdot L \cdot C(R + R_{esr}) + s[L + C \cdot R_L(R + R_{esr}) + (1 - D)^2 . C \cdot R \cdot R_{esr}] + [(1 - D)^2 \cdot R + R_L]}{-s^2 \cdot C \cdot R \cdot R_{esr} \cdot L \cdot I_L + s\{C \cdot R \cdot R_{esr} [(V_d + V_o - V_{CE})(1 - D) - R_L I_L] - R \cdot L \cdot I_L\} + R \cdot [(V_d + V_o - V_{CE})(1 - D) - R_L I_L]} \quad \text{.......(1)}$$

Table 1. Controller Design Parameters

V_{in}	96 V_{DC}
V_o	288 V_{DC}
P_o	3 KW
C	260 µF
R_L	170 mΩ
L	2.77 Mh
R_{esr}	108 mΩ
V_d	0.462 V
V_{CE}	1.5 V
Voltage drop of D	0.87 V

Substitute controller design parameters of Table 3.1 in equation (3.1)

$$G(s) = \frac{-6.737 * 10^{-5} s^2 + 0.06827s + 2498}{2.004 \times 10^{-5} s^2 + 0.00409s + 3.242} \quad \text{.........(3)}$$

In this paper, the switching frequency is 20 kHz and voltageloop bandwidth will be less than 2 kHz. And the phase marginshould be more than 45. to enhance the noise immunity. The bandwidth is 7.73Hzand the phase margin is 91.8 .The proposed integrated circuit which acts as inverter/boost converter and DSP control board to give PWM control signals of inverter/converter based upon the feedback signals and reference.

IV. SIMULATION AND RESULTS

A. Simulation circuit of Existing System

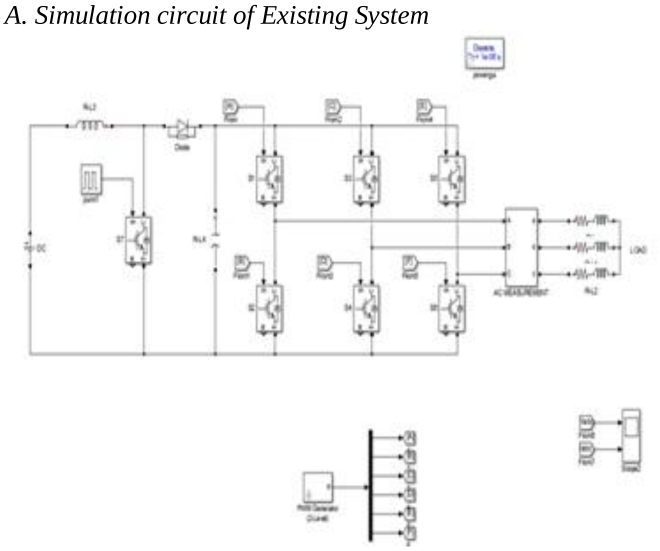

Fig. 11. Simulation of Existing System

B. Output Voltage and Current

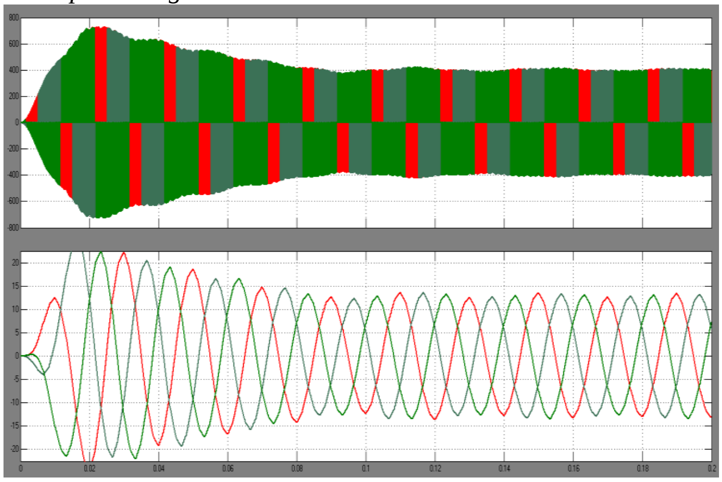

Fig. 11.Output voltage and current of Existing System

C. Simlation circuit of Proposed System

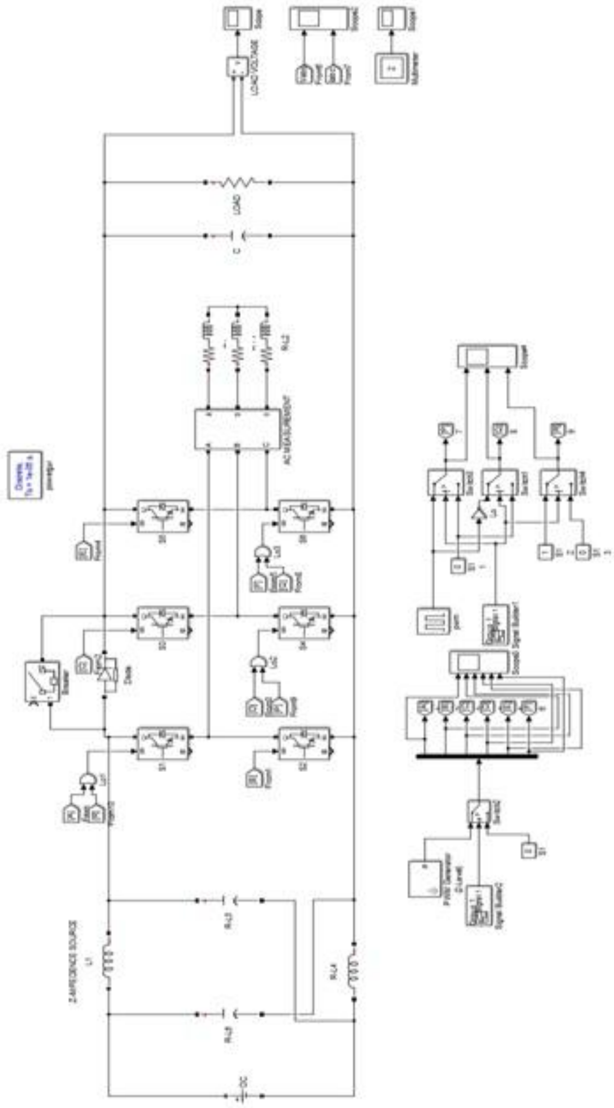

Fig. 13. Simulation of proposed system

D. Simulation Waveform Analysis

Pulse of a,b,c,d,e,f

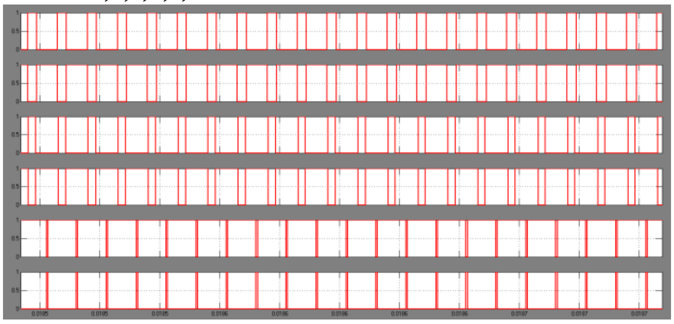

Fig. 14. Pulse signal for IGBT a,b,c,d,e,f

Pulses of p,q,r

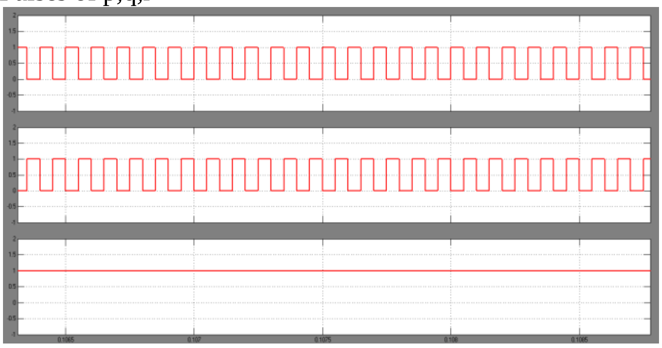

Fig.15. Pulse signal p,q,r

E. Load Voltage

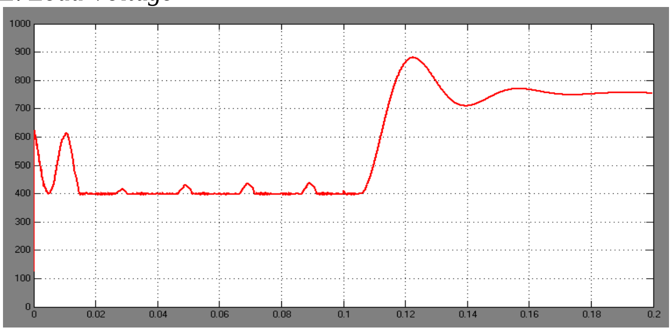

Fig.16. Load voltage

F. Output Voltage and Current

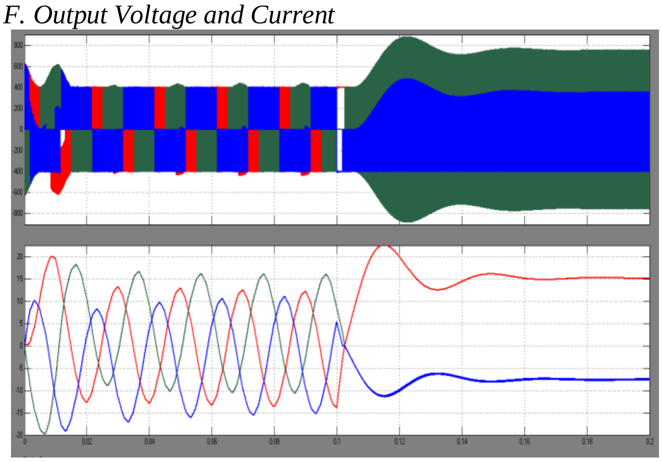

Fig.17. Output voltage and current of proposed system

V. CONCLUSION

The contributions of this paper include:

1) Proposal of a new integrated inverter/converter circuit of motor drives with dual-mode control for EV/HEV applications to significantly reduce the volume and weight;
2) Proposal of a new control method for the integrated inverter/ converter circuit operating in boost converter mode to increase the efficiency;
3) Verification of the proposed integrated inverter/converter circuit;
4) Verification of the proposed control method.

Experimental results show that the voltage boost ratio can go up to 3. Under full-load condition, the maximum efficiency is more than 95% and efficiency can be maintained at more than 91.7% for voltage ratios varies from 1.25 to 3. These results fully confirm the claimed merits of the proposed integrated circuit and control method.

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