Multiphase Bidirectional Flyback Converter Topology for Hybrid Electric Vehicles

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Abstract— **Power electronics is an enabling technology for the development of electric or hybrid electric vehicles. For both ac and dc motor drives used in electric and hybrid electric vehicles, the basic requirement for efficient control is that the power electronic circuit should be capable of handling bidirectional power flow, i.e., energy transfer should be possible from battery to motor during motoring mode and motor to battery during regeneration. For hybrid electric vehicles, the batteries and the drive dc link may be at different voltages. The batteries are at low voltage to obtain higher volumetric efficiencies, and the dc link is at higher voltage to have higher efficiency on the motor side. Therefore, a power interface between the batteries and the drive's dc link is essential. This power interface should handle power flow from battery to motor, motor to battery, external genset to battery, and grid to battery. This paper proposes a multi-power-port topology which is capable of handling multiple power sources and still maintains simplicity and features like obtaining high gain, wide load variations, and capability of parallel-battery energy due to the modular structure. Application of the proposed converter for Drive application is modelled and Matlab results are presented.**

Keywords— **Flyback Converter, Hybrid Electric Vehicles.**

I. INTRODUCTION

Power electronics is an enabling technology for the development of electric or hybrid electric vehicles. For both ac and dc motor drives used in electric and hybrid electric vehicles, the basic requirement for efficient control is that the power electronic circuit should be capable of handling bidirectional power flow, i.e., energy transfer should be possible from battery to motor during motoring mode and motor to battery during regeneration. Now, the need for a bidirectional power converter should be properly examined. A battery can be used as a dc bus if the motor is rated for that voltage level. Thus, bidirectional power flow is not a problem because of the bidirectional power-handling capacity of a standard two-level three-phase inverter and also sinking and sourcing capacity of the battery. However, the traction motor should be rated for higher voltage to achieve higher efficiency for a given power rating. Therefore, the dc bus voltage should be maintained high enough to match the motor voltage rating. This problem can be solved by connecting a number of batteries in series. However, if too many batteries are connected in series, then the volumetric efficiency of the battery comes down. Therefore, there is a need for a bidirectional converter which interfaces the low-voltage battery with a high-voltage dc bus and maintains a bidirectional power flow.

We know that normally the motors are rated for higher voltages so that the current drawn will reduce and the efficiency of the drive will increases. But the battery voltages are normally low and which will not match with the motor voltage. There is a need for the interfacing device between battery and motor. For this a multiphase bi directional flyback converter is used in this project. Various types of dc dc converters and introduction of hybrid electric vehicles is given below.

DC-DC power converters are employed in a variety of applications, including power supplies for personal computers, office equipment, spacecraft power systems, laptop computers, and telecommunications equipment, as well as hybrid vehicle, fuel cell vehicle, renewable energy system. In the electric vehicle applications, an auxiliary energy storage battery absorbs the regenerated energy fed back by the electric machine. So that, bidirectional dc-dc converter is required to draw power from the auxiliary battery to boost the high-voltage bus during vehicle starting, accelerate and hill climbing With its ability to reverse the direction of the current flow, and thereby power, the bidirectional dc-dc converters are being increasingly used to achieve power transfer between two dc power sources in either direction.

Bidirectional converter for a permanent-magnet ac motor-driven electric vehicle described in Ref [2]. Ref [3] described about the use of a cascaded bidirectional buck–boost converter for the use in dc-motor-driven electric vehicle. Both schemes emphasize the importance of bidirectional dc–dc converter for electric vehicle application. Reference [4] proposes ZVS techniques for different non-isolated dc–dc converters. There is a limit on the voltage gain that can be achieved using a buck–boost or a boost converter. Reference [6-10] proposes a coupled-inductor winding technique which reduces the leakage inductance to a very less value and without the use of any snubber, and that very less voltage spike be achieved during switching transients. Next, the paralleling of four batteries is done using a four-phase flyback topology, and outputs of all the four phases are connected to the same dc link. To reduce the current ripple through the dc-link capacitor, all the four phases are switched at a fixed 75% duty cycle with 90°(considering one switching period as 360^{0}) phase difference between subsequent phases. This configuration is also suitable for connecting multiple power sources. For battery charging from mains, a front-end converter is used which uses the same dc bus. Thus, the same flyback converter is used for battery charging. For series–parallel hybrid electric vehicles, the output of the synchronous generator can be connected to the same dc bus through a rectifier.

II. FLY BACK CONVERTER

The fly back converter is based on the buck-boost converter. Fig. 1(a) depicts the basic buck-boost converter, with the switch realized using a MOSFET and diode. In Fig.1(b), the inductor winding is constructed using two wires, with a 1:1 turn's ratio.

The basic function of the inductor is unchanged, and the parallel windings are equivalent to a single winding constructed of larger wire. In Fig.1(c), the connections between the two windings are broken. One winding is used while the transistor Q_1 conducts, while the other winding is used when diode D_1 conducts. The total current in the two windings is unchanged from the circuit of Fig.1(b); however, the current is now distributed between the windings differently. The magnetic fields inside the inductor in both cases are identical. Although the two-winding magnetic device is represented using the same symbol as the transformer, a more descriptive name is "two winding inductor". This device is sometimes also called a "fly back transformer".

Unlike the ideal transformer, current does not flow simultaneously in both windings of the fly back transformer. Figure 1(d) illustrates the usual configuration of the fly back converter. The MOSFET source is connected to the primary-side ground, simplifying the gate drive circuit. The transformer polarity marks are reversed, to obtain a positive output voltage. An 1: n turns ratio is introduced; this allows better converter optimization.

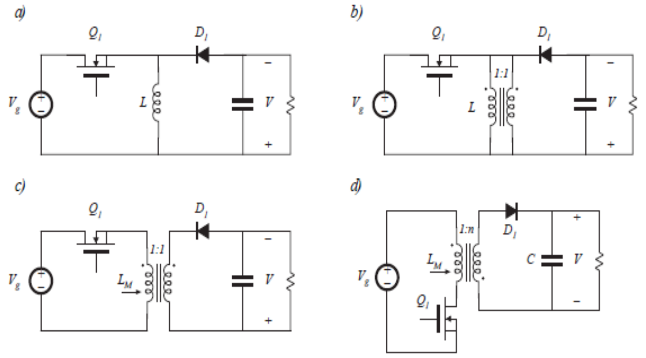


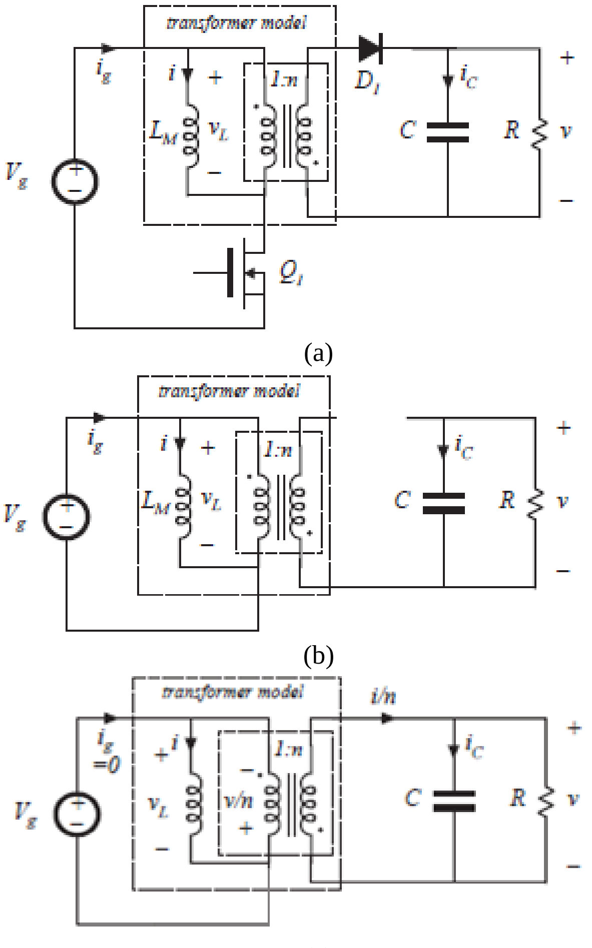
Fig.1 (a) buck-boost converter, (b) inductor *L* is wound with two parallel wires; (c) inductor windings are isolated, leading to the fly back converter, (d) with a1: *n* turns ratio and positive output.

A. Analysis of the fly-back converter

The behavior of most transformer-isolated converters can be adequately understood by modeling the physical transformer with a simple equivalent circuit consisting of an ideal transformer in parallel with the magnetizing inductance.

The magnetizing inductance must then follow all of the usual rules for inductors; in particular, volt-second balance must hold when the circuit operates in steady-state. This implies that the average voltage applied across every winding of the transformer must be zero. Let us replace the transformer of Fig.1(d) with the equivalent circuit described above. The circuit of Fig 2 (a) is then obtained.

The magnetizing inductance *LM* functions in the same manner as inductor *L* of the original buck-boost converter of Fig.2(a). When transistor Q_1 conducts, energy from the dc source *Vg* is stored in *LM*. When diode D_1 conducts, this stored energy is transferred to the load, with the inductor voltage and current scaled according to the 1: *n* turns ratio.



(a)

(b)

(c)

Fig.2 Fly-back converter circuit, (a) with transformer equivalent circuit model, (b) during subinterval *1*, (c) during subinterval *2*.

During subinterval *1*, while transistor Q_1 conducts, the converter circuit model reduces to Fig.2(b). The inductor voltage v_L, capacitor current i_C, and dc source current i_g, are given by

$$v_L = V_g$$
$$i_c = \frac{v}{R}$$
$$i_g = i$$

With the assumption that the converter operates with small inductor current ripple and small capacitor voltage ripple, the magnetizing current *i* and output capacitor voltage *v* can be approximated by their dc components, *I* and *V*, respectively. Then becomes

$$v_L = V_g$$
$$i_C = -\frac{V}{R}$$
$$i_g = I$$

During the second subinterval, the transistor is in the off-state, and the diode conducts. The equivalent circuit of Fig.1 (c) is obtained. The primary-side magnetizing inductance voltage v_L, the capacitor current i_C, and the dc source current i_g, for this subinterval are

$$v_L = \frac{v}{n}$$
$$i_c = \frac{i}{n} - \frac{v}{R}$$
$$i_g = 0$$

It is important to consistently define $v_L(t)$ on the same side of the transformer for all subintervals. Upon making the small-ripple approximation, one obtains

$$v_L = -\frac{V}{n}$$
$$i_c = \frac{I}{n} - \frac{V}{R}$$
$$i_{g=0}$$

The $v_L(t)$, $i_C(t)$, and $i_g(t)$ waveforms are sketched in Fig.3.

Application of the principle of volt second balance to the primary-side magnetizing inductance yields

$$\langle v_L \rangle = D\left(V_g\right) + D'\frac{V}{n}$$

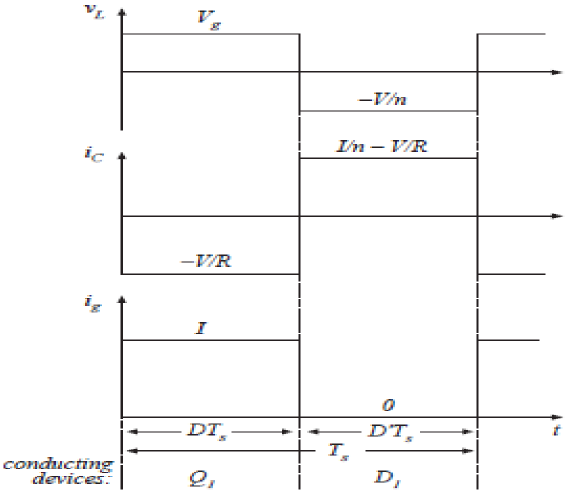


Fig.3 Fly-back converter waveforms, continuous conduction mode

Solution for the conversion ratio then leads to

$$M(D) = \frac{V}{V_g} n \frac{D}{D'}$$

So the conversion ratio of the fly back converter is similar to that of the buck-boost converter, but contains an added factor of n.

$$\langle i_c \rangle = D\left(-\frac{V}{R}\right) + D'\left(\frac{I}{n} - \frac{V}{R}\right) = 0$$

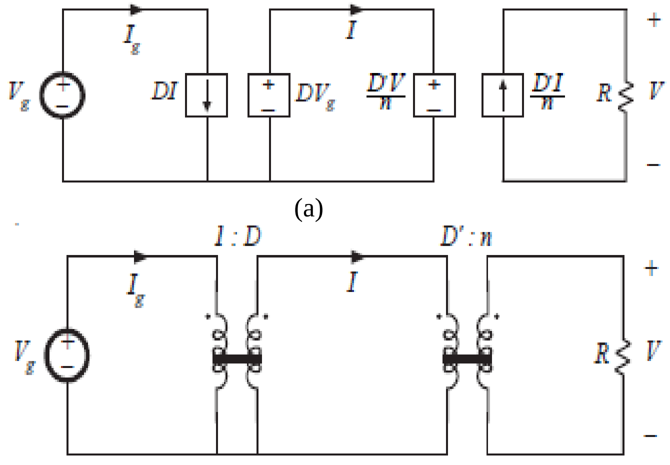
Solution for I yields

$$I = \frac{nV}{D'R}$$

This is the dc component of the magnetizing current, referred to the primary. The dc component of the source current i_g is

$$I_g = \langle i_g \rangle = D(I) + D'(0)$$

An equivalent circuit which models the dc components of the fly back converter waveforms can be constructed. The resulting dc equivalent circuit of the fly back converter is given in Fig.4. It contains a 1: D buck-type conversion ratio, followed by a (1 – D):1 boost-type conversion ratio and an added factor of 1: n, arising from the fly back transformer turns ratio.



(a)

(b)

Fig.4 Fly back converter equivalent circuit model: (a) circuits corresponding to Eqs (b) equivalent circuit containing ideal dc transformers

III. PROPOSED CONFIGURATION

The design of multiphase bi directional fly back converter Provides voltage boost with high gain and also provides bi directional power handling capability. It maintains features like obtaining high gain, wide load variations and lower output current ripple. This paper proposes a multi-power-port topology which is capable of handling multiple power sources and still maintains simplicity and features like obtaining high gain, wide load variations, lower output-current ripple, and capability of parallel-battery energy due to the modular structure.

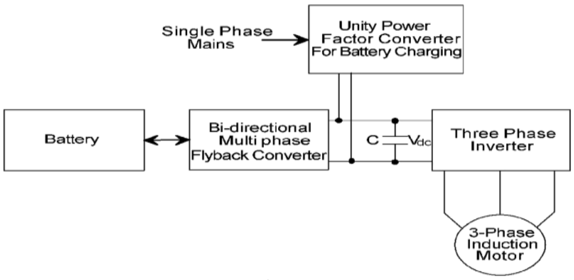


Fig 5 Block diagram of proposed power schematic

The basic block diagram of the prototype of the multi power port (MPP) which is built for hybrid electric vehicle application is shown in Fig.5. The heart of the circuit is the bidirectional flyback dc–dc converter which provides voltage boost with high gain and bi directional power handling capability, because of providing multiple power port this circuit having more flexibility, which can be used for any other purpose by taking power from the port. Here power flows from battery to the dc link through bi directional fly back converter and also power flows from dc link to the battery through bi directional fly back converter. Single phase supply mains are considered for battery charging. Here if we observe the given proposed power schematic it allowing power from different sources and the same is supplying power to the different sources. This is feature is called the Multiple Power Port.(MPP). A four-phase converter is constructed using IGBT's.

The power schematic of the four phase bidirectional dc–dc converter is shown in Fig.6. It has four identical bidirectional flyback dc–dc converters. Each converter has an individual battery, and all the converters are connected to the common dc bus. 4 phases called A, B, C, D and each phase having two switches.

This circuit consisting of totally 8 switches (S1 to S8)**.** Some of the switches are conducting during forward power flow i.e from battery to dc link and the other switches during reverse power flow I.e. dc link to the battery. The conduction of these switches depends up on the firing pulses given to them.

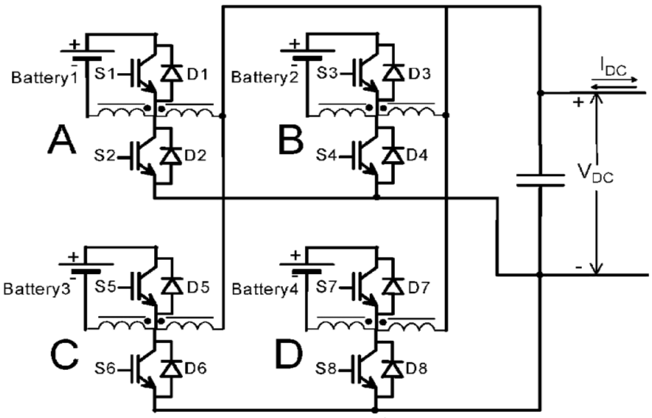


Fig 6 Four phase bi directional flyback converter

The way in which firing pulses are given to the IGBT switches is shown in fig 7. If we consider the first converter, then, during forward power flow, S1 and D2 are active, and during reverse power flow, S2 and D1 are active as well. During forward power flow, active switches S1, S3, S5, and S7 get switching pulses of 75% duty cycle with 90° phase difference between subsequent phases, as shown in Fig.7(a).

We know that in case of fly back converter ouput voltage

$$V_{out} = V_{in} * (D/1-D)$$
$$= V_{in} (0.75/1-0.75)$$
$$= 3\ V_{in}$$

The output voltage is boosted by 3 times the input voltage.

During reverse power flow, active switches S2, S4, S6, and S8 get switching pulses of 25% duty cycle which are 90° phase shifted to each other, as shown in Fig.7(b). During this case

ouput voltage $V_{out} = Vin * (D/1-D)$
$$= Vin\ (0.25/1-0.25)$$
$$= (1/3)\ Vin$$

The output voltage is step down by a factor 3.

Fig. 7(c) and 7(d) shows the ideal switch voltage and current waveforms assuming continuous conduction mode (CCM) for forward and reverse power flows, respectively. CCM is not the only conduction mode for this bidirectional converter. This can also operate in critical conduction mode (CRM) or discontinuous conduction mode (DCM), depending on the load. During forward power flow, if the load is very less, then the converter can go into CRM or DCM, similar to any standard flyback converter.

However, for circuit design, only CCM is considered. As no snubber is used, circuit design involves the design of the inductor and the capacitor. The load connected at the output of the converter is a three-phase inverter connected to the motor. Thus, the capacitor voltage ripple is dominated by the dc-link current ripple of the inverter, and capacitor value is decided depending on that ripple.

The flyback inductor value is selected such that the inductor current ripple is 10% of the full-load current during CCM. DCM and CRM are not considered for circuit design because there is no stringent voltage regulation requirement for the MPP output. The regulation is handled by the downstream inverter.

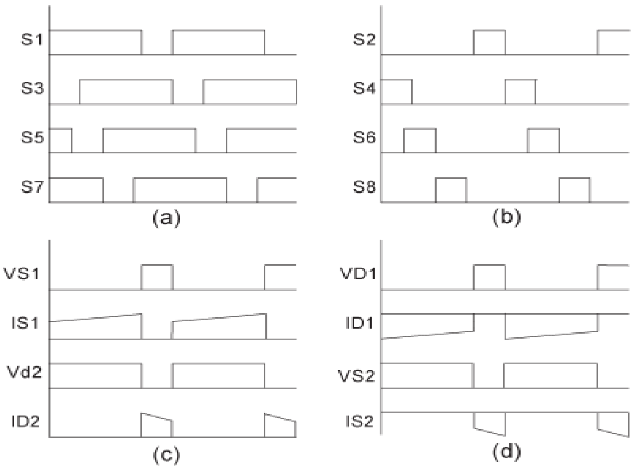


Fig: 7(a) Switching pulses during forward power flow. (b) Switching pulses during reverse power flow. (c) Ideal switch voltage and current waveforms during forward power flow for phase A assuming continuous conduction. (d) Ideal switch voltage and current waveforms during reverse power flow for phase A assuming continuous conduction.

The design of four phase bi directional fly back converter which serves the role of an M.P.P interface for electric and hybrid electric vehicles. The bi-directional nature of the converter allows battery sharing during re generation and also from mains. The multiple phases gives the flexibility of paralling multiple batteries. Since we are operating four converters with 90^0 phase shift with 75 percent duty cycle of operation the capacitor ripple current is also reduced.

Bidirectional DC-DC converters allow transfer of power between two dc sources, in either direction. Due to their ability to reverse the direction of flow of power, they are being increasingly used in many applications such as battery charger/dischargers, dc uninterruptible power supplies, electrical vehicle motor drives, aerospace power systems, telecom power supplies, etc. In this paper a novel multi phase bidirectional fly back converter is presented and implemented. A Simulink based model is developed and the simulation results for the proposed model are obtained by using MAT LAB.

Bidirectional dc-dc converters allow power flow between two dc sources in either direction as shown in Fig. 8. They can reverse the direction of current flow, and thereby power flow while maintaining the voltage polarity of both source ends unchanged. In some necessary case, high-frequency transformer for galvanic isolation can be incorporated inside them. Due to such good features, bidirectional dc-dc converters are being increasingly used in applications such as battery charger and discharger, fuel cell applications, dc uninterruptible power supply, aerospace power systems and motor drives.

Bidirectional dc-dc converters for use in battery charger and discharger are not only to control the battery charging and discharging current, but also to regulate the output voltage of discharger to a predetermined value when again using the stored energy in the battery. In that case, if unidirectional dc-dc converter is adopted instead of bidirectional converter, two separate unidirectional converters should be provided for either direction.

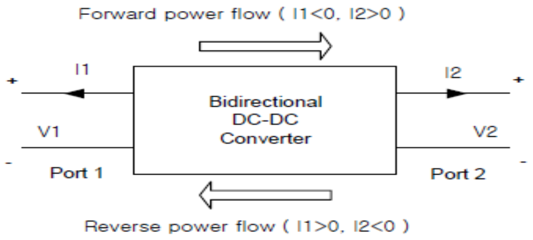


Fig 8. Bi-directional DC/DC Converter

Many bidirectional dc–dc converters have been researched. The bidirectional dc–dc fly back converters are more attractive due to simple structure and easy control. However, these converters suffer from high voltage stresses on the power devices due to the leakage inductor energy of the transformer. In order to recycle the leakage inductor energy and to minimize the voltage stress on the power devices, some literatures present the energy regeneration techniques to clamp the voltage stress on the power devices and to recycle the leakage inductor energy .Some literatures research the isolated bidirectional dc–dc converters, which include the half-bridge and full-bridge types, These converters can provide high step-up and step-down voltage gain by adjusting the turns ratio of the transformer.

For non-isolated applications, the non-isolated bidirectional dc–dc converters, which include the conventional boost/buck multilevel [three-level] sepic/zeta, switched capacitor, and coupled inductor types, are presented. If higher step-up and step-down voltage gains are required, more switches are needed. This control circuit becomes more complicated. In the three-level type, the voltage stress across the switches on the three-level type is only half of the conventional type. However, the step-up and step-down voltage gains are low. Since the sepic/zeta type is combined of two power stages, the conversion efficiency will be decreased. The switched capacitor and coupled inductor types can provide high step-up and step down voltage gains. The proposed converter employs a coupled inductor with same winding turns in the primary and secondary sides. Comparing to the proposed converter and the conventional bidirectional boost/buck converter, the proposed converter has the following advantages:

1) Higher step-up and step-down voltage gains and 2) lower average value of the switch current under same electric specifications.

IV. RESULTS AND DISCUSSION

A. *Bidirectional fly-back converter*

Proposed circuit is simulated in MATLAB 7.1. The Simulink models for four phase bi directional flyback converter are shown in Fig 9. In order to verify the performance of the proposed converter, the specifications and circuit components are selected as

- Nominal battery voltage-60Volts
- Switching frequency-20k.hz
- Pulse width.
  forward switches-75% (%of period)
  backward switches-25% (%of period)
- IGBT Parameters*:*
  - Internal resistance-1e-3
  - Snubber resistance-1e5
  - Inductor parameters:
  - Winding1 self impedance
    - R=0.0003
    - L=1.1e-05
  - Winding 2 self impedance
    - R=0.0003
    - L=1.1e-05
    - Output capacitor-1000 UF

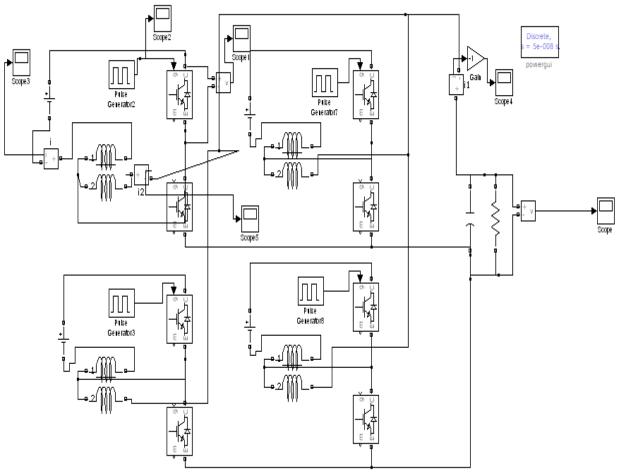


Fig. 9 Matlab/Simulink model of four phase bidirectional flyback converter

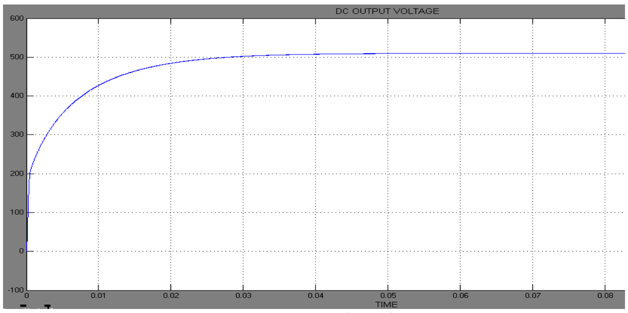


Fig.10 The output voltage of the flyback converter

Fig.10 Shows the output voltage of the flyback converter. The output voltage waveform of the flyback converter as shown in fig.10 if we observe the waveform the output voltage i.e the voltage across the capacitor is around 500 volts. The output voltage is boosted to 500V.

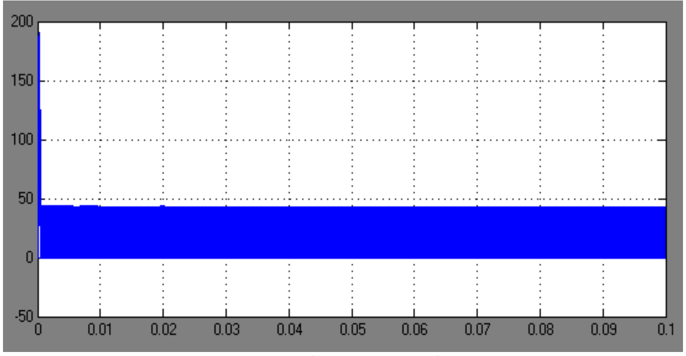


Fig.11 primary current flowing in the flyback converter.

The current flowing on the flyback converter is shown in fig.11. if we observe the above wave form initially the current is very high for a fraction of seconds. This value of current may damage the electronic switches and to avoid that it should be reduced to rated value. This high current can be reduced by using soft switching technique, which will avoid the sudden rise of current at starting.

B. Bidirectional fly-back converter with soft switching

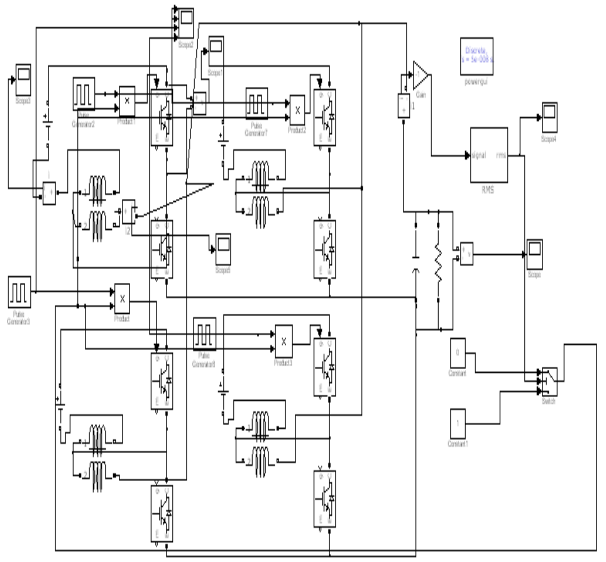


Fig 12. Simulink model of four phase bidirectional flyback converter with soft start

Matlab/Simulink model of four phase bidirectional flyback converter in soft start is shown in fig 4.4. Here in this circuit the output current is measured and compared with a pre set value. If the measured value is more than pre set value then gate pulses are not applied to IGBT switches. This will avoid high current at starting.

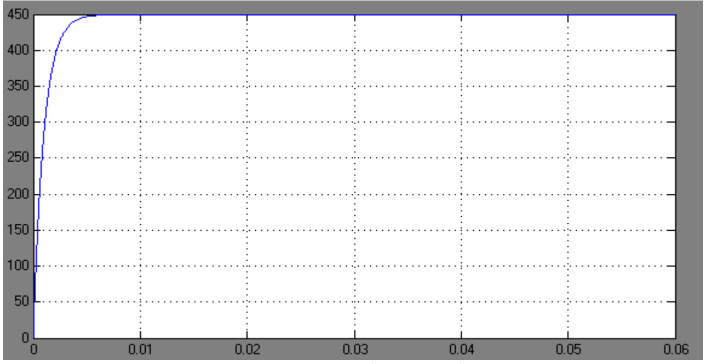


Fig 13 Output Voltage waveform in soft start.

Output Voltage waveform in soft start is shown in fig 13. The output voltage is similar to the voltage obtained in normal starting. No difference in output voltage but current differes from normal starting.

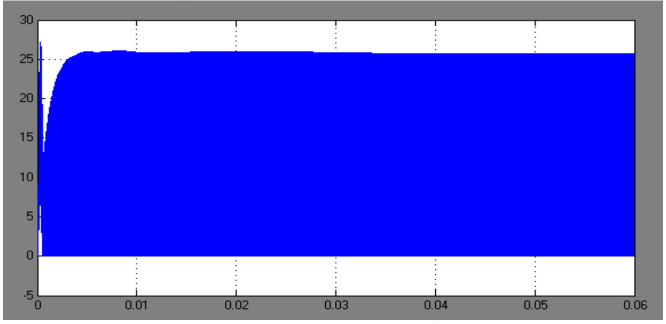


Fig 14. Output current using Soft start

The output current using soft start technique is shown in fig 14 it is observed that the starting current is differs from the normal starting. At starting the current is reduced to around 25 amps. Finally the current is steady around 25 amps only.

C. Bidirectional fly-back converter with Drive

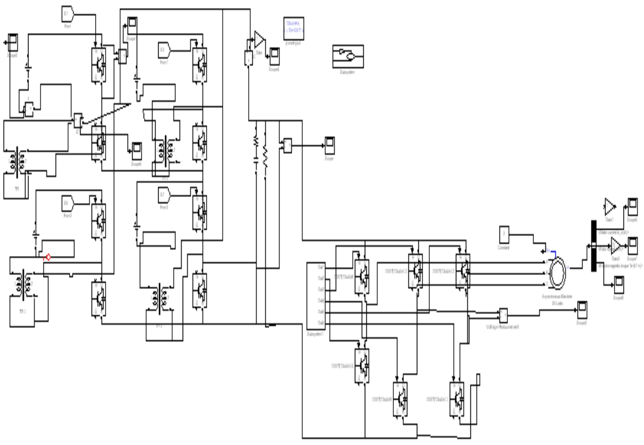


Fig 15 Simulink of Proposed Four-phase bidirectional fly-back converter Applied to induction motor drive

Simulink of Proposed Four-phase bidirectional fly-back converter Applied to induction motor is shown in figure 15. An induction motor is connected at the output terminals through an inverter. Induction motor is run and the results are observed.

Induction motor parameters are
Nominal power 10000 watts
voltage 700 (L-L)
frequency-50Hz
Stator resistance and inductance – 2, 0.01
Rotor resistance and inductance – 2, 0.01

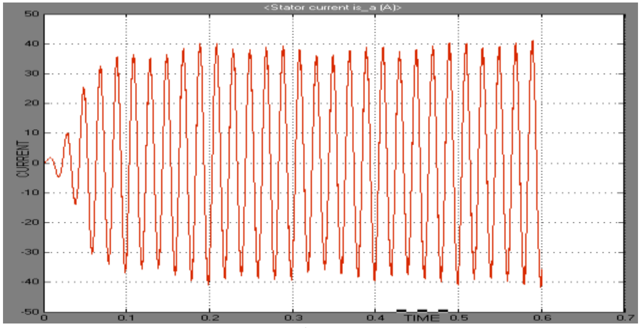


Fig 16 Stator Current of the Induction Motor Drive

The Stator Current of the Induction Motor Drive is shown in fig 16.

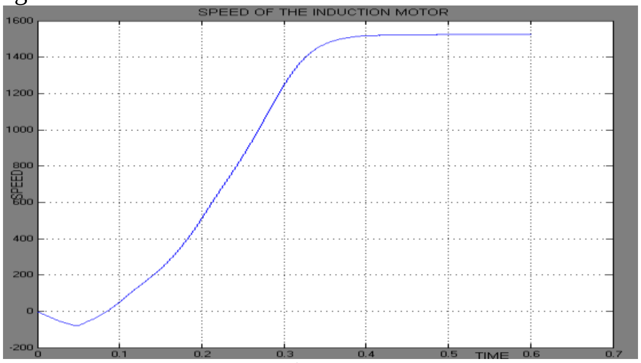


Fig.17 Speed of the induction motor.

The speed of the induction motor is shown in the fig 17. It is observed that the speed is steady at 1500 RPM.

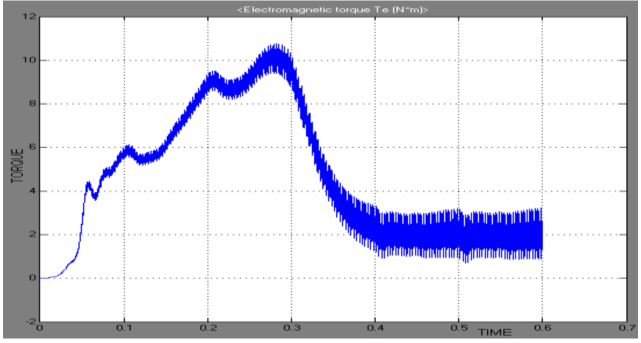


Fig.18. Electromagnetic torque of the induction motor

Electromagnetic torque of the induction motor is shown in fig 18.

V. CONCLUSION

This paper proposes a four phase bidirectional flyback dc-dc converter which serves role of an MPP interface for electric and hybrid electric vehicle applications. In This paper the four phase bi-directional flyback Converter has been simulated and the results are verified. During simulation, it is observed that the voltage at the output terminals is nearly 500 volts. Also observed that the current at the time of starting is very high. This value of current is decreased by using a technique called soft start. With this technique the current value is normal at the time of starting. The features obtained by this converter is very much suited for hybrid electric vehicles. Finally this converter is applied to an 3-ph induction motor through an inverter. Matlab/Simulink model for the entire circuit is developed and simulation results are presented.

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