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INTEGRATED BI-DIRECTIONAL DC-DC CONVERTER DESIGN FOR ELECTRIC TROLLEY

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Abstract – **The demand for battery fed electrical vehicle (BFEV) is expected to ascend with the rapid depletion of the earth's petroleum resources. But the range of BFEV is still limited due to the limitation in energy conversion efficiency, energy recovery during braking operation and fast transient operation. So, the analysis and improvement of energy conversion system for BFEVs is strongly recommended. This paper presents a highly efficient electrical circuit for BFEVs with the combination of a PI controlled bi-directional DC-DC converter and a Ćuk converter. First, the PI controlled isolated DC-DC bi-directional converter is designed to provide desired battery voltage for dc motor control and to run the flow of power under both steady-state and transient conditions. A boost converter is designed by using one IGBT and one MOSFET in parallel to condense the conduction loss and to guarantee a high output voltage. A comparati ve performance analysis between a Ćuk and a boost converter technique for BFEVs is also presented. An equivalent MATLAB/Simulink simulation model of the both system is developed to investigate the performance of both electrical circuits at different operating conditions. The Ćuk converter technique exhibits higher efficiency and better performance as compared to the proposed boost converter technique.**

Keywords—***PI Controlled Bi-Directional Isolated DC-DC Converter; IGBT; MOSFET; Boost converter; Parallel operation; Ćuk Converter.***

I. INTRODUCTION

Every day environment and human life is greatly affected by the pollution of large number automobiles around the world. In the recent years, global warming, air pollution and the rapid depletion of the earth's petroleum resources are becoming a concerning problem. It is highly e xpected that electric vehicles (EVs) will replace the conventional vehicles in the near future to reduce the pollution and hence to save the environment. Some supremacy of BFEVs over conventional vehicles are, guaranteed load levelling, nearly zero emission, energy recovery during braking operation and fast transient operation. As a result in the recent years researchers are working on electric vehicles performance enhancement topology. Current estimates put the global EVs fleet at over 140 million in 2012 with sales in 2013 topping 32 million. These are amazingly high figures and overwhelming the majority of these vehicles are electric vehicles. In future, a number of instantaneous changes in ICE technology, in energy storage device and energy conversion system, the efficiency of BFEVs will be increased that will attract more consumer.

Necessary parts of BFEV are bi-directional DC-DC converter, boost converter, battery, DC machine and controlling unit, where heart of the BFEVs is DC-DC bi-directional converter. There are two energy sources namely, battery section and generator section in this system. According to power electronics point of view, when power is transferred between two energy sources, an efficient energy interference system or power chain has to be developed. For hybrid vehicles, the dc drive link and the battery may be at different voltage levels. DC link may be at high voltage stage to have higher efficiency on the motor and batteries are at low voltage stage. Therefore, an efficient interfacing system between the drives dc link and the batteries is essential [1]. In BFEVs, the power stream is from battery to motor over acceleration and normal modes, while the kinetic energy of the motor is renewed into electrical energy and fed back to battery during regenerative mode. The interfacing system will control these two modes. This paper is focused on improvements of effectiveness and efficiency of converters and the total interfacing system for BFEVs.

Recently, BFEV system is widely researched, where the efficiency and performance improvement of the converter (especially, bi-directional DC-DC converter) is the key concentration of researchers [6-10]. Researcher offers soft switching technique to increase the transfer efficiency for bi-directional DC-DC converter [10]. Bi-directional DC-DC converters have been reported using coupled inductor intended for soft-switching technique with hysteresis current controller [7]. Zero-current-switched (ZCS) and zero-voltage-switched (ZVS) techniques is established for minimizing switching losses and to improve the reliability of bi-directional DC-DC converter [11]. During regenerative mode, the performance of overall power transfer through the electrical circuit of BFEV depends on the effective combination of step up converter and bi-directional DC-DC converter. For efficient operation researchers mainly analyse the performance of BFEVs by the combination of boost converter and bi-directional DC-DC converter. A high ripple output current of the boost converter is the main drawback of this method [12].

Therefore, this paper proposes a new design of converter circuits which combines a Ćuk and a PI controlled DC-DC bi-directional converter to provide the desired battery voltage for BFEV applications. This paper also presents a comparative study in selection of various converters. Results indicate that the efficiency of the proposed converter circuit is better than that of the conventional boost converter circuits.

II. BI-DIRECTIONAL DC-DC CONVERTER

To transfer the power between two DC sources in either direction bi-directional DC-DC converters are commonly used. These converters are being increasingly used in various applications such as dc uninterruptible power supplies, battery charger/dischargers, aerospace power systems, electrical vehicle

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motor drives, telecom power supplies, etc due to their capability to overturn the direction of power flow [2].

A. Conventional bi-directional DC-DC converter

Figure 1 shows the circuit arrangement of a conventional bi-directional DC-DC converter. When power flows from left to right the converter acts as a step up converter and S_1 acts as main switch whereas S_2 remains off. During opposite power flow the converter acts as a step down converter where S_2 acts as main switch and S_1 remains off.

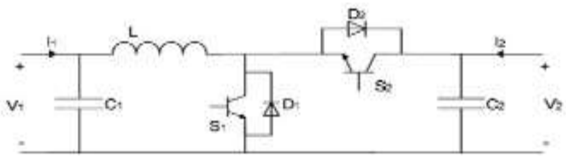

Fig.1: Circuit arrangement of bi-directional DC-DC converter.

During step down mode L, C1 and efficiency are given by (1), (2), and (3), respectively,

$$□ = \frac{V2 - V1}{\Delta iL(p-p)} DTs \quad (1)$$

$$□1 = \frac{\Delta iL(p-p)}{8\Delta Vc1(p-p)} Ts \quad (2)$$

$$5(□□e□\ □ow□) = \frac{Po}{Ps} = \frac{V2*(-I1)}{(V1*I1)} \quad (3)$$

During step up mode L, C2 and efficiency are given by (4), (5), and 6), respectively,

$$□ = \frac{V1}{\Delta iL(p-p)} DTs \quad (4)$$

$$□2 = \frac{-I2}{\Delta Vc2(p-p)} DTs \quad (5)$$

weakness of this conventional converter is that if the input of the converter is changed or distorted slightly it affects the output to a great e xtent as the output voltage is directly dependent on input voltage.

Fig.2: Input current and output voltage waveform of conventional bi-directional DC-DC converter during step down mode.

Fig.3: Input current and output voltage waveform of conventional bi-directional DC-DC converter during step up mode.

B. Proposed bi-directional DC-DC converter

Figure 4 shows a PI controlled isolated bi-directional DC-DC converter. A PI controller is used to provide the triggering pulse to the IGBTs to control both sides of the converter depending on the operating modes. As shown in Fig. 4 PI controller first takes the value of output voltage of the converter then compares it with the required output voltage or set value then it provides trigger signal to obtain a

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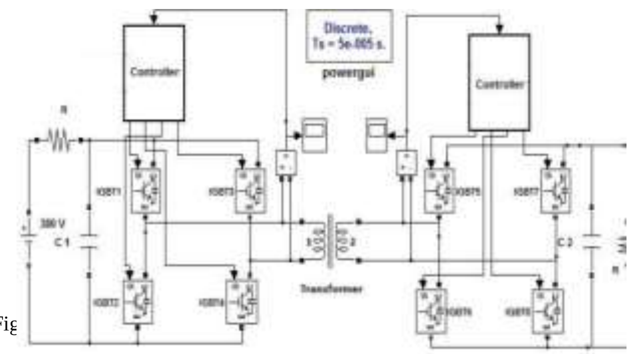
$$5(\square\square e\square\ \square\square) = \frac{P_o}{P_s} = \frac{V1*(-I1)}{(V2*I2)} \qquad (6)$$

where, duty cycle D = $T_{(ON)}/T_s$. $T_{(ON)}$ is the turn-on time and T_s is the total switching period, $\Delta i_{L(p-p)}$ and $\Delta V_{c1(p-p)}$ are the peak-to-peak ripple current of the inductor and the peak-to-peak ripple voltage of the capacitor [3]. The drawback of this converter is that the input current becomes discontinuous during step down mode due to turn on and turn off action of the main switch.

Figure 2 shows the discontinuity of input current during step down mode. To control the ripple below prescribed level an input filter composed of capacitor and inductor is required. Due to the turn on and turn off actions of the main switch output current and voltage becomes discontinuous during step up mode. Figure 3 shows the inductor current and output voltage during step up mode. To control the voltage and current ripples within the prescribed limit, a larger inductor or capacitor filter is required. Another



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voltage side is controlled by the PI controller and low voltage side acts as a rectifier and vice versa for step down mode [3]. During step down mode, a continuous input current flows through this converter and during step up mode this converter offers a continuous output current and voltage unlike conventional converter. Furthermore, during step up and step down modes additional filters are not required in the proposed converter.

Table -I: COMPARISON BETWEEN CONVENTIONAL AND PROPOSED BI-DIRECTIONAL DC-DC CONVERTER

Boost Mode			Buck Mode		
Input (V)	Conventional Output (V)	PI Controlled Output (V)	Input (V)	Conventional Output (V)	PI Controlled Output (V)
42	308	359	355	25	44.5
45	320	360	360	32	45.5
48	331	361.5	365	38.5	47

Table-I shows that in the case of PI controlled bi-directional isolated DC-DC converter, there is less variation in output voltage for different input voltages as compared to the conventionalbi-directional DC-DC converter.

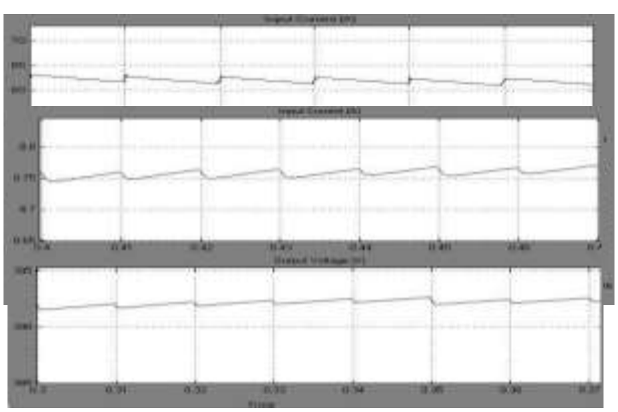

Fig. 5: Input current and output voltage waveform of the proposed bi-directional DC-DC converter during step down mode.

Fig. 6: Input current and output voltage waveform of the proposed bi-directional DC-DC converter during step up mode.

Figures 5 and 6 show that in the case of proposed bi- directional DC-DC converter during both step down and step up modes input current and output voltage becomes continuous and output voltage ripples are also reduced as compared to that of the conventional one.

III. STEP UP DC-DC CONVERTER

In BFEV circuit, a boost converter is required at regenerative

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mode. In this mode DC machine operates as a generator and generates a medium level of voltage. Then this voltage is increased up to a required level to ensure the voltage level of bi-directional DC-DC converter. Generally, this can be achieved by using a boost converter or Ćuk converter [5]. Figure 7 shows a boost converter where a MOSFET and IGBT are in parallel operation to reduce the conduction and off stage loss [6].

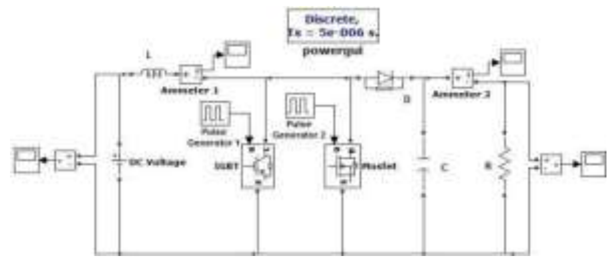

Fig. 7: Boost converter with parallel IGBT and MOSFET.

Figure- 8 shows the gate pulses of MOSFET and IGBT. As on-state losses of IGBT is less than that of MOSFET, so for the period of ON-state condition when IGBT and MOSFET conduct concurrently the MOSFET conveys only a small proportion of current whereas IGBT conducts the majority of the current.

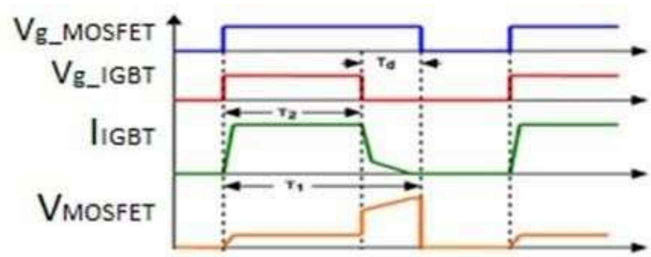

Fig. 8: Gate pulses of IGBT and MOSFET.

When the power IGBT is turned off, the power MOSFET carries most of the load current and IGBT demonstrates tail current while the terminal voltage of IGBT is very s mall due to parallel conduction of the MOSFET. Thus, the turn-off loss of the power IGBT is reduced. After a little impediment T_d, the power MOSFET will be turned-off. Hence, the turn- off losses of IGBT depend on discharging time which should be less than T_d [7].

A Ćuk converter is capable of stepping up and stepping down the voltage depending on the applications and operating condition and this is controlled by controlling the duty ratio of the single switch. A Ćuk converter produces a negative output voltage that is output voltage with respect to the same input ground. Figure-9 shows the circuit diagram of a Ćuk converter. Main dissimilarity of the Ćuk converter with the other non isolated dc converter is that the energy is transferred from input to output through a coupling capacitor [8].

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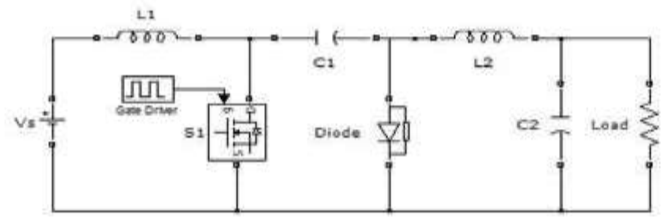

Fig. 9: Circuit arrangement of Ćukconverter.

Main drawbacks of boost converter is that the input current through the inductor is s mooth but the output current that flows through the capacitor load combination is pulsating which requires a very large capacitor filter to make it smooth. If this pulsating current is fed to a bi-directional DC-DC converter, it generates a distorted alternating square wave. To mitigate this problem instead of conventional boost converter, a Ćuk converter is used in BFEVs. In the case of Ćuk converter, the input and output current through the inductor is smooth, so there is no need of a large capacitor filter unlike boost converter. Figure-10 shows the output current waveform of a boost and Ćuk converter which illustrates boost converter provides a pulsating current where as Ćuk converter offers a smooth inductor output current.

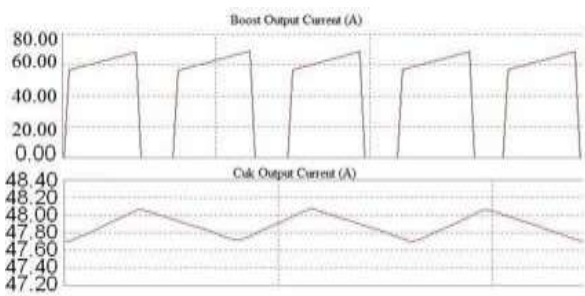

Fig. 10: Output current waveform of conventional boost and Ćuk converter.

IV. Circuit Design Techniquesfor BFEV

The electrical circuit of BFEV requires a DC machine, a step up converter, a bi-directional converter and an energy storage device as shown in Fig. 11.

A. Simulation Model of Conventional Boost and PI Controlled Bi-Directional Isolated DC-DC converter :

Figure 11 shows MATLAB/Simulink based simulation model of electrical circuit for BFEV using a boost and bi-directional isolated DC-DC converters. The simulation model incorporates a separately e xcited DC machine which can be utilized as either motor or generator by altering the polarity of the mechanical input that is torque (T_L), a 48 volt-6.5 Ah Ni-MH generic battery model which is used as a storage device, a boost converter is used as step up converter and a PI controlled bi-directional DC-DC converter. A transformer is used to change the voltage levels and also to

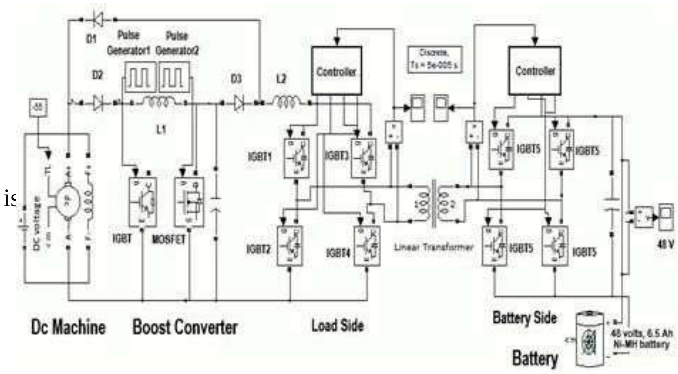

Fig. 11: Circuit arrangement of BEFV using a boost and PI controlled bi-directional DC-DC converter.

This circuit has two key operational modes; acceleration and regenerative mode. In acceleration mode, power flows from storage device (battery) to dc machine. The battery side of the bi-directional converter is controlled by PI controller to obtain a satisfactory voltage level for transformer where the load side converter (IGBTs 1-4) acts as a rectifier. First, 48 Vdc is inverted into 48 Vac and fed to the transformer to boost up to 400 Vac which is further rectified as 400 Vdc. Then 400 Vdc is fed to the dc machine (acts as motor) through the forward diode D1. The DC Machine acts as a motor which runs at approximately 3800 rpm at 400 Vdc. This mode is also called boost mode of the circuit. Figures 12-15 show the responses at different terminals of BFEV during acceleration mode [9].

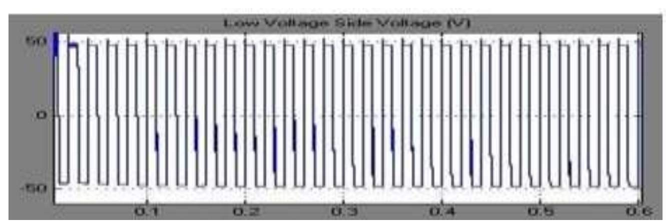

Fig. 12: Voltage waveform of low voltage side of bi-directional DC-DC converter.

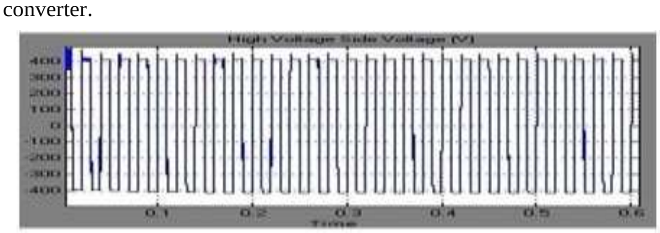

Fig. 13: Voltage waveform of high voltage side of bi-directional DC-DC converter.

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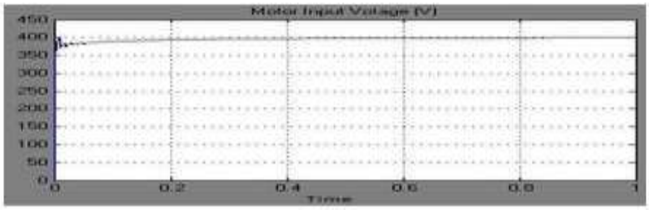

Fig. 14: Motor input voltage waveform.

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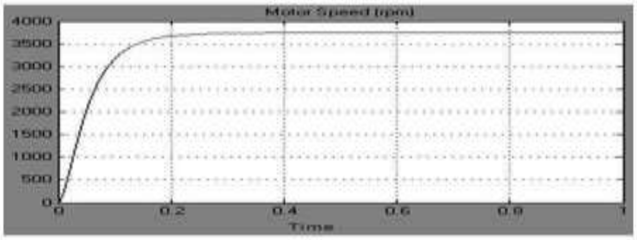


Fig. 15: Motor speed response.

In regenerative mode, the power flows from dc machine (acts as generator) to storage device (battery). DC machine supplies 140Vdc which is fed to a boost converter through the forward diode D2 to boost up to (395±10)Vdc. In boost converter the duty cycle of IGBT and MOSFET is set at 80% and 95% respectively. This technique helps to reduce the on-state loss of MOSFET and off-state loss of IGBT. Then this (395±10)Vdc flows to the bi-directional converter through the forward diode D3. The motor side of b i-directional converter is controlled to obtain a fixed 400Vac to the transformer, whereas, the battery side acts as a rectifier to produce 48Vdc, which is fed to the battery. It is called buck mode of the circuit. Figures 16-20 show the responses at various terminals of BFEV during regenerative mode. Figure-16 shows that, 140Vdc is produced by the generator whereas figure-17 shows the output voltage waveform of boost converter with a high transient value. Figure-18 and 19 shows the output voltage waveform of bi-directional DC-DC converters for high and low voltage side respectively whereas figure-20 represents the battery charging stage during regenerative mode.

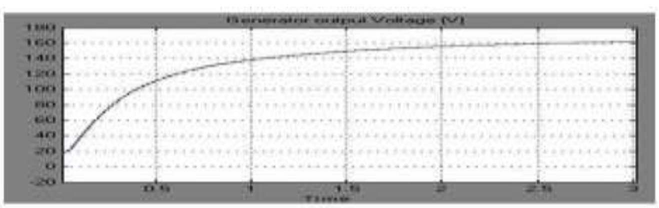


Fig. 16: Generator output voltage waveform.

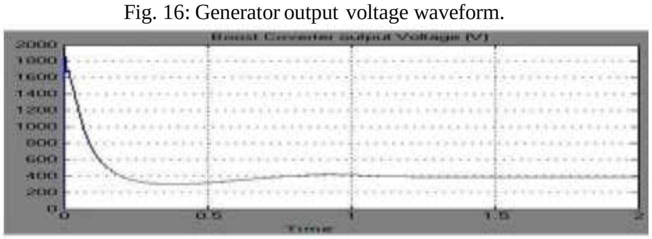
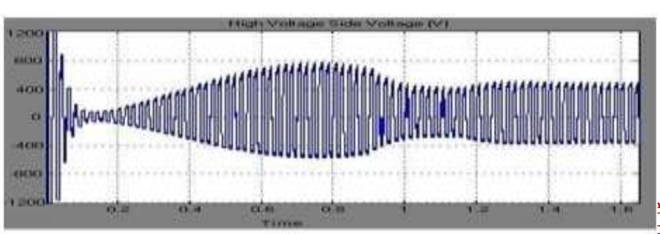


Fig. 17: Boost converter output voltage waveform.



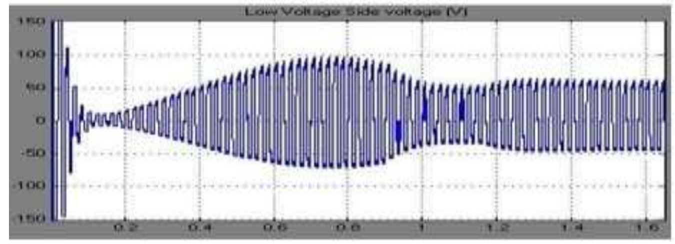


Fig. 18: Voltage waveform of high voltage side of bi-directional DC-DC converter.

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Fig. 19: Voltage waveform of low voltage side of bi-directional DC-DC converter.

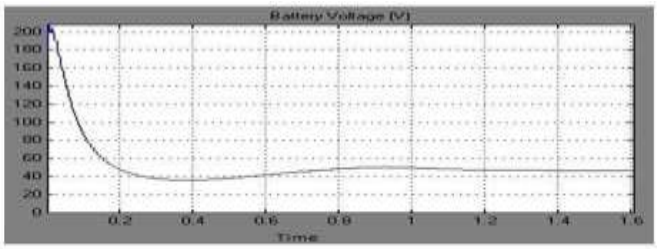
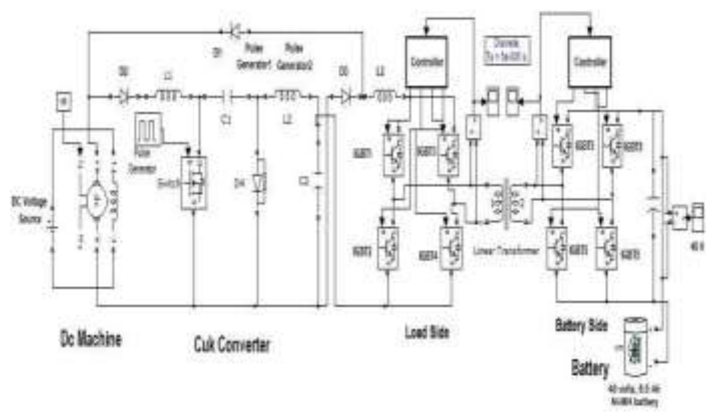


Fig. 20: Battery input voltage waveform.

B. Simulation Model using Ćuk converter and bi-directional isolated DC-DC converter

Figure 21 shows MATLAB/Simulink based simulation model of electrical circuit for BFEV using Ćuk and bi-directional isolated DC-DC converters.

Fig. 21: Circuit arrangement of BEFV using a Ćuk converter and PI controlled bi-directional DC-DC converter.



The operation of this model is identical to the previous one for acceleration mode. During regenerative mode a Ćuk converter is used to step up the DC generator voltage up to the required level for bi-directional DC-DC converter. Figures 22-25 show the output curves at various terminals of BFEV during regenerative mode. It is clear seen from Figs. 16-26 that for the boost converter technique both low and high voltage side of bi-directional DC-DC converter contain a large amount of ripple due to pulsating current and takes approximately 1.2 ms to reach to the stable position. As a result, at battery terminal a high pulse appears before saturation condition is obtained. On the other hand, in case

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of Ćuk converter technique both low and high voltage side of bi-directional DC-DC converter contains a very low amount of ripple and they take only 0.3 ms to reach to the stable position. Ćuk technique also offers a suitable battery voltage without a high initial pulse.

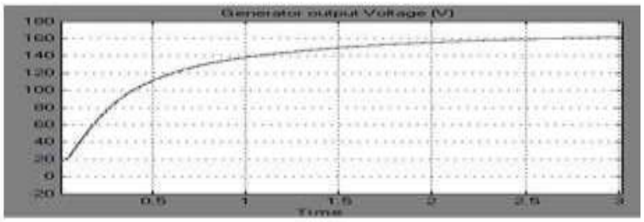

Fig. 22: Generator output voltage waveform.

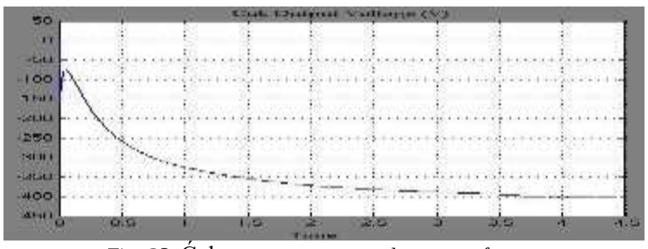

Fig. 23: Ćuk converter output voltage waveform.

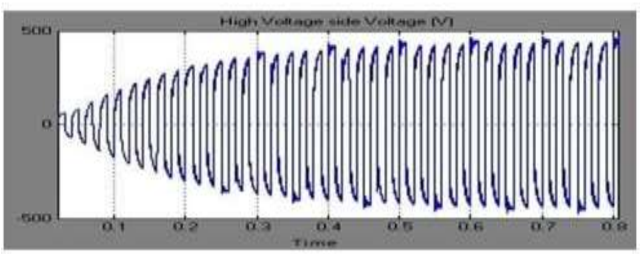

Fig. 24: Voltage waveform of high voltage side of bi-directional DC-DC converter.

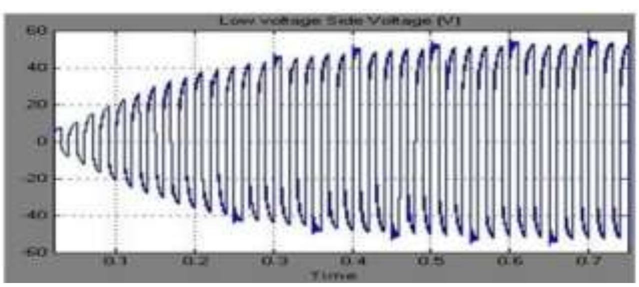

Fig. 25: Voltage waveform of low voltage side bi-directional DC-DC converter.

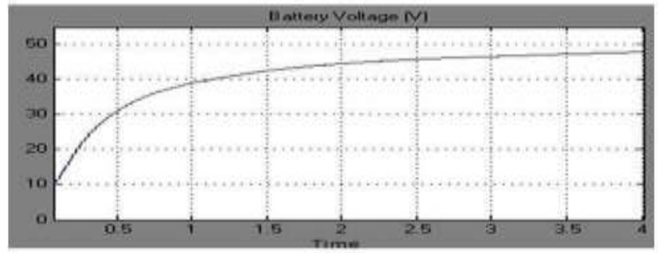

Fig. 26: Battery voltage waveform.

V. CONCL U SION

The proposed equivalent electrical circuit for BFEV containing a Ćuk converter and a PI controlled bi-directional DC-DC converter offers a ripple free and stable output at both acceleration and regenerative mode as compared to the parallel switch based boost converter technique. This circuit does not need large capacitive filters at both sides of the bi-directional converter and thus, increases the efficiency of BFEVs . As a future work, a super capacitor bank for this system can be introduced and fuzzy technique can be used for converter control.

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