Abstract—Batteries, ultra capacitors, fuel cells, and solar arrays are widely used in electric and hybrid vehicles (EVs/HVs) as an electric power source or an energy storage unit. In the structure of the electric power system of modern EVs/HVs, more than one of these units may be employed to improve the performance and efficiency; hence utilization of a multi-input dc–dc converter is inevitable to obtain a regulated bus dc voltage. In this paper, a review of multiple input dc–dc power electronic converters (MI-PEC) devoted to combine the power flow from several on-board energy sources of an EV/HV is presented. Several multi-input dc–dc converters based on various topologies are studied and analyzed. The operating modes of each topology is presented and compared with other topologies.

I. INTRODUCTION

EVs and HVs are gaining popularity compared to internal combustion engine (ICE) vehicles as they can save energy which is lost during various acceleration and deceleration cycles of the conventional ICE vehicles. In order to achieve this, different power sources or energy storage systems are employed in the EVs/HVs. Several power sources are required so that one input can run at the optimal rating with maximum efficiency, say the ICE for example and then any additional acceleration requirement can be fulfilled by another input source; say the ultra capacitor or battery unit. During deceleration reverse regenerative braking can be employed and the energy can be stored in batteries and ultra capacitors. Customer demands for greater acceleration performance and vehicle range in EVs and HVs increase the appeal for combined on-board energy storage systems.

In conventional approaches for two/multiple voltage sources connected in series, a control switch has to be provided for each dc voltage source to act as by-pass short-circuit for input current of other supply. However for a parallel connection, because of the difference between two dc voltage amplitudes, only one of the two sources can be connected at a time. Multi-input dc–dc converters, as shown in Fig. 1, are the unique solution to combine several input power sources whose voltage levels and/or power capacity are different and to get regulated output voltage for the load from them.

Various multi-input power electronic converter topologies have been proposed in the literature to interface traction drive requirements with on-board energy sources [1-4]. The proposed techniques are mainly based on (i) pulse width modulation (PWM) dc–dc converter for high/low voltage sources, (ii) the concept of flux additivity, and (iii) converters for energy storage units including advanced batteries and ultra capacitor banks. In this paper, without loss of generality, only two or three input voltage sources are considered. The concept can further be extended to various numbers of input sources.

Chen in [1] proposed a converter circuit topology with two input voltages and a regulated output voltage. In order to implement the double-input PWM dc–dc converter for high/low voltage sources two dc sources are put in parallel by using a coupled transformer. In [2], the concept of the magnetic flux additivity, where the input dc sources are combined in magnetic form by adding up the produced magnetic flux together in the magnetic core of a coupled transformer has been employed to combine two current-fed full-bridge dc/dc converters. A multiple input dc–dc power converter devoted to combine the power flow of a multi-source on board energy system is presented by Napoli in [3]. The employed energy system includes a generator, an ultra capacitor (UC) tank, and a battery system.

In this paper, three different multi-input power converters are studied and classified based on their characteristics. Furthermore, the basic circuitry and the topological arrangements of these converters are illustrated and analyzed. The various modes of operation of the converters are discussed. The advantages and
disadvantages of using these arrangements to run the hybrid electric propulsion drives are studied. An attempt is made to investigate the optimal and feasible solution by utilizing the benefits of all these designs.

II. MULTI-INPUT CONVERTER USING HIGH/LOW VOLTAGE SOURCES

The circuit diagram of this topology is depicted in Fig. 2. This topology consists of two input voltage sources, high voltage source $V_H$ and low voltage source $V_L$, and an output voltage of $V_o$ where $V_H > V_o > V_L$ [1]. When the power switches $M_H$ and $M_L$ are turned off, diodes $D_H$ and $D_L$ will provide the by-pass path for the inductor current to flow continuously. By applying the PWM control scheme to the power switches $M_H$ and $M_L$, the proposed double-input dc-dc converter can draw power from two voltage sources individually or simultaneously.

The four different modes of operation based on the status of the power switches, as depicted in Fig. 3, can be explained as follows [1]:

**Mode I** ($M_H$:on / $M_L$:off): Switch $M_H$ is turned on and $M_L$ is turned off. Because of conduction of $M_H$, power diode $D_H$ is reverse biased and treated as an open circuit and diode $D_L$ will provide a by-pass path for the inductor current as shown in Fig. 3(a). In this mode, $V_H$ charges inductor $L$, capacitor $C$, and provides the electric energy for the load.

**Mode II** ($M_H$:off / $M_L$:on): Power switch $M_H$ is turned off and $M_L$ is turned on. This results in power diode $D_H$ to turn on as a short circuit and $D_L$ to turn off as an open circuit as depicted in Fig. 3(b). During this operation mode, $V_L$ will charge inductor $L$, while the load is supplied by output capacitor $C$.

**Mode III** ($M_H$:off / $M_L$:off): Both of switches $M_H$ and $M_L$ are turned off. Diodes $D_H$ and $D_L$ are disconnected from the double-input converter. The electric energy stored in $L$ and $C$ will be released into the load.

**Mode IV** ($M_H$:on / $M_L$:on): $M_H$ and $M_L$ are turned on which results in $D_H$ and $D_L$ to turn off with reverse biased voltages, $V_H$ and $V_L$ are connected in series to charge inductor $L$. The demanded power for the load is now provided by capacitor $C$ as depicted in Fig. 3(d).

For the same switching frequency, the turn-off synchronization in which $M_H$ and $M_L$ are synchronized by the same turn-off transition with different turn-on moment is considered. Fig. 4 shows typical voltage and current waveforms of this converter [1]. From top to bottom are the waveforms of high voltage source input current $i_H$, low voltage source input current $i_L$, and unfiltered output current $i_o'$.
power is transferred to the load when two switches of the same leg in each input stage circuit are turned on. This is because the input current is freewheeling through these turned on switches. The output can be regulated by controlling the time ratio of the power transferring stage to the freewheeling stage. The operation of the converter over one full switching cycle is divided into twelve different operation modes. Current waveforms of the primary side $i_{p1}$ and $i_{p2}$ and the secondary side of the transformer $i_s$ are illustrated in Fig. 6 [2].

The six operation modes within the one half of switching cycle are symmetrical to the other six operation modes. Therefore, only the first six operation modes over one half switching cycle are described below [2].

**Mode 1: ($t_0 \leq t < t_1$)** At time instant $t_0$, $M_3$ is turned off. Power starts to flow from the first input-stage circuit through the transformer to the load. The current source, $I_{s1}$, in the first input-stage circuit will flow through the first transformer winding, $T_1$, via switches $D_1$, $M_1$, $D_4$, and $M_4$, while $I_{s2}$ is still kept freewheeling in the second input-stage circuit. The magnetic flux produced by the first winding current, $i_{s1}$, will induce voltages on other transformer windings. Induced voltages across transformer windings, $T_1$, $T_2$, and $T_3$, are clamped to $(n_1V_o)/n_1$, $(n_2V_o)/n_2$, and $V_o$, respectively. Diodes, $D_2$ and $D_3$, in the output-stage circuit will be turned on because of the induced transformer winding voltage, $V_o$, which results in the conduction of the body diode of Switch $M_8$.

**Mode 2: ($t_1 \leq t < t_2$)** At time instant $t_1$, $M_8$ is turned on at zero voltage due to the conduction of its body diode in the previous operation mode. During this mode, $M_8$ is turned on but conducts no current. The input current $I_{s2}$ is still kept freewheeling through $D_5$, $M_5$, $D_8$, and $M_7$ in the second input-stage circuit. Operations of the first input-stage and the output-stage circuits remain unchanged.

**Mode 3: ($t_2 \leq t < t_3$)** This mode begins when switch $M_7$ is turned off at $t_2$. The current source, $I_{s2}$, in the second input-stage circuit will flow through the second transformer winding, $T_2$, via switches $D_2$, $M_5$, $D_8$, and $M_8$ and start to transfer power to the load. During this operation mode, both of the first and the second input-stage circuits are delivering power to the load individually and simultaneously. The total magnetic flux linkage in the coupled transformer is increased because of the additional magnetic flux produced by the second winding current, $i_{s2}$. The operation of the output-stage
circuit and the clamped transformer winding voltages stay unchanged.

Mode 4: \( (t_5 \leq t < t_6) \) At time instant \( t_5 \), both \( M_2 \) and \( M_6 \) are turned on. Switches \( M_1 \) and \( M_5 \) are still kept on but conduct no current. All of the diodes in the output-stage circuit will be reverses biased since all of transformer winding voltages are clamped to zero because of the freewheeling currents in the two input-stage circuits. No power is transferred from any input-stage circuit to the output-stage circuit. The power demanded by the load is provided by the output filter capacitor, \( C \).

Mode 5: \( (t_6 \leq t < t_7) \) Switches \( M_1 \) and \( M_5 \) are turned off with zero current at \( t_6 \). The current sources \( I_{S1} \) and \( I_{S2} \) are kept freewheeling in the input-stage circuits, and no power is delivered to the load.

Mode 6: \( (t_7 \leq t < t_8) \) At time instant \( t_7 \), \( M_3 \) is turned on at zero voltage due to the clamped zero voltage across the first transformer winding, \( T_1 \). The rest of the circuit is the same as described in the previous operation mode. Two current sources are freewheeling in the input-stage circuits and no power is delivered to the load. Mode 7 begins when \( M_4 \) is turned off at \( t_8 \). This mode is similar to mode 1. The polarity of transformer voltages and currents are opposite to these shown in mode 1. Consequently, modes 8 through mode 12 can be found to be symmetrical to mode 2 through mode 6, too.

IV. MULTI-INPUT DC-DC CONVERTER FOR ENERGY STORAGE UNITS

The circuit topology of the multi input dc-dc converters for energy storage units like advanced batteries and ultra capacitor banks is shown in Fig. 7. This arrangement is suitable to connect high and low voltage power sources \([3]-[4]\). In the generator systems, UC tanks, and battery systems the numbers of elements connected in series are limited to improve the system reliability. The regulated output voltage is load and the battery system state of charge (SOC) dependent.

This topology is generally used to drive traction loads, for instance a hybrid vehicle. Therefore, a bidirectional converter is selected such that the converter acts as step up converter (boost converter) for one mode of operation and as step down converter (buck converter) for other mode of operation. Each power source is connected to the dc link by means of this bidirectional step up or step down dc-dc converter. Step up mode of operation is used in order to transfer energy from each power source to the dc-link, where as step down operation is used to charge both UC tank and battery storage system and to recover the braking energy.

The converter is composed of two controlled switches, two diodes, one input inductor and output capacitor. Volume saving strategy is applied to the converter under consideration. This is prevalent by the useless presence of switch and diode concerning the step down configuration in the generator systems side of the converter, where energy can not be recovered during braking mode of operation. The control switches are controlled in order to supply the dc link following the traction power demand. The control manager shares the power flow on the basis of UC and battery SOC. The desired dc-link voltage level is accomplished in every working condition by operating on battery-side converter.

V. CONCLUSION

Multi-input power converters are considered and three topologies were discussed. Their characteristics were studied and comparisons were made between them. Future work will be addressed to carry on simulations on these three designs being used in an electric or hybrid vehicle. More emphasis will be given to finding the optimal and feasible designs by incorporating all the advantages of these designs.

REFERENCES