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RESEARCH ARTICLE

A NOVEL MULTI CHANNEL DC-DC CONVERTER FOR HYBRID ENERGY SOURCES

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Abstract

In this paper, we proposed a new boost converter for hybridizing alternative energy sources. In fact by hybridization of energy sources advantages of different renewable sources are achievable. In this converter power can be flexibly distributed without any distortion between input sources. This converter has several outputs with different voltage levels which make it suitable for interfacing different inverters. Using different inverters leads to reduction of voltage harmonics. The converter has two inductor and two capacitor. Depending on charging and discharging states of the energy storage system, two different power operation modes are defined for the converter. The validity of the proposed converter and its control performance are verified by stimulation and experimental results for different operation conditions

Keywords: DC-DC Converters, hybrid power systems, phase voltage divider, multiple-input-multiple-output (MIMO)

1. INTRODUCTION

Increasing rapidly population and energy consumption in the world, increasing oil and natural gas prices, and the depletion of fossil fuels are justifiable reasons for using electrical vehicles (EVs) instead of fossil-fuel vehicles. The interest in developing the EVs with clean and renewable energy sources as a replacement for fossil-fuel vehicles has therefore steadily increased. The EVs are proposed as a potential and attractive solution for transportation applications to provide environmentally friendly operation with the usage of clean and renewable energy sources [1], [2]. In the EVs, the fuel cell (FC) stack usually used as clean energy source. The FCs are energy sources that directly convert the chemical energy reaction into the electrical energy. Currently, FCs is acknowledged as one of the promising technologies to meet the future energy generation requirements.

FCs generates electric energy, rather than storing it, and continues to deliver the energy, as long as the fuel supply is maintained. However, there are some well-known technical limitations to FCs: they have slow power transfer rate in transitory situations, and a high cost per watt. This case is the reason for which FCs are not used alone in the EVs to satisfy the load demands, particularly during startup and transient events. So, in order to solve these problems, usually FC is used with energy storage systems (ESSs) such as batteries or super capacitor (SC). Furthermore, the association of FC and ESSs leads to a reduction of the hydrogen consumption of the FC [3]–[7]. FC and ESSs such as battery and SC have different voltage levels. So, to provide a specific voltage level for load and control power flow between input sources, using of Dc–dc converters, high-frequency transformer are used in order to make electric isolation. High frequency transformer provides electric isolation and impedance matching between two a dc–dc converter for each of the input sources is need. Usage of a dc–dc converter for each of the input sources leads to increase of price, mass, and losses. Consequently, in hybrid power systems, multi-input. Dc–dc converters have been used. Multiinput converters have two main types, isolated multiinput dc–dc converters and nonisolated multiinput dc–dc converters. In the following sections, two main types of multiinput converters are investigated. In isolated multi-input sides of converter. In general, isolated dc–dc converters use leakage inductance as energy storage for transferring power between two sides of

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converter. Usually isolated dc–dc converters, in addition to high-frequency transformer, have high-frequency inverter and rectifier.

The power flow between input and output sides is controlled by adjusting the phase shift angle between primary and secondary voltages of transformer [8]–[10]. Isolated dc–dc converters have several types such as half-bridge isolated converters, full-bridge isolated converters, boost half-bridge isolated converters, and combinational multiport isolated converters [11]–[13]. Due to using of transformer, isolated dc–dc converters are heavy and massive. These converters require inverters in input sides of transformer for conversion of input dc voltage to ac and also need rectifiers in outputs of transformer for conversion of ac voltage to dc. Therefore, all input and output terminals of these converters, several switches are applied which leads to increase of cost and losses. Furthermore, transformer has losses in its core and windings.

2. RELATED WORK

Isolated multi-input dc–dc converters, usage of non isolated multiinput dc–dc converters in electric vehicle applications seems more useful. In [14], a nonisolated multiinput dc–dc converter which is derived from H-bridge structure has been proposed. In fact, by cascading two H-bridges with different dc-link voltages, different voltages due to addition or subtraction of H-bridges outputs are accessible. Modes in which either output voltage of the H-bridges is negative are not considered here because they are related to bidirectional double-input converters, which were beyond the scope of paper. By eliminating the fore mentioned non-useful modes, a simplified double input Dc–dc converter is obtained. The advantage of this converter is its less number of passive elements, and its drawback is unsuitable control on the power which is drawn from input sources. In [15]–[17], a multi-input dc–dc buck converter is introduced. In fact, this converter consists of paralleling two buck converter in their inputs. One switch is series to each input source to prevent short circuit of sources. The advantage of this converter is reducing the number of inductors and capacitors which lead to reduction in cost, volume, and weight of converter. Lack of proper power flow control between input sources with each other is a short coming of the proposed converter. In [18], multiinput z-source dc–dc converter is presented. The structure of proposed converter is changed such that the number of inductors and capacitors is equal to a single input z-source converter. Nevertheless, two inductor and capacitor is applied in the proposed converter. In [19], multiphase converter is introduced. The proposed converter has four input by different voltages. In this converter, each of the energy sources can deliver or absorb energy from load and other sources. Employment of a separate inductor for each input source is the drawback of this converter. In [20], a triple input converter for hybridization of battery, photo voltaic cells, and fuel cell is introduced by the author. By proper switching of converter, charge and discharge of battery by means of other sources and load is possible, respectively. In [21], a systematic approach for derivation of nonisolated multiinput converter topologies by combination of buck, boost, buck and sepic is presented. According to this paper, mentioned converters are divided to two types, pulsating voltage source converters (PVSC) and pulsating current source converters (PCSC). Because PVSC is considered as a voltage source, it can put series with current buffer (inductor) branch or output of other converter to form a double input converter. Also, because PCSC is considered a sa current source, it can be located in parallel with a voltage buffer (capacitor) branch or output of other converter to form a double input converter. In [22], a new converter for power and energy management between battery, SC, and electric motor in an electric vehicle is proposed. In this converter, instead of two separate inductors as energy storage element, a coupled inductor is used. It is claimed that utilization of coupled to 22%–26% volume reduction in comparison with two separated inductors. However, volume of coupled inductors is more than one inductor. Also, regeneration of brake energy to battery and SC in this converter is possible. In [23], a multi-input converter with just one inductor is proposed which is able to distribute load power between input sources. Also, in this converter, transferring power between sources is possible. In [24], a new extendable single stage multiinput dc–dc/ac boost converter proposed by the author. On the other hand, it is important in electric vehicles to have low-torque ripple. Torque ripple has direct relation to voltage harmonics in ac motors. One way to reduce voltage harmonics is using of multilevel inverters. To generate multilevel voltage by multilevel inverters, dc sources with different or equal voltage level is required. One way to generate several dc-links is usage of multi-output dc–dc converters. In [25] and [26], a single inductor multi-output dc–dc converter is proposed which can generate several different voltage levels in its outputs.

3. PROPOSED CONVERTER STRUCTURE AND OPERATION MODES

As mentioned in the Introduction, in [25], a multi-output converter is presented. The proposed converter is a single input converter. On the other hand, use of just one input energy source in electric vehicles cannot provide load requirements because the load is dynamic and its power has variation. Therefore, hybridization of different sources is essential. As mentioned in the introduction, in [23], a nonisolated multiinput dc–dc converter for hybridization of energy sources is proposed which has just one inductor. In this paper, a nonisolated multiinput multi-output dc–dc converter based on the combination of these two converters is proposed. The structure of the proposed converter is presented in Fig. 1.

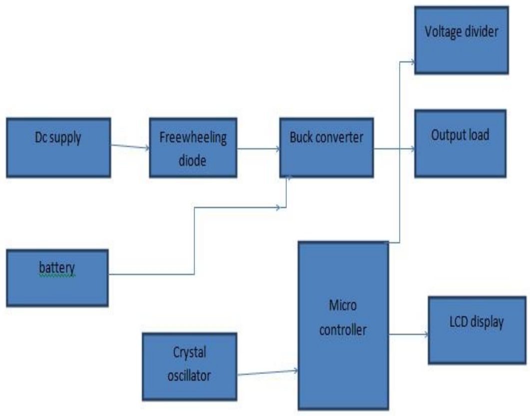

Figure.1. Proposed Converter Architecture

As seen from the figure, the converter interfaces *m* input power sources $V_{in1}, V_{in2}, V_{in3}, \ldots, V_{inm}$ such that $V_{in1} < V_{in2} < V_{in3} \ldots < V_{inm}$. The proposed converter has just one inductor, *n* capacitors in its outputs and $m + n$ switches. The R_1, R_2, $R_3 \ldots R_n$ is the load resistances, which can represent the equivalent power feeding a multilevel inverter. By proper switching of switches, control of power flow between input sources in addition to boost up input sources voltages is possible. Outputs are capable to have different or equal voltage level which is appropriate for a connection to a multilevel inverter. The proposed converter is suitable alternative for hybridizing of FC, battery, or SC. In this paper, for convenience, proposed converter with two-input two-output is analyzed. In Fig. 2, the proposed converter with two-input, two-output is shown. In this figure, $R1$ and $R2$ is the model of load resistances that can represent the equivalent power feeding a multilevel inverter. Different types of multilevel inverters can be used in connection to this converter. Multilevel inverter which is used must be with nonfloating dc-links. Four power switches $S1$, $S2$, $S3$, and $S4$ in the converter structure are the main controllable elements that control the power flow and output voltages of the converter. In the proposed converter, source Vin1 can deliver power to source Vin2 but not vice versa. So, in EV applications, FC which cannot be charged is located where Vin1 is placed in circuit. Also, usually where Vin2 is placed, mode when the loads power and battery charging current have low values, it is possible that the converter works in discontinuous conduction mode (DCM). So, the condition in which the converter goes to DCM is investigated. It should be noted that each of input sources can be used separately. In other words, the converter can work as a single input dc–dc. Two main operation modes of the converter have been investigated as follows:

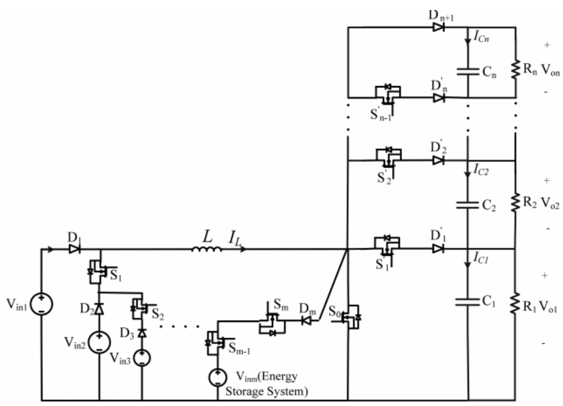
Figure.2. Proposed converter structure.

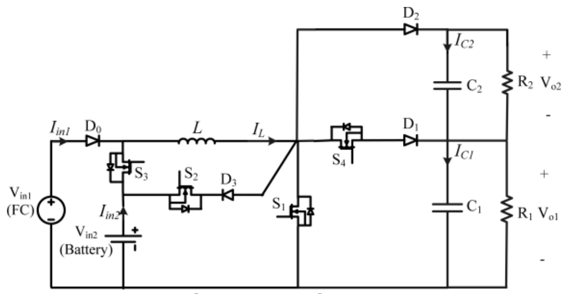

Figure.3. Proposed converter with two-input, two-output.

A. First Operation Mode (Battery Discharging Mode)

In this operation mode, two input power sources V_{in1} and V_{in2} (battery) are responsible for supplying the loads. In this mode, S_2 is OFF entirely and S_1, S_3, and S_4 are active. For each switch, a specific duty is considered. Here, $S1$ is active to regulate source 2 (battery) current to desired value. In fact, $S1$ regulates battery current to desired value by controlling inductor current. Regulation of total output voltage $VT = VO1 + VO2$ to desired value is duty of the switch $S3$. Also, output voltage $VO1$ is controlled by $S4$. It is obvious that by regulation of VT and $VO1$, the output voltage $VO2$ is regulated too. Gate signals of switches and also voltage and current waveforms of inductor are shown in Fig. 3. According to switches states, there are four different operation modes in one switching period as follows:

1) Switching State 1 ($0 < t < D3T$*):*

In this state, switches $S1$ and $S3$ are turned ON. Because $S1$ is ON, diodes $D1$ and $D2$ are reversely biased, so switch $S4$ is turned OFF. Since $S3$ is ON and $Vin1 < Vin2$, diode $D0$ is reversely biased. Equivalent circuit of proposed converter in this state shown in figure.4 (a). In this state, $Vin2$ charges inductor L, so inductor current increases. Also, in this mode, capacitors $C1$ and $C2$ are discharged and deliver their stored energy to load resistances $R1$ and $R2$, respectively.

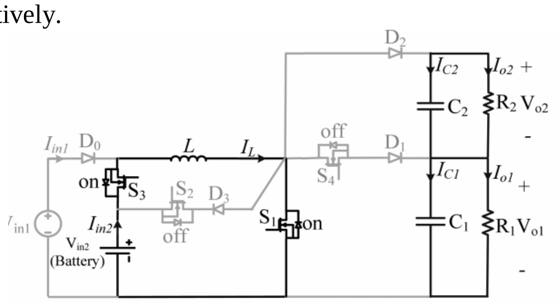

Figure.4 (a). Switching state 1

2) Switching State 2 ($D3\,T < t < D1\,T$*):*

In this state, switch $S1$ is still ON and $S3$ is turned OFF. Because $S1$ is ON, diodes $D1$ and $D2$ is reversely biased, so switch $S4$ is still OFF. In this state, $Vin1$ charges inductor L, so inductor current increases. In addition, capacitors $C1$ and $C2$ are discharged and deliver their stored energy to load resistances $R1$ and $R2$, respectively shown in figure.4 (b).

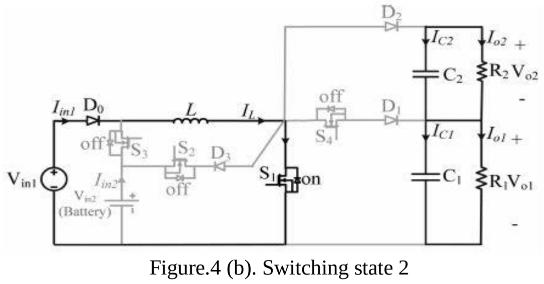

Figure.4 (b). Switching state 2

3) Switching State 3 ($D1T < t < D4\,T$*):*

In this mode, switch $S1$ is turned OFF and switch $S3$ is still OFF. Also, switch $S4$ is turned ON. Diode $D2$ is reversely biased. In this state, inductor L is discharged and delivers its stored energy to $C1$ and $R1$, so inductor current is decreased. In this state, $C1$ is charged and C_2 is discharged and delivers its stored energy to load resistance R_2 shown in figure.4 (c).

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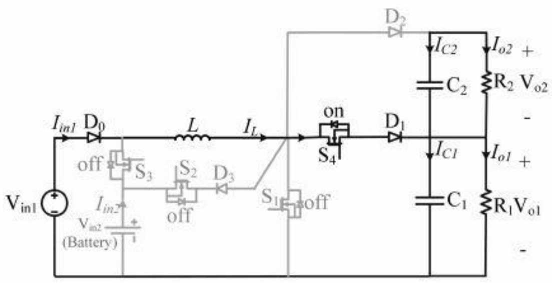

Figure.4 (c). Switching state 3

4) Switching State 4 ($D4T < t<T$):

In this mode, all of three switches are OFF. So, diode $D2$ is forward biased. In this state, inductor L is discharged and delivers its stored energy to capacitors $C1$, $C2$, and load resistances $R1$ and $R2$. Also, in this mode, capacitors $C1$ and $C2$ are charged shown in figure.4 (d).

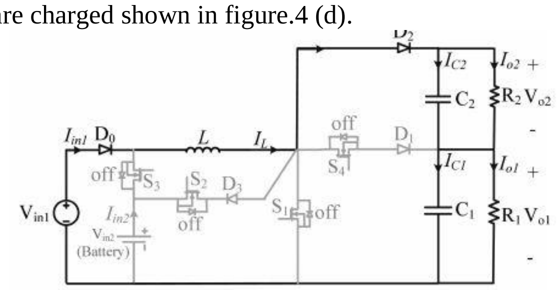

Figure.4 (d). Switching state 4

B. Second Operation Mode (Battery Charging Mode)

In this mode, Vin1 not only supplies loads but also delivers power to Vin2 (battery). This condition occurs when load power is low and battery requires to be charged. In this operation mode, switches $S1$, $S2$, and $S4$ are active and switch $S3$ is entirely OFF. Like previous operation mode of the converter in this mode, for each switch, a specific duty is considered. $S1$ is switched to regulate total output voltage $VT = VO1 + VO2$ to desired value. Regulation of the battery charging current (Ib) to desired value is the duty of switch $S2$. Also, output voltage $VO1$ is controlled by switch $S4$. It is clear that by regulation of VT and $VO1$, the output voltage $VO2$ is regulated too. In Fig. 5, gate signals of switches and voltage and current waveforms of inductor are shown. According to different switches states, there are four different operation modes in one switching period which is discussed as follows:

1) Switching State 1 ($0 < t < D1T$):

In this state, switch $S1$ is turned ON, so $S2$ and $S4$ are reverse biased and cannot be turned ON. Also, diode $D2$ is reversely biased and does not conduct. Equivalent circuit of proposed converter in this state is shown in Fig. 5(a). In this state, Vin1 charges inductor L, so inductor current is increased. Also, in this mode, capacitors C_1 and C_2 are discharged and deliver their stored energy to load resistancesR_1 and R_2, respectively.

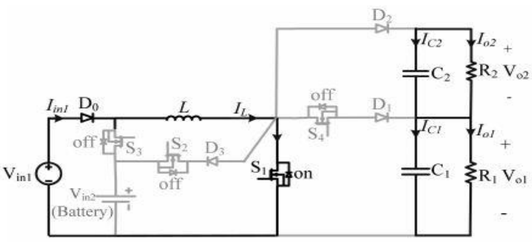

Figure.5 (a). Switching state 1.

2) Switching State 2 ($D_1T < t<D_2 T$):

In this mode, switch S_1 is turned OFF and switch S_2 is turned ON. Diode D_1 and D_2 are reversely biased; consequently, S_4 is still OFF. Equivalent circuit of proposed converter in this state is shown in Fig. 5(b). Since $V_{in1} < V_{in2}$, therefore, in this period of time, inductor current decreases and inductor delivers its stored energy to battery (V_{in2}). Also, in this mode, capacitors C_1 and C_2 are discharged and deliver their stored energy to load resistances R_1 and R_2 respectively.

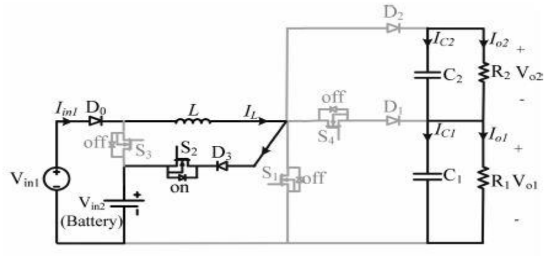

Figure.5 (b). Switching state 2

3) Switching State 3 ($D_2T < t < D_4T$):

In this mode, switch S_1 is still OFF and switch S_2 is turned OFF and switch S_4 is turned ON. Also, diodeD_2 is reversely biased. In Fig. 5(c), equivalent circuit of proposed converter in this state is shown. In this state, inductor L is discharged and delivers its stored energy to C_1 and R_1. So the inductor current is decreased. In this state, capacitors C_1 is charged and capacitor C_2 is discharged and delivers its stored energy to load resistance R_2.

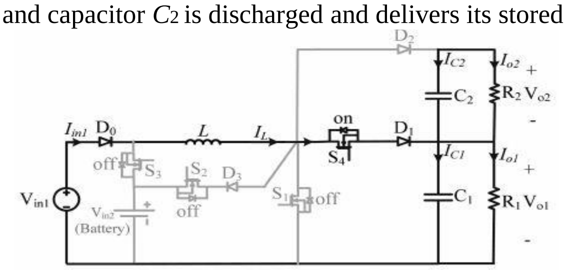

Figure.5 (c). Switching state 3

4) Switching State 4 ($D4T < t < T$): In this mode, all the three switches are OFF. Therefore, diode $D2$ is forward biased. In this state, inductor L is discharged and delivers its stored energy to capacitors $C1$, $C2$, and load. The resistances $R1$ and $R2$. Also, in this mode, capacitors $C1$ and $C2$ are charged shown in figure. 5 (d).

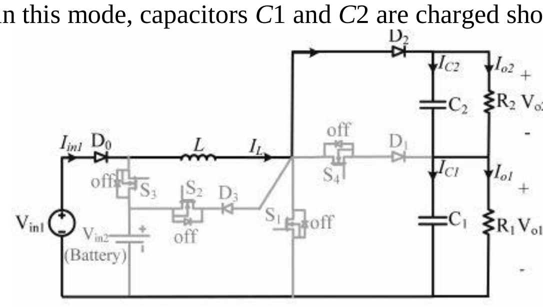

Figure.5 (d). Switching state 4

4. Experimental Results

In order to verify the effectiveness of the proposed converter, a low power range laboratory prototype was built as shown in Fig.6. Two different input power sources utilized. A dc power supply and a 48-V battery consist of four series 12-V, 7.5 Ah lead–acid battery are employed in the prototype as the input sources. For the experimental setup, the dc power supply is set at constant voltage values 35V which can represent FC source. The control scheme is implemented by PIC18F452.

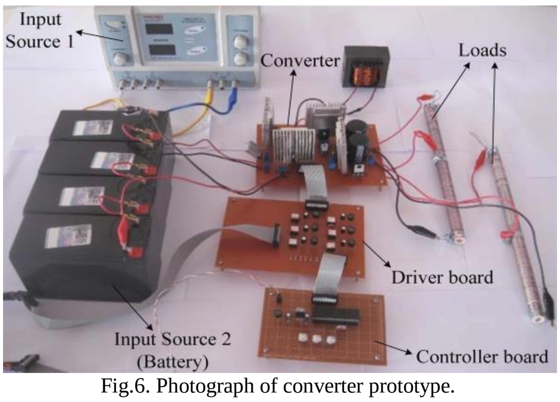

Fig.6. Photograph of converter prototype.

The reference value of the output voltages are $VO1-\text{ref} = 80$Vand $VO2-\text{ref} = 40$ V and two resistive loads are used in the prototype. The experimental setup is examined in two different operation modes of converter. The experimental results for battery discharging and charging modes are described in detail as follows.

A. Battery discharging mode:

In this mode, the reference current of the battery and output voltages are defined $Ib-\text{ref} = 3\text{A}$, $VO1-\text{ref} = 80\text{V}$, *and* $VO2-\text{ref} = 40\text{V}$, also $R1 = R2 = 35\ \Omega$(less than 35 Ω). Under this condition the output voltages of the converter. In this figure output voltage $VO1$ and total output voltage $VT = VO1 + VO2$ are shown. On the figure, by a circle the transition between batteries discharging mode to battery charging mode is shown. The waveforms of voltages at the times before mode changing are related to battery discharging mode. It is obvious that the output voltages are regulated very well. The average value of battery current is approximately equal to 3A. In current which is drawn from source 1(dc power supply) is shown. Also, inductor current in this operation mode. By regulating of battery current, proper distribution of loads power between input sources is achievable. In this mode, $P\text{in}1=150\text{W}$, $Pb = 143\text{W}$, $PO1= 189\text{W}$, and $PO2=47\text{W}$.

B. *Battery charging mode:* In this mode, the loads power is low. So source 1 can supply loads and also charge the battery. In this mode, the reference of battery charging current and output voltages are defined $Ib-\text{ref} = -0.9$ A, $VO1-\text{ref} = 80\text{V}$ *and* $VO2-\text{ref} = 40\text{V}$, respectively, also $R1=R2= 70\ \Omega$ (less than 70 Ω). Under this condition, the output voltages of the converter. In this figure, the times after M mode changing are related to battery charging mode. It is worth noting that in this operation mode, current of source 1 is equal to inductor current. In this mode, $P\text{in}1=214\text{W}$, $Pb= 51\text{W}$, $PO1= 96\text{W}$, and $PO2= 25\text{W}$. Also, the operation of the proposed converter from battery discharging mode to battery charging mode is investigated. First, the converter had been operated in battery discharging mode and then in appropriate time the load resistances have been increased. In battery discharging mode, the load resistances are $R1=R2= 35\Omega$ and in battery charging mode, the load resistances are $R1=R2= 70\Omega$. Also, the battery current reference which in battery discharging mode was 3 A is changed to – 0.9 A. So under such condition, the battery current and inductor current respectively.

5. CONCLUSION

A new multiinput multi-output dc–dc boost converter with unified structure for hybridizing of power sources in electric vehicles is proposed in this paper. The proposed converter has just one inductor. The proposed converter can be used for transferring energy between different energy resources such as FC, PV, and ESSs like battery and SC. In this paper, FC and battery are considered as power source and ESS, respectively. Also, the converter can be utilized as single input multi-output converter. It is possible to have several outputs with different voltage levels. The converter has two main operation modes which in battery discharging mode both of input sources deliver power to output and in battery charging mode one of the input sources not only supplies loads but also delivers power to the other source (battery).

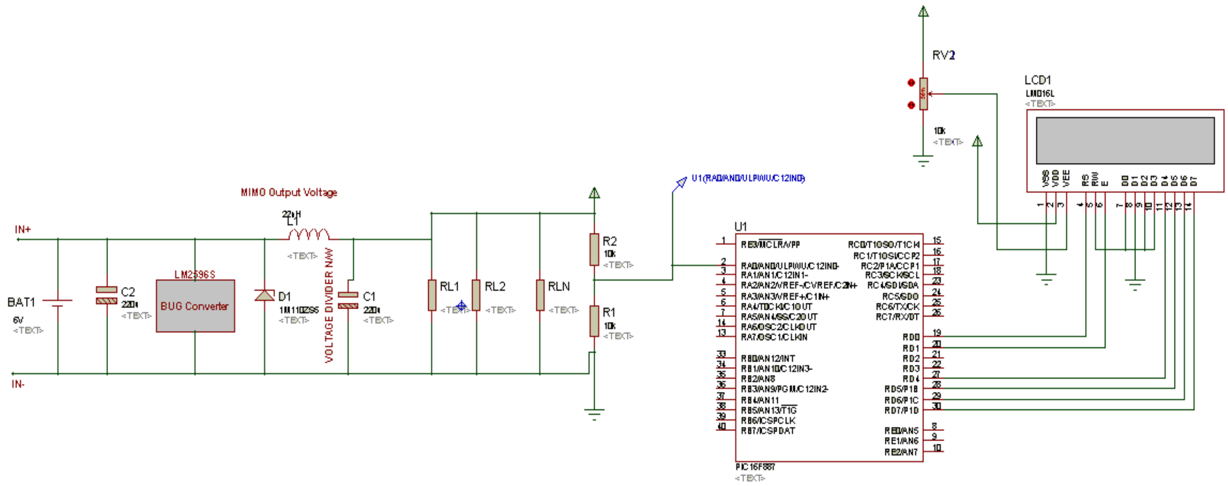

Figure. 7 Architecture Prototype for charging and discharging nodes

For each modes, transfer functions matrices are obtained separately and compensators for closed loop control of the converter is designed. It is seen that under various conditions such as rapid rise of the loads power and suddenly change of the battery reference current, output voltages and battery current are regulated to desired values. Outputs with different dc voltage levels are appropriate for connection to multilevel inverters. In electric vehicles, using of multilevel inverters leads to torque ripple reduction of induction motors. Also, electric vehicles which use dc motors have at least two different dc voltage levels, one for ventilation system and cabin

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lightening and other for supplying electric motor. Moreover, in grid connection of renewable energy resources like PV, using of multilevel inverters is useful. Finally, operation of this converter was experimentally verified using low-power range prototype.

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