An effective control structure of on-board battery charger for electric vehicles

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ABSTRACT
The plug-in electric vehicles (PEVs) including plug-in hybrid electric and all-electric vehicles will play a key role in the transportation future throughout the World. Consequently, a variety of works must be done to decrease the cost, improve the structure and increase the convenience of PEVs. This study proposed a single-phase, non-isolated and on-board battery charger with no use of any transformer which reduced the volume and weight of the system for PEVs. The main purpose is to provide an accurate control structure in order to achieve an acceptable charging in the wide range of voltage. The proposed structure is simulated by matrix laboratory (MATLAB) software. The results showed a high-power density, high efficiency and appropriate power factor from the structure of the non-isolated and single-phase charger.

Keywords: Buck-boost converters Electric vehicles High power density Non-isolated charger On-board battery charger

1. INTRODUCTION
According to vehicle technologies office (VTO) of the United States (U.S.) department of energy, improving vehicle efficiency in U.S. is essential to reducing consumers’ fuel costs, supporting domestic industry, minimizing pollution, and increasing energy security through low-cost, secure, and clean energy technologies [1]. The relationship between energy and fuel efficiency, environmental pollution and focus on the clean energy is driving the transportation to develop electric vehicle (EV) industry [2], [3]. Furthermore, the pollutions, greenhouse gases and landfills are the major environmental issues in recent years [4], [5] which has attracted a lot of attention for efficiency improvement of power systems and electrical machines [6], [7]. Power electronics technology, vehicle design and batteries have provided a significant opportunity to achieve cleaner energy sources in the automotive industry that pushed the development of EVs. The general schematic of a typical EV is shown in Figure 1. Accordingly, a structure with the capability of high efficiency, high power density, low price, and appropriate control methods is required to increase the life cycle of battery and optimal use of stored energy in EVs. They should also have the ability to modify the network power factor. These chargers are designed and used in two main types such as on-board and off-board [8].

The on-board battery chargers are installed on EVs which have some advantages such as direct charge from distribution network, needless of charging station, simple system configuration, longer battery life and lower cost [9]–[14]. These chargers are common in automotive industry due to their availability and comfort [9]. However, these chargers have limited power because of their volume and weight. In some cases, the on-board battery chargers are integrated with the vehicle's electric drive to avoid extra inductors and
switches that are only used to charge the battery [15]. The off-board battery chargers are some systems in the charging stations that all the devices of charging sectors installed at the center. The off-board systems have faster charging capability but their high cost and volume are the main disadvantages for many users [9], [16]. Chargers of EVs are divided into 3 categories in terms of charge levels. Level 1 charger has the slowest charging method that uses the standard with a voltage of 120 V and 11 A in the U.S.

Figure 1. The schematic of an EV

Level 2 charger is suitable for public and private places and can charge with a voltage of 208-240 V and a maximum of 80 A and a maximum power of 19.2 kW. Level 3 charger can charge in less than an hour and at a three-phase voltage level of 480 V and above which is suitable for charging stations [2], [17]–[19]. Battery chargers (BCs) can also be classified into two types in method of charging including the conductive and inductive systems. The conductive charger has a physical link among the power electronic interface and power supply for charging, while the inductive charger operates wireless without any physical connection among power electronic interface and supply. Inductive chargers are mainly intended for slow charging applications [19]–[23]. The basic structure of BC system in EVs is displayed in Figure 2 [18].

Figure 2. The structure of BC system in EVs

Another feature used to classify BCs is galvanic isolation, which is used for security reasons and at the same time makes the structure larger and heavier and requires complex controllers [22]. Finally, there are two sorts of BCs including the two-way charger that receive/inject energy from/into the grid and one-way charger which is only used to charge the battery. Two-way structures are larger and heavier than one-way types and require more components to operate in both directions. Furthermore, the structure of BCs in EVs can be divided into two kinds such as isolated and non-isolated. Isolated structures use high-frequency transformer to have the various range of voltage and an isolation layer that reduce the efficiency. Weight, volume, and parts of non-isolated types are less than the isolated ones. Few research works have been
reported on non-isolated strategies for BC applications due to their output voltage and limited power capacity [24].

A non-isolated on-board BC structure was integrated with a high-power, low-voltage direct current (DC)-DC converter to charge low-voltage auxiliary batteries via [25]. The non-isolated BC is a single-stage diode bridge with a three-phase cascade interlude buck-boost converter. Due to the usage of an isolated DC/DC converter the overall efficiency of the circuit is reduced. Earlier studies [26] showed a conventional DC/DC boost converter with a rectifier as a one-way BC which provided a new phase shift control to achieve the unit power factor. An on-board single-phase BC is introduced by [27] with auxiliary charging system. A topology based on governed power factor and fixed current is used for charging the high voltage battery. The strategy is simple and reliable with the advantage of auxiliary battery charging system but switching losses are high. A high-efficiency on-board single-phase charger with a full diode bridge converter is presented by [28]. The main feature of this system is that no need of DC link capacitor. A research by [29] proposed a multifunctional converter to charge EVs based on grid and solar sources. The important feature of the circuit is to cover various modes of EVs such as charging, propulsion and regenerative braking. The outcome indicates a good performance for proposed converter. A new integrated single-phase converter for electric chargers of hybrid vehicles is presented by [30], [31] for reduction in weight and size of circuits. The introduced system is suitable for different range of voltage with longer life. This study presents a non-isolated structure for charging EV batteries with control circuits for power factor correction. Some advantages of the proposed strategy are including the high efficiency, low number of elements, low cost, volume, and weight, as well as high reliability and flexibility.

2. RESEARCH METHOD

2.1. Recommended structure of single-phase battery charge

A diode rectifier with two interlude buck-boost converters is proposed as a single-phase BC. The advantages of this structure over other non-isolated buck-boost converters are uniformity of input and output voltage polarity, low voltage stress on semiconductor elements, better performance than other topologies due to a common inductor between the buck area and the boost area, and having a common ground. Figure 3 shows the system structure considering the input source switch off and on.

According to the Figure 3, when the switch is off, energy is conducted from the input source to the inductors. Energy is injected into the battery through a capacitor parallel when it is on and the charging process begin. Therefore, the performance of the above system can be considered similar to a buck-boost converter in energy transfer and the following equations can be provided to calculate the output voltage of the converter.

\[ i_{L, on}(t) = \frac{1}{L} \int_0^t V_{in} dt + I_{min} \]  \hspace{1cm} (1)

\[ I_{max} - I_{min} = \frac{V_{in}}{L} DT \]  \hspace{1cm} (2)

\[ i_{L, off}(t) = \frac{1}{L} \int_0^t (-V_{out}) dt + I_{max} \]  \hspace{1cm} (3)

\[ I_{max} - I_{min} = \frac{V_{out}}{L} (1 - D) T \]  \hspace{1cm} (4)
\[
\frac{V_{in}}{L} pT - \frac{V_{out}}{L} (1 - D)T = 0
\]  
(5)

\[
V_{out} = \frac{D}{1-D} V_{in}
\]  
(6)

Where \(i_{L,on}\) and \(i_{L,off}\) are the inductor currents for on and off conditions, respectively, \(L\) is the inductance, \(I_{\text{min}}\) and \(I_{\text{max}}\) are the minimum and maximum currents, respectively, \(t\) is the time, \(V_{in}\) and \(V_{out}\) are the input and output voltages, respectively, \(T\) is the control period and coefficient \(D\) is the working coefficient of the buck-boost converter which determines the ratio between input and output voltages. The output voltage is controlled in a wide range of input voltage between 86 V and 265 V using a control algorithm. A switching strategy based on three functional modes as buck, boost and cascade is applied. Table 1 summarized the switching modes. The three functional modes for charging of battery are shown in Figure 4. The buck functional mode is shown in Figure 4 (a), the cascade functional mode is shown in Figure 4 (b), and the boost functional mode is shown in Figure 4 (c).

![Circuit diagram](image)

Figure 4. Circuit functioning in three switching modes: (a) buck functional mode, (b) cascade functional mode, and (c) boost functional mode

<table>
<thead>
<tr>
<th>Functional mode</th>
<th>Buck</th>
<th>Boost</th>
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<tbody>
<tr>
<td>Buck</td>
<td>Off</td>
<td>Switching</td>
</tr>
<tr>
<td>Cascade</td>
<td>Switching</td>
<td>Switching</td>
</tr>
<tr>
<td>Boost</td>
<td>Switching</td>
<td>On</td>
</tr>
</tbody>
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Table 1. Switching mode of converter
3. RESULTS AND ANALYSIS

The proposed system is analyzed using matrix laboratory (MATLAB) software. The system parameters are indicated in Table 2. Two different cases are considered. In the first case, the input voltage was 208 V and the output voltage was in the range of 280-320 V as shown in Figure 5. Figure 5 (a) is the input and Figure 5 (b) is the output voltages of the converter. It is clear that the values are in the desired range. The related input and output currents are displayed in Figure 6. Figure 6 (a) is the input and Figure 6 (b) is the output voltages of the converter. It can be observed that the DC output current is 5 A while the input current is sinusoid and has some fluctuations. One of the features of the designed circuit is to reduce of total harmonic distortion (THD) injected into the network, which is caused by the converters. According to fast fourier transform (FFT) analysis, the amount of harmonic injected into the network is about 5.84%, which is a small and acceptable value as shown in Figure 7.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal power</td>
<td>( P_{\text{max}} )</td>
<td>3.7 kW</td>
</tr>
<tr>
<td>Nominal voltage</td>
<td>( V_{\text{in}} )</td>
<td>120-208-240 V</td>
</tr>
<tr>
<td>Maximum input voltage</td>
<td>( V_{\text{in,max}} )</td>
<td>265 V</td>
</tr>
<tr>
<td>Minimum input voltage</td>
<td>( V_{\text{in,min}} )</td>
<td>85 V</td>
</tr>
<tr>
<td>Output voltage range</td>
<td>( V_{\text{out,DC}} )</td>
<td>270-430 V</td>
</tr>
<tr>
<td>Output current range</td>
<td>( I_{\text{out,DC}} )</td>
<td>0-13.8 A</td>
</tr>
</tbody>
</table>

![Figure 5. Voltages of converter: (a) input and (b) output](image)

![Figure 6. Currents of converter: (a) input and (b) output](image)
Another advantage of the proposed circuit is the proper operation in abnormal conditions. For instance, decrease or increase of input voltage frequency has less effect on the output and performance of the system. Accordingly, the system for network frequency of 70 Hz are examined. It can be concluded from Figure 8 that variation of frequency had little effect on the relevant curves and the battery still charged due to the proper control algorithm in the system. The THD value of the network current was also increased by only 0.14%, which is a small value as shown in Figure 9.

The proposed converter and its control algorithm operate at high efficiency and suitable power factor in all switching modes. The efficiency and power factor of the system in the case of input voltage of 208 V are presented in Figure 10. Figure 10 (a) shows the efficiency and Figure 10 (b) shows the power factor of the converter for $V_{in}=208$ V. As can be seen, the values of power factor and efficiency in all cases had an acceptable value which prove that the proposed converter operates at high efficiency.
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4. CONCLUSION

This study introduced an on-board BC for EVs with focus on reducing the size and enhancing the efficiency which is mandatory for new vehicles. A control strategy is defined for various input and output situations to achieve the high efficiency. Some of the advantages of the proposed system are including less elements are used compared to ordinary BCs, high efficiency is attained using a single stage construction without the high frequency transformer and excellent performance was achieved in battery charging.

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