A High Power Density Drivetrain-Integrated Electric Vehicle Charger

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Abstract—This paper presents a new architecture for an isolated level 2 on-board electric vehicle (EV) battery charger which is integrated with the EV’s drivetrain dc-dc boost converter. The proposed charger leverages many of the existing stages of a highly efficient and power-dense composite-architecture-based drivetrain boost converter. This composite boost converter comprises a buck, a boost and a dc transformer (DCX) stage. In selecting the proposed charging architecture, four alternative approaches to drivetrain integration are identified, explored and compared quantitatively in terms of added weight and charging losses. Out of the considered approaches, the proposed charging architecture provides an effective tradeoff between additional weight and charging losses. This drivetrain-integrated charger adds only a bridgeless-boost-based power factor correction (PFC) ac-dc stage, plus an H-bridge and a single winding to the composite boost converter, to achieve high-power on-board charging functionality without substantial additional weight. A 6.6 kW prototype of the proposed charger has been designed and its PFC stage built and tested. The PFC stage uses a digital implementation of a current sensor-less control strategy and employs effective ways of mitigating zero crossing distortion. The proposed charger architecture reduces the additional weight required for the on-board charging functionality, while achieving greater than 97% peak efficiency for the added charger module PFC stage.

Index terms—drivetrain integrated charger, EV on-board charger, battery charger, PFC boost DCM, PFC zero crossing distortion, power regulation stage.

I. INTRODUCTION

A high power on-board charger provides convenience, reduces range-anxiety and is considered vital to accelerate the adoption of electric vehicles (EVs) [1]. However, the additional weight of a high power on-board charger can reduce the range of the vehicle and its volume can impose unfavorable design constraints. Hence, reducing the weight of on-board chargers is an important goal for vehicle manufacturers. Different approaches to implementing on-board electric vehicle chargers have been proposed [2], [3]. However, in all of these approaches, the on-board charger is considered a separate power electronic converter. Some attempts have also been made to integrate on-board charging capability with the electric drivetrain by leveraging the windings of the electric motor [1], [5], [6]. However, this approach introduces complexity into the design of the electric motor and can impact its cost and reliability. Hence, there is a need to explore alternative ways of integrating on-board charging functionality that minimize added weight and maintain high efficiency.

Recently a new drivetrain architecture for electric vehicles that utilizes a composite boost dc-dc converter between the vehicle battery and the motor drive has been introduced [7]. The proposed composite boost dc-dc converter comprises dissimilar converter modules combined into a power conversion system with superior performance in terms of efficiency and power density compared to the traditional drivetrain boost converter. The architecture of the composite boost dc-dc converter is shown in Fig. 1. This modular approach to boost the battery voltage provides an opportunity to leverage some of its power conversion stages as part of the charging function. Such charger integration can result in minimal additional weight, while providing high power on-board charging capability, increasing the on-board charger power density. This paper identifies, explores and quantitatively compares alternative architectures for integrating the charging function with the composite boost converter. The architecture among these that provides an effective trade-off between added weight and charging losses is selected for detailed design and testing. This drivetrain-integrated charger only adds a bridgeless boost based power factor correction (PFC) ac-dc stage, an H-bridge and a single winding to the composite boost dc-dc converter. Hence, it significantly reduces the additional weight required for the on-board charging functionality. A 6.6 kW prototype of this proposed charger has been designed and its PFC stage tested. It achieves greater than 97% peak efficiency for the added charger module PFC stage.

This paper is organized as follows. A brief review of the composite boost dc-dc converter is presented in Section II. Multiple approaches to integrate the charging functionality with the composite dc-dc converter are discussed in Section III, with a quantitative comparison presented in Section IV. Based upon the quantitative results, a drive-train-integrated charger architecture is identified and discussed in detail in Section V. Section VI presents prototype design and
simulation and experimental results of the proposed charger architecture. Finally, Section VII summarizes key results and conclusions.

II. DC-DC COMPOSITE BOOST CONVERTER ARCHITECTURE

The architecture of the composite boost dc-dc converter [7] is shown in Fig. 1. This architecture comprises of a buck module, a boost module and a dual active bridge operated as a dc transformer (DCX). The composite boost converter achieves a high voltage gain by connecting the outputs of the boost and the DCX modules in series. The buck module forms a cascade with the DCX stage, and its input is parallel-connected to the input of the boost module. This architecture allows the composite boost converter to achieve high output voltages with relatively low breakdown voltage switches having low on-resistance and fast switching speed. Each module of the composite converter processes only a fraction of the total power processed by the converter. This approach enables efficiency and power density optimization of the overall converter by utilizing a control strategy that maximizes the amount of direct power processed by the converter across a wide range of operating conditions. These factors enable the composite boost converter to achieve greater efficiency and power density than a traditional boost converter. In addition to these benefits, the modular nature of the composite boost converter opens up the possibility of integrating the charging functionality within the drivetrain, as discussed in detail in the next section.

III. ALTERNATIVE DRIVETRAIN-INTEGRATED ELECTRIC VEHICLE CHARGER ARCHITECTURES

The charging functionality can be integrated with the composite boost architecture in multiple ways. Four of the most promising approaches to integrate an on-board charger into the composite boost converter are shown in Fig. 2. Figure 2(a) shows architecture A, a bridgeless boost stage followed by a phase-shifted full-bridge isolated dc-dc converter. The bridgeless boost stage is operated as a power factor correction (PFC) rectifier, and the phase-shifted full-bridge isolated dc-dc converter provides isolation and also regulates the battery charging current. Although this architecture involves only two cascaded power stages, resulting in relatively low losses, the added weight of this architecture is the highest among the four considered charging architectures. This is due to its relatively weak integration with the composite boost converter, as it only utilizes the composite converter’s
Figure 3: Drivetrain integrated charger architecture comprising a bridgeless boost converter, followed by a dual active bridge (DAB) and a buck converter.

boost stage filter. Figure 2(b) shows architecture B, which comprises a diode rectifier followed by an isolated full-bridge boost stage to achieve power factor correction and isolation. The full-bridge boost converter integrates into the existing drivetrain by adding an additional winding to the transformer of the DCX and utilizing its secondary side H-bridge for rectification. These stages are then followed by the drivetrain buck converter that regulates the battery current. While this architecture provides strong integration with the composite boost converter, increased losses in the isolated boost stage degrades its efficiency. Figure 2(c) shows architecture C, which comprises a bridgeless boost converter followed by a dual active bridge (DAB) converter and the drivetrain buck converter. The bridgeless boost converter at the front end is operated as a PFC stage. The DAB is used to provide isolation and the drivetrain buck converter is then used to regulate the battery current. The DAB is implemented by adding a primary side H-bridge and an additional transformer to the existing drivetrain DCX. The secondary side H-bridge of the drivetrain DCX is reused in the charging operation. This architecture can be further integrated with the composite boost converter by integrating the two DAB transformers. This can be achieved by utilizing a three winding transformer in the DAB stage, as shown in architecture D of Fig. 2(d). Architecture D achieves strong integration by effectively utilizing the existing drivetrain stages and appears highly promising.

IV. QUANTITATIVE COMPARISON OF THE ALTERNATIVE DRIVETRAIN-INTEGRATED CHARGER ARCHITECTURES

In order to quantitatively compare the proposed integrated charger architectures shown in Fig. 2, loss models are developed to estimate their losses over a line cycle. These loss models include switch conduction and switching losses, and inductor and transformer core and winding losses. In addition, models to compute the weight of each architecture are also developed. The weight models consider the weight of the magnetic and capacitive components, as well as the heat sinks, since they constitute the largest fraction of the converter weight. The computed weights and losses from these models for the four considered architectures are shown in Table I. It can be observed that architecture A has the least losses but contributes the most additional weight. On the other hand architecture B adds substantially less weight but has high losses. Note that architecture B adds least components but not the least weight due to increased size of the heat sink. Since in an EV application both weight and efficiency are important considerations, architecture D appears to provide an excellent tradeoff between these attributes as it effectively leverages the existing modules of the composite boost converter. Thus architecture D is selected for detailed design, fabrication and testing.

Table I: Comparison of proposed integrated charger architectures in terms of added weight and full-power losses for a 6.6 kW on-board EV charger.

<table>
<thead>
<tr>
<th>Architecture</th>
<th>Added Weight [kg]</th>
<th>Losses [W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2.67</td>
<td>238</td>
</tr>
<tr>
<td>B</td>
<td>1.97</td>
<td>322</td>
</tr>
<tr>
<td>C</td>
<td>2.07</td>
<td>268</td>
</tr>
<tr>
<td>D</td>
<td>1.90</td>
<td>265</td>
</tr>
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</table>

V. DRIVETRAIN-INTEGRATED CHARGER DESIGN AND CONTROL

The schematic of the proposed drivetrain-integrated charger is shown in Fig. 3. The first stage of the architecture is a bridgeless boost PFC. The second stage is an H-bridge forming a dual-active bridge with the existing H-bridge of the composite converter’s DCX stage. This is then followed by the drivetrain buck converter to regulate the battery power.

A. AC-DC Bridgeless Boost Converter

The bridgeless boost topology is well suited for high efficiency ac-dc power conversion since it eliminates the passive rectifier bridge used in traditional PFC rectifiers, resulting in
reduced component count and decreased conduction losses [4]. An additional advantage of this topology compared to a totem-pole bridgeless boost is that the active switches are referenced to the same node, simplifying gate driver requirements.

A detailed design of PFC stage of the proposed drivetrain-integrated charger is conducted and optimizations were performed to minimize losses over the line cycle. More details on the optimizations are presented in Section VI. As a result of optimizations, discontinuous conduction mode (DCM) of operation of the circuit was selected. DCM operation results in reduced inductor size and switching losses.

Operating the bridgeless boost converter in DCM provides additional benefits related to control implementation. In DCM operation, PFC functionality can be implemented without sensing the inductor current which typically requires a high-bandwidth sensor. Thus, only the input and output voltages of the converter need to be sensed to implement the control. In DCM, the average inductor current can be expressed as [8]:

\[ \langle i_l \rangle_{T_s} = \left( \frac{T_s}{2L} \right) \left( \frac{d^2}{1 - \frac{v_{in}}{v_{bus}}} \right) v_{in}. \] (1)

Here \( \langle i_l \rangle_{T_s} \) is the average inductor current, \( v_{in} \) is the input line voltage, \( v_{bus} \) is the dc bus voltage, \( T_s \) is the switching period, \( d \) is the duty ratio and \( L \) is the bridgeless boost inductance. The control objective for achieving PFC functionality is:

\[ \langle i_l \rangle_{T_s} = \frac{v_{in}}{R_e}. \] (2)

It can be observed from (1) that the average input (inductor) current can be made proportional to input voltage, as required to achieve the control objective (2), by adjusting the duty ratio such that the term in parenthesis becomes constant.

\[ \frac{T_s}{2L} \left( \frac{d^2}{1 - \frac{v_{in}}{v_{bus}}} \right) = \frac{1}{R_e}. \] (3)

This can be manipulated to yield the following control law [9], [10]:

\[ d = \sqrt{\frac{2L}{R_e T_s} \left( 1 - \frac{v_{in}}{v_{out}} \right)} . \] (4)

Here \( R_e \) is the emulated input resistance of the converter. The value of this emulated resistance can be adjusted by a PI compensated outer voltage loop.

For the bridgeless boost converter, since the converter has two active switches, the control strategy can be implemented as:

\[ d_1 = \begin{cases} d, & v_{in} > 0 \\ 1, & v_{in} < 0 \end{cases} \] (5)

\[ d_2 = \begin{cases} 1, & v_{in} > 0 \\ d, & v_{in} < 0 \end{cases} \] (6)

Here \( d_1 \) and \( d_2 \) correspond to duty cycles of the two active switches of the bridgeless boost converter. The control architecture falls in the category of hybrid feedforward-feedback control architecture embedded inside a feedback loop [11]. A digital implementation of this control strategy using a microcontroller is selected for the PFC stage. The microcontroller senses the input voltage and output voltage of the converter and processes them as given by (5) and (6) to modulate the duty ratio of the converter in each switching interval. As can be observed from the duty ratio modulation equation, the operations of square root, division, multiplication and subtraction are required to implement the control. This can be easily performed in a modern micro-controller.

The converter outer voltage loop is designed to adjust the emulated input resistance of the converter. The outer voltage loop is designed as is a traditional practice, by assuming that the input current control loop works ideally at low frequencies and the ideal rectifier model adequately represents the low-frequency system behavior [8]. When the converter outer voltage loop is designed properly, it regulates the converter output voltage \( v_{bus} \). Any tolerance in the converter inductance value, which may appear to affect the performance of the inner current control loop (as the converter duty ratio given by (4) depends on the inductance value), is automatically corrected by the outer voltage loop. Since the output of the outer voltage loop compensator appears as a multiplicative factor with the circuit parameters in (4), inaccuracy in any other circuit parameters also get corrected by the action of outer feedback loop.

Zero crossing distortion is a common problem in PFC converters [12]. The fundamental reason that the distortion appears around input voltage zero crossing in the operation of the converter operating in DCM is because of inaccurate input voltage sensing and delays in the control loop and the gate driver. Figure 5(a) shows when the actual input voltage crosses zero volts and Fig. 5(b) shows that the sensor senses input voltage zero crossing before it actually happens. If the controller is implemented as given by (5) and (6), then due to inaccurate input voltage sensing, the controller causes two legs of the H-bridge to switch their operation before it should actually happen. This causes the two switches of the converter to remain on for interval II as marked in Fig. 5. Notice that
Figure 5: Sensor error in sensing input voltage zero crossing: (a) Actual zero-crossing; (b) zero crossing sensed when the input voltage sensor detects the zero crossing before it actually happens; (c) zero crossing sensed when the input voltage sensor detects the zero crossing after it actually happens; and (d) proposed solution of overlapping the switching time of the two half-bridge legs around input-voltage zero crossing solves the problem.

Even though the controller commands switch $Q_2$ to switch in interval II, the transistor remains on due to conduction of body diode, as the current only changes polarity when the input voltage changes polarity in DCM. This causes input voltage to appear across the inductor for the time interval II. Since, small inductors are normally employed in DCM converters, even a small input voltage around zero crossing can cause spikes in inductor current. In order to mitigate this issue, both transistors of the bridgeless boost converter are switched on and off at the same time around the zero crossing. This prevents a large build-up in the inductor current, as the current is periodically interrupted by the switching of the two transistors and enables smooth commutation of the current from one leg of the converter to the other, as shown in Fig. 5(d). Notice that in the operation of the bridgeless boost converter, one of the two switches of the converter remains on for half line cycle. Thus normal operation of the converter remains unchanged by overlapping the switching time of the two switches around input voltage zero-crossing. This zero-crossing mitigation can be expressed as:

$$d_1 = \begin{cases} d, & v_{in} > -\delta V \\ 1, & v_{in} < -\delta V \end{cases}$$  \hspace{1cm} (7)$$

Here $\delta V$ is the estimated inaccuracy in the input voltage sensing. The two transistors are switched from $-\delta V$ to $\delta V$, allowing current to naturally commute between the two legs of the half bridge. This sensing inaccuracy when accounted in the micro-controller can cause switching of the two legs of the converter to overlap around the input voltage zero crossing, preventing inductor current spikes. Furthermore, the control strategy has benefits of simple implementation and improved converter performance. In case when the input voltage sensor senses the voltage zero crossing after it actually happens, as shown in Fig. 5(c), the effects observed are similar and the proposed control strategy solves the problem. Finally, it is interesting to note that the current commutation is called natural as the commutation happens when the control scheme is implemented without any effort on the part of controller to detect the input voltage zero crossing accurately.

B. Dual-Active Bridge Converter

The second stage of the charger is a dual-active bridge (DAB) converter which is integrated with the drivetrain using a three winding transformer, implemented by simply adding one extra winding to the existing drivetrain DCX. One side of the transformer, which corresponds to the output of the DCX is turned off while the charger is charging the battery. The power transfer takes place from the grid side DAB full bridge to the battery side DAB full bridge. For charging purposes, the DAB converter provides isolation and regulates the voltage at its output.

The control of the DAB converter is done by switching the primary and secondary H-bridges at approximately 50% duty cycle and controlling the phase shift between two H-bridges [13]. The control is based on sensing the converter output voltage, comparing it with the reference and passing the error through compensator to generate the converter phase shift. This control loop is designed to have much lower bandwidth than the twice the line frequency. The twice line frequency ripple present on the grid side of the DAB is buffered by both the grid side and the battery side capacitors ($C_1$ and $C_2$) in Fig. 3.

C. Power Regulation Boost Converter

The final stage of the charger is the drivetrain bi-directional buck, which functions as a boost converter during the charging operation. The converter regulates the current flowing into the battery. To realize the controller on this boost converter, inductor current is sensed and used in a standard feedback architecture to generate the duty ratio command. Since the inductor is present at the input of the converter, current control is not done in a standard fashion by sensing the battery current and comparing it with the reference current. Instead, as the control objective is to regulate the battery power, the controller is synthesized to make the converter behave as a power sink.
at the input port [8]. Since in steady state the converter has no net energy storage, the input power comes out of the converter output port and the output port behaves as a power source, which charges the battery at constant power. The schematic, the large signal model and the control architecture of this power regulating boost stage is shown in Fig. 6.

![Figure 6: Boost converter acting as a power regulation stage to regulate the battery power. (a) Boost converter topology (b) Large signal model and (c) Controller implemented to achieve input power sink characteristics.](image)

To make the converter act as a power sink at the input port, the input voltage of the boost converter is sensed and used to generate the converter current reference. The converter current reference can be expressed as:

\[ i_{\text{ref}} = \frac{P_{\text{ref}}}{v_{\text{bst}}} \]  

(9)

The converter feedback loop is designed to achieve input current regulation of the converter, which in case of ideal operation of current control loop can be expressed as:

\[ \langle i_{\text{bst}} \rangle T_s = i_{\text{ref}} \]  

(10)

Thus in steady state, the converter input power can be expressed as:

\[ P_{\text{in}} = v_{\text{bst}} i_{\text{ref}} = P_{\text{ref}} \]  

(11)

Ignoring the losses in the converter, as they are small compared to the input power, the converter output power can be expressed as:

\[ P_{\text{out}} = P_{\text{ref}} \]  

(12)

When this control is implemented, the output power of the converter can be controlled without directly sensing the battery current. It can be noted here that the converter input voltage has twice line frequency ripple. The ideal power regulation stage will get rid of this twice line frequency ripple and charge the battery with constant current. Thus bandwidth of the inner current loop is designed to be much larger than twice line frequency to track the ripple in input current reference appearing because of ripple in input voltage of the converter.

VI. PROTOTYPE DESIGN AND EXPERIMENTAL RESULTS

A 6.6 kW electric vehicle charger integrated with a 30 kW composite boost dc-dc converter has been designed and its PFC stage is tested.

A detailed design of the PFC stage is conducted. The design variations considered span a large design space, including continuous and discontinuous conduction modes of operation, switching frequencies spanning 20 kHz to 80 kHz, wide range of component values and different component types. For example, within each system level design iteration, optimal inductors are designed for the PFC boost stage by iterating over various core materials, core geometries and winding parameters. The optimization is performed using an exhaustive search based numerical approach that computes the overall converter weight and line-cycle average losses for each considered design. The final design is selected by searching for solutions that minimize losses while staying within specified weight limits. As a result of this optimization, a switching frequency of 20 kHz and discontinuous conduction mode (DCM) for the bridgeless boost converter are selected for the prototype design. The design details of the optimized inductor for the bridgeless boost stage are given in Table II. The active switches in the bridgeless boost stage are implemented using silicon super-junction MOSFETs while the rectifier diodes are realized using silicon-carbide Schottky diodes. The details of the components used in bridgeless boost converter are presented in Table II.

<table>
<thead>
<tr>
<th>Component</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOSFETs</td>
<td>IPW65R041CFD2 650 V, 68.5 A</td>
</tr>
<tr>
<td>Diodes</td>
<td>Silicon Super Junction FET C5D50065D SiC</td>
</tr>
<tr>
<td>Output capacitor</td>
<td>40 μF, 500 V</td>
</tr>
<tr>
<td>Coupled Inductor</td>
<td>29 μH Amorphous alloy 10 turns of 1000-strands 38 AWG litz wire</td>
</tr>
<tr>
<td>Microcontroller</td>
<td>TI-TMS320F28069 32 Bit CPU, 90 MHz</td>
</tr>
</tbody>
</table>

The PFC stage was tested at full power. Figures 7 and 8 show waveforms of the bridgeless boost stage operating at a power level of 950 W and 6.7 kW, respectively. Lag in input current with respect to input voltage is due to capacitive filters employed at the converter input to filter out switching current from line current. It can be seen that the input current is fairly
The peak-to-peak dc bus voltage ripple is designed to be 30%, as can be seen from Fig. 8. Figure 9 shows the waveforms for the switch-node voltage, the inductor current and the MOSFETs gate-to-source voltage.

Figure 7: Input voltage $v_{\text{in}}$, input current $i_{\text{in}}$ and output voltage $v_{\text{out}}$ waveforms of PFC converter with $V_{\text{in}} = 80 \, V_{\text{rms}}$, $I_{\text{in}} = 11.8 \, A_{\text{rms}}$ and $V_{\text{OUT}} = 144 \, V$.

Figure 8: Input voltage $v_{\text{in}}$, input current $i_{\text{in}}$ and output voltage $v_{\text{out}}$ waveforms of PFC converter with $V_{\text{in}} = 240 \, V_{\text{rms}}$, $I_{\text{in}} = 28 \, A_{\text{rms}}$ and $V_{\text{OUT}} = 378 \, V$.

Figure 9: Switching waveforms of the bridgeless boost ac-dc converter.

The effectiveness of the zero-crossing distortion mitigation strategy is shown in Fig. 10. As can be seen in Fig. 10 the line current transitions across the line zero crossing with no visible distortion. Both active switches of the converter switch around zero crossing to allow for seamless zero crossing.

The efficiency of the PFC stage across a more than 10:1 output power range with an input line voltage of 240 Vrms has been measured and is shown in Fig. 11. It can be seen that the PFC stage achieves a peak efficiency of 97.7% and maintains efficiencies above 97% across a 6:1 output power range. The worst case measured efficiency is 96.3%.

Simulated input and output voltage and current waveforms of the boost stage are shown in Fig. 14. It can be observed that the input voltage and input current of the boost converter has twice line frequency ripple, while the output current is almost constant. The fast current regulating loop of the boost converter allows the converter input port to act as a constant power sink which appear at the converter output port as a constant power source, thus eliminating twice line frequency current ripple from the output current.

VII. CONCLUSIONS

A new architecture is presented for an isolated level 2 on-board electric vehicle (EV) battery charger which is integrated.
Digital controller implementation is selected to realize the good performance and simpler controller implementation. A less control strategy implemented on the PFC stage achieves zero crossing distortion in the PFC stage. The current-sensor-less control strategy and employs effective ways of mitigating designed, built and tested. The front-end power factor corrector functionality, while achieving greater than 97% peak efficiency for the added PFC stage.

Experimental results of the proposed charger’s PFC stage are also presented. The proposed charger architecture reduces the additional weight required for the on-board charging functionality. Out of the considered approaches, the proposed charging architecture provides an effective trade-off between additional weight and charging losses. This drivetrain-integrated charger adds only a bridgeless boost based power on-board charging functionality without substantial additional weight.

A 6.6 kW prototype of the proposed charger’s PFC has been designed, built and tested. The front-end power factor correction stage of the proposed architecture uses a current sensorless control strategy and employs effective ways of mitigating zero crossing distortion in the PFC stage. The current-sensorless control strategy implemented on the PFC stage achieves good performance and simpler controller implementation. A digital controller implementation is selected to realize the control on the converter. Furthermore, effects of zero crossing distortion observed in PFC boost converter operating in DCM are analyzed and a simple controller is presented that can mitigate the problem and allows current to naturally commute between the two legs of the bridgeless boost converter.

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