Onboard Isolated Unidirectional EV Battery Charger with Half-bridge Inverter and Active Boost PFC

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***Abstract*—Electric vehicles (EVs) use grid power to charge their batteries. Since the battery is charged only when the car is parked -except for regeneration at braking-, using the on-board traction system components to form an integrated charging device is made possible. The major benefit of on-board charging is that it uses readily-available AC power and, via an extension lead, the vehicle can be plugged into any of the billions of outlets installed in every building. This paper proposes an onboard unidirectional charging topology that uses a standard full bridge diode rectifier and boost PFC along with a half bridge inverter and a high frequency transformer to step down the voltage and provide isolation between the high voltage and low voltage side.**

Keywords—Battery charger, half bridge inverter, automatic power factor correction.

I. Introduction

Rapid depletion of fossil fuels with increased CO2 emissions and the approaching threat of climate change are driving people to move for the efficient and environment-friendly option of Electric Vehicles (EV). One of the most important issues affecting the development and spread of electric vehicles (EVs) are battery chargers that are used to supply power from the network/grid to the battery pack. These chargers, however, act as a non-linear load in the power system which can lead to problems such as weak power factor and excessive total harmonic distortion in the network. The harmonics generated pollute not only the grid (which in turn affects every other user) but can also damage the battery (and thereby the vehicle) as well.

Generally the battery chargers are designed in one of the two forms known as off-board and on-board chargers, where each can be subdivided as unidirectional or bidirectional power flow types.

Unidirectional charger is a power converter with a simple control structure that supplies power from the network to the battery pack in one direction. They usually reduce the equipment size, simplify interconnection problems as well as the batteries are known to last longer. On the other hand, bidirectional chargers can charge the battery pack from the grid as well as transmit power to the grid if needed. These can be used (if carefully designed) to increase the sustainability and reliability of the grid.

The table below compares on-board and off-board charger characteristics.

On Board Battery Charger	Off-Board Battery Charger
Generally lower KW charging	Generally higher KW charging
Battery management system is managed by on-board rectifier	Battery management system is more complicate
Less concern about battery heating	Battery heat must be controlled
Add weights to vehicle	Removes weight from vehicle
Level 1 and Level 2 charger	Level 3 charger
Slow and semi-fast charging	Fast charging

Fig. 1. Comparison between on board battery charger and off board battery charger.

Commercial single phase electric vehicle battery chargers mainly consist of two stages:

- Stage 1 - AC-DC converter and active power factor correction
- Stage 2 - DC-DC converter

AC-DC conversion is needed to convert the AC supply current to DC to be used by the rest of the charger circuitry before being finally passed on to the battery. Since the load of an electric vehicle is varying in nature, passive power factor correction is insufficient and thus active power factor correction is needed. Power factor correction is carried out by ensuring that the current tracks the voltage. This provides a higher quality of power being passed on to the later stages of the charger as a result of maximizing the power factor and minimizing the harmonic currents. DC-DC conversion is necessary to step down the voltage and provide the battery with the correct voltage level.

Studies have revealed various methods for implementing these two stages, namely,

- For AC-DC conversion and Active power factor correction stage:
    - Boost power factor correction
    - Bridgeless boost power factor correction
    - Interleaved boost power factor correction
    - Bridgeless interleaved boost power factor correction
- For DC-DC conversion stage:
    - Isolated DC-DC conversion
        - Unidirectional & Bidirectional
    - Non-isolated DC-DC conversion
        - Unidirectional & Bidirectional

Using these methods, numerous battery charger topologies can be designed and implemented for on-board/off-board & high/low power applications, namely;

- Unidirectional single phase boost PFC combined with unidirectional DC-DC buck converter [1]
- Single phase bidirectional battery charger using dual active bridge DC-DC converter [2]
- Modified bridgeless landsman converter fed EV battery charger [3]
- Single phase unidirectional EV battery charger with Interleaved DC-DC converter [4]
- Single phase AC/DC PWM buck converter for PHEV [5]

II. Topology of The Proposed Design

In this paper a standard full bridge diode rectifier and boost PFC is proposed for the AC-DC stage with isolated half bridge DC-DC converter and a high voltage battery as the load. However, differing from the conventional methods, a high frequency film capacitor is used instead of a bulky electrolytic capacitor, at the DC link of this stage. This helps prevent unwanted voltage transients during switching operation of the DC-DC converter [6].

In the DC-DC conversion stage, a high frequency transformer is utilized to provide isolation between the high voltage and low voltage side, limiting the effect of faults on the circuit. A half bridge inverter converts the output of the first stage to a high frequency input for the high frequency transformer, which steps it down to the desired voltage and is rectified by the full bridge diode rectifier. A current controller provides the PWM signals necessary to operate the MOSFETS of both stages.

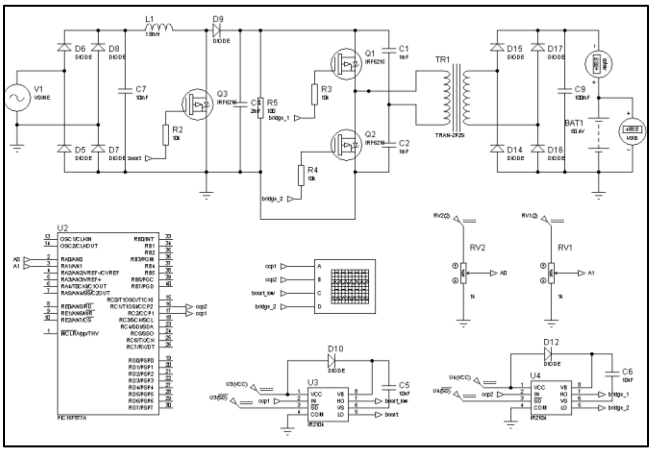


Fig. 2. Circuit Schematic for the proposed single phase unidirectional charger design.

The bridge rectifier is a circuit that converts an ac input voltage to a pulsating dc output. The term full wave refers to the fact that both halves of the input cycle are rectified. A filter capacitor is usually connected to smooth out the output voltage waveform. The rectifier circuit and its output voltage and current waveforms are shown below.

As discussed earlier, the current in non-linear loads flows only in bursts and only during periods when the input voltage is "peaking" as shown below. This periodic but non-sinusoidal nature of the current significantly lowers the power factor.

The current flows through a rectifier only when the rectified voltage is peaking. This is due to the fact that the rectified voltage still has ripple contents and the diodes only conduct when the rectified voltage across the capacitor is greater than the input sine waveform .

Therefore, a sinusoidal current waveform can be achieved if somehow the rectified voltage is always kept larger than the input rectified voltage. This is done with the help of a boost converter. Boost converters step-up(or boosts) a dc voltage to a higher value determined the duty cycle of the switch. Hence all we need is a boost converter inserted in between the rectifier and the filter capacitor as shown below.

The boost PFC circuit basically cycles between two modes during each half cycle of the input. The value of inductance L is chosen such that the inductor operates in continuous conduction mode (CCM) throughout both cycles [7].

In continuous conduction mode, the inductor current must never reach zero. The inductor starts off with an initial current, charges up to a final current and then discharges back but never reaches zero.

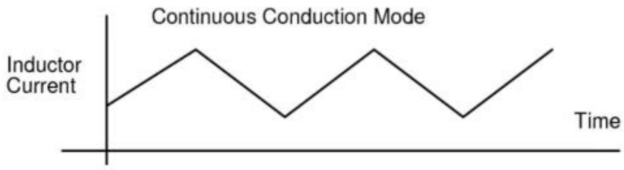


Fig. 3. Inductor current during continuous condution mode (CCM) [7].

The value of inductance for the continuous conduction mode of the inductor is given by the following equation [8]:

$$L = \frac{Vin \times k}{\Delta I \times f} \qquad (1)$$

$$C_{Boost} = \frac{I_{out}(D)}{f_{switch}(\Delta V_{out})} \qquad (2)$$

The value of smoothing capacitors used can be obtained using the following formula:

$$V_{Ripple} = \frac{I_{load}}{2fC} \qquad (3)$$

If an LC filter is used instead, the value of inductance and capacitance can be calculated from using the cutoff frequency and the characteristic impedance of the circuit, using the following equation:

$$Z_0 = \frac{1}{2\pi f_c C} = \sqrt{\frac{L}{C}} \qquad (4)$$

When the switch is closed, the inductor gets charged and the inductor current rises. The closed switch provides a short path for the current and therefore the diode remains reverse biased in this mode and the filter capacitor discharges to provide energy to the load [7].

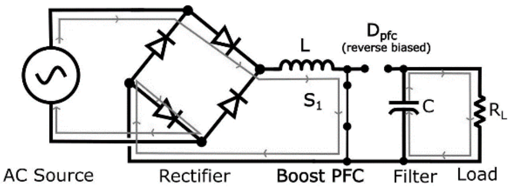


Fig. 4. Path of current flow when the MOSFET is in the ON state [7].

When the switch is open, the diode becomes forward biased and the inductor discharges through the capacitor and the load. During this period the capacitor gets charged.

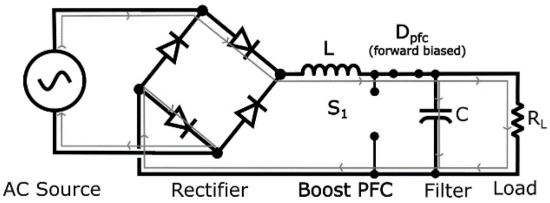


Fig. 5. Path of current flow when the MOSFET is in the OFF state [7].

The switching is usually done at a frequency of 20k Hz. Since the duty cycle determines how much the inductor current rises and decreases, the average inductor current can be adjusted by varying the duty cycle. By making this average current track the expected current, the inductor current envelope (and therefore the input current) waveform can be made sinusoidal and thus greatly reduce the harmonic contents thereby increasing the power factor [7].

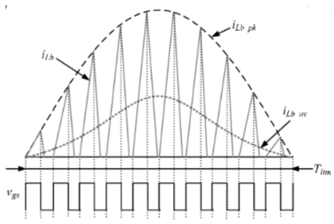


Fig. 6. Sinusoidal envelope of the current waveform obtained by high frequency switching [7].

It should be noted that the actual inductor current is not a sinusoid but is rapidly increasing and decreasing in a manner that produces the sinusoidal envelope. In this way the rectified current (inductor current) can be made to track the rectified voltage (sinusoid) and hence increase the power factor.

Inverters are devices that convert dc power to ac power. They can be classified as either half bridge (2 switches) or full bridge (4 switches) [9]. The major difference between the two is that the output ac voltage of a half bridge inverter is one half of the supplied dc voltage.

The Half bridge inverter consists of a dc supply and 2 switches (MOSFETs for example), each with an anti-parallel diode, and a load R arranged as shown in the figure below. The switches are turned on in a complementary manner (i.e, when the first switch is ON the second switch will be OFF and vice versa). In practice, since power switches require some time to turn on/off, a delay called dead time is introduced to avoid short circuits. The output frequency of this type of inverter may be controlled by controlling the switch ON and switching OFF time of the switches [10].

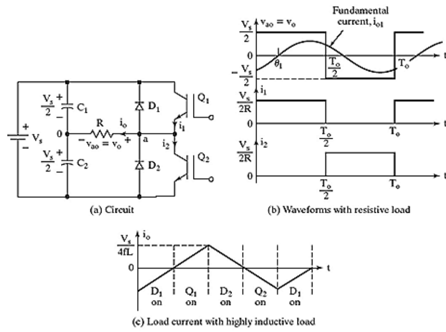


Fig. 7. Half bridge inverter using MOSFETs and Capacitors [10].

When Q1 is ON, Q2 is OFF and the voltage at the terminal a of the load is +Vs/2 irrespective of the direction of current through the load. Similarly, when Q2 is ON, the Q1 is OFF and the potential at point a is –Vs /2. The result is that the load voltage is an alternating square-wave of amplitude Vs /2 as shown below with a frequency (1/T) Hz [10].

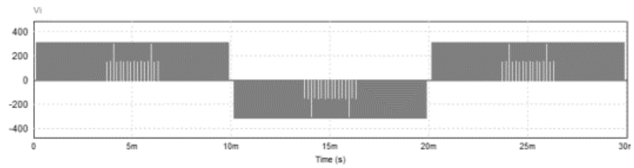


Fig. 8. Output voltage for half bridge inverter with a input of 312V [10].

III. Results and Discussion

Figure 9 shows the output curves obtained from simulations. The steady state output voltage obtained was 60.4V with minimal ripple. This shows that the circuit was successfully able to rectify the input 220V RMS AC voltage to 312V DC and then step it down to 60.4V DC and can thus be said to be capable of charging a 60V battery bank safely. The steady state output current obtained was 4.9A. The PWM signals used to operate the MOSFETS is also shown in **Figure 9**, and it can be seen that the necessary duty cycles were properly generated by the microcontroller.

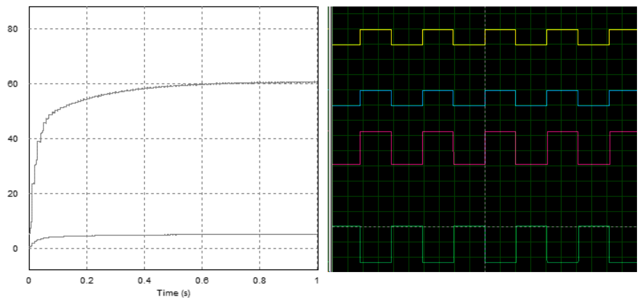


Fig. 9. Output voltage and current waveforms, and PWM signals used to operate the switches of the DC-DC converter and Boos power factor correction stage.

A. *Power Factor and Total Harmonic Distortion*

The power factor (PF) is defined as the ratio of the real power absorbed by the load to the apparent power flowing in the circuit, and ranges from 0 to 1. A power factor less than one indicates the voltage and current are not in phase, reducing the average product of the two. Real power is the instantaneous product of voltage and current and represents the capacity of the electricity for performing work. Apparent power is the product of RMS current and voltage. Due to energy stored in the load and returned to the source, or due to a non-linear load that distorts the wave shape of the current drawn from the source, the apparent power may be greater than the real power. In an electric power system, a load with a low power factor draws more current than a load with a high power factor for the same amount of useful power transferred. The higher currents increase the energy lost in the distribution system, and require larger wires and other equipment. Because of the costs of larger equipment and wasted energy, electrical utilities will usually charge a higher cost to industrial or commercial customers where there is a low power factor. Power-factor correction increases the power factor of a load, improving efficiency for the distribution system to which it is attached. Linear loads with low power factors (such as induction motors) can be corrected with a passive network of capacitors or inductors. Non-linear loads, such as rectifiers, distort the current drawn from the system. In such cases, active or passive power factor correction may be used to counteract the distortion and raise the power factor. In the proposed topology, active power factor correction is carried out using the boost power factor correction stage. To obtain the power factor of the proposed design, the circuit was remodeled in PSIM as shown in **Figure 10**.

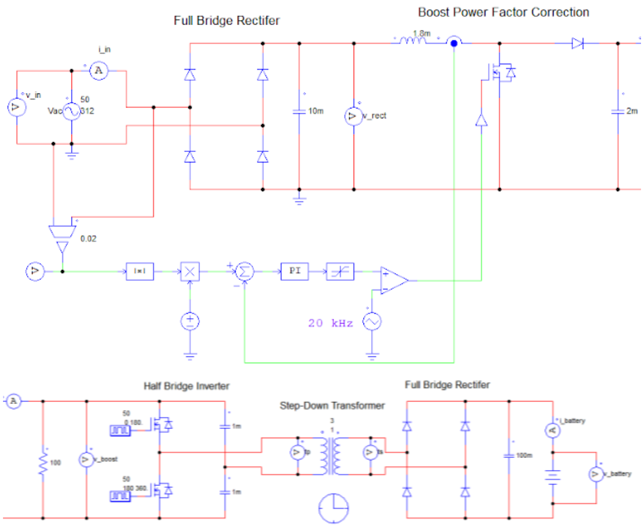
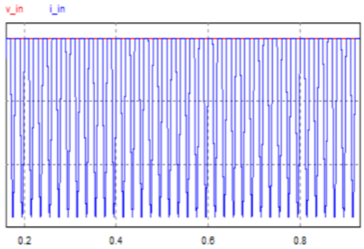


Fig. 10. Proposed design remodeled in PSIM for power factor and total harmonic distortion analysis.

The control circuit was designed in such a way that with increasing magnitude of the input voltage, the duty cycle of the boost converter decreases, as the capacitor at that point is discharging resulting in current flowing across the inductor. The current detects the inductor current and provides it as a feedback signal to the control circuit. In this manner the current is made to track the voltage thus increasing the power factor. **Figure 11** shows the PF calculated from the input side of the circuit. It can be seen that a power factor of 0.71 was obtained. Finer tuning of the control circuit can yield power factor values closer to 1. It should be noted that the voltage and current curves shown in **Figure 11** are not sinusoidal in nature due the presence of harmonics.

Total harmonic distortion (THD) is a measure of how much of the distortion of a voltage or current is due to harmonics in the signal. Harmonics or harmonic frequencies of a periodic voltage or current are frequency components in the signal that are at integer multiples of the frequency of the main signal. This is the basic outcome that Fourier analysis of a periodic signal shows. Harmonic distortion is the distortion of the signal due to these harmonic components. Therefore, THD in most cases should be as low as possible.



Time From	5.0000000e-006
Time To	1.0000000e+000
v_in vs. i_in	7.0710755e-001

Fig. 11. Input voltage and current curves and corresponding power factor value.

A voltage or current that is purely sinusoidal has no harmonic distortion because it is a signal consisting of a single frequency. A voltage or current that is periodic but not purely sinusoidal will have higher frequency components in it contributing to the harmonic distortion of the signal. In general, the less that a periodic signal looks like a sine wave, the stronger the harmonic components are and the more harmonic distortion it will have. So, a purely sinusoidal signal has no distortion while a waveform obtained in **Figure 11**, which is periodic but not sinusoidal, contains high amounts of harmonic distortion. The total harmonic distortion can be calculated using the following formula:

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty} V_{n\_rms}^2}}{V_{fund\_rms}} \qquad (7)$$

However, for the proposed design the total harmonic distortion was analyzed using PSIM. The THD of the system was 0.99. This indicates high levels of harmonics present in the system. To visualize this, fast Fourier transform (FFT) was used to obtain the frequency domain representation of the input voltage and current, as shown in **Figure 12**. It can be seen that the fundamental component (50Hz) has the highest magnitude since the supply frequency was 50Hz. It is evident that harmonics of lower and higher orders are present which resulted in the distortion of the sinusoidal input.

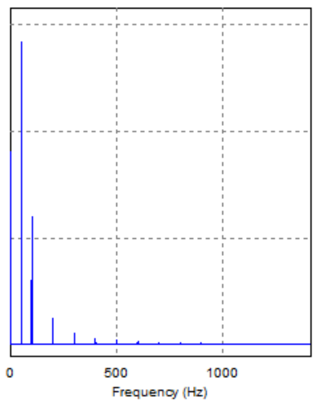


Fig. 12. Harmonics present in the input signal illustrated in the frequency domain.

B. *Matlab Implementation*

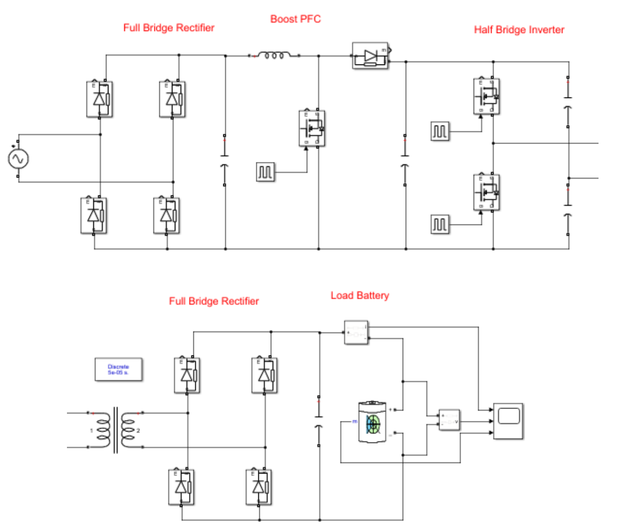


Fig. 13. Proposed design remolled in Matlab Simulink environment.

To further test the results in a separate platform, the same circuit model was designed and simulated as a MATLAB Simulink model. For this purpose, several components from the Simscape Specialized Power System toolbox were utilized to create the circuit as shown in **Figure 13**. In addition, as a non-ideal battery model was available in Simulink, the resistive load in PSIM was replaced by a lithium-ion battery with a nominal voltage of 60V and a rated capacity of 5Ah. The rest of the circuit parameters were kept the same. The MOSFETs were driven by a pulse generator with an amplitude of 15. For the half bridge inverter, the gate pulses were delayed by each other by T/2 seconds, where T = 1/50 = switching period. The linear transformer used had its inductance and coil resistance set as 0 to simulated ideal conditions. Finally, the output current and voltage across the battery was obtained as shown in **Figure 14.**

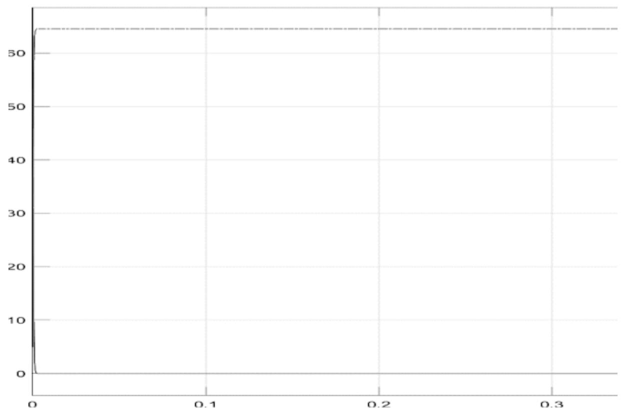


Fig. 14. Output curve obtained in Matlab Simulink for the proposed design.

IV. Conclusion

The current paper presents an onboard unidirectional charging topology that uses a standard full bridge diode rectifier and boost PFC along with a half bridge inverter and a high frequency transformer to provide isolation between the high voltage and low voltage side, that is capable of charging the 60V battery bank of an electric vehicle. However, differing from the conventional methods, a high frequency film capacitor is used instead of a bulky electrolytic capacitor, at the DC link of this stage. This helps prevent unwanted voltage transients during switching operation of the DC-DC converter. In the DC-DC conversion stage, a high frequency transformer is utilized to provide isolation between the high voltage and low voltage side, limiting the effect of faults on the circuit. A half bridge inverter converts the output of the first stage to a high frequency input for the high frequency transformer, which steps it down to the desired voltage and is rectified by the full bridge diode rectifier. A microcontroller provides the PWM signals necessary to operate the MOSFETS of both stages. The circuit parameters were obtained using the respective stage’s equations pertaining to capacitance, inductance, switching frequency and points. Simulations were performed in the PROTEUS, PSIM and MATLAB SIMULINK environments. The results showed that a steady state DC output of 60.4V and 4.9A was obtained indicating that the charging system was functional as per specifications and paves the path for future work towards optimizing the input power factor and total harmonic distortion, and PCB implementation.

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