A Modified Z-source Converter based Single Phase PV/Grid Inter-connected DC Charging Converter for Future Transportation Electrification

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***Abstract*—Use of renewable sources of energy for charging of electric vehicle(EV) batteries have generated tremendous interest. The use of off-board DC chargers to reduce the weight and increase space inside an electric vehicles has been an important area of interest. Harvesting solar energy to charge electric vehicle batteries can result in large inefficient systems when multiple power conversion stages are present. On the other hand,integration of renewable sources of energy with the grid can reduce the dependency on the AC grid while charging an Electric Vehicle(EV) and also the use of fossil fuels to generate more energy. In this paper, a single stage PV grid integrated modified z source inverter is presented. The component sizing, modeling and different modes of operation have been presented.**

***Keywords*: Battery chargers;Electric vehicles;Energy storage; photovoltaic (PV) power generation; quasi-Z-source inverter (qZSI); Z-source-inverters; single-phase systems;Bidirectional power flow;Energy harvesting; transportation electrification; Solar energy; distributed power generation.**

I. Introduction

Both in literature and in practice, there has been various topologies that have been used to charge electric vehicle directly from the grid. [1] [2] [3] Renewable sources of energy are free sources of energy which can be used to charge EVs and HEVs thereby reducing the dependency on the AC grid. With the advancement of photovoltaic (PV) technology, solar arrays can now be installed at convenient locations such as residential rooftops and in semi commercial locations such as office parking spaces and shopping malls. The solar energy harvested from the photo-voltaic arrays can be pushed into the grid or used for local energy storage or both. Recently there has been a great need to use solar energy to charge electric vehicles at convenient locations. Use of installed solar panels at residential houses can convert these houses into personal charging stations. Photovoltaic-grid interconnected systems can have three possible modes of operation, i.e., PV to Grid, PV and Grid to EV battery and EV battery to Grid (V2G). There are a number of step-up transformerless inverter topologies.[4] Among them Z-source converter topologies have been of great interest for use in photovoltaic grid interconnected systems. Z-source converters, due to the use of passive components are highly versatile and can be modified into EV battery charging topologies.[5][6] One of the most important features of these topologies is the ability to buck or boost the input PV voltage to a desired voltage and invert it to a nominal split phase grid voltage of 220V/240V AC grid.[7] Use of split phase connection can avail the use of SAE level II charging. For residential charging applications upto 10kW, single phase inverters are preferred.[8] This paper will present the modeling of a single stage photo-voltaic grid integrated impedance source charger and simulation results for different modes of operation for the designed model.

II. Single Phase Modified Z Source Inverter Based DC Charging Converter

Z source inverter was first proposed in [9]. It uses two inductors and two capacitors to boost low voltage source such as a photovoltaic array or a fuel cell to match a higher voltage demanded by the load.[10] In [11], the technical considerations were discussed for various topologies used for DC charging and the modified z source topology for DC charging was proposed with various power flow modes.Various issues was discussed that need to be addressed to achieve the desired power flow,i.e, PV array to BAT,grid to BAT, PV array to grid, and BAT to grid in the decreasing order of importance. The proposed topology has a half bridge DC-DC converter charger integrated into a Z source converter. The two capacitors are split and act as individual primaries with a single secondary which is connected to the EV battery as shown in Fig.1. The isolated half bridge DC/DC charger is operated in open loop at 50% duty cycle. Few of the main static equations from [9],

$$V_{g_{PK}} = V_C \frac{D}{1-D_0} \tag{1}$$

where $V_{g_{PK}}$ is the peak voltage of the AC grid, D is the active duty ratio of the ZSI switches, D_0 is the shoot through duty ratio of the ZSI and V_C is the capacitor voltage.

$$D_0 = \frac{V_C - V_{PV}}{2V_C - V_{PV}} \tag{2}$$

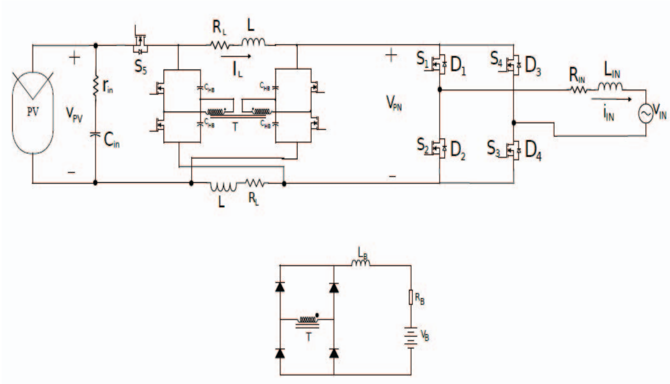

Fig. 1. Proposed Modified Z source converter based single stage topology

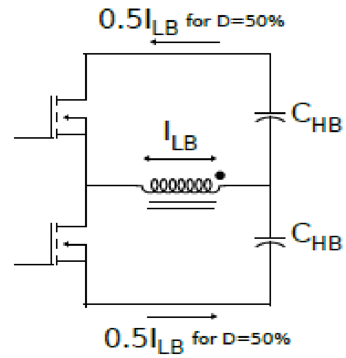

Fig. 2. Half of the DC/DC converter circuit(Primary Side)

$$I_L = \frac{D}{1-2D_0} I_{IN} \tag{3}$$

$$\hat{V_{PN}} = \frac{1}{1-2D_0} V_{PV} \tag{4}$$

A. Component Design

In DC charging applications, bulky electrolytic capacitors result in decrease in power density of the system. Since half the charging power is provided by the PV array and the other half by the AC grid, the Capacitors should be able to handle the total power,P used for charging.

$$P_{charge} = P_{PV} + P_{GRID} \tag{5}$$

Usually a ripple voltage of 10% of the capacitor voltage is considered to be a reasonable choice. The capacitor voltage rating should be the same as the battery voltage multiplied by the converter gain of the DC-DC converter topology used as a charger. Here a half bridge is used to simulate, thus the capacitor voltage is twice the battery voltage. For a EV battery voltage range between 275-450V, the capacitor voltage range should be between 550V to 900V. The capacitor is designed for a voltage,V_C of 550V considering worst cast scenario,

$$C_1 = C_2 = \frac{P}{2\omega V_C \Delta V_C} \tag{6}$$

During the shoot through state, the capacitor voltage V_C is impressed on the inductor and high frequency ripple current is generated which have to be taken into consideration while designing the inductors L_1 and L_2. The peak shoot through D_0 is calculated considering the worst case scenario,i.e, at minimum PV voltage $V_{PV(min)}$ and maximum battery voltage $V_{B(min)}$

$$D_0 = \frac{V_{C(max)} - V_{PV(min)}}{2V_{C(max)} - V_{PV(min)}} \tag{7}$$

The inductor values are calculated as follows,

$$L_1 = L_2 = \frac{D_{0(max)} V_{C(max)}}{F_{SW} \Delta I_L} \tag{8}$$

where F_SW is the converter switching frequency, $V_{C(max)}$ is the maximum capacitor voltage, $D_{0(max)}$ is the maximum shoot through duty ratio and ΔI_L is the ripple current through the inductor. A higher ripple current can increase conduction losses in semiconductor devices and can be limited by factors like saturation level of the magnetic material of the inductor core and the current capability of the capacitors but a higher value can reduce the size of the inductors which in turn reduces the quality factor of the Z source circuit, making it easier to design the compensation.

B. Derivation of the Equivalent Average Circuit of the Half Bridge DC/DC Charger

Each primary of the transformer can be simplified, as shown in Fig. 2. The average transformer current over one cycle can be considered zero, while the average current into the MOSFETs is $\frac{1}{4}$ I_{LB} (50%, due to the parallel primaries sharing current, and another 50%, due to the duty-cycle). The average rectified secondary voltage is 50% of V_C. Hence, the derived average model is straightforward, and is shown in Fig.3 . Thus, the DC/DC converter and battery load can simply be modeled as a parallel branch on the Z-circuit capacitors, as shown in Fig. 3. Fig. 4.depicts a simple technique to derive the equivalent circuit of the DC/DC converter, as seen from the Z-circuit. Unfortunately, this derivation is oversimplified, as it does not consider some parasitic components. In order to get a more precise model, including all the ESRs. Also, only $\frac{1}{2}$ of the circuit needs to be shown, as long as the secondary side is split into two parallel paths. Fig. 2 and 3. Show the two topological configurations of the circuit, as the switches are on 50% of the time, in complementary fashion. It is easy to obtain average equation for the inductance $2L_B$ and capacitors C_{HB} for both the operations.

$$C_{HB} \dot{V_{HB}} = i_L - i_{IN} - \frac{1}{4} i_B \tag{9}$$

$$L_B \dot{i_B} = V_{HB} + (i_L - i_{IN}) R_{HB} - \frac{1}{2}(R_{HB} + 2R_B) i_B - V_B \tag{10}$$

where,

$$C = \frac{1}{2} C_{HB} \tag{11}$$

$$r_C = \frac{1}{2} R_{HB} \tag{12}$$

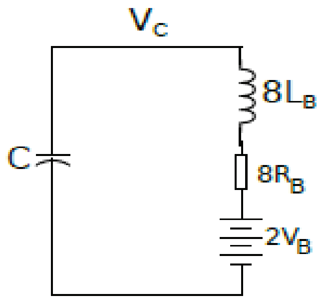

Fig. 3. Equivalent Circuit of one of the primary circuits in the proposed topology

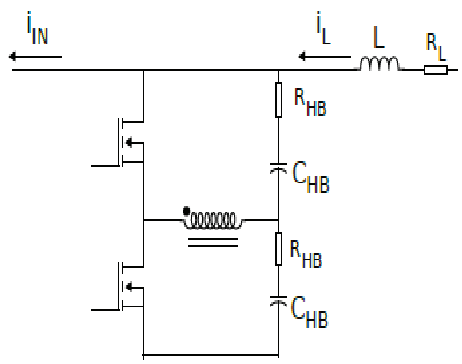

Fig. 4. One of the primary circuits in the Modified Z source converter

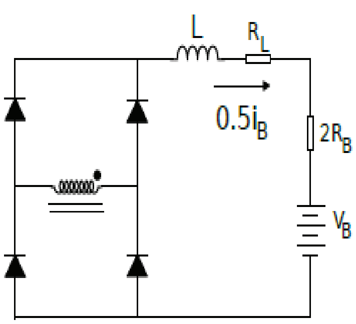

Fig. 5. Equivalent Circuit for the Secondary Side Circuit for DC-DC Charger Section

C. Equivalent Model of Z source converter with battery

The final equivalent model of the Z source converter is shown in Fig.6.By the state space average method for the shoot-through and non shoot-through states, the state space equation for the entire system is given as,

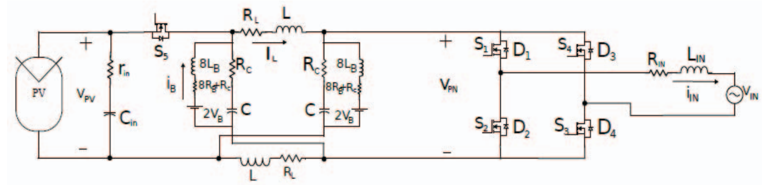

Fig. 6. Final Equivalent circuit for the modified Z source converter charger with battery.

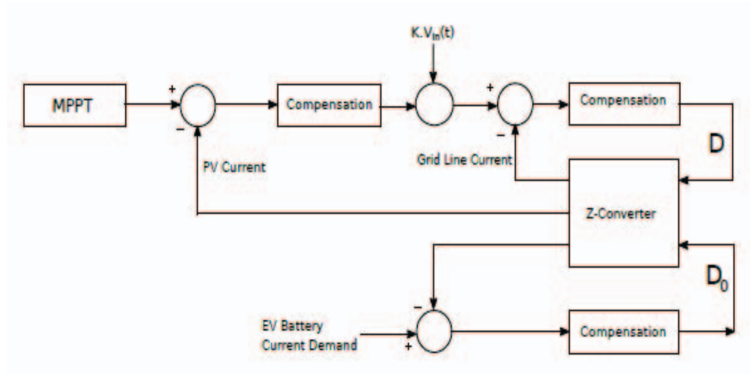

Fig. 7. Block Diagram of Control of the proposed topology with Battery Based Control

$$\begin{bmatrix} \dot{i_L} \\ \dot{V_C} \\ \dot{i_{IN}} \\ \dot{i_B} \end{bmatrix} = \begin{bmatrix} \frac{-[R_C+R_L]}{L} & \frac{(2D_0-1)}{L} & \frac{DR_C}{L} & \frac{R_C(1-2D_0)}{4L} \\ \frac{1-2D_0}{C} & 0 & -\frac{D}{C} & \frac{-1}{4C} \\ \frac{2DR_C}{L_{IN}} & \frac{2D}{L_{IN}} & \frac{-2DR_C+R_{IN}}{L_{IN}} & \frac{-DR_C}{2L_{IN}} \\ \frac{R_C}{2L_B} & \frac{V_C}{2L_B} & -\frac{(\frac{R_C}{4}+R_B)}{L_B} & \frac{-2R_B+\frac{1}{2}R_C}{2L_B} \end{bmatrix} \begin{bmatrix} i_L \\ V_C \\ i_{IN} \\ i_B \end{bmatrix} + \begin{bmatrix} \frac{(1-D_0)}{L} \\ 0 \\ \frac{-D}{L_{IN}} \\ 0 \end{bmatrix} [V_{PV}] + \begin{bmatrix} 0 \\ 0 \\ \frac{-1}{L_{IN}} \\ 0 \end{bmatrix} [V_{IN}] + \begin{bmatrix} 0 \\ 0 \\ 0 \\ \frac{-2}{2L_B} \end{bmatrix} [V_B]$$

D. Controller Block Diagram with the Modified Z source converter with battery

The proposed topology has a battery based controller as shown in Fig.7. The PV current reference generated from the maximum power point tracker (MPPT)is used to generate the grid reference voltage wiith the sine template from the grid voltage $KV_{in}(t)$. The PV current and the grid current loop generates the active duty cycle D_0. The Battery Current Control loop generates the shoot through duty cycle D_0. Carrier based modified PWM is used for the to insert the shoot through states in the Z source inverter.[12] The presence of second harmonic oscillations is one of the main challenges in a single phase inverter. To dampen the oscillations a decoupling technique has been used.[13]

TABLE I
QZSI SYSTEM SPECIFICATION

Parameters	Value
Peak Battery Charge Power Demand, P_{charge}	10 kW
Maximum PV Voltage, V_{PV}	375V
Peak Photo-voltaic Power, P_{PV}	5.3 kW
Capacitor Voltage, V_{C1}	550V-800V
Peak Shoot Through Duty Ratio, D_{0MAX}	0.35
Switching Frequency, F_{SW}	25kHz
Grid Voltage, V_g	240V(RMS)

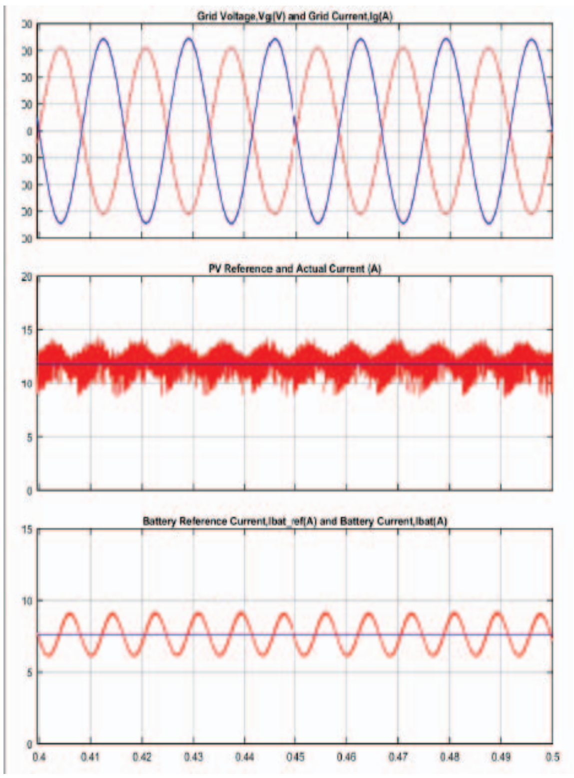

Fig. 8. Waveform for Grid Voltage(red) and Grid Current(Blue)(top),PV reference current(blue) and Actual current(Red)(middle) and Battery Reference Current(Blue) and Actual Current(Red)(bottom) for PV and AC Grid charging an EV battery.

III. SIMULATION RESULTS

The Modifed Z source Photovoltaic Grid connected Charger system was designed and simulated using Matlab/SIMULINK. The parameters for the simulated system is shown in Table II. Since Z source inverters in PV-Grid connected mode has been extensively covered in previous literature, here only the results for the PV and Grid to EV battery and EV battery to Grid are shown here. The battery voltage is 330V in the simulation.

A. PV and AC Grid to EV battery

The system shown in the fig.5, has been simulated for a split phase grid voltage of 240V. The Modified ZSI capacitance and inductances are C=2200uF and L=650uH from equation 6 and 8 respectively. In Fig. 8(top), the grid current(blue) is in 180° difference with the grid voltage(red). The grid current shown

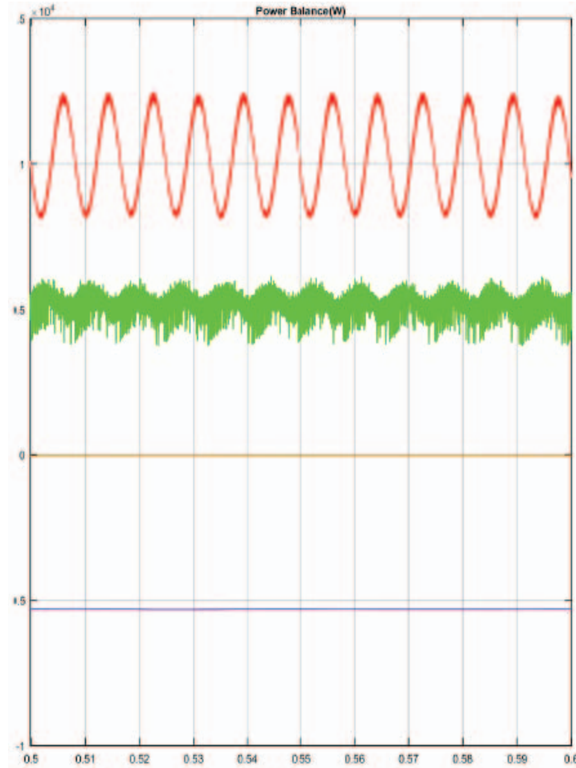

Fig. 9. Waveform for Battery Charging Power(Red), PV Power(Green),active power of the inverter output(Blue) and reactive power of the inverter(Orange)for PV and AC Grid charging an EV battery.

in blue has been magnified 10 times. In Fig. 8(middle), the photovoltaic current follows the reference current generated by the MPPT. In Fig. 8(bottom), the EV battery reference current is half of the actual reference current as explained in the equivalent circuit modeled and shown in Fig.5. The power flow from the PV and the AC grid to an EV car battery is shown in figure 9. The charger simulated here has a power demand of 10kW. The AC grid active power(Blue) and the PV array power(green) contribute half each. The battery power(red) has second harmonics oscillations present, which can be eliminated using a DC side active power filter proposed in[14] for Z source inverter topologies.

B. EV to Grid battery(V2G)

During night time, the electric vehicle battery can discharge into the grid. In Fig.10(top), the grid current(blue) is flowing into the AC grid at unity power factor. The current magnified 10 times, overlaps with the grid voltage. The discharge rate is determined by the battery,the current rating of the semi-conductor switches and the protection circuits of the AC grid. Fig.10(middle), demonstrates the case where the PV current is 0 or during night time discharge into the grid. Fig. 10(bottom) shows the reference discharge current demand(blue) and the actual discharge current(red).In Fig. 11 showing the battery discharging 5 kW into the grid, the PV power is zero and the grid injected power efficiency times the battery discharge power.

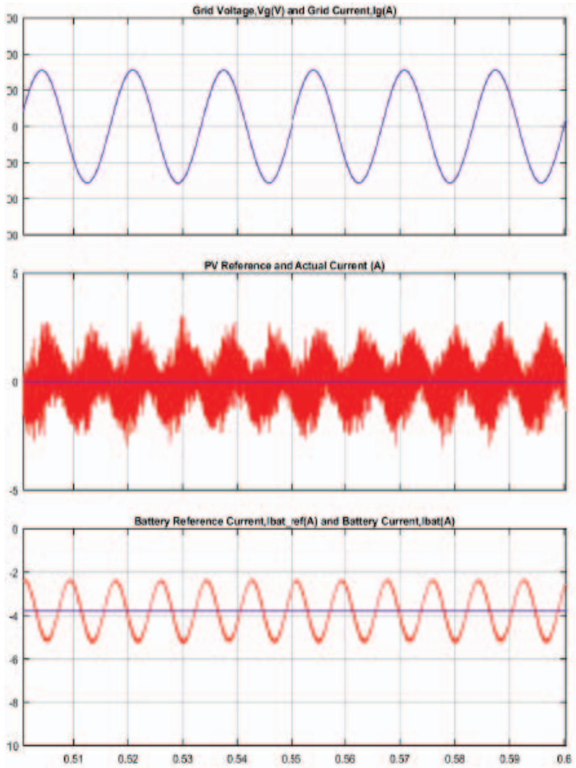

Fig. 10. Waveform for Grid Voltage(red) and Grid Current(Blue)(top),PV reference current(blue) and Actual current(Red)(middle) and Battery Reference Current(Blue) and Actual Current(Red)(bottom) for the EV discharging into the AC grid.

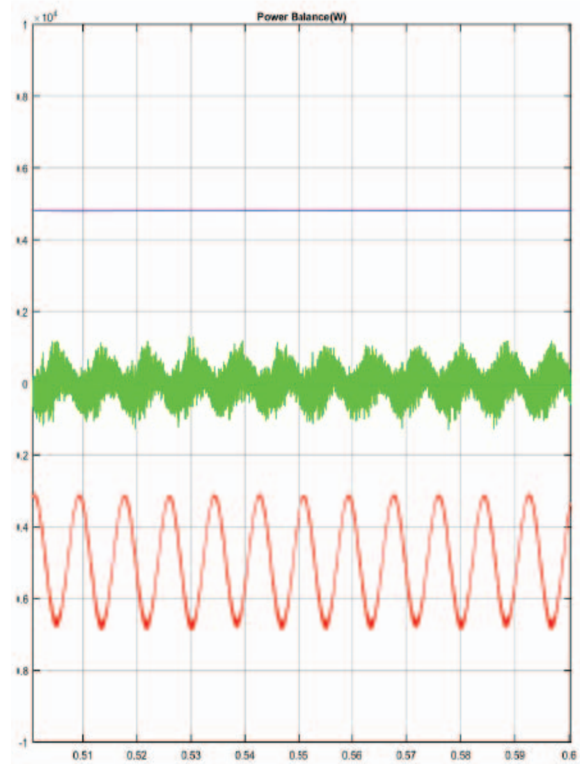

Fig. 11. Waveform for Battery Discharging Power(Red), PV Power(Green),active power of the inverter output(Blue) and reactive power of the inverter(Orange)for PV and AC Grid charging an EV battery.

IV. CONCLUSIONS

The designed procedure of a single phase single stage modified z source based DC charger has been presented. The DC-DC converter charger has been modeled and integrated into the Z source topology.Use of such single stage PV-Grid integrated topologies can improve the efficiency of the solar harvesting systems making if more economical to charge electrical vehicles considering the number of EVs that are going to need charging in the future. The proposed topology can be a strong contender for off-board charging because of its compact, highly efficient and ease of control.It has the capability of operating in different modes of operation. One of the future challenges is to reduce the second harmonics present in this topology without reducing the power density of the system.

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