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# Modified Z-source Integrated PV/Grid/EV DC Charger/Inverter Modeling, Design, Control, and Implementation

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**Abstract**—Sun based Energy has been the most well known wellsprings of sustainable power source for private and semi business applications. Vacillations of sunlight based vitality gathered because of climatic conditions can be moderated through vitality stockpiling frameworks. Sun oriented vitality can likewise be utilized to charge electric vehicle batteries to lessen the reliance on the network. One of the prerequisites for a converter for such applications is to have a decreased number of changes organizes and give seclusion. Z-source inverter (ZSI) topology can expel various stages and accomplish voltage lift and DC-AC power transformation in a solitary stage. The utilization of latent parts additionally exhibits a chance to coordinate vitality stockpiling frameworks (ESS) into them. This paper presents demonstrating, plan and activity of an altered Z-source inverter (MZSI) incorporated with a split essential secluded battery charger for DC charging of electric vehicles (EV) batteries. Reenactment and exploratory outcomes have been displayed for the evidence of idea of the activity of the proposed converter.

**Index Terms**—quasi-Zsource inverter (qZSI); Z-source-inverters; Active filter; energy storage; photovoltaic (PV) power generation; single-phase systems; transportation electrification; Solar energy; distributed power generation,inverter.

## I. INTRODUCTION

Charging of electric vehicles at present heavily involvethe use AC grid. The various methods of chargingexclusiveyuse AC grid, such as wireless charging or plug-incharging can still cause pollution irrespective of how highlyefficient the topology is. The amount of fossil fuels that areconsumed to generate the energy to charge an electric vehiclegives a clearer picture of the carbon footprint that is left behindwhile charging an electric vehicle. To achieve lower carbonfootprints, one of the ways is to integrated renewable energysources into a charging infrastructure to reduce the dependencyon the AC grid.A major requirement for designing an EV battery charger isthe use of isolation transformers in the converter topologies,to provide galvanic isolation at the user end from the

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rest ofthe high voltage (HV) system as a safety measure [1].The galvanic isolation can be provided either on the ACgrid side or on the charger side. The size of the isolationtransformer on the grid side is usually much larger than theone on the charger side [2]. Due to the improvement insemiconductor technology, high frequency switching facilitatesthe use of smaller size transformers for galvanic isolation.Photovoltaic grid interconnected systems have been usedin the past for commercial charging infrastructure [3]. Thesesystems reduce the dependency of the charging infrastructureon the AC grid. The use of solar and grid interconnectedsystem is an attractive solution for residential charging systemsfor EVs. For systems upto 10 kW, single phase inverters canbe used for residential applications [4][5]. For interconnectionof the residential solar PV to the grid, various isolated andnon isolated topologies are available with multiple stages [4]-[6]. Residential photovoltaic systems for EV charging requirefeatures such as isolation and voltage boost capability to matchthe solar PV array voltage to the grid voltage requirements.The ZSI topology was first introduced in [7]. It has an abilityto buck or boost and invert the input DC voltage in a singlestage. It has gained tremendous interest in photovoltaic-gridconnected applications. The ZSI topology uses two capacitorsand two inductors to boost the input DC voltage to match theinverter side AC output voltage requirements. The operationof a ZSI is heavily dependent on the passive components. Itpresents an opportunity to integrate energy storage units intosuch a system.

In this paper a proof of concept of a single phase MZSIbased solar grid connected charger has been presented as anapplication towards a string inverter configuration. In sectionII, the basic operation principle for a ZSI have been discussedalong with the component design. Section III, discusses thesizing of components, modeling and control of the converter.Section IV, presents the simulation results for the operationof a 3.3 kW proposed inverter charger and results from anexperimental setup built as a proof of concept. Section V,presents the conclusion.

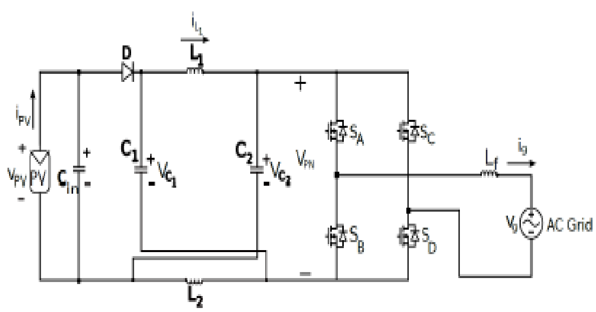


Fig. 1. Schematic of a Photovoltaic/AC grid inter-connected Z-source Inverter(ZSI)

## II. TRADITIONAL ZSI

The ZSI topology, shown in Fig.1, utilizes two modes ofoperation: the shoot through state and the non shoot throughstate [7]. For symmetrical operations,

$$i_L = i_{L1} = i_{L2} \quad (1)$$

$$V_C = V_{C1} = V_{C2} \quad (2)$$

From Fig.1, in the shoot through state, all four switches, S1,S3, S2 and S4, are conducting at the same time. The durationof this shoot through state is described by the duty cycle D0and the switching frequency FSW.The shoot through state can be implemented by a modifiedPWM technique presented in [7].Therefore, the two capacitor voltages are expressed as [7]:

$$V_C = \frac{1-D_0}{1-2D_0} v_{pv} \quad (3)$$

Thus, maintaining a higher peak voltage at the input of theDC link, VPN. The peak DC link voltage, VP^N, is given by[7]:

$$\hat{V_{PN}} = \frac{1}{1-2D_0} v_{pv} \quad (4)$$

The power balance equation between the DC and AC sideof the ZSI is expressed as [7],

$$(1-D_0)\hat{V_{PN}} I_{PN} = i_{grms} v_{grms} \quad (5)$$

where IPN and VP^N are the peak DC link current and voltage.The peak AC voltage of the ZSI is [7]:

$$V_g = M\hat{V_{PN}} \quad (6)$$

where the M is the modulation index, grid voltage, vg=Vgsin!tand the grid current ig=Igsin(!t+_). For _=0 for grid connectedapplications. From equation (11) and (13) the RMS ofthe output AC voltage of the ZSI is [7]:

$$V_{grms} = \frac{M v_{pv}}{\sqrt{2}(1-2D_0)} \quad (7)$$

## III. COMPONENT SIZING, MODELING AND CONTROL OFPROPOSED MZSI

Fig. 2 shows a modified Z source inverter has been proposedhaving an integrated charger. The two capacitors C1 and C2from Fig.1 are split and each of them act as one of thelegs of one of the two primaries of the split primary isolatedhalf bridge converter. The MOSFET SR allows bidirectionaloperation of the MZSI when required. The diode DPV blocksthe reverse flow of current back into the PV. Rin is theinternal resistance of the input capacitor Cin. For symmetricaloperation of the MZSI, a split primary isolated DC to DCconverter has been proposed for the integration of the chargerside into the ZSI. The split primaries contain two half bridgeconverter (HBC) primaries isolated from a single full bridgesecondary through a high frequency transformer. The HBCprimaries and thesecondaries are operated at 50% duty cyclein open loop. The output current of the secondary is connectedto a energy storage unit such as a lithium-ion (Li-ion) battery.The energy storage unit clamps its own voltage, vB, across
the input of the HBC primaries, VC, such that,

$$V_C = 2v_B \qquad (8)$$

### A. Maximum Shoot Through Duty Ratio,D0max

As a result of the energy storage unit being connected acrossthe capacitors, the maximum shoot through duty ratio, D0maxis calculated based on the minimum input voltage, vpvmin andthe maximum battery voltage, VBmax connected across thecapacitors and is expressed as:

$$D_{0max} = \frac{2V_{Bmax} - v_{pvmin}}{4V_{Bmax} - v_{pvmin}} \qquad (9)$$

SAE J1772 standard defines the standard battery voltages forDC charging between 200V-500V.

### B. Inductor L1 and L2 design

The inductors L1 and L2 are sized for high frequencypeak to peak current ripple assumed between 15-25% of the

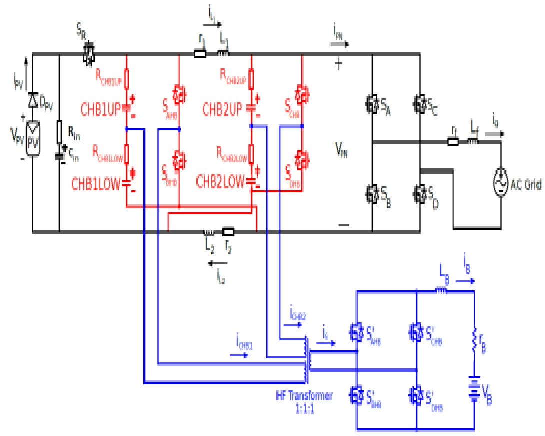


Fig. 2. Detailed Schematic of Proposed MZSI

inductor current during the shoot-through time interval D0T/2as follow [8]:

$$L_1 = L_2 = \frac{V_{Cmax} D_{0max}}{2\Delta i_L f} \qquad (10)$$

### C. Capacitor C1 and C2 design

The capacitors are sized to absorb the second order harmoniccomponent in the capacitor voltages as follow [8]:

$$C_1 = C_2 = \frac{P}{2\omega \Delta V_C V_C} \qquad (11)$$

where VC is the average voltage across the capacitors VC1 andVC2 and _VC is the predetermined voltage ripple limit. ! isthe second order harmonics expressed in rad/s.In single phase Z source inverters, oversized electrolytic capacitors for second order harmonics suppression can resultin a bulky system. A DC side Active Power Filter(APF) proposedin [9], can be used to reduce the capacitance required.It operates independent of the operation of the MZSI.For the proposed topology, maximum capacitor voltagerating is equal to at least twice the peak voltage of the energystorage device clamped across it.

### D. Average Modeling of the Integrated Half-Bridge DCDC Converter Charger

When a energy storage unit is connected to the secondaryside of the charger then each of the split primaries operatesalternately and supplies half the required battery current. Eachof the primaries of the DC-DC converter is connected acrossthe capacitors of either legs. The voltage across the capacitorsis defined by the equation (15). The detailed average modelingof the split primary DC-DC converter is explained in [10].Each of the two primaries can be represented using a RLEcircuit connected parallel to each of the capacitor, C1 and C2,as shown in the simplified equivalent model of the the Fig.4.

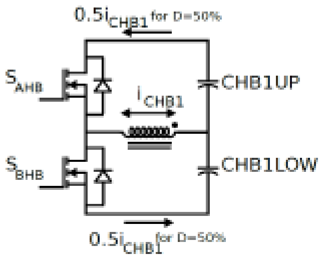


Fig. 3. Schemetic of one the Primary across CHB1 operating at 50%duty cycle.

**E. State Space Average Modeling of the Single Stage**

Inverter ChargerThe detailed state space average modeling was presented in[10]. The equivalent diagram of the modeled MZSI is shownin the Fig. 4, During the non shoot-through state, the KVLequation is given by:

$$L\frac{di_L}{dt} = v_{pv} - i_L r + R_{HB} + (2i_g + \frac{i_B}{2})R_{HB} - V_C \quad (12)$$

The KCL equation is:

$$C\frac{dV_C}{dt} = i_L - i_g - \frac{i_B}{4} \quad (13)$$

During the shoot-through state, the KVL equation is:

$$L\frac{di_L}{dt} = V_C - i_L(R_{HB} + r) - \frac{i_B}{2}R_{HB} \quad (14)$$

The KCL equation is written as:

$$C\frac{dV_C}{dt} = -i_L - \frac{i_B}{4} \quad (15)$$

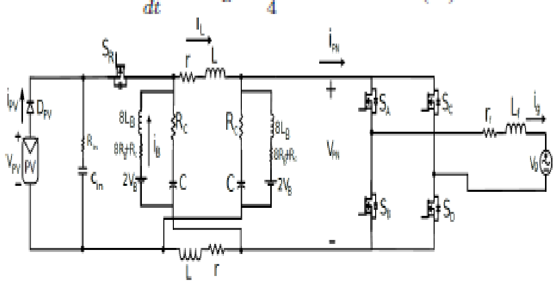

Fig. 4. Equivalent Model of the proposed Modified Z-source Inverter(MZSI) with battery

From equation (12)-(15), state space equations for theentire system can be written as:

$$\begin{bmatrix} \dot{i}_L \\ \dot{V}_C \\ \dot{i}_B \end{bmatrix} = \begin{bmatrix} -\frac{-(r+2R_{HB})}{L} & -\frac{1-2D_0}{L} & \frac{(1-2D_0)}{2}R_{HB} \\ \frac{1-2D_0}{C} & 0 & -\frac{1}{4C} \\ \frac{1-2D_0}{L_B}R_{HB} & \frac{1}{2L_B} & -\frac{R_{HB}+R_B}{2L_B} \end{bmatrix} \begin{bmatrix} i_L \\ V_C \\ i_B \end{bmatrix} + \begin{bmatrix} \frac{2(1-D_0)R_{HB}}{L} \\ -\frac{1-D_0}{C} \\ -\frac{(1-D_0)R_{HB}}{L_B} \end{bmatrix} [i_d] + \begin{bmatrix} \frac{(1-D_0)}{L} \\ 0 \\ 0 \end{bmatrix} [v_{pv}] + \begin{bmatrix} 0 \\ 0 \\ -\frac{1}{L_B} \end{bmatrix} [V_B] \quad (16)$$

Fig. 4 shows the positive directions of the battery current,

iB, and the grid side AC current, ig.Fig. 5 shows the block diagram for the controller for theproposed MZSI topology. It consists of three loops: the PVcurrentipv loop, grid current ig loop and the battery currentiB loop.

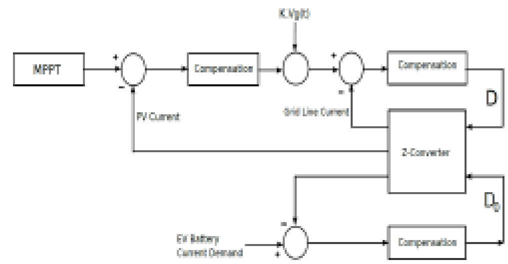


Fig. 5. Block diagram of the Control Scheme Proposed Modified Zsource Inverter Charger

In literature, the ZSI capacitor voltage is controlled togenerate the reference current for the H-bridge inverter output current [11] or generate the shoot through duty ratio D0 [12].In this paper the reference current is generated by controllingthe peak input photovoltaic current [13]. If a stiff voltage VCis connected across either or both capacitors, the shoot throughduty ratio, D0, will depend on VC.Since the battery current loop do not require fast dynamicchanges battery loop control is the slowest response comparedto the input current control. For the battery loop control thetransfer function is given by:

$$\frac{I_B(s)}{d_0(s)} = \frac{-sC[4R_{HB}i_L - 2R_{HB}i_d] - [2i_L - i_d]}{2L_BCs^2 + sC[R_{HB} + 2R_B] + 0.25} \quad (17)$$

A feedforward is added to the battery control loop,

$$FF_B = \frac{2V_B - v_{PV}}{4V_B - v_{PV}} \quad (18)$$

where VB is the output voltage of the HBC and vPV is thetracked PV voltage.The output AC side current controller should have the fastestresponse.

**F. Energy Management Scheme for the Proposed Converter**

Fig. 6 shows a simplified block diagram of the proposedsystem. When an ESS is integrated into a ZSI, the equation (5) is modified as follows [14]:

$$v_{PV}i_{PV} = v_b i_b + i_{grms}v_{grms} \quad (19)$$

that the single phase AC grid power Pg balances the powerfluctuation of the photovoltaic source Ppv thus a constantcharge power, PB, is obtained at the ESS.For EV battery charging using both the single phase AC grid and the photovoltaic power, the direction of the AC gridcurrent ig changes to negative while drawing power from thegrid.The inverter side can be operated bidirectionally and the PVand the grid provides power for the charger, maintaining thepower balance.

$$v_{PV}i_{PV} + i_{grms}v_{grms} = v_b i_b \quad (20)$$

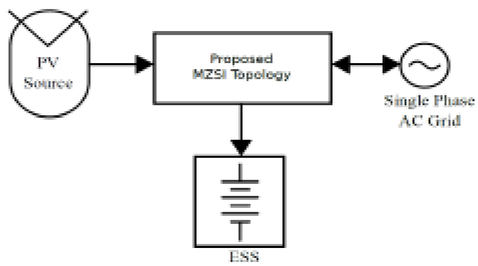


Fig. 6. Simplified Block Diagram of the System

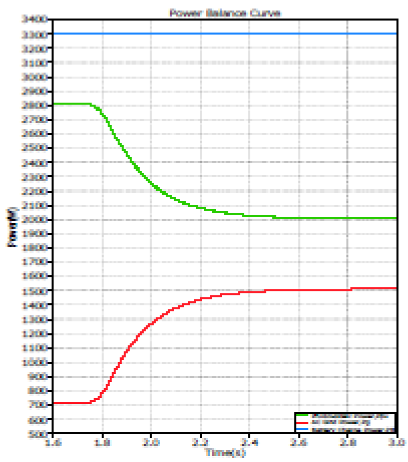


Fig. 7. Simulation Waveform for the power balance between thePhotovoltaic input power, the AC Grid side and the battery power.

Photovoltaic input power, the AC Grid side and the battery powerAs long as the voltage across the input capacitor Cin ismaintained to atleast the minimum value of the PV voltage,the MZSI can be operated as a grid connected rectifier/chargerin the absence of the PV [15]-[16].Anti-islanding protection techniques for the ZSI topologyhave been addressed in literature previously in [17].

## IV. SIMULATION AND EXPERIMENTAL RESULTS

### A. Simulation study for a MZSI operation

The simulation studies to demonstrate the behaviour of theproposed topology have been carried out using PLECS 4 for a3.3 kW charger for a string inverter configuration. Simulationhas been carried out for the system shown in Fig.2Fig.7 shows at simulation time t=1.75 s, the input PV powerreduces from 2.8 kW to 2 kW, the grid power increases from710 W to 1500 W to maintain the output charger power to3.3kW and the corresponding grid current, DC link voltage,capacitor voltage and the battery current is shown in Fig.8.

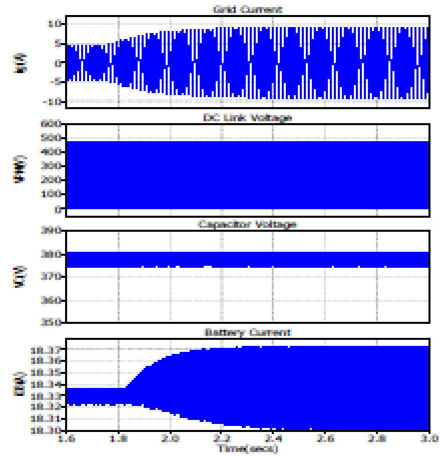


Fig. 8. SimulationWaveform of the grid current,Ig, DC link voltage,VPN,Capacitor Voltage,VC1, and Battery current,ib for the power balancebetween the Photovoltaic input power, the AC Grid side and the batterypower.

TABLE I MODIFIED ZSI BASED CHARGER SYSTEM SIMULATION SPECIFICATIONS

| Parameters | Value |
|---|---|
| Input Voltage, $V_{in}$ | 286 V |
| Input Current, $I_{in}$ | 9.8 A |
| Inductor Value, $L_1$=$L_2$ | 500 uH |
| ZSI Switching Frequency, $F_{SW}$ | 25 kHz |
| Grid Voltage (RMS), $V_g$ | 240 V |
| Inverter Output Filter Inductor, $L_f$ | 7.5 mH |
| PV Input Power, $P_{PV}$ | 2.8 kW |
| Input Capacitor, $C_{in}$ | 2 mF |
| HBC Switching Frequency, $f$ | 50 kHz |
| HBC Output Filter, $L_B$ | 1 mH |
| Battery charge power, $P_B$ | 3.3 kW |

TABLE II COMPONENT MODELS USED FOR LOSS MODELING OF THE PROPOSED SYSTEM

| Component | Value |
|---|---|
| Diode, D | STTH6010W |
| ZSI MOSFETs [$S_A$, $S_B$, $S_C$ and $S_D$] | APT28M120L |
| HBC MOSFETs [$S_{AHB}$, $S_{BHB}$, $S_{CHB}$ and $S_{DHB}$] | APT28M120L |
| HBC Diodes, [$S'_{AHB}$, $S'_{BHB}$, $S'_{CHB}$ and $S'_{DHB}$] | STTH6010W |
| Capacitor, $C_{in}$, $C_1$ and $C_2$ | ECE-T2VP182FA |

### B. Loss Modeling

The loss modeling for the proposed system shown in Fig.2 has been carried out by modeling the actual components inPLECS 4.0. The switching components used for the modelingis shown in the Table II,For the loss modeling of the passive components, theinternal resistance of the inductors, L1, L2 and Lf are r=100m and the ESR, RHB for the capacitors C1, C2 and Cin

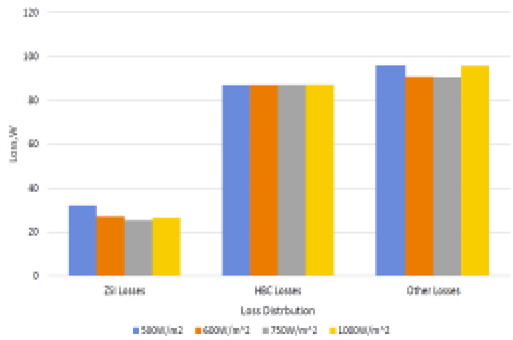


Fig. 9. Loss distribution chart for the MZSI topology for a fixed chargingpower PB=3.3 kW at 25 _C, under varying irradiation

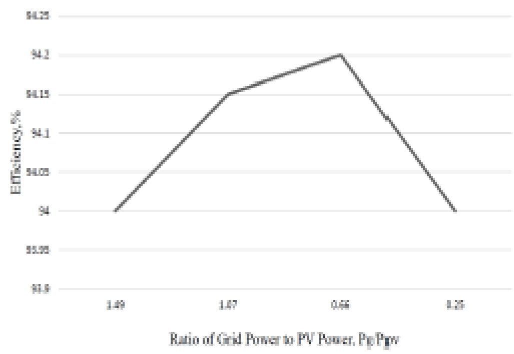


Fig. 10. Efficiency curve for different ratios of AC Grid Power Pg toPhotovoltaic Power Ppv curve for a fixed charging power PB=3.3 kW at25 _C under varying irradiationare 138 m.

Fig. 9 shows the loss distribution between the ZSI (conductionand switching losses of the MOSFETs and diode D), theHBC (conduction and switching losses of the MOSFETs andsecondary diodes) and other losses in due to the inductor, capacitors,leakage losses in the high frequency transformer andbattery series resistances in the system for varying irradiationsfor a constant charging power PB=3.3 kW.Fig. 10 shows the efficiency is around 94% from theefficiency curve for various ratios of AC Grid Power,Pg, toPhotovoltaic Power, Ppv for a fixed charging power, PB=3.3kW at 25 _C, for varying irradiation between 500W=m2to 1000W=m2. Although the efficiency variations is small,the efficiency is the highest when the sharing between thephotovoltaic power Ppv and the grid power Pg is equal.For a constant frequency of operation,the HBC MOSFETlosses remain constant for a fixed value VB and chargingpower,PB. Although in reality, this might not be the case. The efficiency of the converter will change with the change inthe battery voltage. Fig. 11 shows the distribution of the lossesbeween the ZSI losses,the HBC MOSFETs and the losses due

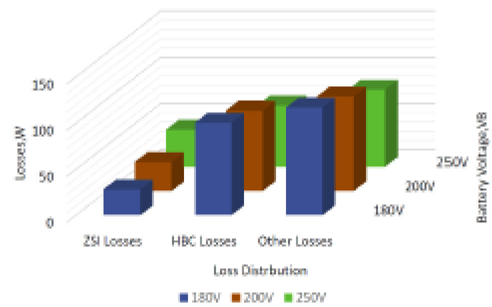


Fig. 11. Loss distribution for various battery voltages,VB, for a fixedcharging power,PB=3.3 kW, at 45 _C

TABLE IIIMODIFIED ZSI BASED CHARGER SYSTEM PROTOTYPE ELECTRICALSPECIFICATIONS

| Parameters | Value |
|---|---|
| Input Voltage, $V_{in}$ | 38 V |
| Input Current, $I_{in}$ | 3.82 A |
| Inductor Value, $L_1$ & $L_2$ | 500 uH |
| Peak DC Link Voltage, $V_{PN}$ | 63.33 V |
| Modulation Index, M | 0.75 |
| Shoot Through Duty Ratio, $D_{0MAX}$ | 0.2 |
| Switching Frequency, $F_{SW}$ | 25 kHz |
| Grid Voltage, $V_g$ | 34 V(RMS) |
| Inverter Output Filter Inductor, $L_f$ | 2.5 mH |
| HBC switching frequency, $f_{HBC}$ | 50 kHz |

transformer and battery series resistances in the system forvarious battery voltages. From Fig.11,at 45 _C, the vpv dropsto 258V and it can be observed that with the increase in batteryvoltage the ZSI losses increase but the HBC losses and thelosses in the passive components reduce.

**C. Experimental Verification of the MZSI power balanceoperation**

In this paper as proof of concept, a scaled down 175Wexperimental setup was built using MATLAB/Simulink and dSPACE 1103.The setup has the following specificationsshown in table III.Fig. 12 shows the PWM scheme for the HBC. Each ofthe split primary operate for half the HBC switching period.Each MOSFET SAHB, SBHB, SCHB and SDHB operatesexclusively for one quarter of the entire HBC switching period.Equation (23) can be written in terms of the current sharingbetween the AC load(grid) and the battery as:

$$i_{PV} = \frac{1 - D_0}{2(1 - 2D_0)} i_b + \frac{M}{\sqrt{2}(1 - 2D_0)} i_g \quad (21)$$

where M is the modulation index and D0 is the shoot throughduty ratio. For D0=0.2,

$$i_{PV} = \frac{2}{3} i_b + \frac{\sqrt{3}}{2} i_g \quad (22)$$

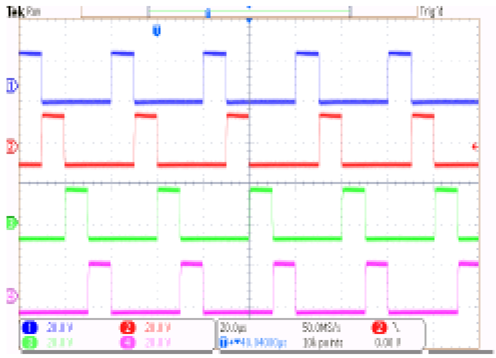

Fig. 12. PWM logic for the isolated HBC

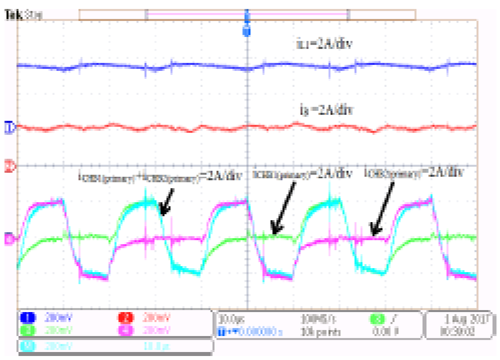


Fig. 13. Experimental setup waveforms for the Inductor current(top),charger output current(middle) and the primary currents of the splitcharger(bottom)

From equation (22), at D0=0.2, for an input current iPV =3.82A and fixed HBC output current ib=2 A, the ZSI AC outputcurrent ig is calculated to be 2.87 A.Fig.13 shows the the inductor current iL1, the battery currentiB and the split primary current iCHB1 and iCHB2 and thetotal primary current. Each of the primary operate alternately.The total primary current is a high frequency alternatingcurrent of fHBC=50 kHz.From Fig. 13 and Fig. 14, the charger ouput current ismaintained at 2 A using a Chroma Programmable AC/DCElectronicsLoad(Model 6304). The PV input current is maintainedat 3.82 A using a Magna-power LXITM solar emulator.The output grid current is observed to be 2.66 A. Fig. 15 showsthe experimental setup for the proof of concept.The lower values of the output current is a result of thelosses in the circuit. The practical PI values for the ACside current control was KP =0.03 and the battery loop wasKPB=.0003 and KIB=.09 and the input PV current loop wereKPin=0.005 and KIin=2.

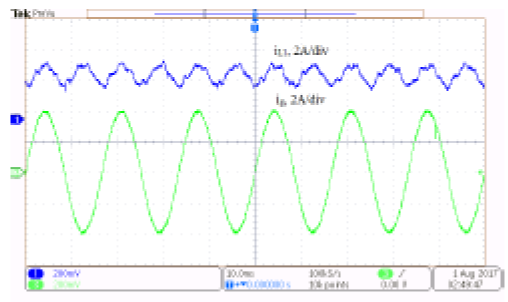


Fig. 14. Experimental waveform input current(blue) and output current(green) between the charger and the AC output of the MZSI

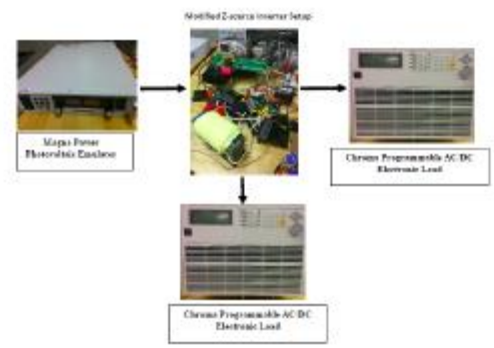

Fig. 15. Experimental setup

Table IvIsolated Half Bridge Dc-Dc System ElectricalSpecifications

| Parameters | Value |
|---|---|
| Input Voltage, $V_C$ | 50.667 V |
| Output Voltage , $V_B$ | 25.335 V |
| Switching Frequency, $F_{sw(H B}$ | 50 kHz |
| Filter inductor, $L_B$, | 330 uH |

## V. CONCLUSION

A modified ZSI topology has been proposed in this paper isan attractive solution for photovoltaic grid connected chargingsystems. It consist of a single stage photovoltaic grid (PV-Grid)connection and an integrated charger for PV-Grid connectedcharging or energy storage. This topology can be applied tocentralized configuration for charging in semi-commercial locationssuch as a parking lot of a shopping mall. For residentialapplications, this idea can be extended to string inverters withthe charger side of the string inverter configurations connectedin series or parallel for current sharing. The paper proposes aan energy storage topology using Z source converter through
symmetrical operation of its impedance network.

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