DESIGN AND IMPLEMENTATION OF TWO PARALLEL INTERLEAVED DC-DC CONVERTER FOR EV FAST CHARGING

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Abstract - ***In this paper, a single-phase EV charger and its control strategy are presented with the potential to achieve desired power factor. In the proposed configuration, the dual-stage (AC-DC and DC-DC) integrated charger is composed of a single-phase AC/DC converter and the parallel interleaved DC-DC converter sharing the same dc-link. The entire system is designed for a 1-ϕ, 10 kW rating with a broad range DC output voltage of 200–400V for EV batteries and 230V, 50 Hz input supply Total harmonic distortion (THD) and the performance obtained are examined. The hardware prototype of the same is implemented.***

Key Words: **Parallel interleaved converter, AC-DC Converter, DC-DC Converter, Electric Vehicle, Fast Charging, Total harmonic distortion, Pulse Width Modulation, Matlab, Simulink**

1. INTRODUCTION

Electric mobility makes a significant contribution to the development of sustainable and effective alternatives in the transportation sector given the severe regulations on emissions, fuel efficiency, global warming challenges, and limited energy resources [1-7]. In [8], an assessment based on the current environment and anticipated technological advancements for electric vehicle (EV) propulsion is offered. The electric vehicle (EV) has a number of benefits over traditional gasoline-powered cars. The researcher must focus deeply on the electrification of transportation to incorporate it effectively. In order to incorporate them into the present distribution system, it is required to establish specific efficient control mechanisms must be created [9-11]. Number of strategies related to the power quality issues associated with charging battery packs present are explained for the EV chargers [12-13].

The process of charging the EV refers to the electronic communication between the EV battery and the grid power supply. The purpose is to avoid overloading and to confirm safety. There are various kinds of energy storage systems (batteries). Li-ion batteries have highest energy density and low self-discharging rate, compared to other batteries, and hence, has a potential world market. Li-ion storage cells are generally functional in EVs because of their light weight. EVs use grid supply to charge the batteries. OBC's allow users to charge their EV batteries wherever there is an availability of electric power channel [15]. The EV-battery is charged only when the car is at standstill, except for regeneration at decelerating, so, using the on-board traction system components to form an unified charging device is made possible.

EV charging systems are classified into **Slow Charging System** and **Fast-Charging Systems**:

Level 1 and Level 2 on-board charging systems are commonly referred to as **Slow Charging Systems.** It takes 8 to 10 hours for Level 1 on-board charging systems to fully charge a power battery. Their output power is usually less than 10 kW, and they are mostly utilized in residential buildings. On the other hand, Level 2 charging systems charge a battery to its full capacity faster than Level 1 systems.

Fast-Charging Systems, sometimes referred to as Level 3 charging systems, have the capacity to produce high currents of up to 400 A and can finish charging power batteries in 20 to 30 minutes, with a typical range of 50 kW to 350 kW.

2. METHODOLOGY

Figure 1 depicts the methodology of the proposed system. It consists of dual-stage conversion: a single-phase AC-DC stage and an interleaved DC-DC stage. Single-phase AC/DC converters, consists of four- active switches (S_1,S_2,S_3,S_4), coupled to two split capacitors ($C_1 and C_2$), connects to a DC link. Virtually all capacitors have neutral potential at their midpoint. EV charger applications that require high DC input voltages and low duty ratios are suitable for the DC link voltage that feeds a parallel IBC.

The recommended DC-DC stage is an interleaved buck DC-DC converter with zero resonant current switching, which is suitable for low-voltage and high-current applications. This converter is made from the standard buck converter by connecting a second order LC filter.

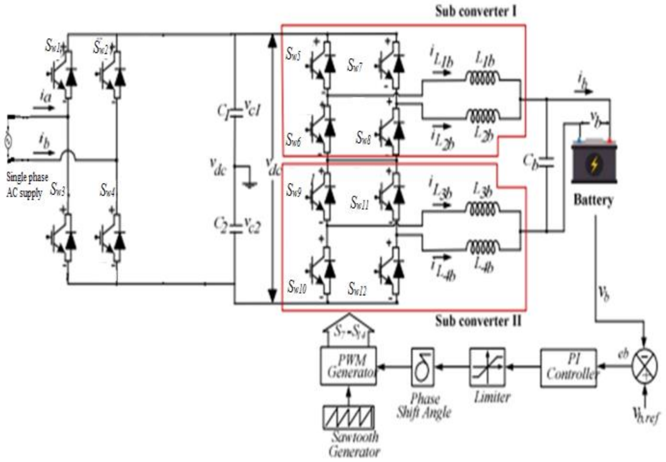


Figure 1: Methodology of the Proposed System

Two pairs of switches (S_{W5} and S_{W8}) for sub-converter I and switches (S_{W9} and S_{W12}) for sub-converter II are connected in parallel. This converter works with a single-controller and a single-switching frequency due to an adequate control scheme, producing a frequency that is double the original. All the harmonic filter inductors of interleaved DC-DC converter are identical. Switches (S_{W5} and S_{W6}) and (S_{W7} and S_{W8}) carrier signals include an 180^0 phase shift to remove harmonics and dc ripple. The EV charger draws sinusoidal line current that is in-phase with input voltage.

PI controllers are often used in the organization, especially when response speed is not always an issue. The P-I controller is used specifically to deal with frequent state errors caused by the P (proportional) controller. This controller is basically used in areas where system speed is not always a problem. Since the controller does not have the ability to reverse future errors of the device, it does not reduce the increase time and does not eliminate the oscillations.

3. MODE OF OPERATION

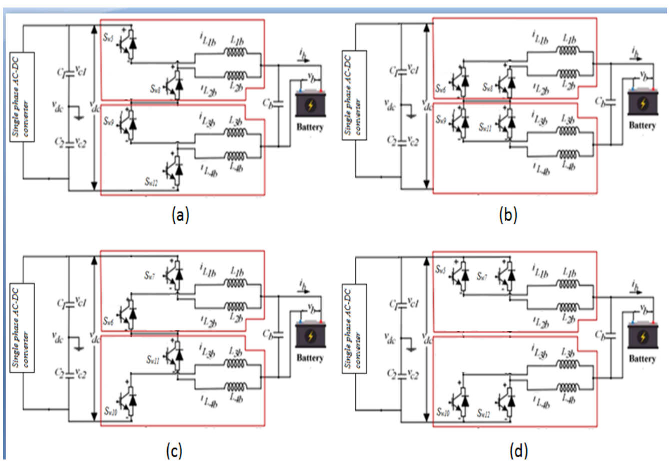


Figure 2: mode of operation

Mode of operation of sub-converter1 is explained below:

MODE 1- In this mode, switches S_{W5}, S_{W8}, S_{W9} and S_{W12} are turned ON, the inductors L_{1b}, L_{4b} is charging and the inductors L_{2b}, L_{3b} is discharging. The Mode 1 Equivalent Circuit of Parallel Interleaved DC-DC Converter is shown in Figure 2(a).

MODE2- In this mode, switches S_{W6}, S_{W8}, S_{W9} and S_{W11} are turned ON. All the inductors L_{1b}, L_{2b}, L_{3b} and L_{4b} are discharging. The Mode 2 Equivalent Circuit of Parallel Interleaved DC-DC Converter is shown in Figure 2(b).

MODE3- The Mode 3 Equivalent Circuit of Parallel Interleaved DC-DC Converter is shown in Figure 2 (c). With the activation of Switches S_{W6}, S_{W7}, S_{W10} and S_{W7}, the inductors L_{1b}, L_{4b} is discharging and the inductors L_{2b}, L_{3b} is charging.

MODE4- The Mode 4 Equivalent Circuit of Parallel Interleaved DC-DC Converter is shown in Figure 2(d). In this mode, switches S_{W5}, S_{W7}, S_{W10} and S_{W12} are turned ON. All the inductors L_{1b}, L_{2b}, L_{3b} and L_{4b} are charging.

4. DESIGN OF PARALLEL INTERLEAVED CONVERTER

The Two Parallel Interleaved DC-DC Converter delivers 200-400V DC for various ranges of EV battery charging using an input DC voltage of 760 Volts. Considering the given specifications for the converter shown in table 1.

Table 1: Design Specifications

	PARAMETERS	VALUE
SINGLE PHASE AC SUPPLY	Input Voltage	230 Volts
	Frequency	50 Hz
DC-DC CONVERTER	Input Voltage	760 Volts
	Output Voltage	400 Volts
	Switching Frequency	25 kHz
	Output Power	10 kW
	Output Current	50 A
BATTERY	Type	Lithium ion
	Nominal Voltage	180 Volts
	Rated Capacity	150 Ah
	Initial State of Charge	50 %

The duty ratio, D for the proposed converter, is calculated as,

$$D = \frac{V_o}{V_{in}} \qquad (1)$$

Where, V_o = Output voltage,
V_{in} = Input voltage

$$D = \frac{200}{760} \& \frac{400}{760}$$

D= 0.263 to 0.53.

The average of the inductor currents is provided by,

$$I_{L1} = I_{L2} = I_{L3} = I_{L4} = \frac{I_0}{2} \quad (2)$$

Where, $I_{L1} = I_{L2} = I_{L3} = I_{L4}$ = Inductor Currents,
I_o = Output Current

$$I_{L1} = I_{L2} = I_{L3} = I_{L4} = \frac{50}{2} = 25\ A$$

The inductor ripple current is given by,

$$\Delta I_{L1} = \Delta I_{L2} = \Delta I_{L3} = \Delta I_{L4} = \left(\frac{I_0}{4}\right) \times 5\% = 0.625\ A \quad (3)$$

The Inductance value is calculated from the equation,

$$L_{1b} = L_{2b} = L_{3b} = L_{4b} = \left(\frac{V_{in} - V_{Omin}}{\Delta I_L \times n \times f_s}\right) \times D \quad (4)$$

Where, ΔI_L= Inductor ripple current,
V_{Omin} = Minimum output voltage,
f_s = Switching frequency

$$L_{1b} = L_{2b} = L_{3b} = L_{4b} = \left(\frac{760 - 200}{0.625 \times 2 \times 25000}\right) \times 0.263 = 4.71\ mH$$

The output capacitor is calculated from the following equation,

$$C_b = \frac{I_{Omax}}{8 f_s \times \Delta V_{cb}} \quad (5)$$

$$C_b = \frac{50}{8 \times 25000 \times 6}$$

$$C_b = 41.7\mu F$$

The values of the DC link capacitors C_1 and C_2 are,

$$C_1, C_2 = \frac{P_o}{4 \times f_c \times [V_{dc}^2 - (V_{dc}^2 - \Delta V^2)]} \quad (6)$$

Where, ΔV^2 = 5% allowable ripple in the DC-link voltage,
f_c = Rectifier switching frequency
P_o = Output power of AC-DC converter,
V_{dc} = Output voltage of AC-DC converter.

$$C_1, C_2 = \frac{10000}{4 \times 5000 \times [760^2 - (760^2 - 38^2)]}$$

C_1, C_2 = 346.26 µF.

Table 2. Design Parameters

SYMBOL	PARAMETERS	DESIGN VALUE
V_g	Line Voltage	230 V
F	Line Frequency	50 Hz
V_{dc}	DC Link Voltage	760 V
P_o	Output Power	10 kW
F_c	Rectifier Switching Frequency	5 kHz
F_s	Two Phase Interleaved DC-DC Converter Switching Frequency	25 kHz
C_1 & C_2	DC Link Split Capacitors	346.26 µF
L_{1b}, L_{2b}, L_{3b}, L_{4b}	Coupled Inductor	4.71 mH
C_b	Output Capacitor	41.6 µF

5. SIMULATION RESULTS

The simulation circuit of single-phase AC-DC converter fed two parallel interleaved DC-DC converter for EV fast charging is shown in figure 3. A single phase AC source of 230V, 50 Hz is provided as supply to the AC/DC converter whose output is 760V and 10KW which in turn provides supply to the two parallel interleaved DC/DC converters in order to charge the battery of 180V, 150Ah.

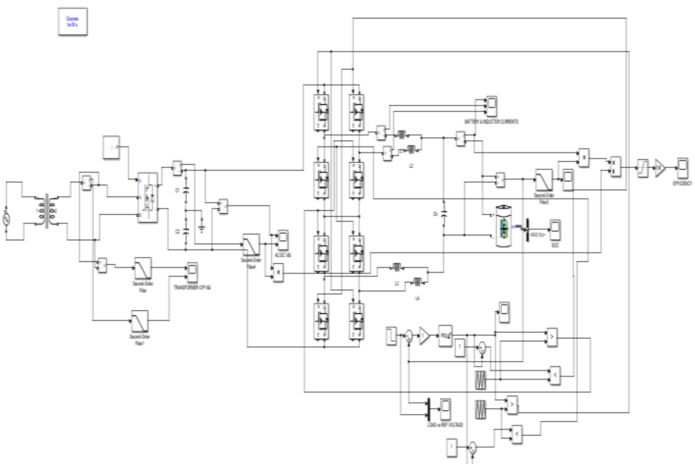


Fig3: Simulation Circuit

Figure 4, shows the output voltage and output current waveforms of the single-phase AC-DC converter. The output voltage is around 760V and current is around 14A.

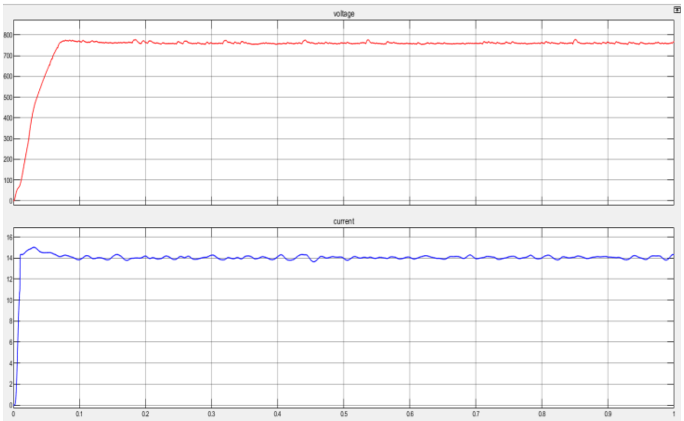


Figure 4: Output Voltage and Current of AC/DC Converter

The reference voltage for interleaved converter control is initially provided as 400V and changed to 200V at t=0.6s. Figure 5, shows the battery voltage compared with reference voltage at different intervals. In this the reference voltage (blue line) is initially of 400V and reduced to 200V at t=0.6s and the measured voltage (red line) is following the reference voltage in both conditions.

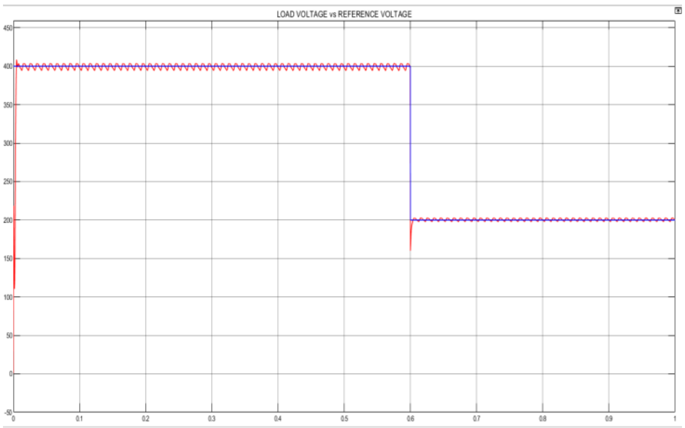


Figure 5: The Load (Battery) Voltage Compared With Reference Voltage Waveform

Figure 6, shows the batter and inductor current waveforms. The battery current is of 24A initially with inductor currents are shared equally of 12A and at t=0.6s, when the voltage reference is reduced to 200V, the battery current is increased to 40A with both inductors sharing 20A individually.

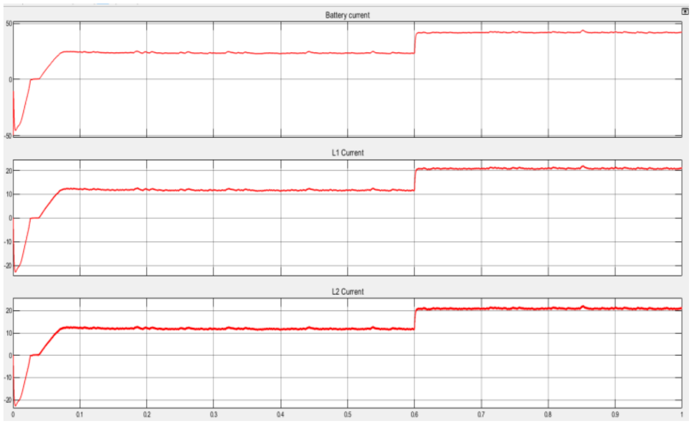


Figure 6: The Battery Current Along With Inductor Currents Waveforms

Figure 7, shows the percentage state of charge (SOC) of battery waveform. The %SOC is increasing from 50% as the battery is charging and after t=0.6s, the rate of charging is increased due to increase in converter output current. This proves that the battery is charging.

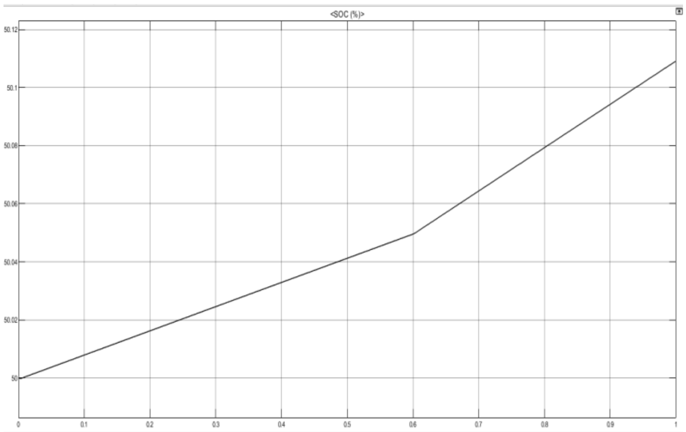
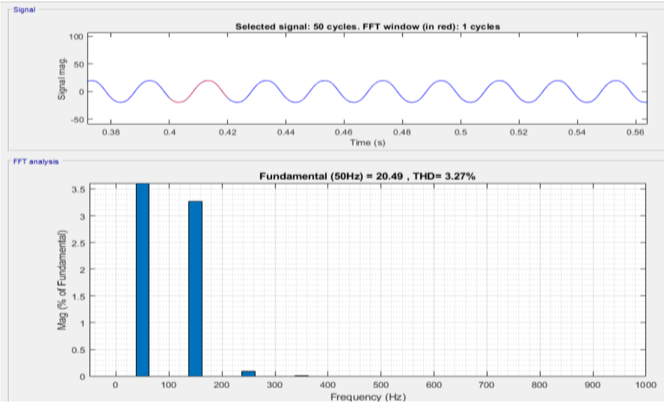
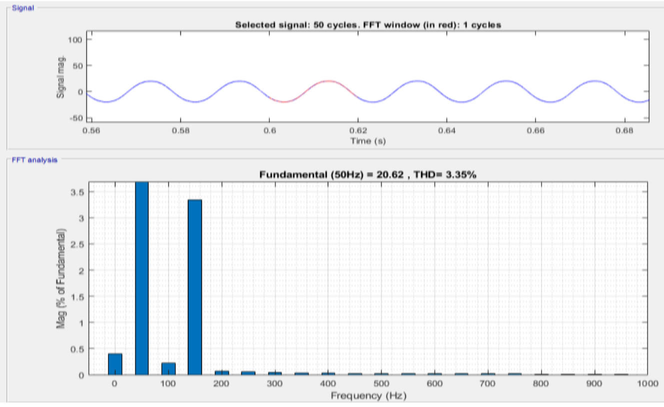


Figure 7: The %SOC of The Battery Waveforms

Figure 8, shows the total harmonic distortion(THD) obtained from fast fourier transform(FFT) analysis for 400V and 200V respectively. The %THD of the source current when reference voltage is 400V is around 3.27% figure(a) and when reference voltage is 200V is around 3.35% figure (b).



(a)



(b)

Figure 8: The %THD of The Source Current At Reference Voltage Of (a) 400V (b) 200V

6. HARDWARE SPECIFICATIONS

Table 3: Parameters of the Two Parallel Interleaved Circuit considered for the Hardware

	PARAMETER	MODEL/ VALUE
SINGLE PHASE AC SUPPLY	Phase to Phase Voltage	230 Volts
	Frequency	50 Hz
AC-DC CONVERTER	Input Voltage	24 V
	Output Voltage	48 V
	Step-down Transformer	12-0-12 V, 3 A
	MOSFET	IRFP250
	Capacitor	1000 µF,63 V
TWO PARALLEL INTERLEAVED	Input Voltage	24 V
	Output Voltage	13 V
DC-DC CONVERTER	MOSFET	IRFP250
	Inductor	15 Turns
	Capacitor	1000µF,100 V
DRIVER CIRCUIT	Step-down Transformer	0-12 V, 1 A
	Diode Rectifier	S1WB60
	Buffer IC	CD4050UBC
	Driver	TLP250
	Diode	1N4007
	Capacitor	1000 µF, 25 V
	Resistor	100 Ω
BATTERY	Type	Lead Acid
	Nominal Voltage	12 Volts
	Rated Capacity	1.3 Ah

7. HARDWARE CIRCUIT

The hardware circuit of three-phase AC-DC converter fed two parallel interleaved DC-DC converter for EV fast charging is shown in figure 9. Single phase input AC supply i.e.,230 volts, is provided to step-down transformer of 230/24V, 3A , which is then to the AC-DC converter. The AC-DC converter gives an output voltage of ~47 volts which is further connected to the two parallel interleaved DC-DC converter. The parallel interleaved DC-DC converter provides an output of 13 volts to charge the battery of 12volts, 1.3Ah capacity.

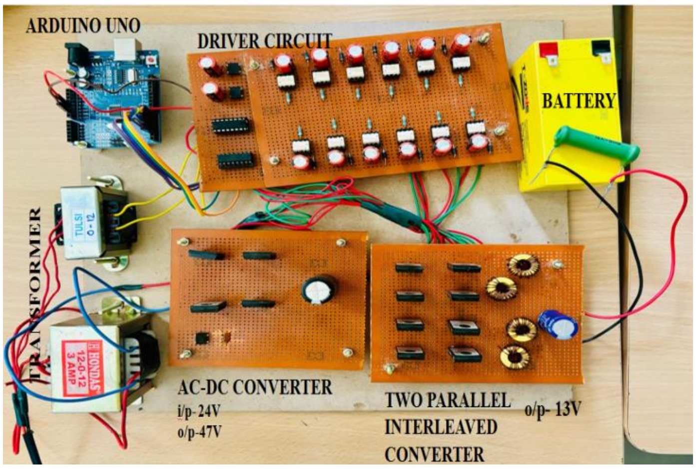


Figure 9: Hardware Circuit Top View

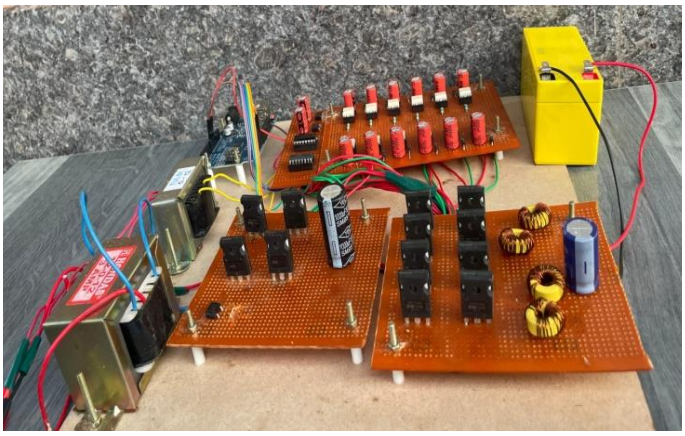


Figure 10: Hardware Circuit Side View

8. HARDWARE RESULTS

Figure 11, shows the gate pulse waveform generated from the driver circuit. The pulse is viewed in the Cathode ray oscilloscope (CRO).

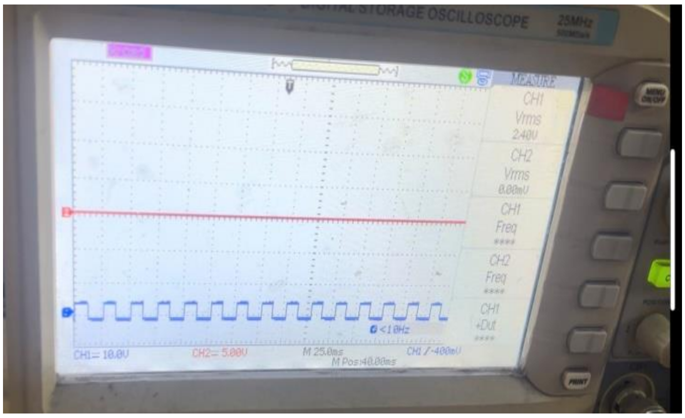


Figure 11: Gate Pulse Waveform

The input ac voltage is converted to dc voltage in the AC-DC converter is around 48V which is shown in figure 12.

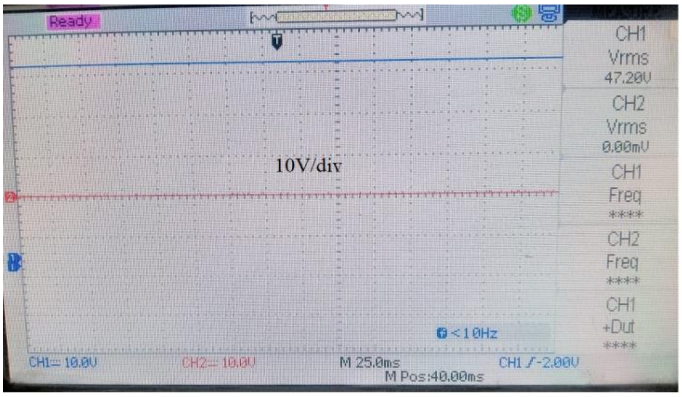


Figure 12: AC-DC Output Voltage Waveform

The output voltage of interleaved converter is around 12.8V, which is fed to the battery, to charge the battery. Figure 13, shows the output voltage of the two parallel interleaved DC-DC converter.

Figure 13: Interleaved Converter Output Voltage Waveform

9. CONCLUSION

A Two parallel interleaved DC-DC converter for EV fast charging was proposed. In the proposed configuration, a single phase AC source of 415V, 50 Hz is provided as supply to the AC/DC converter whose output is 760V and 10KW which in turn provides supply to the two parallel interleaved DC/DC converters in order to charge the battery of 180V, 150Ah. The THD for 400V was found to be 3.27% and THD for 200V was found to be 3.35%.The theoretical analysis of this unique design was empirically validated using the MATLAB Simulink platform. The hardware was implemented for lower ratings to prove the concept of the proposed converter. A single phase AC supply was fed to the proposed system to charge a 12V battery and the hardware results of the same were analysed.

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