INTERNATIONAL JOURNAL OF ADVANCE RESEARCH, IDEAS AND INNOVATIONS IN TECHNOLOGY

ISSN: 2454-132X
Impact factor: 4.295
(Volume 4, Issue 3)
Available online at: www.ijariit.com

Fuzzy controller based boost PFC converter for EV application

Sajilamol S
sajilashams123@gmail.com
Mar Athanasius College of Engineering, Kothamangalam, Kerala

Elizabeth Paul
sajilashams123@gmail.com
Mar Athanasius College of Engineering, Kothamangalam, Kerala

Mohitha Thomas
sajilashams123@gmail.com
Mar Athanasius College of Engineering, Kothamangalam, Kerala

ABSTRACT

The scarcity of fossil fuel and the increased pollution leads to the use of Electric Vehicles (EV) and Hybrid Electric Vehicles (HEV) instead of conventional Internal Combustion (IC) engine vehicles. In EVs and HEVs, a battery is used as the main power source, so that battery charger is treated as the core technology. Battery charger based on a unidirectional non-isolated boost power factor correction (PFC) converter for electric vehicles (EV) is introduced here. This non-isolated high gain boost PFC converter automatically balances the output voltages for an unbalanced load without the need for any additional control strategy or auxiliary circuit. For EV charging application one of the important factors is that the battery chargers should consume sinusoidal current with controlled power factor for contribute to the power quality in the future Smart Grids and high voltage gain for charging the battery. This converter can improve the power quality and can control the output voltage according to the demand of the battery. Due to these advantages, it can be used for electric vehicle charging application. Fuzzy control has been used for switching pulse generation in the converter. The topology has been simulated in MATLAB2014a and the various waveforms were analyzed. The control circuit was implemented using dsPIC30F2010. An experimental prototype of the converter was setup and the results were verified.

Keywords: *Electric vehicle (EV), Power factor correction (PFC), Total harmonic distortion (THD).*

1. INTRODUCTION

Conventional Internal Combustion (IC) engine vehicles use petroleum products (i.e. petrol, diesel, or LPG) as the source of energy for driving purpose. The shortage of fossil fuel is the most critical issue over worldwide. Moreover, conventional IC engine vehicles emit carbon dioxide and various green house gasses by making it harder to satisfy environmental regulations. The solution leads to adopting alternate fuel vehicles such as Electric Vehicles (EV) and Hybrid Electric Vehicle (HEV). EV does not emit pollutants like particulates, ozone, volatile organic compounds, carbon monoxide, hydrocarbons, lead and oxides of nitrogen which plays a vital role in air pollution and greenhouse gas.

In EVs and HEVs, a battery is used as the main power source, so that battery charger is treated as the core technology. The charger can be unidirectional or bidirectional. Both isolated and non-isolated topologies can be employed for the charger [5]. To achieve high efficiency with small in size and space, the non-isolated battery charger is one of the promising solutions. Two-stage approach which is generally used for charging batteries [8]. The first stage converts AC to DC with near unity Power Factor (PF) while the second stage is used to control the battery charging voltage and current. However, this approach has the disadvantage of the high part count, low power density, and low efficiency. Some of the authors have proposed a single stage approach [9]. Power factor correction has to be considered in the charging system, not only to comply the required international standards but also to reduce the impact to the power grid that connected. PFC function includes not only shaping the input current waveform but also regulating the output voltage. For the PFC application, the boost converter is the most popular topology than the other ones due to its continuous current [3].

Continuity of the output should be ensured whatever be the input, inorder to make the system reliable. To ensure these various control strategies are available such as proportional integral (PI), proportional integral derivative (PID) and fuzzy logic control (FLC). A PID controller continuously calculates an error value e(t) as the difference between the desired set point(SP) and a measured process variable (PV) and applies a correction based on based on proportional, integral and derivative term. PID controllers have the disadvantage of when used alone, can give poor performance when the PID loop gains must be reduced.

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They also have difficulties in the presence of non-linearities. The PI controller has some disadvantages such as high starting overshoot, sensitivity to controller gains and sluggish response to sudden disturbances [10]. Fuzzy controllers fulfill the same tasks like a classic controller [6]. Fuzzy controller differs from the classic one in that it manages the control complex space in a heuristic manner. However, the fuzzy controller can approximate, with any precision level, linear and non-linear control functions. In many situations is easier to obtain a fuzzy controller with high performance than a classic controller with same performances.

In this paper, a single stage battery charger with non-isolated high gain boost PFC converter [1] topology is employed for EV application. The voltage gain of this converter is twice as high as that of the conventional TLB converter. More importantly, this converter has inherent (automatic or self-correcting) output voltage balancing features, which is not reported in previous literature [2] [3] [4]. Furthermore, the current stress of the three switches (S1, S2, and S4) is reduced to one half of the input current. Also, the non-isolated boost PFC converter controls the output voltage according to the demand of the battery while the unity PF is corrected. That is this only one converter is used for both power factor correction and for battery voltage regulation. The input supply voltage is first rectified by a diode bridge rectifier and a boost converter added to the later stage to make current sinusoidal and charges the battery to the required high voltage.

2. FUZZY CONTROLLER BASED BOOST PFC CONVERTER FOR EV BATTERY CHARGING

The boost PFC converter is controlled by the fuzzy controller is used for EV charging application. Block diagram of the converter with a fuzzy controller is shown in fig. 1. Power factor is one of the essential parameters that every distribution sectors have to look into it. Power factor, source current/ voltage distortion are the main factors that need attention. Poor power factor at the source side results in increased system losses and leads to poor performance. The boost PFC converter boost the rectified voltage to the required battery voltage and also improves the power factor. This only one converter is used for both power factor correction and charging the battery.

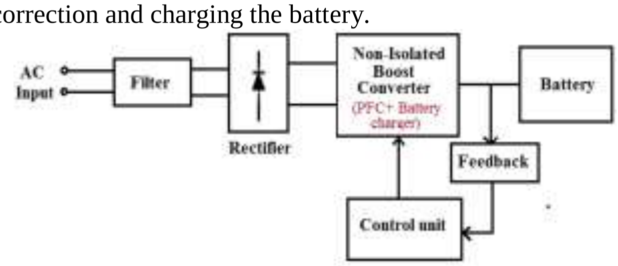

Fig 1: Block diagram boost PFC converter with fuzzy for EV charging

2.1 Circuit Configuration of Boost PFC Converter

The circuit configuration of the converter is shown in fig. 2. It consist of four switches, two inductors and two capacitors. The two load resistors Ro1 and Ro2 is connected across the two capacitors Co1 and Co2 respectively. The voltage across the two load resistors are always balanced. The inductor L_{in} is input inductor. The inductor L_s is additionally added to the converter. This inductor is used for output voltage balancing.

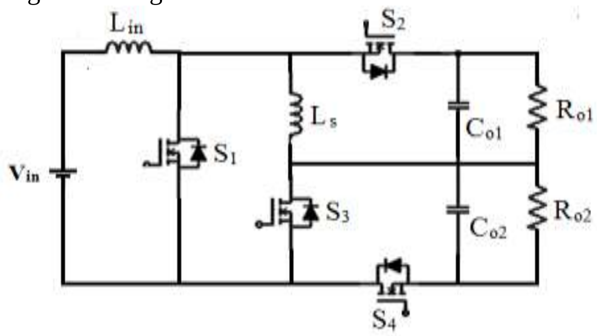

Fig. 2: Schematic of non-isolated boost PFC converter

By additionally adding the inductor Ls, the converter having the predominant features such as voltage gain of the converter is twice as high as that of the conventional TLB converter, reduces the current stress of the three switches (S_1, S_2, and S_4) and converter has inherent output voltage balancing function.

2.2 Operating Modes

There are four operating modes for the converter and are briefly discussed. Mode I and mode III are same. The operating modes are shown in Fig. 3.

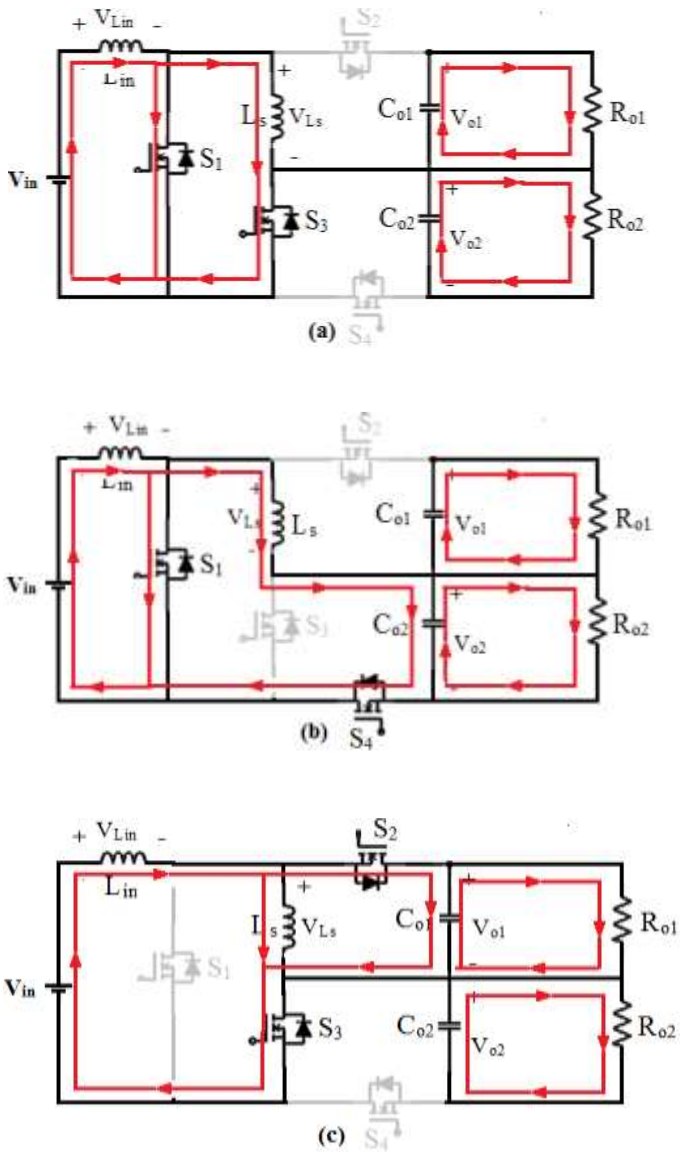

Fig. 3: Operating modes (a) Mode I & III (b) Mode II, (c) Mode IV

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Mode I [0- DTs/2]: During this interval, the switches S_1 and S_3 are turned on and S_2 and S_4 are turned off. The input inductor L_{in} charges to the input voltage and the voltage across L_s is zero. Both the capacitors supply the load.

Mode II [DTs/2-Ts/2]: During this interval, the switches S_1 is still in turn-on state while S_3 is turned off and S4 is turned on. The voltage across L_{in} still equal input voltage and the capacitor Co2 charges through L_s and S_4.

Mode III [Ts/2-(1+D)Ts/2**]:** This mode is same as that of mode I. Here also switches S_1 and S_3 are turned on and S_2 and S_4 are turned off. The input inductor L_{in} charges to the input voltage. Both the capacitors supplies the load.

Mode IV [Ts/2-(1+D)Ts/2]: During this interval, the switches S_3 is still in turn-on state and S_2 is turned on. Switches S1 and S4 are turned off**.** Here, the capacitor C_{o1} is charged.

3. CONTROL STRATEGY

In order to make the system reliable, continuity of the output should be ensured whatever be the input. To ensure these various control strategies are available and fuzzy logic control is one of them.

3.1 Fuzzy logic controller

Fuzzy logic control includes establishing a fuzzy inference system with the input and output membership functions and defining the rules related to it. Here, we have two input membership functions:1)Error in output voltage-"error" and 2)Changing error- "delta error". The only output membership function is the duty cycle-"output1". The input membership functions "error", "delta error" and output membership function "output1" is shown in fig. 4.

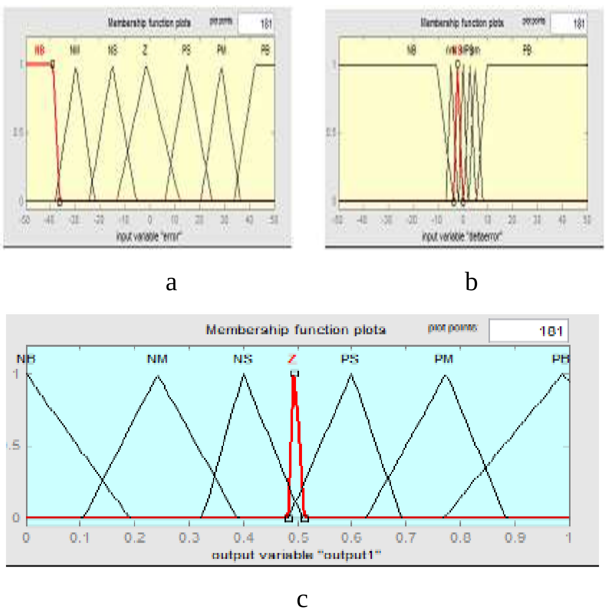


Fig. 4: Membership function plots of (a) error (b)delta error (c)output error

The next important step is to define the rules of the fuzzy inference system [11]. The error and change of error of the output voltage will be the inputs of the fuzzy logic controller. These 2 inputs are divided into five groups; NB: Negative Big, NS: Negative Small, ZO: Zero Area, PS: Positive small and PB: Positive Big. The fuzzy rule base is shown in table 1.

Table 1. Fuzzy Rule base [11]

e/Δe	PB	PM	PS	Z	NS	NM	NB
PB	NB	NB	NM	NM	NS	NS	Z
PM	NB	NB	NM	NM	NS	Z	PS
PS	NM	NM	NM	NS	Z	PS	PM
Z	NM	NS	NS	Z	PS	PM	PM
NS	NS	NS	Z	PS	PS	PM	PM
NM	NS	Z	PS	PM	PM	PM	PB
NB	Z	PS	PS	PM	PM	PB	PB

4. SIMULATION RESULTS AND ANALYSIS

The fuzzy controller based boost PFC converter with battery charging application is simulated using MATLAB Simulink. For an input of 120 Vrms, supply frequency of 50 Hz and 20% duty ratio, the obtained output is 600 V. By proper design 180µF capacitor is used as output capacitors.

The input voltage and current are shown in Fig.5, it can be seen that the voltage and current are almost in phase and the obtained power factor is 0.95. The input current is 19A.

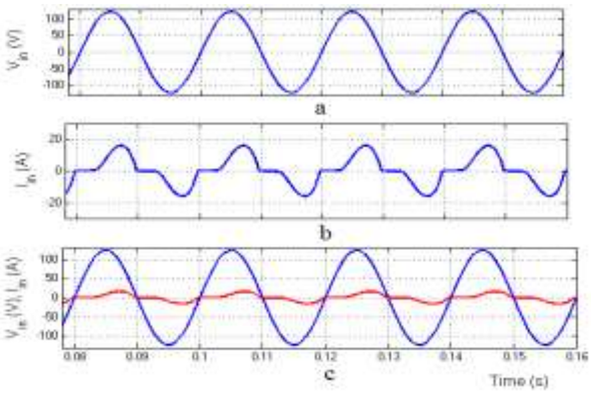


Fig. 5: (a) Input Voltage, V_{in} (b) Input Current, I_{in} (c) Input voltage & current

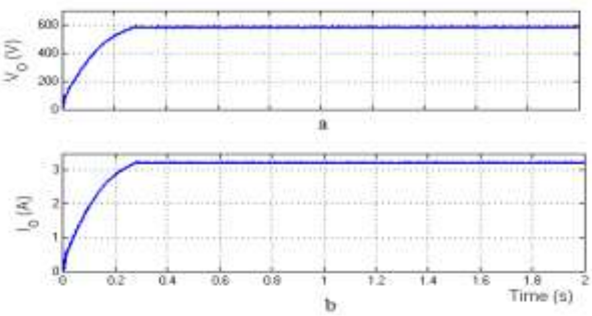


Fig. 6: (a) Output Voltage, V_o (b) Output Current, I_o

For an input of 120 V_{rms}, the obtained output voltage is 600V is shown in Fig. 6 (a). The output current is about 3.5A and is shown in Fig.6 (b).

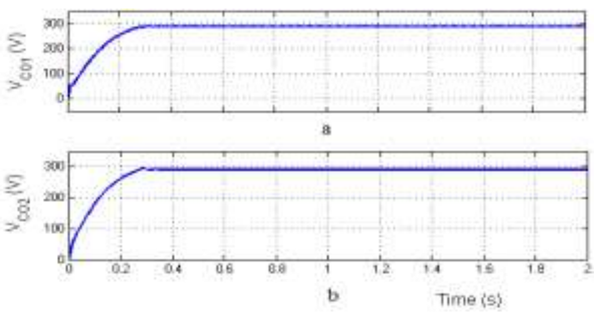


Fig. 7: (a) Voltage across the capacitor, C_{o1} (b) Voltage across the capacitor, C_{o2}

The voltage across the two capacitors are well balanced and is shown in Fig. 7 and the obtained voltage is 300 V across each capacitor.

The status of battery charge condition is shown in fig. 8. State of charge shows that battery is charging continuously from 10% and also during charging battery voltage gets increased periodically and battery current getting constant.

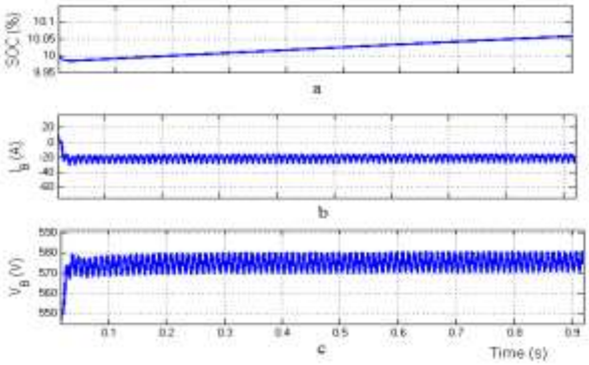


Fig. 8: Battery (a) state of charge (b) current, I_B

4.1 Comparison of simulation results with PI controller and Fuzzy controller

Non-isolated boost PFC converter is simulated using a PI controller and fuzzy controller. The obtained output voltage waveforms of the converter are shown in fig.9. From fig. 9(a) it is clear that with PI controller the overshoot is nearly 860V. But by using fuzzy the peak overshoot in output voltage is slightly above the obtained output voltage which is less than PI controller.

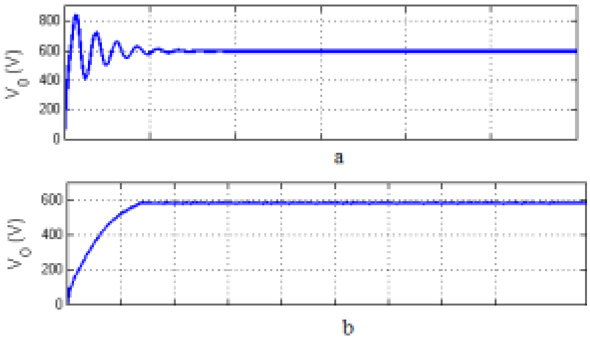


Fig. 9: Output voltage with (a) PI controller (b) Fuzzy controller

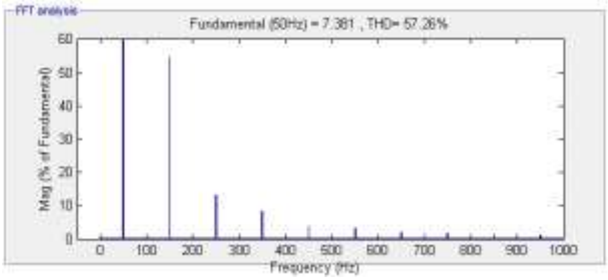
From the output waveforms obtained, the time domain specifications are verified and the results show that the fuzzy controller improves the settling time, peak time and reduces ripple. Different time domain specifications with PI and the fuzzy controller is given in table 2.

Table 2: Comparison of time domain specifications

Controllers used	Rise time (s)	Peak time (s)	Peak overshoot (v)	Settling time (s)	Transient behavior
PI	.06	.01	2.6	.11	Oscillat-ory
Fuzzy	.02	.03	.3	.03	Smooth

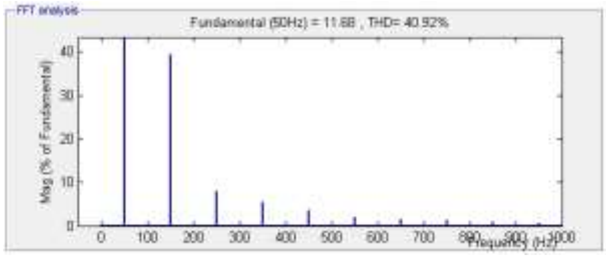
4.2 THD analysis of converter circuit with basic battery charger

The harmonic spectrum computed using Matlab/Simulink for the source current with basic battery charging circuit, non-isolated boost converter with open loop and with a fuzzy controller is shown in fig.10. The obtained THD of the basic battery charger is 56.26%, and for a converter with open loop the THD is 40.92%. But by using boost PFC converter with the fuzzy controller the obtained THD is 34.08%, which is less compared to other circuits.



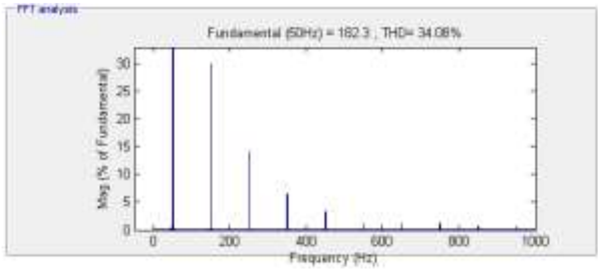
a

$$\left(\text{THD} = 57.26,\ \text{pf}= \sqrt{1/(1+THD^2)} = 0.86\right)$$



b

$$\left(\text{THD} = 57.26,\ \text{pf}= \sqrt{1/(1+THD^2)} = 0.9\right)$$



c

$$\left(\text{THD}= 34.08,\ \text{pf}= \sqrt{1/(1+THD^2)} = 0.95\right)$$

Fig.10: THD spectrum of supply current with (a) Basic battery charger circuit (b) boost converter with open-loop (c) boost converter with fuzzy controller

5. EXPERIMENTAL SETUP AND RESULT

A downsized laboratory prototype of 24V input with a 10W output power of the system is developed to validate the theoretical and simulation results.

Hardware setup of the converter is shown in fig.11. The converter is controlled using dsPIC30F2010. Due to the difficulty of implementing high voltage battery (120V), it is not included in the hardware. Instead of battery, a load resistor is connected. MOSFET IRF540 is used in the power circuit.

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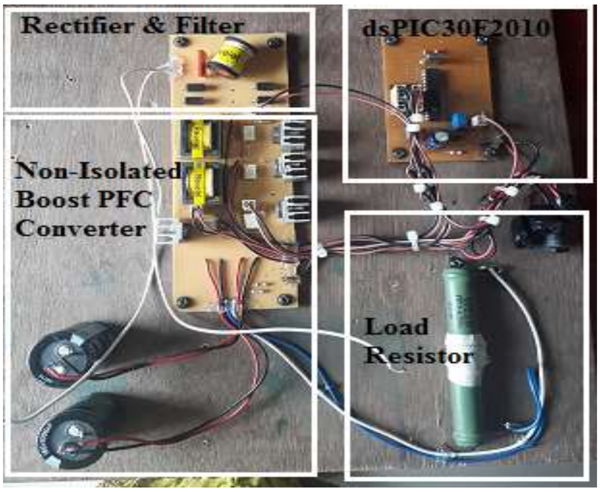

Fig. 11: Different hardware sections

The experimental outputs obtained from the converter is shown in fig. 12. For an input of 24V, the output of 130V is obtained.

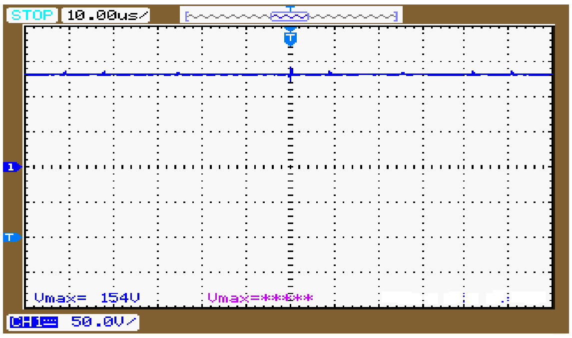

Fig. 12: Converter output

The voltage across the two output capacitors are shown in fig. 13. From the figure it is clear that the two capacitor voltages are well balanced.

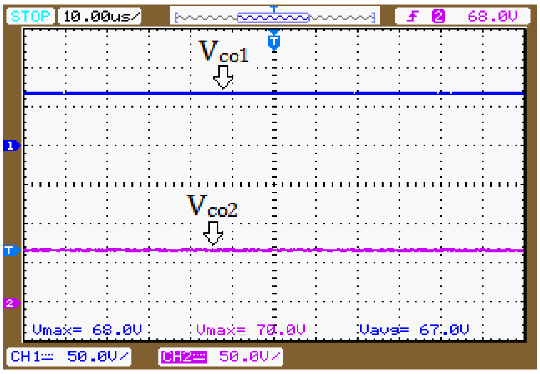

Fig. 13: Voltage across two output capacitors

6. CONCLUSION

Non-isolated boost PFC converter with inherent output voltage balancing is used for EV battery charging application. A 10W prototype of the converter is built and tested. This converter has inherent power factor correction capability without any power factor correction block. The minimum THD of the system is 34.08% and nearly 0.94 power factor is obtained. ie, the power factor is improved by 8.5% compared to the basic battery charger. Also, the non-isolated boost PFC converter controls the output voltage according to the demand of the battery while the unity PF is corrected. So, this only one converter is used for both PFC stage and for charging the battery which reduces the size of the system. The current stress of the three switches (S1, S2, and S4) is reduced to one half of the input current. A control strategy using a fuzzy controller is implemented which improves settling time, reduce ripples in the output voltage waveform and improve source current waveform. The system is used for high voltage and high power EV applications.

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