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Battery Charger with Improved Power Quality Cuk Derived Power Factor Correction Converter

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Abstract**:** ***In this paper, a single switch single stage switched inductor based cuk converter with power factor correction control techniques is proposed. The main features of the proposed converter is low current stress, high voltage conversion ratio, reduction of components, high efficiency, low THD, etc., The operation of the proposed converter is explained in several modes along with the design of the converter. The performance of the proposed converter with different loads such as resistive, battery and motor loads with CC and CV control is analyzed and various factors such as power factor, efficiency and THD are compared. The Simulation work is carried out in MATLAB/Simulink software.***

Keywords: Battery charging application, Electric vehicle. Single inductor, single stage converter, power quality improvement.

I. INTRODUCTION

In recent days, the usage of electric vehicles is increasing which leads to the necessity of study and research of various battery charging techniques for higher efficiency and also to reduce the power quality issues which can affect the grid (1-4). In conventional converters, due to filter capacitance associated with the rectifier circuit causes discontinuous high peak current flow which leads to increase in THD and also increases the stress across various components of rectifier and converter (5, 6). According to power quality standards, any converter should have power factor higher than 0.9 and the THD value should be less than 5% (7, 8). To achieve this, we need the converter to operate on continuous conduction mode for all types of loads. Also, for power factor correction, two stage converters are used. The first stage is for power factor correction while the second stage operates as voltage conversion device (9-11). Due to this, the losses are increased and hence the efficiency of the converters are reduced.

Various single stage converters are proposed with single stage and single switch along with control circuits for load voltage regulation and also input current shaping (11, 12). In this topologies, the switch voltage depends on load variations and supply voltage. Due to this, the voltage stress of the switch will be high (13, 14). This causes usage of higher rating devices and huge capacitors. To avoid this, transformers are included which leads to increase in cost and size of the converter.

The single switch converters such as buck-boost, sepic, cuk and flyback converters can be employed for both voltage conversion and power factor improvement purposes (15, 16). But in the above mentioned converters, the switch stress is high and due to this, efficiency of any of these converters is low compared to boost converter (17).

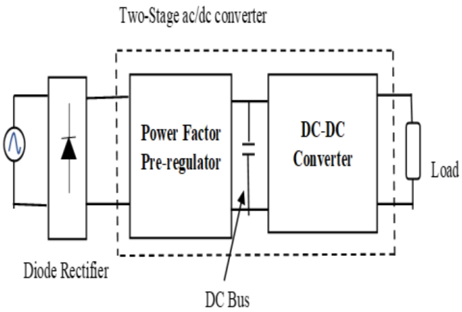

Fig.1. Two stage DC-DC converter with power factor correction

Also, the buck-boost converter cannot operate under wild range of variation of input voltage as the duty cycle is minimum and also due to higher frequencies, the switching losses will be increased. To increase the operating range of the input voltage, a switched capacitor is required (18). Hence cuk, sepic and zeta converter can be modified and used in this proposed system (19-21). This also leads to power factor correction along with reduction in current stress across the switch which results in efficiency improvement. The grid side current can shaped by both CV and CC based battery charging control circuits which can reduce the power quality issues such as harmonics, power factor, etc., The CV control circuit provides the load regulation whereas CC control circuit provides the shaping of grid current by controlling the input side inductor current so that the peak value will not increase beyond the rated current value. In this paper, an switched inductor is added with the existing cuk converter for electric vehicle battery charging of 48V/10.4A, with input voltage variation of (85-230)V. Due to the low current stress, the switch losses are reduced and also with the help of input side inductance, current peaks are reduced and hence the THD can be reduced. Various parameters such as THD, power factor, losses are measured and compared for different loads with CC and CV charging techniques

II. PROPOSED SIC CONVERTER

The proposed switched inductor based cuk converter circuit is provided below:

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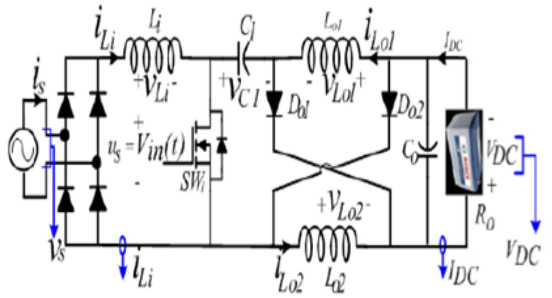

Fig.2. Switched inductor based cuk converter

In this, the single-phase grid is connected to the uncontrolled bridge rectifier from which we can get dc voltage and then it is provided to the switched inductor cuk converter. The proposed converter operates in continuous conduction mode with the help of input side inductor as the inductor current is continuous in a switching time period. The proposed converter is designed for R load, battery and dc motor load. The load side inductor is splitted into two equal inductors (L_{o1}, L_{o2}) along with diode, D_o into D_{o1} and D_{o2}. These inductors and diodes along with switch SW forms switched inductor circuit. These inductors interchange from series to parallel connection for each switching cycles.

The modes are presented depending on the state of the switch i.e when the switch is ON, it is mode1 and when the switch is OFF, it is mode2. For analysis, it is assumed that the circuit operates under ideal conditions.

Mode 1:

In this mode the switch will be ON and all the inductors will be charging and the capacitor C_1 will be discharging. The mode1 operational circuit is provided below:

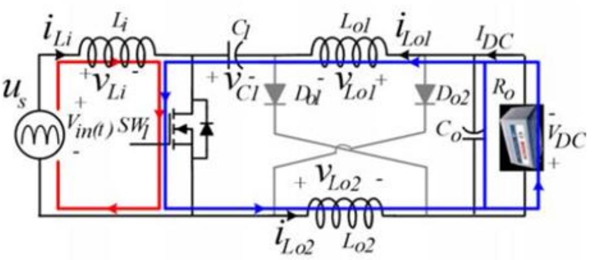

Fig.3.Operational mode 1 of proposed Switched Inductor Cuk converter

The voltage equation for this mode is given as

$$V_{in}(t) - v_{Li} - v_{C1} + v_{Lo1} + V_{DC} + V_{Lo2} = 0 \quad (1)$$

$$v_{Li} = V_{in}(t); \; v_{Lo1} = v_{Lo2} = \frac{V_{in}(t)}{2} \quad (2)$$

The voltage across the capacitor C1 is provided below:

$$V_{C1} = V_{in}(t) + V_{DC} \quad (3)$$

The inductor currents during mode1 are provided in the following equations:

$$i_{Li} = \frac{V_{in}(t)}{L_i} t + I_{Limin}; i_{Lo1} = \frac{V_{in}(t)}{2L_{o1}} t + I_{Lo1min}; \quad (4)$$

$$i_{Lo2} = \frac{V_{in}(t)}{2L_{o2}} t + I_{Lo2min}; \quad (5)$$

The key waveforms explaining the modes of operation of the proposed converter is provided below:

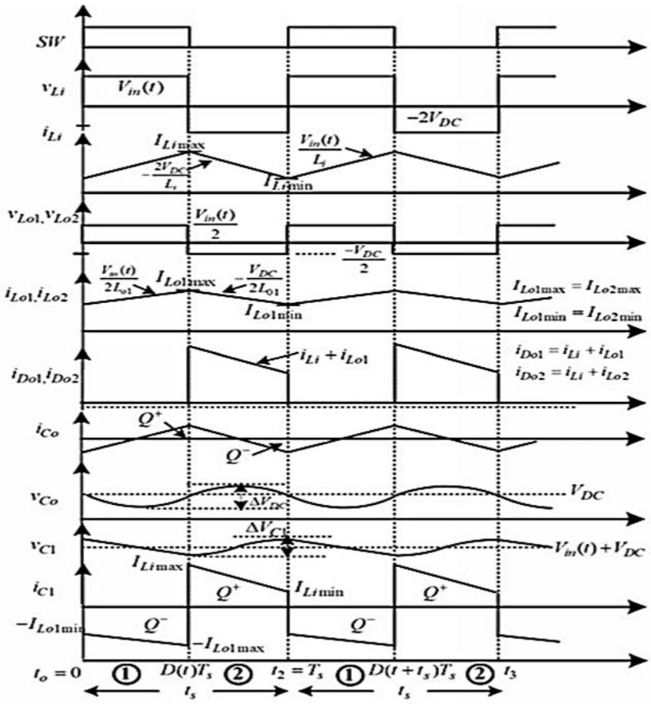

Fig.4.Key waveforms of operational modes of Switched Inductor Cuk Converter

Mode 2:

In this mode the switch will be OFF and all the inductors will be discharging and the capacitor C_1 will be charging. The mode2 operational circuit is provided below:

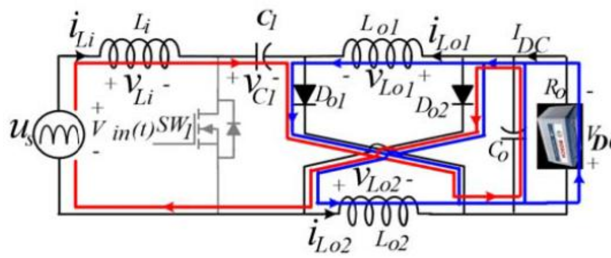

Fig.5. Operational mode 2 of proposed Switched Inductor Cuk converter

The voltage and current equations for this mode is given as

$$v_{Li} = -2V_{DC}\,; \; v_{Lo1} = v_{Lo2} = -V_{DC}\,; \quad (6)$$

$$i_{Li} = -\frac{2V_{DC}}{L_i}\{t - D(t)T_s\} + I_{Limax}\,; \quad (7)$$

$$i_{Lo1} = -\frac{V_{DC}}{L_{o1}}\{t - D(T)T_s\} + I_{Lo1max}\,; \quad (8)$$

$$i_{Lo2} = \frac{V_{DC}}{L_{o2}}\{t - D(t)T_s\} + I_{Lo2max}\,; \quad (9)$$

$$i_{SW} = 0\,; \; i_{Do1} = i_{Li} + i_{Lo1}\,; \; i_{Do2} = i_{Li} + i_{Lo2}\,; \quad (10)$$

III. CONTROL ALGORITHM FOR PROPOSED SIC CONVERTER

The schematic diagram for the control circuit of the proposed sic converter is provided below:

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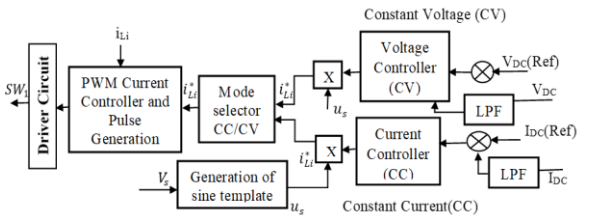

Fig.7. Schematic diagram of SICC control circuit

In this, to get the unity power factor either voltage multiplier or current multiplier approach is used. Here we are having both CV and CC mode of battery charging control circuit. At any particular instant any one of the control strategy is used.

In CV mode, the battery voltage is measured and compared with the reference voltage and error voltage is generated.

$$V_e(k) = V^*_{dc}(k) - V_{dc}(k) \quad (11)$$

The error signal is multiplied with sine wave generated from the grid voltage to get reference inductor current which is then compared with the measured inductor current.

$$i^*_u(k) = u_s V_c(k) \quad (12)$$

The compensation current is provided to the pwm pulse generation unit and the pulses will be provided for the switch.

In CC mode, the load current is measured and compared with the reference current and the error signal is multiplied with sine wave generated from the grid voltage.

$$i^*_u(k) = u_s I_c(k) \quad (13)$$

It is then compared with the measured input side inductor current and the error signal generated is termed as compensation current which is then provided for pulse generation. The PI controller is used for both the voltage control and current control modes. The modes are selected based on the battery conditions.

IV. DESIGN PROCEDURE FOR PROPOSED SIC CONVERTER

The design process of the proposed switched inductor based cuk converter includes the design of inductors (L_1, L_{o1} and L_{o2}) and capacitors (C_1 and C_o). The main purpose of this converter is to provide load voltage regulation and power factor improvement.

The duty ratio, D is provided by the following relation:

$$D = \frac{2V_{dc}}{2V_{dc} + V_{in}} \quad (14)$$

The average of input side inductor current is provided in the following equation:

$$I_{Li} = I_{DC} \cdot \frac{V_{DC}}{V_{in}} \quad (15)$$

The input side inductance is calculated from the equation below:

$$L_{icrit} = \frac{2(1-D)^2 R_o T_s}{D} \quad (16)$$

The inductance value above calculated is termed as critical inductance. To ensure that the proposed converter operates in CCM under any load conditions, we should use larger inductors than that of calculated values.

The ripple inductor currents are taken as 20% of the actual inductor current values for both intermediate and input side inductances.

The intermediate inductance value can be calculated using the following equation:

$$L_{o1crit} = (1-D) R_o T \quad (17)$$

The coupling capacitor is calculated from the following equation:

$$C_1 = \frac{DT_s}{2\frac{\Delta V_{C1}}{V_{DC}} . R_o} \quad (18)$$

The ripple voltage of coupling capacitor (ΔV_{c1}) is taken as 1% of the actual coupling capacitor voltage (V_{c1}).

The output capacitor is calculated from the following equation:

$$C_o = \frac{\Delta I_{C1} T_s}{8 \Delta V_{DC}} \quad (19)$$

The ripple voltage of output capacitor (ΔV_{co}) is taken as 1% of the actual output capacitor voltage (V_{co}).

The switching time period, Ts is calculated from the switching frequency as shown below:

$$T_s = \frac{1}{F_s} \quad (20)$$

V. SIMULATION SETUP AND RESULTS

The simulation parameters are provided in the following table:

TABLE -I Simulation Parameters

Grid Voltage	(85-230) V
Frequency	50 HZ
Switching Frequency	25 KHZ
Output Voltage	48V
Load Power	500 W
Inductance	L_1=6.4mH, L_{o1}=L_{o2}=0.13 mH
Capacitance	C_1=21µF C_o=260µF
Load Resistance	4.6Ω

The simulation circuit for the proposed converter is provided

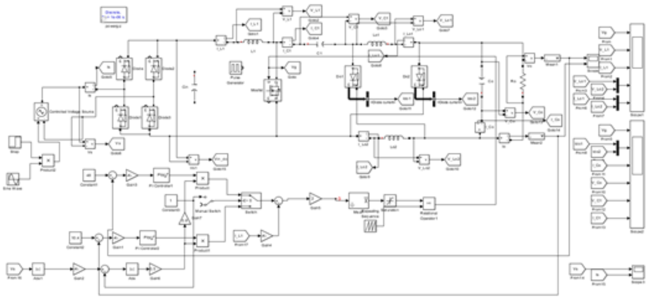

Fig.8. Simulation circuit of SIC converter

The simulation circuit for the proposed converter is In this the input voltage is varied from 85V to 230V at t=0.2s. The key waveforms for the proposed converter at steady state conditions are provided in the following graph:

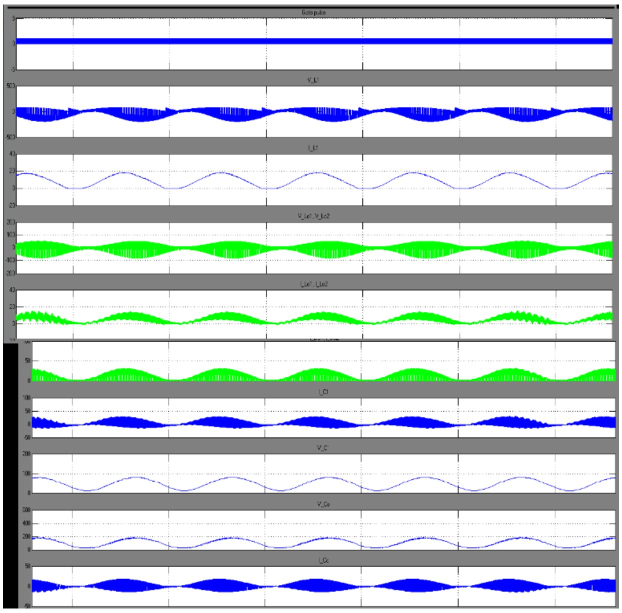

Fig.9. Simulation of SIC converter

In this the input voltage is varied from 85V to 230V at t=0.2s. The key waveforms for the proposed converter at steady state conditions are provided in the following graph:

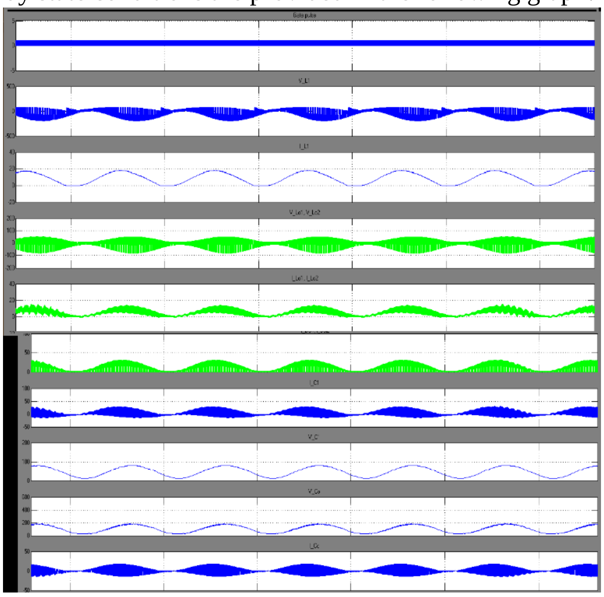

Fig.10. key waveforms of proposed converter in steady state conditions

The input voltage and current waveforms are shown in the following graph:

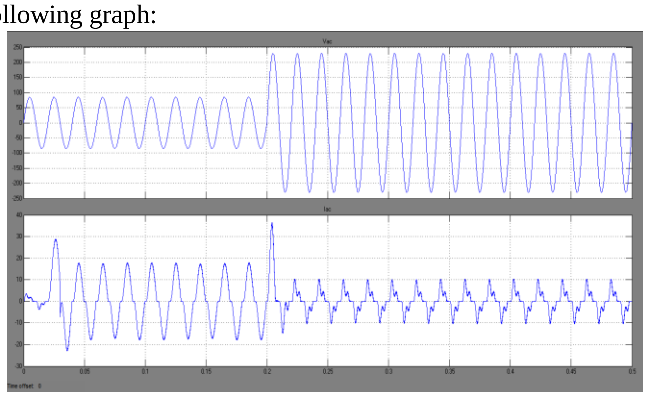

Fig.11. Input voltage and current waveforms

In the above graph, the input voltage is initially 85V and changes to 230V at t=0.2s. As the voltage is increased, the peak value of current is reduced as the load power is constant of 500W.

The key waveforms when the change in input voltage occurs is provided below:

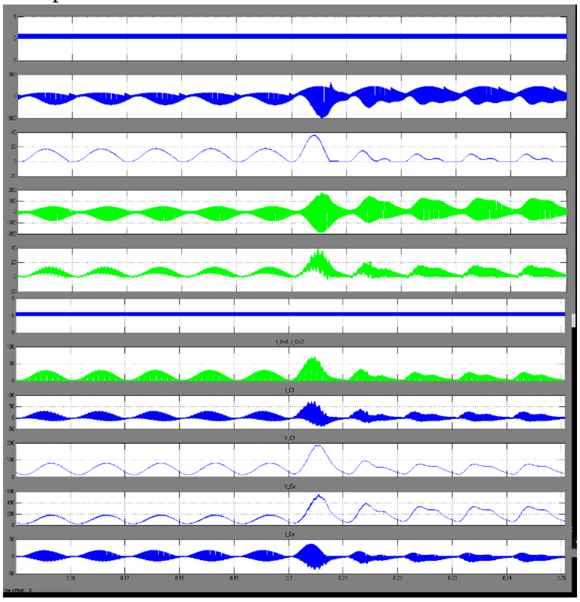

Fig.12. key waveforms of proposed converter in transient conditions

The load voltage and current waveforms are shown in the following graph:

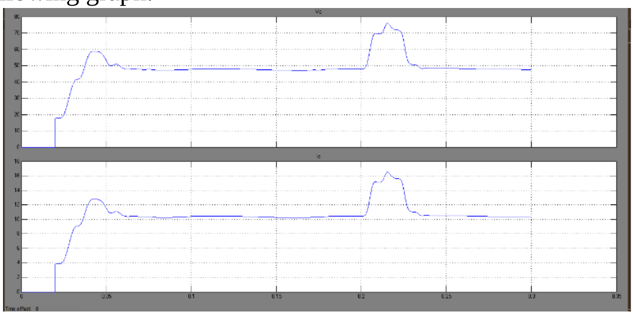

Fig.13. Load voltage and current waveforms

In this, even when the input voltage is increased, the load voltage is maintained as constant with the help of PFC control circuit. The battery voltage and %SOC is provided in the following graph:

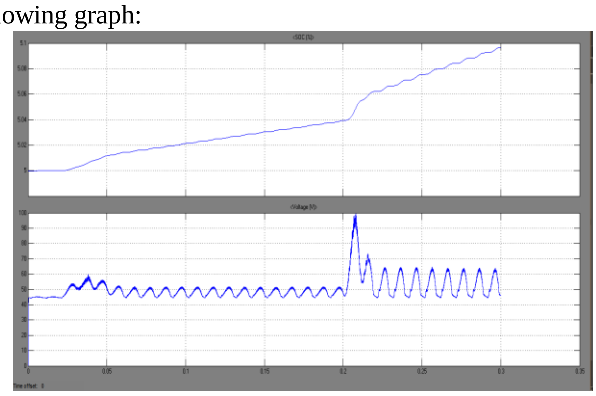

Fig.14. Battery voltage and %SOC

In this the initial %SOC is 5% and when the supply is provided, then the battery starts to get charged and the %SOC starts to increase. A dc motor of 48V, 1HP is provided as load and the speed and torque waveforms are provided in the following graph:

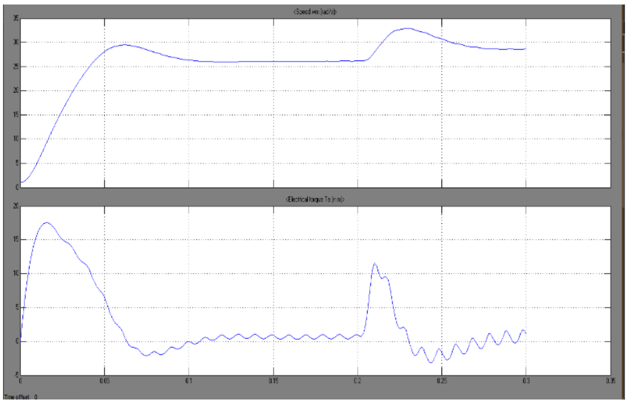

Fig.15. Rotor speed and Torque waveforms of dc motor load

Various parameters such as power factor, %THD, efficiency and switching losses are compared in both CV and CC mode in the following table:

TABLE -II Various Parameters Comparison

Parameters		V_{in} =85V	V_{in} =230V
Switching losses	CV	14.63W	14.07W
	CC	14.63W	14.07W
Efficiency	CV	92.3%	97.65%
	CC	92.3%	97.8%
%THD	CV	1.04%	0.85%
	CC	0.93%	0.85%
Power Factor	CV	0.94	1
	CC	0.94	0.99

VI. CONCLUSION

A new switched inductor based cuk converter is analysed, designed and simulated under both steady state and transient conditions. The proposed converter is tested with different loads such as resistive load, battery load and dc motor load. A control circuit is designed with CV and CC charging techniques which is used to regulate the load voltage and also shaped the input current so that the power factor is improved along with the reduction of THD. The performance of the proposed converter with both CV and CC charging circuits for different input voltages is studied and tabulated.

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