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IMPROVED POWER QUALITY SWITCHED INDUCTOR CUK CONVERTER FOR BATTERY CHARGING APPLICATION

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Abstract - *In this project, a single- stage switched inductor CUK converter based power factor correction converter is proposed which offers high step-down gain, low current stress and high efficiency and reduced component counts. The operational analysis and design equations for various components of proposed converter are carried out in continuous current mode (CCM). The performance investigation of proposed converter with respect to power quality indices like voltage THD, current THD and total power factor are carried out with various types of load such as resistive load and battery load in both constant voltage (CV) and constant current (CC).*

Key Words*: *Diode Bridge Rectifier; Cuk Converter; Power Factor Correction; Harmonics

1. INTRODUCTION

In the present scenario, emissions of greenhouse gases and other toxic elements are due to overuse of petroleum fuels fed automobiles which have caused significant amount of environmental hazards, health issues and degradation of non-renewable resources. In last decades, electric vehicles/electric hybrid vehicles are the alternate choice for inter-city transport which have several advantages like low maintenance, high efficiency, no greenhouse gas emission and cost effectiveness. However, due to rapid increase in the growth of electric vehicles in future, there will be a probability of power quality problems in the charging stations. The power quality problems causes increased risk in harmonic level in power distribution systems which reduces the life of distribution transformers in battery charging stations. Conventionally, existing system consist of diode bridge rectifier followed by bulky filter capacitor draws a highly distorted non-sinusoidal and peaky supply current with high harmonic current THD of 70-80%, from single phase ac mains with low power factor of order 0.75-0.8 lagging and high crest factor.

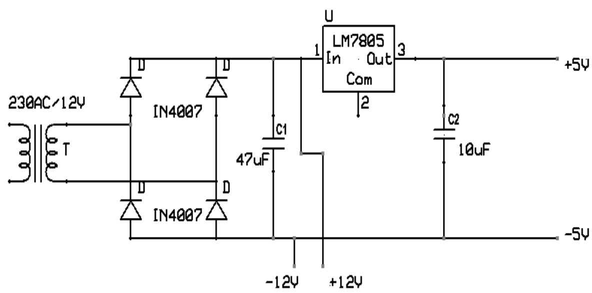
As per international standards for power quality, it is essential for any product to satisfy load demand for power factor above 0.9 and current THD should be below 5%. To meet the guidelines recommended international standards for power quality usage of two stage PFC converters are widely practiced in which the power factor correction is carried output in first stage and voltage/current regulation is done in the second stage. However these two stage conversion suffer from poor efficiency and high component count. In order to overcome the problem, a switched capacitor converter is proposes as an off-line power factor corrector, utilizing the inherent advantages of low line efficiency improvement with reduced voltage stress across switches.

A switched inductor CUK converter based improved power quality converter for universal input voltage (85V-265V) is proposed for the application of electric bike battery charging whose battery pack nominal voltage is around 48V dc. This converter facilitates the reduction in conduction and switching losses due to low switch current stress. The inductor at input side, the peaky current problem is absent. As the duty cycle is more compared to conventional buck boost based topologies, the associated problems are narrow input voltage range is absent in the proposed topology. This paper consist proposed systems block diagram, methodology and conclusion.

2. BLOCK DIAGRAM OF PROPOSED SYSTEM

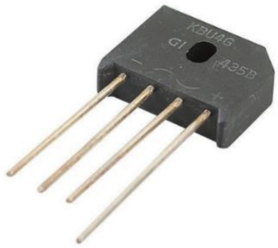
2.1 POWER SUPPLY UNIT

All invention of latest technology requires source power. So, we need proper power source which will be suitable for a particular requirement. All the electronic components require DC supply ranging from +5v to +12v. We are using the same cheapest and commonly available energy source 230V-50Hz.



2.2 RECTIFIER UNIT

In the power supply unit, rectification is done using a solid state diode. The property of diode is to let the electron flow easily in one direction at proper biasing condition. When the diode is given an AC supply, electrons only flow when the anode and cathode is negative. Electron will not flow, when polarity is reversed.

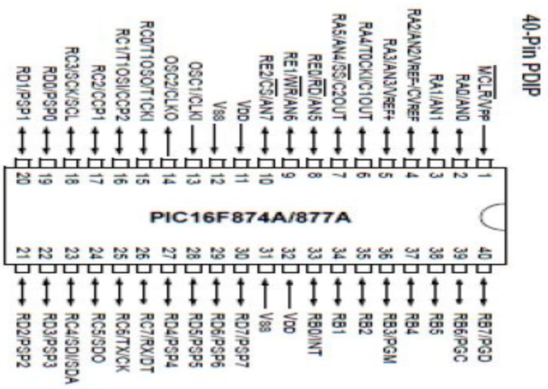


2.3 CUK CONVERTER

The CUK or step down-step up regulator regulates the average DC output voltage at lower and higher level then the input or source voltage and there is a polarity reversal on the output this is accomplished through a controlled switching where the DC input voltage is turned on and off periodically, resulting in a higher and lower average output voltage.

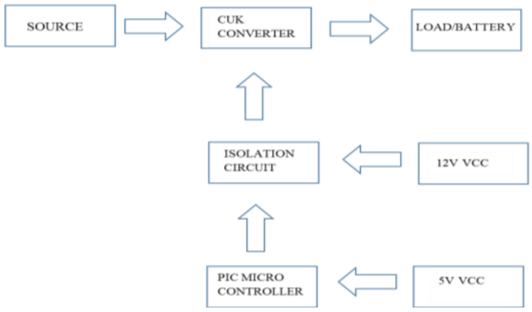
2.4 PIC CONTROLLER

PIC microcontroller was used in this project to obtain the gate signal of the inverter switches using SPWM. PIC 16F877A was used to generate the Modified Sine Wave gate signals and PIC 16F887 was used to generate Sine Wave gate signals. Both have 40 pins with different functions.



2.5 LOAD/BATTERY

An electric battery is a device consisting of one or more electrochemical with external connections provided to power electrical devices such as lights and electric bike battery has two nodes positive is said to cathode and negative is said to be anode. The terminal marked negative is the source of electrons that will flow through an external electric circuit to the positive terminal.



3. METHODOLOGY

3.1 OPERATION OF PFC CONVERTER

The operation of converter depends on switching state of switch SW1. The connection of intermediate capacitors (C_1, C_3) changes from series to parallel connection as switching state of switch SW1 changes from ON to OFF. The equivalent circuit during ON and OFF state of the switch SW1 are depicted in Figure 2a and Figure2 b. The Cuk-derived PFC converter is designed to operate in continuous conduction mode i.e. the current through inductor (i_{Li}) is continuous over one switching period. Figure 2c shows the voltage and current waveforms over one switching cycle. The detailed mode-wise analysis is carried out with assumptions that all the circuit elements are ideal. The output filter capacitor (C_o) is assumed to be large such that the output voltage ripple is neglected.

MODE I: When the switch SW1 is turned ON, the output diode Do is forward biased. Power diodes (D_{o1}, D_{o2}) are in reversed biased by the negative voltage (V_{C1} + V_{dc}) that appears across them. The equivalent circuit during this mode is shown in Figure 2a. During this mode, the input inductor current (I_{Li}) increases gradually from its minimum value (I_{Lmin}) and stores energy as shown in Figure 2c. The intermediate capacitors (C_1, C_3) start discharging in series through path indicated in Figure 2a and charges the output capacitor as shown in Figure 2c. At the end of the mode-I, inductor current reaches to its maximum value (I_{lmax}) as shown in Figure 2c.

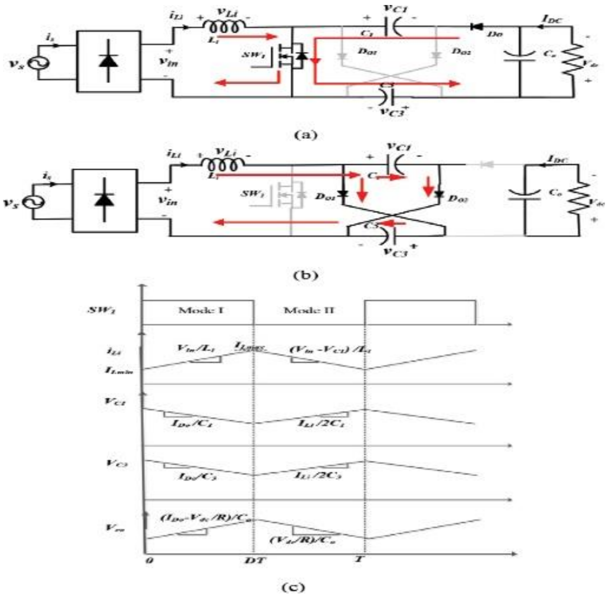


Figure 2 Equivalent circuit during operating modes over one switching cycle (a) mode-I (b) mode-II (c) voltage and current waveforms during switching.

MODE II: This mode start with the turning OFF of the switch SW1. The equivalent circuit is depicted in Figure 2b. In this mode of operation both power diodes (D_{o1}, D_{o2}) are in forward biased at the same time, which gives rise to a path for inductor current. The output diode Do is reversed biased by the negative voltage ($V_{C1} - V_o$). In this interval, the input inductor current charges both capacitors $C_1$and C_3. Simultaneously, output capacitor C_o discharges energy by supplying power to load as shown in Figure2b.

3.2 CONTROL ALGORITHM FOR PFC CONVERTER

In order to achieve unity power factor control, the current multiplier or voltage multiplier based approach for CCM and DCM are used. In this section a brief description of the control scheme is presented. The reference voltage $V_{dc}^*(k)$ is compared with the sensed dc-link voltage $V_{dc}(k)$ to generate a voltage error $V_e(k)$, where voltage error $V_e(k)$ at any instant 'k' is given as,

$$V_e(k)=V_{dc}^*(k)-V_{dc}(k)$$

The voltage error $V_e(k)$ is fed to proportional-integral (PI) controller for generation of a controlled output $V_c(k)$ as
$V_c(K)=V_c(k-1)+k_{pv}\{V_e(k)-V_e(K-1)\}+k_{iv}V_e(k)$

Where, *kpv, kiv* are the proportional gain and integral gain of the voltage PI controller. The reference current $i_{Li}^*(k)$ is generated by multiplying the controller output $V_c(k)$, with the unit template of supply voltage $u_s(k)$ as follows

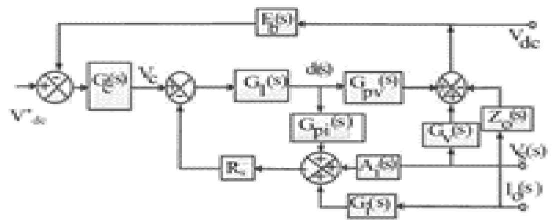
$$u_s(k)=\left|\frac{v_s(k)}{V_m}\right|; \quad i_{Li}^*(k)=u_s V_c(k); \quad i_{Li}^*(k)=u_s I_c(k)$$

Where $U_s(k)$ is the unit template of supply voltage $V_s(k)$ represents the amplitude of supply voltage at any instant k. This reference current $i_{Li}^*(k)$ is compared with the sensed input current $i_{Li}(k)$ to generate the PWM signal for PFC converter switch (SW_1). Based on state of battery charge, the selection of constant current (CC) or constant voltage (C V) mode is carried out. The charging cycle of a Li-ion battery (or a similar battery) consists of a constant-current mode and a constant-voltage mode. To reflect these two modes, the design of control block contains two feedback paths as shown in Fi g.1. One feedback path regulates the battery voltage in the CV mode. The voltage obtained is compared with the reference to regulate the loop. The second feedback path regulates the battery current in the CC mode. At a time one method is implemented via mode selector block which depends on the state of battery charge. Small signal model is obtained by state space averaging, perturbation and linearization of converter. Accordingly we get,

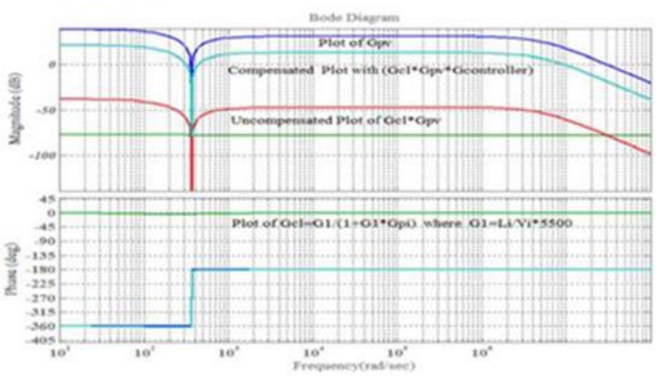
$$\frac{\hat{v}_{DC}(s)}{\hat{d}(s)}=\frac{24V_{in}L_iL_{o1}C_1R_o^2C_o^2[a_3s^3+a_2s^2+a_1s+a_0]}{(1-D)[b_4s^4+b_3s^3+b_2s^2+b_1s+b_0]}$$

$$\frac{\hat{i}_L(s)}{\hat{d}(s)}=\frac{2V_{in}[m_3s^3+m_2s^2+m_1s+m_0]}{(1-D)^2C_1L_iL_{o1}[b_4s^4+b_3s^3+b_2s^2+b_1s+b_0]}$$

where(ao,a1,a2,a3,bo,b1,b2,b3,b4,mo,m1,m2,m3) are the coefficients. The block diagram describing the closed loop current mode control is given by Fig.3a.



(a)



(b)

(b) Fig.3 Block Diagram of current mode controlled converter (a) Control block diagram (b) Bode plot of compensated and uncompensated system Where, $G_{pv}(s)$ is the duty-cycle to output voltage transfer function given by equation (4), $G_{pi}(s)$ is the duty-cycle to inductor current transfer function given by equation (5), $G_1(s)$ is called the current error to duty cycle transfer function given by,

$$G_1(s) = \frac{Li}{V_i T_s R_s}$$

Where, Rs is the sense resistor. The control voltage to duty cycle transfer function $G_d(s)$ generated by the internal current loop is given by following equation,

$$G_d(s) = \frac{\hat{d}(s)}{\hat{v}_c(s)} = \frac{G_1(s)}{1 + G_1(s).G_{Pi}(s).R_s}$$

The transfer functions of other blocks in the block diagram are $G_c(s)$: transfer function of the compensator; $A_i(s)$: input voltage to inductor current transfer function; $G_i(s)$ output current to inductor current transfer function; $Z_o(s)$ output impedance. $G_v(s)$ is the audio susceptibility. The change in input and output voltage is assumed to be negligible over a switching cycle neglecting the feed-forward gai ns. Thus the compensator transfer function $G_c(s)$ is designed based on the open loop gain given by $G_c(s).G_d(s).G_{pv}(s).F_b(s)$. The design of $G_c(s)$, to the meet the transient and steady state response is carried out by freq uency response method meeting the sufficient phase margin with gain cross over frequency of 600 radians/second as shown Fig. 3(b) by the bode plot.

4. RESULT AND DISCUSSION

The switched inductor Cuk converter based IPQC, rated for 500 W, 48V/10.4A is developed using Simulink and SIM power system toolbox of MATLAB and validated through hardware implementation of the converter of same specification. Performance of converter is evaluated under steady state and dynamic conditions for various range of load. To assess the power quality (PQ) features of the converter, waveforms of supply voltage (v_s) and supply current (i_s) and their total harmonic distortions (THDs) are observed and its other features such as dc output voltage (V_{dc}), inductor's currents (i_{li} , i_{LO1} , $i_{Lo\ 2}$) intermediate capacitor's voltage ($V_{C\ 1}$), switch voltage (V_{sw1}),and switch current (i_{SW1}) are also examined. PQ indices such as PF, displacement power factor (DPF), and THD of supply current are analyzed for determining PQ at ac mains.

4.1 SIMULATION STUDY OF THE CONVERTER

Simulink model of switched inductor Cuk based PFC converter is developed with Simulink and SIM Power System toolbox of MATLAB software. The circuit parameters selected for the simulation studies are tabulated in appendix-A.

4.2 STEADY STATE PERFORMANCE OF CONVERTER FEEDING THE BATTERY LOAD

Fig. 4 shows the steady state performance of the converter feeding battery load in CC and CV modes, with 230V input source. It shows voltage and current waveforms at supply side and load side along with SOC of battery. It is observed that a sinusoidal source current in phase with supply voltage is obtained which demonstrates the unity power factor operation of converter. A constant current of 10A is supplied to battery during charging that increases the state of charge (SOC) of the battery. The voltage of battery is also observed to grow during this period.Fig.5 shows the THD of the input voltage and input current at 500W battery load charging in CV and CC mode.

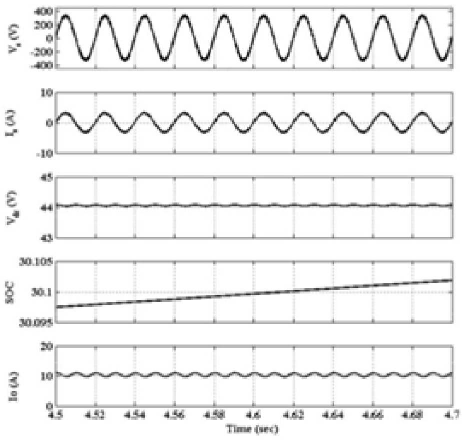


Figure 4 Voltage and current waveform during battery charging (in CC mode).

Appendix –A

Supply voltage: Single phase 230V, 50Hz ; Input inductance 5m H; Intermediate capacitor 4.5μF; Output Inductors 1.8m H; Output capacitor 8mF; Switching Frequency 5 kHz; Gains of PI controller k_p= 75, k_i=1.875 for constant voltage m ode operation and k_p=0.005 and k_i =10, for constant current mode operation.

5. CONCLUSION

Thus by using single stage conversion with the help of cuk converter the power factor problem, harmonics which arises during electric vehicle battery charging process are rectified and improved, the power factor indices like THD and PF at AC side are evaluated to assess the power quality performance of the converter.

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