Coupled Inductor Based Single Phase CUK Rectifier Module for Active Power Factor Correction

Jidhun K Murali and Arun Rajendran

Abstract--- Nowadays power supplies with active Power Factor Correction (PFC) techniques are becoming necessary for many types of electronic equipment to meet harmonic regulations and standards, such as the IEC 61000-3-2. Power Factor Correction shapes the input current of power supplies in such a way to maximize the real power available from the mains. This paper analyses the function of high quality CUK rectifier module as a power factor correcting device in continuous conduction mode. The converter is designed by utilizing the idea of integrated magnetics. The control scheme consists of an inductor current calculator and an output voltage loop. Both Experimental and Simulation results are presented.

Keywords--- Power Factor Correction(PFC), Coupled Inductor, Current THD, Single Phase Converter

NOMENCLATURE

C_a, C_b	Intermediate capacitor.
C_0	Output capacitor.
CCM	Continuous Conduction Mode
d	Duty-cycle.
D	Diode.
L_1	Input side inductor.
L_2	Output side inductor.
M, nTr	The voltage relation in CCM; the turns ratio between primary and secondary.
T_{sw}	Switching period.
I_{L1}	Inductor current.
I_{vr}	Correcting signal from PI controller.
I_{Lrefi}	Reference value for the peak value of input inductor current.
I_m	Peak value of input inductor current.
K_a	Conduction parameter.
V_g	Rectified input voltage.
V_0	DC output voltage.
I_{load}, I_0	Load current.

I. INTRODUCTION

MOST of the electronic or electrical apparatus often requires dc power at multiple voltage levels. In the case of AC-DC-DC switching power supply, a full wave rectifier with a parallel capacitor are often used to obtain the initial DC voltage for the subsequent dc to dc converter. As the rectifier is non-linear and the capacitor is an energy-storage component, the combination of them will make the input current distort greatly. The pulsating input current contains a large amount of harmonic components. This will cause the reduction of input power factor as well as, a lot of current harmonic emission will create the line voltage distort and damages to adjacent equipments. In order to lessen the pollution caused by input harmonic current of ac to dc converter and improve the input power factor, measures should be taken to reduce the harmonic components of the input current [14].

So the dc to dc conversion is an important element in the power electronic field. Now a day in industries, commercial, residential, aerospace, electronic equipment, telecommunication & computer systems the high class rectifiers have a great value [1]. These converters have to meet with international standards for electronic compatibility & accurate regulation, therefore most of the converter uses an active Power Factor Correction circuit which reduces the input harmonic distortions [5].

The majority of the high quality rectifier uses boost converter for Power Factor Correction. The PFC is achieved by controlling the switching action of the converter. This will create the input current to follow a reference sinusoidal current and to attain the input power factor close to unity. But boost converter has got some limitation. Basic limitations of boost converter can overcome by using CUK converter. CUK converter can be attractive for PFC applications because it offer easy implementation of transformer isolation[3][11], inherent inrush current limitation during start-up and overload conditions, and ability to generate arbitrary output voltages[9][10]. Integration of magnetic components is also possible in the case of CUK converters, with zero current ripples in both input and output inductors [2]. The further benefits can be achieved by the magnetic integration such as lower operating frequency, high power density, high efficiency, low cost, low noise and EMI, and small-size filtering component at the input and output side. So a single phase CUK rectifier module is proposed [1].

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Figure 1 shows a single phase CUK rectifier module with input and output inductor coupled. It consist of two sections an input and an output section. Input section is similar to a boost converter, while the output section resembles that of a buck stage. It produces negative output voltage from a positive input voltage. Here the Coupled Inductors reduces input and output current ripples and the transformer provide proper isolation

Figure 1: Single Phase CUK Rectifier Module

II. POWER FACTOR CORRECTION

Most of the switch mode power supplies draw non sinusoidal current. When the current is not sinusoidal and the voltage is sinusoidal the power factor consist of two factors

- The displacement factor related to phase angle
- Distortion factor related to wave shape

$$\text{Power Factor} = \frac{I_{\text{rms}(1)}}{I_{\text{rms}}} \cos \theta$$

$I_{\text{rms}(1)}$ – RMS value of Fundamental component of current

I_{rms} – RMS value of current

The measure of line distortion usually used in total harmonic distortion (THD), which is a measure of the harmonic content of a waveform. THD is given by

$$\text{THD} = \sqrt{\frac{\sum_{n \neq 1} I_n^2}{I_1^2}}$$

THD and power factor are related since distortion increases the RMS current drawn from the line. It can be shown that power factor and THD are directly related.

$$\text{PF} = \sqrt{\frac{1}{1 + \text{THD}^2}}$$

So the system performance can be improved by increasing the power factor or reducing the THD [8]. The basic idea behind APFC is to force the line current to follow the waveform of the line voltage.

III. DESIGN PROCEDURE

Single Phase CUK Rectifier was designed with the following characteristics:

Input voltage, V_s	= 220 V $\pm$ 10%
Line frequency	= 50 Hz
Power factor	≥ 0.95
Load resistance	= 10 Ω
Output dc voltage, V_o	= -48V
The turn ratio between Primary and Secondary nTr	= 0.5

The basic equation of an isolated CUK converter is

$$\frac{V_o}{V_g} = \frac{nTr d}{(1-d)} \quad (1)$$

To operate in CCM,

The dc voltage conversion ratio

$$m_{\theta} = V_o / (\hat{V}_g |\sin \theta|) \quad (2)$$

The M ratio is,

$$M = \frac{V_o}{\hat{V}_g} = .1543 \quad (3)$$

2) The conduction parameter of the CUK PFC circuit

$$K_a > \frac{1}{2(M + nTr |\sin \theta|)} > 1.167 \quad (4)$$

Here, K_a is chosen to be equal to 2.

3) An equivalent inductance

$$L_{eq} = \frac{RT_{sw} K_a}{2} = .3072\text{mH} \quad (5)$$

By choosing the input inductor current with 30% current ripple, $\Delta i_{L1} = 0.482$ A. The design of L_1 and L_2 is made using the desired ripple value of the input current. When the nominal duty cycle $d = 0.235$, the input-side inductor L_1 is chosen based on the specified maximum current ripple [1] [7].

$$L_1 = \frac{V_g d T_{sw}}{\Delta i_{L1}} = 5.068\text{mH} \quad (6)$$

The measured inductance of the designed input inductor is 5mH at 30 kHz.

For the Coupled Inductor extension of CUK converter, the output-side inductor L_2 is then selected using the normalized plot of amplitude of current ripples input and output inductor current as a function of turns ratio [13].

Figure 2: Normalized Plot of Amplitude of Current Ripples i_1 and i_2 as Function of Turns Ratio

Figure 2 shows the normalized value of current ripples as a function of turns ratio. Notice zero ripple current can be obtained in the secondary when $k_1 = N_1/N_2$ and similarly zero ripple in primary current if $k_2 = N_2/N_1$, where N_1 & N_2 number of turns in primary and secondary of Coupled Inductor & k is the

coupling coefficient. By selecting suitable values for N_1 & N_2 ripple current elimination is possible [4][12].

From Figure 2 the value of inductor for minimum ripple in both primary and secondary can be calculated.

Select $n = N_2/N_1 = 0.8666$, for maximum ripple reduction in the primary and secondary side.

$$\begin{aligned} L_1 &= 5 \text{ mH} \\ L_2 &= n^2 L_1 = 3.698 \text{ mH} \end{aligned} \quad (7)$$

The design of the intermediate capacitor C_a considering a resonant frequency of 3.5 kHz, which is a good initial approximation for C_a , is given by

$$C_a = \frac{1}{\omega_r^2 (L_1 + L_2)} = .55 \mu\text{F} \quad (8)$$

Let $C_a = 0.68 \mu\text{F}$ ($C_a = C_b$). The output dc capacitance C_0 is determined according to the hold-up time Δt_h . By choosing $\Delta t_h \geq 2 \text{ ms}$,

$$C_{0 \min} = \frac{2P_0 \Delta t_h}{V_0^2 - V_{0 \min}^2} = 10683 \mu\text{F} \quad (9)$$

Minimum capacitor value ($C_{0 \min}$) must be derated for capacitor tolerance (ΔC_{tol}), 20% in this case, in order to guarantee that minimum capacitance requirement is satisfied, thus assuring minimum hold-up time.

$$C_0 = \frac{C_{0 \min}}{1 - \Delta C_{\text{tol}}} = 13,353 \mu\text{F} \quad (10)$$

Let $C_0 = 13,600 \mu\text{F}$ for given V_0 and $V_{0 \min}$, the larger the power P_0 and or the longer the hold-up time Δt_h , the larger the energy-storage capacitor C_0 that needs to be used.

IV. CONTROL SCHEME

Figure 3 shows control structure and detailed control block and the control scheme based on power balance control [1].

For the control block operations following quantities are to be sensed

1. Supply voltage V_s

2. Inductor current I_{L1}

3. Output voltage V_0 and current and I_0

Measured output voltage is compared with the reference voltage and the error is given to the PI controller whose output (I_{vr}) is added with peak value of input inductor current. Using the sensed values of V_0 and I_0 , the peak value for input inductor current is calculated based on power balance concept as follows.

$$V_{\text{rms}} * I_{\text{rms}} = V_0 * I_0 \quad (11)$$

$$I_m = (1.414 * V_0 * I_0) / V_{\text{rms}} \quad (12)$$

$$I_{L \text{refi}} = I_m + I_{vr} \quad (13)$$

$I_{L \text{refi}}$ is the reference value for the peak value of input inductor current. I_{L1} is the input inductor current. I_{vr} is the correcting signal from PI controller. The inductor reference current is then obtained by multiplying it with sine wave template, ie.

$$I_{L \text{ref}} = I_{L \text{refi}} * |\sin \omega t| \quad (14)$$

After obtaining the actual current and reference current switching signals can be generated by using peak current control. Main advantages of peak current control is constant switching frequency and no need of current error amplifier and its compensation network [6][15].

The advantages of the proposed system are: high power factor, modularity, simple control strategy, and design. The output voltage is regulated [1].

V. SIMULATION AND RESULT

This section discusses the simulation of proposed high quality single phase CUK rectifier and normal AC – DC rectifier and its results.

Figure 4 shows the circuit diagram of AC-DC rectifier & Fig. 5(a) & 5(b) shows its corresponding input current and input voltage waveform respectively. In this case the input current THD is very high, this can be reduced by replacing this rectifier with a high quality CUK rectifier module.

Figure 3: Control Structure and Detailed Control Block

Figure 4: AC – DC Rectifier Circuit

Figure 5(a): Input Current Vs Time

Figure 5(b): Input Voltage Vs Time

The proposed system configuration shown in figure 1 is simulated using SIMULINK program. A rated operation of 250 W output power and -48 V of dc output voltage with 220V of ac line to neutral voltage in rms are assumed. Table 1 shows design values for simulation.

Table 1: Specification and Parameters of a Single Phase CUK Rectifier Module

Characteristic	Power Modules
Input phase voltage	220V
Input frequency	50Hz
Output Power	250 W
Switching frequency	30 kHz
Output Voltage	-48V
L_1	5.068mH
L_2	3.67mH
$C_a = C_b$	0.68 μ F
C_0	13600 μ F

Figure 6(a): Regulated output DC voltage

Figure 6(b): Input Current

Figure 6(c): Input Voltage

Figure 6(d): FFT Analysis of Input Current

Figure 6(e): Input Inductor Current

Figure 6(a) shows the regulated dc output voltage. Figure 6(b) and figure 6(c) shows the input current and input voltage waveform respectively, graph clearly shows that input current is nearly sinusoidal and also the figure 6(d) shows the FFT analysis of input current.

Figure 6(e) shows the input inductor current waveform. The input current THD is only 2.43 %, it meets international standards for harmonic regulation such as IEC 61000-3-2. International regulation is that THD should be less than 5%, which is satisfied in the simulation results.

VI. HARDWARE EXPERIMENTS

Input Voltage	: 10-15 V
Load Resistance	: 20-200 Ohm, 2.5A
Load Voltage	: -7 V

A prototype of single phase ac-dc converter has been built with components value same as shown Table 1, instead of -48V output voltage the prototype is tested for only -7V output voltage. The main objective is to improve the input current power factor and a regulated output voltage. Control circuitry is implemented using analog circuits.

Figure 7(a): Hardware Results of Input Voltage and Input Phase Current

Figure 7(b): Hardware Results of Input Inductor Current

Figure 7(c): Hardware Results of Output Voltage

Figure 7(d): Hardware Results of Input Current THD

Figure 7(a), 7(b), 7(c) and 7(d) shows the hardware experimental results input voltage and input current, inductor current, output voltage and input current THD respectively. As we can see that input current is sinusoidal in shape. Also total current THD is found to be 13.8%. Compared to THD obtained during simulation (2.43%) hardware results show increased THD. There are many reasons for this irregularity. In the simulation everything was assumed to be ideal. For example the supply voltage is assumed to be purely sinusoidal in shape, which is not the practical case. Since the same waveform is used as the unit template it will affect the performance of the system. Other possible reasons are the non-linearity which may be present in the control circuit.

Most of the PFC converter uses boost converter, Table 2 shows comparison of proposed converter with most commonly used boost PFC converter.

Table 2: Comparison of Proposed Converter with Single Phase PFC Boost Converter

Characteristics	Single Phase CUK converter	Single Phase Boost PFC Converter
Efficiency of the converter	Good	Fair
Range of Output Voltage	Tight output voltage regulation, Both buck and boost operation is possible.	Output voltage is always greater than input voltage; second stage converter is required for step down the output voltage to its required level.
Quality of Input Current	Inductor coupling reduces the current ripples. So input current quality is excellent.	Current quality is good.
Output Current	Small amount of ripples are present.	Pulsed
Complexity of control circuitry	Easily implement using analog or digital circuits.	Easily implement using analog or digital circuits.
Isolation	Easy to add	Difficult

	isolation transformer	
Magnetic Volume	Large	Small
Application	Medium power application, Low or High voltage	Medium power application, High voltage

VII. CONCLUSION AND FUTURE SCOPE

A single phase high quality CUK rectifier module with active Power Factor Correction simulated using Matlab/Simulink software. This system reduces the number of conversion stages and provides proper isolation. The Coupled Inductor reduces input and output current ripples, reduces the core cost, EMI filtering components and constant switching frequency can be achieved by peak current control. The results obtained are regulated -48V dc voltage with THD 2.43% and power factor of 0.98 which satisfies international harmonic regulation standards such IEC 61000-3-2. Hardware results a single phase CUK rectifier module provides a regulated output voltage of -7V with input current THD 13.8% this increase in THD may be due to the non-linearity's present in the control circuit and THD of the input line voltage, which is observed as around 8%. By comparing ordinary rectifier with cuk rectifier module, present system gives low THD value with improved input power factor.

Results show that the controller is working properly with tight output voltage regulation and input current wave shaping. So input current THD can be reduced by incorporating the power balance control in dc to dc converter and thereby it achieves better input power factor.

- In the present implementation only the inductors are coupled. But it is possible to integrate inductors and isolation transformer on a single magnetic core so that ripple current can be further reduced.
- In the implemented hardware the supply voltage waveform is used as the unit template current reference waveform. But distortions in the voltage waveform will affect the performance of the system. In order to avoid this, a reference line-to-neutral

voltage may be generated by mean of using a phase locked loop (PLL) system.

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