

Average current control of DC-DC Cuk Converters as Power Factor Corrector

Ashima Kulshreshtha*, Anmol R. Saxena**, A. K. Wadhvani***

*Research scholar, Department of Electrical Engineering, MITS, Gwalior

** Assistant professor, Department of electrical & electronics Engg, National Institute of Technology, Delhi

***Professor, Department of Electrical Engineering, MITS, Gwalior

ABSTRACT

The era of electronic devices in all loads due to the manufacturing technologies replaced many conventional electrical or mechanical loads including lighting loads where Light Emitting Diodes (LEDs) is becoming an emerging technique with many advantages. High frequency switching dc-dc converter is a new technology to control the load and the supply side simultaneously. Due to additional harmonics generated by these switching converters power factor correction has become a necessity in utility side. This paper focuses on the power factor correction of the supply side when employing an ideal LED load with dc-dc Cuk converter. This paper also illustrates the controlling of the power factor correction employing high switching frequency dc-dc converters. The control loops employed are discussed and the strategy for designing the compensator is also explained. The simulated results have been shown to ascertain the accepted performance of the power factor correction converter.

Keywords- Cuk converter, Current control, DC-DC Converters, FFT Analysis, Light emitting diodes (LEDs), Power Factor Correction, Voltage Regulation

I. INTRODUCTION

Rapid advances in material and manufacturing technologies have made the light emitting diodes (LEDs) the most convenient choice for lighting sources [1-2]. Lighting sources represent approximately 25 % of the total electrical energy consumed in the world [1]. LEDs are investigated as a source of artificial light because of its many advantages such as long life, high luminous efficacy, dimmable environment friendly due to less mercury contents, low maintenance, flicker less start, robust in structure and least affected by vibrations etc. [2]. Nowadays, a topic of interest in this perspective is the design of the electronic driver in order to take the advantages of LEDs performances. The brightness aspect of LEDs depends on the current controllability of the driver, so an efficient control is needed to regulate the LED current. The driver accepts the universal input voltage 90 V to 230 V rms and delivers it to the LED lamp which operates with DC current. The driver not only performs the power factor correction but also regulates the LED current. The size, life time and cost are also other concerns of the driver. The driver must be in a small size and with the lowest permissible cost and highest performance.

The life of the LED driver should match that of the LED that is 50,000 hours of driver operation & warranty addresses LED life expectations [3]. LED loads falls under Class-C equipments as per the IEEE standards [1].

The switching power supplies employ high switching frequency operations causing additional harmonics in the supply current. The utilities have to supply additional current for it and install extra thick cables. The distortion due to increasing number of such electronic devices will have necessity for power factor correction.

For LEDs, telecommunication industries, computers, microprocessors and other sensitive loads, regulated voltage is required to supply & for proper operation. Nowadays, dc-dc converters are employed for this purpose as it employs high switching frequency which means reduced size of inductors and capacitors. DC-DC converters have many topologies based on the location of the switching and passive elements. For power factor correction those converters with inductor in the input side is often utilized.

This paper focuses on power factor correction of Cuk converter by modeling of the controlling technique for power factor correction. The mathematical modeling for dc-dc converters are explained which enlighten to the steady state and perturbation analysis required for controlling the output voltage and input current.

II. DC-DC CONVERTERS AS POWER FACTOR CORRECTOR

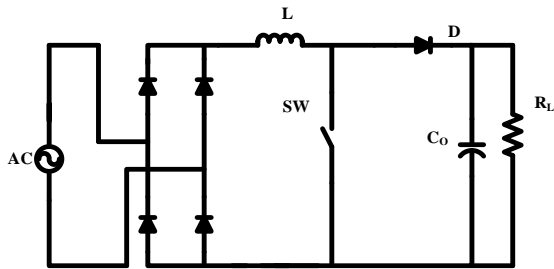


Fig.1 PFC Boost converter.

Most PFC rectifiers utilizes boost converter at their front-end. Boost based PFC converter for LED application has been introduced in [12]. Various variations in this topology is implemented to improve the performance of this converter & is enveloped in [13]. However boost converters have some major practical drawbacks such as the dc output voltage cannot be less than the peak input voltage and high start up inrush current. Therefore, for low output voltage application such as lighting loads, computer or telecommunication industry, an additional converter is required to step down the voltage [14].

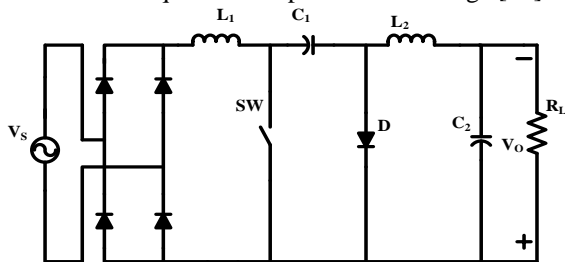


Fig. 2 PFC Cuk converter.

Cuk & SEPIC converters are used in these applications as PFC converters. Cuk topology has been introduced for LED application in [1]. The ease of implementation for transformer less electromagnetic interference (EMI) associated with the discontinuous conduction mode (DCM) topology has made fourth order converter preferable over second order boost converter [6-8]. Unlike the SEPIC converter, the Cuk converter has both continuous input and output currents of the converter, the Cuk converter seems to be a potential candidate in basic converter topologies [7].

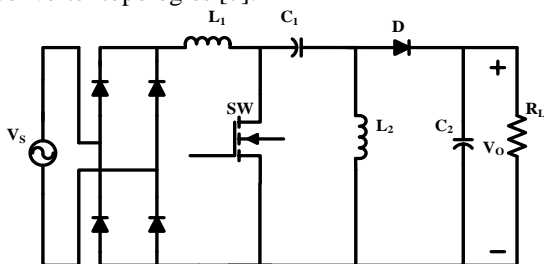


Fig. 3. PFC SEPIC Converter.

SEPIC based PFC converter is introduced in [16]. This paper presents a comparative analysis of Cuk and SEPIC converter on the basis of their steady-state performance. The controlling of DC-DC converters is done in such a manner so that it regulates output voltage with nearly unity power factor and operates at wide input and output voltage range.

III. REVIEW OF PFC CONTROLLING TECHNIQUES

For PFC, there are many control techniques which can give unity power factor on the input side. These techniques were reviewed in detail in [17].

- Peak current control
- Average current control
- Hysteresis control
- Borderline control
- Discontinuous current PWM control

3.1 Peak Current Control

The sinusoidal input current is shaped by amplifying the output of error compensator of the voltage loop. According to the output of error amplifier, switching ON & OFF of switch takes place. Hence small rippled sinusoidal current waveform is generated.

3.2 Average Current Control

This control method allows a better input current waveform. This technique has two control loops: outer voltage loop & inner current loop. Outer voltage loop regulates the output voltage & inner current loop shapes the input current. The current to be control is inductor current as its shaping is easy with switching. The outer voltage loop generates an average reference current which is to be followed by actual input current with ripples. This technique is compatible with converter operating in continuous conduction mode.

3.3 Hysteresis Control

Two sinusoidal current references I_{pref} , I_{Vref} are generated, one for the peak and the other for the valley of the inductor current [17]. According to this control technique, the switch is turned on when the inductor current goes below the lower reference I_{VREF} , and is turned off when the inductor current goes above the upper reference I_{PREF} , giving rise to a variable frequency control [18]. Also with this control technique the converter works in CICM.

3.4 Borderline Control

In this control approach the switch on-time is held constant during the line cycle and the switch off-time depends on the control loop signal given to the switch. It is turned on when the inductor current falls to zero, so that the converter operates at the boundary

between Continuous and Discontinuous Inductor Current Mode (CICM-DICM) [19]. This type of control is a particular case of hysteretic control in which the lower reference I_{VREF} is zero anywhere.

3.5 Discontinuous Current PWM Control

With this approach, the internal current loop is completely eliminated, so that the switch is operated at constant on-time and frequency [20]. With the converter working in DCM, this control technique allows unity power factor when used with converter topologies like flyback, Cuk and Sepic. Instead, with the boost PFC this technique causes some harmonic distortion in the line current [21].

IV. AVERAGE CURRENT CONTROL OF SWITCHED MODE POWER SUPPLIES

4.1 Voltage Regulation.

The output voltages of dc power supplies are regulated to be within a specified tolerance band. This is accomplished by using a negative-feedback control system, where converter output voltage, v_o is compared with its reference value, v_{oref} . The error amplifier produces the control voltage v_c , which is used to adjust the duty ratio d of the switch in converter.

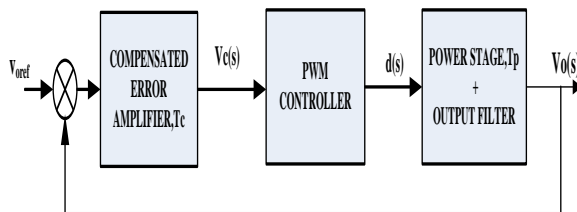


Fig.4. Feedback control system of voltage regulation.

4.1.1 Mathematical modeling of Power stage, T_p

The goal of following analysis is to obtain a small signal transfer function $v_o(s)/d(s)$, where v_o & d are small perturbations in the output voltage and duty ratio respectively, around their steady state dc operating values V_O & D . the transfer function, T_p can be derived by state space analysis with inductor currents and capacitive voltages as state variables, x , input voltage, V_S as input, u and output voltage, V_o as output, y . These are formulated in state space equations.

$$\dot{x} = Ax + Bu$$

$$y = Cx + Du$$

Formulation of the value of state variables can be done by using Kirchhoff's voltage and current law (KCL & KVL) for both the cases i.e. when switch is ON & OFF. Averaging the state variables in both the mode and segregating steady state and small ac perturbations we get,

$$T_p(s) = \frac{v_o(s)}{d(s)}$$

4.1.2 Modeling of Error Compensator, T_c

Compensated Error amplifier is designed by considering the open loop transfer function of the negative feedback system. It is given by,

$$T_{OL} = T_p(s)T_c(s)$$

The bode plot of open loop transfer function is observed. The compensator should be designed such that it has high gain at low frequencies to minimize the steady state error in power supply output. Its gain crossover frequency at which open loop gain falls to 0 dB, should be as high as possible but lower than the switching frequency. The phase margin should be 45° - 70° for improved transient response with sudden load change.

4.2 Power Factor Correction Control.

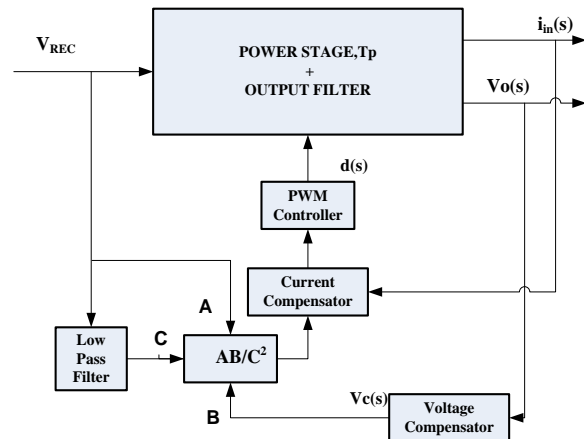


Fig. 5 Current Control for PFC DC-DC converter.

4.2.1 Mathematical modeling of power stage, T_p

The dc-dc converter is modeled for power factor correction by deriving by inductor-to-duty ratio control, as duty ratio will control the inductor current. By state space analysis shown in section A, inductor current-to-duty ratio is also derived.

$$\frac{x(s)}{d(s)} = \frac{i_L(s)}{d(s)}$$

4.2.2 Inner Current Control Loop.

Current compensator is implied on Inductor current-to-duty control ratio, T_p to form an open loop gain. The open loop gain for power factor correction will be same as explained in section A (ii).

4.2.3 Outer Voltage Control Loop

A low frequency small signal model is developed to design voltage compensator. For a constant load, a voltage compensation of 45° phase margin is adopted. The control, v_c -to-output, v_o

transfer function, G_V and voltage compensator, G_{cv} forms an open loop transfer function.

As the output voltage is constant with small second harmonic component which distort its shape, the voltage loop bandwidth is selected such that it blocks the 100 Hz or 120 Hz ripple. So the voltage loop bandwidth is much smaller than 100 Hz.

4.2.4 Feed-forward loop compensation

Feed-forward loop is applied so that there is no effect on the output voltage, V_O or input current, i_{in} with the small variations in input supply voltage, V_S . Any changes in input voltage will distort the reference current for the current compensator.

$$i_{ref} = \frac{AB}{C^2}$$

$$\frac{\Delta i_{ref}}{i_{ref}} = \frac{\Delta B}{B} - 2 \frac{\Delta C}{C}$$

Feed-forward loop is inserted to compensate the line voltage variation. It is derived from the second order low pass filter. The cut off frequency of the feed-forward low pass filter should be based on the maximum acceptable THD of the input current.

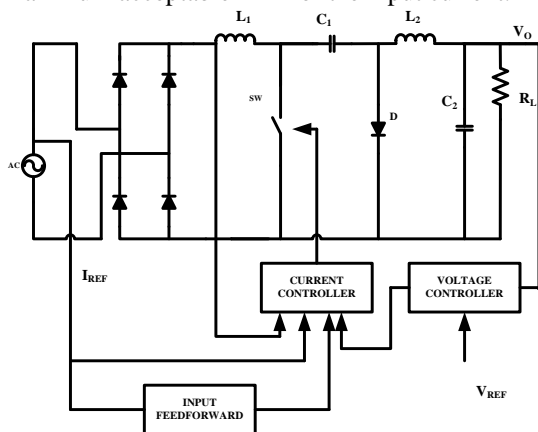


Fig. 6 PFC Current control for DC-DC Cuk converter.

Fig. 6 shows an example of controlling of PFC converter employing Cuk converter. The design of analog current controller or current compensator using op-amps is as shown in Fig. 7.

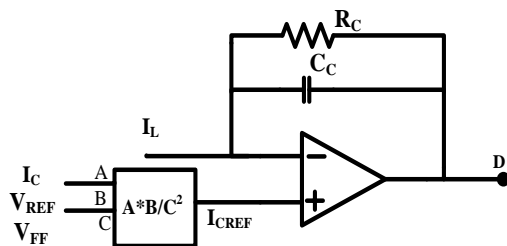


Fig. 7 Analog Current Compensator of a PFC converter.

V. RESULTS & DISCUSSION

The main objective of the modeling and simulation in MATLAB-SIMULINK is to support the design of the PFC Cuk converter in the function of a lamp driver for LEDs which assures nearly unity power factor with low THD at the AC supply side, 220 V rms and low voltage percentage ripple at 72 V using closed loop control. Fig.8 shows the input voltage (V_S), input current (I_S), output DC voltage (V_O) at 72 V LED load. The input current (I_S) is closed to pure sinusoidal waveform superimposed on input voltage (V_S). CICM of input current is ensured in the result shown. Fig. 9 shows FFT analysis of input current confirming low total harmonic distortion (THD).

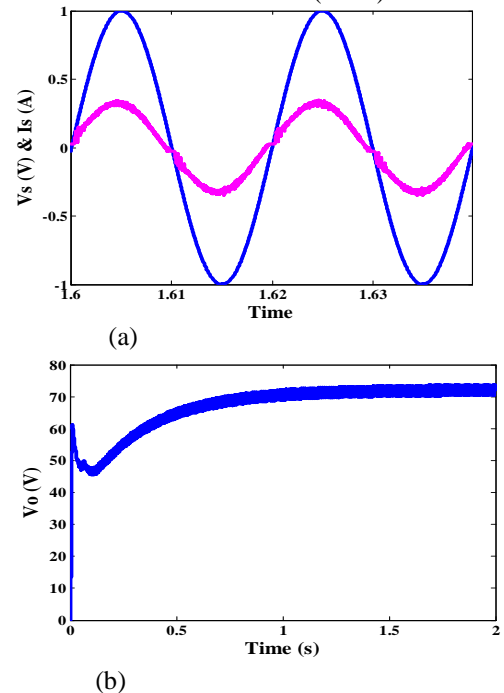


Fig. 8 Simulated results of PFC Cuk converter (a) input voltage, V_s & current, I_s .(b) output voltage, V_o .

VI. CONCLUSION

This paper has given a very fundamental but significant idea about the power factor correction utilizing dc-dc Cuk converter with current controlled LED load. Besides, the literature review has been developed to explore a wide perspective of controlling techniques for PFC converters so that it can be used as useful reference guide for power electronic professionals working on ac-dc converters & also the end users of ac-dc converters. The exposition of average current control technique for PFC converter by modeling the converter using state space analysis to mutate input current into pure sinusoidal waveform is also explained. The result showing input current shaped in the form of input voltage & output voltage with low percentage ripple

& less settling time endorse the operation of PFC Cuk converter. A detailed analysis of harmonic distortion of input current is shown by FFT analysis using MATLAB-Simulink platform.

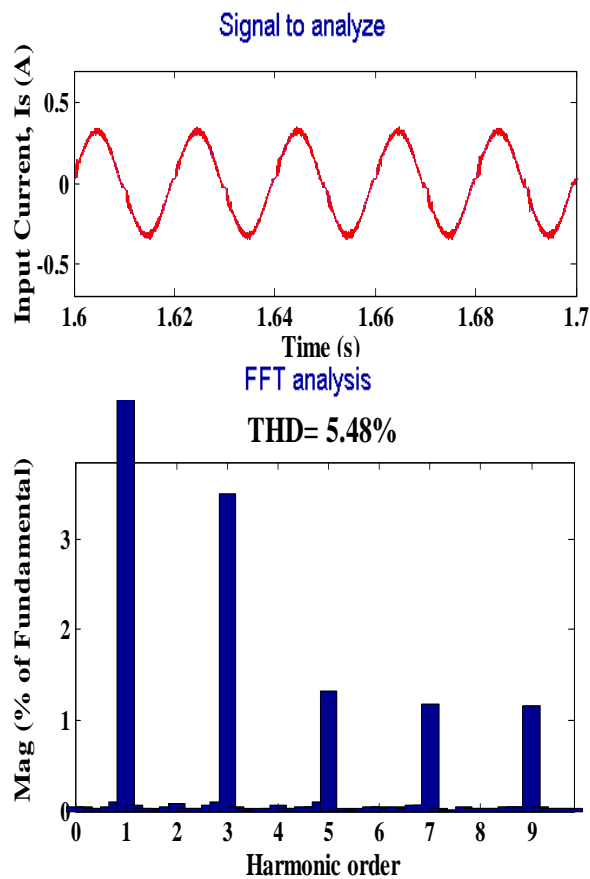


Fig. 9 FFT Analysis of input current showing the optimized performance of PFC converter

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