

HIGH POWER FACTOR RECTIFIER FOR LOW-VOLTAGE ENVIRONMENTS

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Abstract: This paper discusses the Cuk converter in discontinuous conduction mode, which acts as an automatic current wave shaper. An AC to DC converter is not just an integral part of any power supply unit used in the all electronic equipments, but also, it is used as an interface between utility and most of the power electronic equipments. The proposed approach is competitive in the low-voltage environment and it is suitable for smart-power integration.

Keywords: Cuk converter, high power factor rectifier, low-voltage environments, high frequency.

1. INTRODUCTION

Generally, to convert line frequency AC to DC we use a line frequency diode bridge rectifier. An AC to DC converter is not just an integral part of any power supply unit used in the all electronic equipments, but also, it is used as an interface between utility and most of the power electronic equipments. Conventional power converters with diode capacitor rectifier front-end have distorted input current waveform with high harmonic content and a power factor lower than 0.65.

A large filter capacitor is used at the rectifier output to reduce the ripple in the DC output voltage, but this large capacitor makes the current drawn by this converter peaky in nature. This input current is rich in low order harmonics. As power electronics equipments are increasingly being used in power conversion, they inject low order harmonics into the utility making the total harmonic distortion high and the input power factor poor. Due to problems associated with harmonics and low power factor, utilities will enforce harmonic standards and guidelines which will limit the amount of current distortion allowed into the utility and thus the simple diode rectifiers may not be used.

Power factor correction schemes have been initially implemented mainly for heavy industrial loads like induction heating furnaces, induction motors etc.

However, the trend is changing because electronic equipments are being used more often in everyday life. Line currents drawn by the conventional diode rectifier filter capacitor

are peaked pulse currents, which result in distortion of the utility line.

The popular boost converter requires complex control. The ripple currents are limited only by the size of the inductor. As the boost converter is operated in continuous conduction mode (CCM), the inductor required is large, which will increase the crossover distortion.

The boost converter in discontinuous conduction mode (DCM) also acts as an automatic current wave shaper but it requires a high conversion gain to reduce distortion.

The flyback converter in discontinuous conduction mode also can be used for power factor correction. As the ripple currents in discontinuous conduction mode are high, the line harmonics must be filtered.

This paper discusses the Cuk converter in discontinuous conduction mode, which acts as an automatic current wave shaper.

2. POWER FACTOR CORRECTION TECHNIQUES

Single-phase switch-mode AC/DC power converters have been increasingly used in recent years, in environments like industry, military but also in the commercial, residential, and aerospace environments. The main advantages of single-phase switch-mode AC/DC power converters are: high efficiency, smaller weight and size. However, the proliferation of the power converters draw pulsating input current from the utility line, this not only reduce the input power factor of the converters but also injects a significant

amount of harmonic current into the utility line. To improve the power quality, various power factor correction schemes have been proposed.

By the introduction of harmonic norms now power supply manufacturers have to follow these norms strictly for the remedy of signal interference problem.

The various methods of power factor correction can be classified as:

1. Passive power factor correction techniques
2. Active power factor correction techniques

The passive power factor correction technique is simple and rugged but it has bulky size and heavy weight and the power factor cannot be very high. In this technique an L-C filter is inserted between the AC mains line and the input port of the diode rectifier of AC/DC converter. Basically it is applicable for power rating of lower than 25W but for higher power rating it will be bulky.

In active power factor correction techniques, the input current is shaped in phase with the input voltage using switched mode power supply (SMPS) technique. There are different topologies for implementing active power factor correction techniques. Basically in this technique power factor correcting cell is used for tracking the input current in phase of input voltage such that input power factor come up to unity. Comparing with the passive power factor correction techniques, active power factor correction techniques have many advantages such as: reduced harmonics, high power factor, smaller size and light-weight.

The main drawbacks of this approach are the complexity and relatively higher cost. Different topologies of PWM (Pulse Width Modulation) techniques are as follows:

- Buck type
- Flyback type
- Boost type
- Cuk type

In the buck type topology the converter can supply a low output voltage with respect to input voltage and this is the main advantage. The disadvantages is the cost, the input current is discontinuous causing significant current distortion. It is a basic DC-DC converter and it is not used for power

factor correction. The advantages of flyback type topology are:

1. output voltage can be higher or lower than input voltage
2. input and output can be isolated.

The disadvantages are:

1. current rating
2. higher switching device voltage,
3. input current is discontinuous,
4. difficult to program the input current with current mode control.

Advantages of boost type topology are

1. current mode control is easy
2. less EMI (Electromagnetic Interference) means reduced input filtering requirements.

The main disadvantages are more conduction loss, no isolation and output voltage is always higher than input voltage.

Advantages of Cuk type topology are:

1. input current is remain continuous even if the converter operates in discontinuous conduction mode,
2. output voltage can be lower or higher than the instantaneous input voltage.

The disadvantages are the increased voltage and current stress on power devices.

3. CUK CONVERTER

In the following analysis, we consider a switching frequency much higher than the line frequency, so that the averaged signals over a switching period T_s can be regarded in place of the instantaneous quantities. Also, only discontinuous conduction mode operation is considered.

In figure 1 is shown the insulated version of the Cuk converter driven by a rectified sinusoidal voltage. All the converter components are rated on the switching frequency basis, except the output capacitor C_o which must be big enough to filter the low frequency ripple, at twice the line frequency, caused by the input power variation when operating as power factor correction circuit.

The capacitor voltages are:

$$v_{C1}(t) = |v_i| = V_i \cdot |\sin \omega \cdot t| \quad (1)$$

$$V_{C2} = V_{Ro} \quad (2)$$

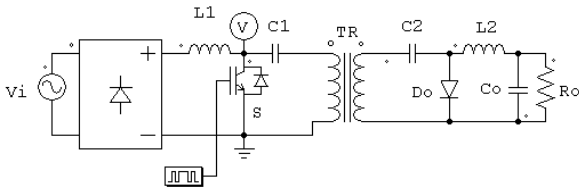


Fig.1. Cuk converter as Power Factor Correction Circuit.

When operating in discontinuous conduction mode, the current waveforms of both inductors look as shown in figure 2.

The circuit behaviour is as follows: when the switch is turned on, the freewheeling diode D_o is reverse biased and the currents rise linearly. During turn-off interval, both inductor currents decrease until their sum becomes zero, causing the freewheeling diode D_o turn off. After that, they remain constant for the rest of the switching period.

The average input current is given by:

$$\bar{i}_{L1}(t) = |v_i| \cdot \frac{\alpha^2}{2 \cdot L_e \cdot f_s} \quad (3)$$

where f_s is the switching frequency and

$$L_e = \frac{N^2 \cdot L_1 \cdot L_2}{L_1 + N^2 \cdot L_2} \quad (4)$$

This relation shows that, for constant switching frequency and duty-cycle, the average input current is proportional to the input voltage, ensuring unity power factor.

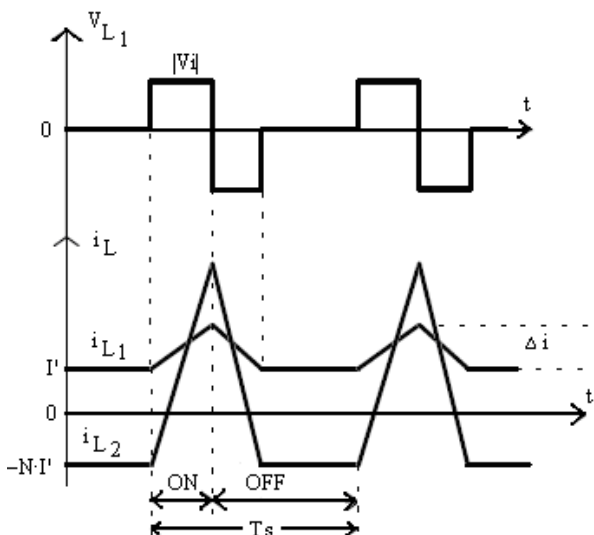


Fig.2. Inductor voltage and currents in DCM for Cuk converter

3.1. LIMITS FOR DCM OPERATION

Let us define the following adimensional parameters:

$$M = \frac{V_o}{V_i} \quad (5)$$

$$K_e = \frac{2 \cdot L_e}{R_L \cdot T_s} \quad (6)$$

The converter duty-cycle is given by:

$$\alpha = M \cdot \sqrt{2 \cdot K_e} \quad (7)$$

which shows that like any other converter operating in DCM, the voltage conversion ratio M depends on the load.

In order to ensure the DCM operation in all conditions, the converter parameters must satisfy the following inequality:

$$K_e < \frac{N^2}{2 \cdot (M \cdot N + 1)^2} \quad (8)$$

Once the value of equivalent inductance L_e is known, from the desired relative input current ripple Δi (peak to peak), the input inductance L_1 is obtained as follows:

$$L_1 = \frac{2 \cdot L_e}{\alpha \cdot \Delta i} \quad (9)$$

With reference to figure 2, it is important to note that current I' must be greater than zero, otherwise the converter operation changes: in fact, current i_{L1} cannot go negative for the presence of the diode bridge.

This latter constrain imposes a minimum value for L_1 , that is:

$$L_1 = \frac{L_2 \cdot N}{M} \quad (10)$$

4. CUK CONVERTER WITH AUXILIARY CIRCUIT FOR SOFT TURN-OFF

In the above Power Factor Correction Circuits the insulation transformer causes severe voltage spikes and ringing due to its leakage inductance, when the current in the primary side reverses.

Figure 3 shows Cuk and SEPIC converters with the proposed auxiliary circuit, which allows zero-voltage turn-off of the main switch while limiting its overvoltage.

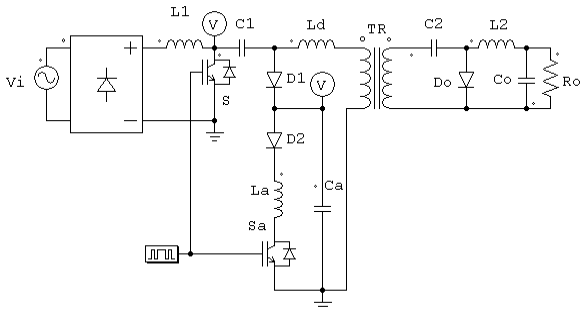


Fig.3. Cuk converter with auxiliary circuit for soft-commutation

Figure 4 shows the converter waveforms during one switching period. The same driving signal is applied to both switches. At the end of t_{off} interval, the voltage on C_a is equal to the reflected output voltage plus the overvoltage caused by the transformer leakage inductance. The freewheeling diode D_o is off. At instant t_0 , both switches are turned on under zero-current condition.

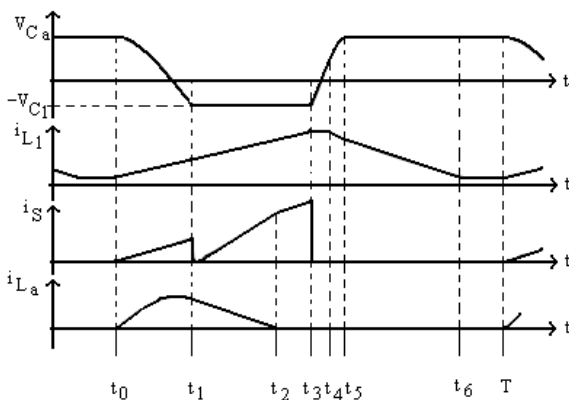


Fig.4. Converter and auxiliary circuit waveforms during a switching period

a) Interval t_0 - t_1 :
Capacitor C_a starts resonance with inductor L_a . At instant t_1 , its voltage reaches the value $-V_{C1}$ and D_1 starts conducting.

b) Interval t_1 - t_3 :
The inductor current i_{L_a} divides between C_a and C_1 , flowing almost entirely through S_a , D_2 , S , C_1 and D_1 , and decreases linearly to zero (instant t_2) with a slope equal to $-\frac{V_{C1}}{L_a}$.

Note that the auxiliary circuit does not cause increased voltage or current stresses in the

main switch. On the contrary, the total current carried by the main switch is lowered.

c) Interval t_3 - t_4 :
At t_3 , the main switch is turned off under zero-voltage condition, and the auxiliary one under zero-current condition. The current flows through D_1 to recharge capacitor C_a . As the current during this small interval is almost constant, the voltage varies linearly. When v_{C1} equals the output voltage reflected to the primary side, D_o starts to conduct (instant t_4).

d) Interval t_4 - t_5 :
Voltage v_{C1} increases above the reflected output voltage in a resonant manner due to the oscillation between L_a and C_a . The corresponding overvoltage depends on the inductor current value and the characteristic impedance of the resonant circuit. The duration of this interval is one fourth of the resonant period.

e) Interval t_5 - t_6 :
At t_5 , diode D_1 stops conduction and current i_{L1} flows through the transformer until the current in the freewheeling diode D_o becomes zero (operation in discontinuous mode).

f) Interval t_6 - T :
The output diode opens at zero current. The voltage reflected to the primary becomes zero and the voltage across the main switch drops to V_{C1} .

5. CONCLUSIONS

A high power factor rectifier employing a Cuk converter operating in Discontinuous Conduction Mode (DCM) is analysed. This solution allows a reduction of the reactive elements at the expense of higher voltage stresses on the power semiconductors. The use of the proposed auxiliary circuit, besides limiting the overvoltage, allows a full soft-commutation converter. A higher switching frequency is therefore possible also with IGBTs, maintaining a reasonably high efficiency. In spite of some low frequency distortion in the line current, the power factor is next to unity and the current harmonics are small.

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