Comparison of Basic Converter Topologies For Power Factor Correction

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Abstract: Basic types of dc-dc converters, when operating in discontinuous conduction mode, have self power factor correction (PFC) property, that is, if these converters are connected to the rectified ac line, they have the capability to give higher power factor by the nature of their topologies. Input current feedback is unnecessary when these converters are employed to improve power factor. In this paper, basic types of dc-dc converter topologies are studied to investigate their self-PFC capabilities. Their input characteristics will be compared and their input line current waveforms will be predicted.

I. Introduction

To improve input power factor of power converters, normally a power factor correction (PFC) circuit is designed and placed in front end of the converter, which in turn interfaced with the load. This power factor correction circuit may be an independent unit, by which the power supply followed, or an inseparable part of circuit incorporated into the power supply of the load. The line is a voltage source and will not be distorted if the line current is a sinusoidal one. Hence, the basic idea of doing PFC is straightforward, by certain means, to force the line current to follow the waveform of the line voltage.

However, there exists an unbalance of instantaneous power between the input power of the PFC circuit, which is an alternative quantity with two times the line frequency, and its dc output power. Therefore, the operation principle of a PFC circuit is to process the input power in certain way that it stores the excessive input energy when the input power is larger than the dc output power, and releases the stored energy when the input power is less than the dc output power. To accomplish the above process, at least one energy storage element must be included in the PFC circuit.

In most PFC circuits, an input inductor has been connected to the bridge rectifier. Because of the current continuity nature of inductor, we usually call such connection as "current driven"[1]. The input inductor can operate in either continuous conduction mode (CCM) or discontinuous conduction mode (DCM). In DCM, the input inductor is no longer a state variable since its state in a given switching cycle is independent on the value in the previous switching cycle[2]. The peak of the inductor current is sampling the line voltage automatically. This property of DCM input circuit can be called "self-power factor correction" because no control loop is required from its input side. This is also the main advantage over a CCM power factor correction circuit, in which multi-loop control strategy is essential. However, the input inductor operating in DCM can not hold the excessive input energy because it must release all its stored energy before the end of each switching cycle. As a result, a bulky capacitor is used to balance the instantaneous power between the input and output. In addition, if discontinuous conduction mode is applied, the input current is normally a train of triangle pulse with nearly constant duty ratio. In this case, an input filter is necessary for smoothing the pulsating input current into a continuous one. Obviously, to ensure high power factor, the average current of the pulsating current should follow the input voltage in both shape and phase.

The DCM input circuit can be one of the basic dc-dc converter topologies. However, when they are applied to the rectified line voltage, they may draw different shape of averaged line current. In this paper, basic buck, boost, buck-boost, flyback, forward, Cuk, Sepic and Zeta converter topologies are investigated. Analysis results show that only some of them are suitable for PFC application.

II. Input Voltage-Current Characteristics of Basic Converter Topologies

In order to examine the self-PFC capabilities of the basic converters, we first investigate their input characteristics. Because the input currents of these converters are discrete when they are operating in

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DCM, only averaged input currents are considered. Since switching frequency is much higher than the line frequency, let's assume the line voltage is constant in a switching cycle. In steady state operation, the output voltage is nearly constant and the variation in duty ratio is slight. Therefore, constant duty ratio is considered in deriving the input characteristics. During the analysis, the following nomenclatures are used:

$v_l(t)=V_{lm}\sin\omega_l t$ — line voltage;

$i_l(t)$ — line current;

$v_1(t)$ — rectified line voltage;

$i_1(t)$ — rectified line current;

$i_{1,avg}(t)$ — average value of rectified line current, (assume $i_l(t) = i_{1,avg}(t)$);

V_o — output dc voltage;

ω_l — line angular frequency;

T_l — line period;

T_s — switching period;

D — duty ratio;

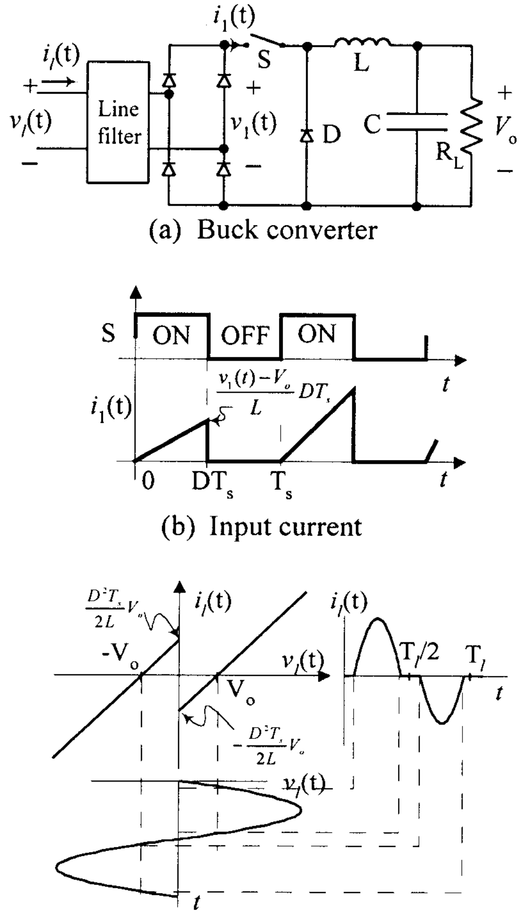
D_1 — input inductor discharging time ratio.

A. Buck converter

The basic buck converter topology and its input current waveform when operating in DCM are shown in Fig. 1(a) and (b), respectively. It can be shown that the average input current in one switching cycle is given by

$$i_{1,avg}(t)=\frac{1}{T_s}\left[\frac{1}{2}\cdot DT_s\cdot\frac{v_1(t)-V_o}{L}DT_s\right] \quad (1)$$
$$=\frac{D^2T_s}{2L}v_1(t)-\frac{D^2T_s}{2L}V_o$$

Figure 1(c) shows that the input voltage-input current V-I characteristics is a straight line. It should be note that this straight line does not go through the original. When the rectified line voltage $v_l(t)$ is less than the output voltage V_o, negative input current would occur. This is not allowed because the bridge rectifier will block the negative current. As a result, the input current is zero near the zero cross point of the line voltage, as shown in Fig. 1(c). Actually, the input current is distorted simply because the buck converter can work only under the condition that the input voltage is larger than the output voltage. Therefore the basic buck converter is not a good candidate for DCM input power factor correction



(a) Buck converter

(b) Input current

(c) Input V-I Characteristic

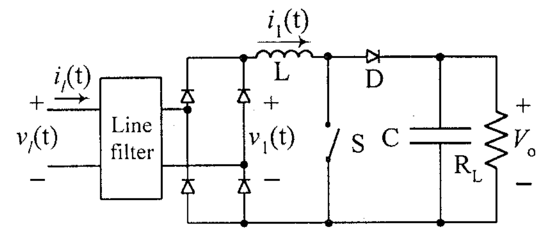
Fig. 1 Input V-I Characteristic of basic buck converter operating in DCM

B. Boost converter

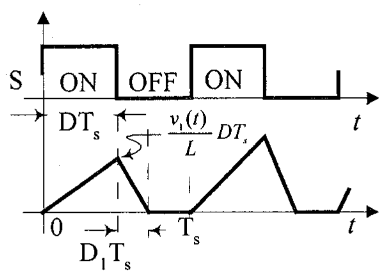
The basic boost converter and its input current waveform are shown in Fig. 2(a) and (b), respectively. The input V-I characteristic can be found as follows:

$$i_{1,avg}(t)=\frac{1}{T_s}\left[\frac{1}{2}\cdot(D+D_1)T_s\frac{v_1(t)}{L}DT_s\right] \quad (2)$$
$$=\frac{D^2T_s}{2L}\frac{v_1(t)V_o}{V_o-v_1(t)}.$$

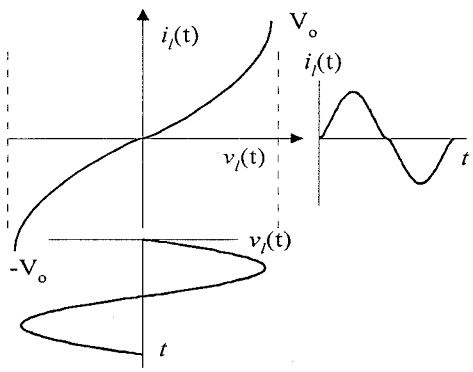
By plotting Eq. (2), we obtain the input V-I characteristic curve as given in Fig. 2(c). As we can see that as long as the output voltage is larger than the peak value of the line voltage in certain extent (depending on D_1), the relationship between $v_1(t)$ and $i_{1,avg}(t)$ is nearly linear. When the boost converter connected to the line, it will draw almost sinusoidal average input current from the line, shown as in Fig. 2(c).



(a) Boost converter



(b) Input current



(c) Input V-I Characteristics

Fig. 2 Input V-I Characteristic of basic boost converter operating in DCM

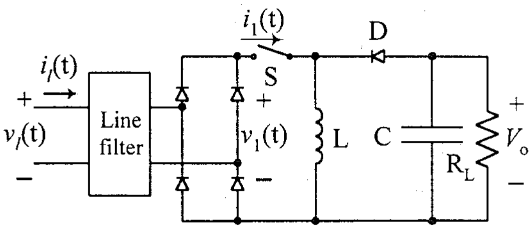
As one might notice from Eq. (2) that the main reason to cause the non-linearity is the existence of D_1. Ideally, if $D_1 = 0$, the input V-I characteristic will be a linear one. In practice, to reduce the discharge period D_1, by properly configuring the circuit topology, a higher voltage, instead of V_o, can be created to be applied to the inductor during D_1 to discharge the inductor[3].

Because of the above reasons, boost converter is comparably superior to most of the other converters when applied to do PFC [3-5]. However, it should be noted that boost converter can operate properly only when the output voltage is higher than its input voltage. When low voltage output is needed, a step-down dc-dc converter must be cascaded.

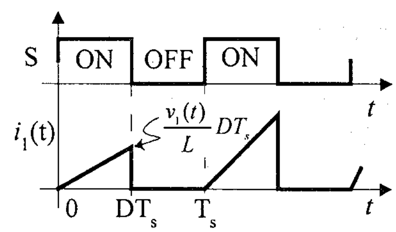
C. Buck-boost converter

Figure 3(a) shows a basic buck-boost converter. The averaged input current of this converter can be found according to its input current waveform, shown in Fig. 3(b).

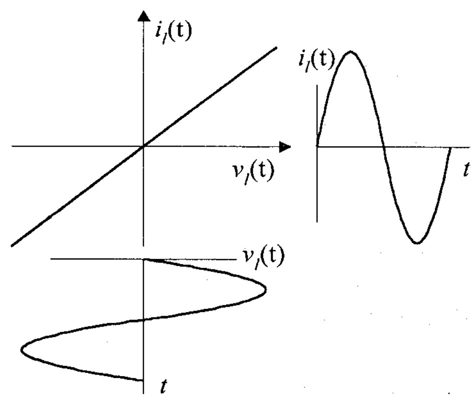
$$i_{1,avg}(t) = \frac{D^2 T_s}{2L} v_1(t) . \tag{3}$$



(a) Buck-boost converter



(b) Input current

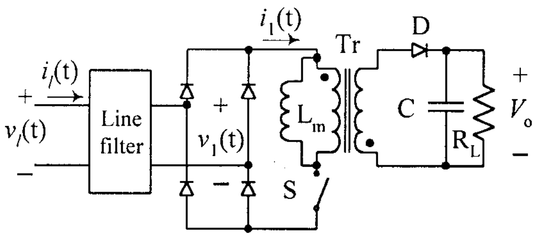


(c) Input V-I Characteristics

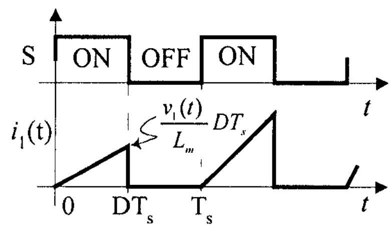
Fig. 3 Input V-I Characteristic and input waveforms.

Equation (3) gives a perfect linear relationship between $i_{l,avg}(t)$ and $v_l(t)$, which proves that a buck-boost has excellent self-PFC property. This is because the input current of buck-boost converter does not related to the discharging period D_1. Its input V-I characteristics and input voltage and current waveforms are shown in Fig. 3(c). Furthermore, because the output voltage of buck-boost converter can be either larger or smaller than the input voltage, it demonstrates strong availability for DCM input technique to achieve power factor correction. So, theoretically buck-boost converter is a perfect candidate. Unfortunately, this topology has two limitations: 1) the polarity of its output voltage is reversed, i.e., the input voltage and the output voltage don't have a common ground; and 2) it needs floating drive for the power switch. The first limitation circumscribes this circuit into a very narrow scope of applications. As a result, it is not widely used.

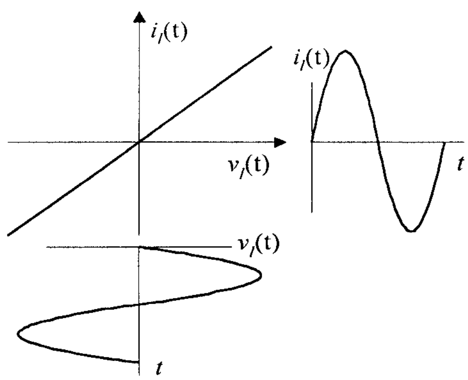
D. Flyback converter



(a) flyback converter



(b) Input current



(c) Input V-I Characteristics

Fig. 4 Input V-I Characteristic of basic flyback converter operating in DCM

Flyback converter is an isolation converter. Its topology is shown in Fig. 4(a). Figure 4(b) shows its input current waveform. The input voltage-input current relationship is similar to that of buck-boost converter:

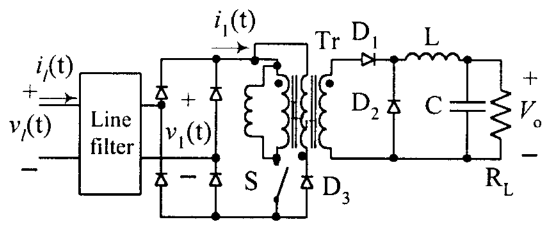
$$i_{1,avg}(t)=\frac{D^2T_s}{2L_m}v_1(t)\,. \tag{4}$$

Where, Lm is the magnetizing inductance of the output transformer.

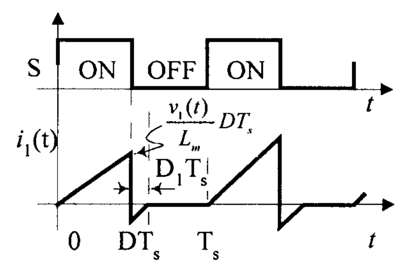
Therefore, it has the same input V-I characteristic, and hence the same input voltage and input current waveforms as those the buck-boost converter has, shown in Fig. 4(c).

Comparing with buck-boost converter, flyback converter has all the advantages of the buck-boost converter without any limitation. What's more, input-output isolation can be provide by flyback converter. These advantages make flyback converter most preferable in power factor correction with DCM input technique [6-8].

E. Forward converter



(a) forward converter



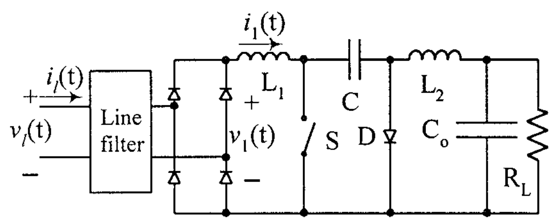
(b) Input current

Fig. 5 Forward converter and its input current waveform

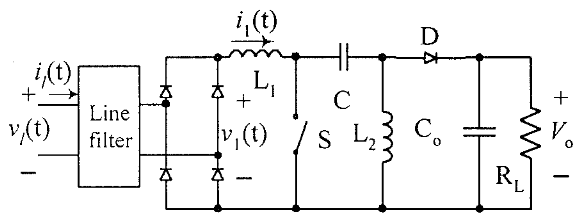
The circuit shown in Fig. 5 is a forward converter. In order to avoid transformer saturation, it is well know that forward converter needs the 3rd winding to demagnetize (reset) the transformer. When a forward converter is connected to the rectified line voltage, the demagnetizing current through the 3rd winding is blocked by the rectifier diodes. Therefore, forward converter is not available for PFC purpose.

F. Cuk converter, Sepic converter and Zeta converter

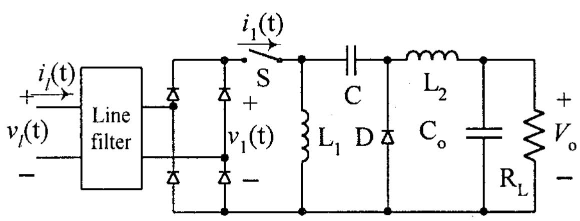
It can be shown that Cuk converter, Sepic converter and Zeta converter given in Figs. 6(a), (b) and (c), respectively, have the same input V-I characteristic. Each of these converter topologies has two inductors, with one located at its input and the other one at its output. Let's consider the case when the input inductor operates in DCM while the output inductor operates in CCM. To investigate the input characteristic of these converters, let's take the Cuk converter as an example. One should note that the results from the Cuk converter are also suitable for Sepic converter and Zeta converter.



(a) Cuk converter



(b) Sepic converter



(c) Zeta converter

Fig. 6 Basic topologies of Cuk, Sepic and Zeta converters

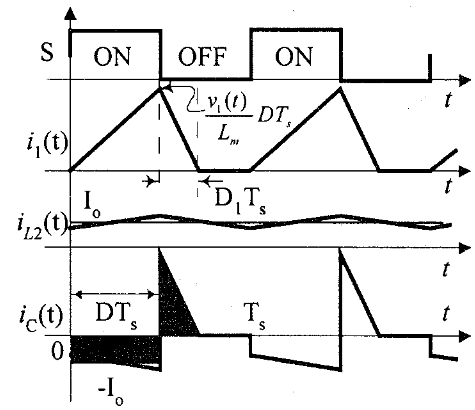
The waveforms of the Cuk converter, shown in Fig. 6(a), for input inductor current (=input current), output inductor current and the current through the capacitor C are depicted in Fig. 7(a). Assume that the output current is I_o. Then the average output inductor current is I_o. In steady state, employing charge equilibrium principle, we obtain

$$D_1 = \frac{2L_1 I_o}{T_s v_1(t)} \tag{5}$$

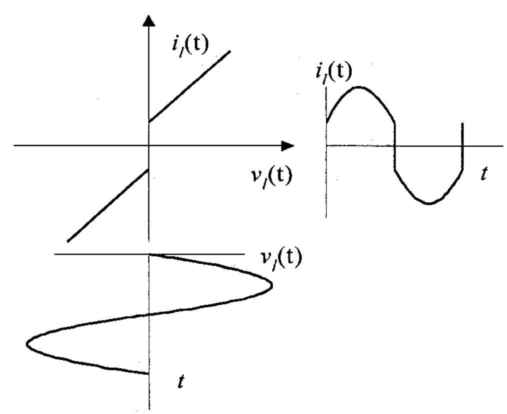
Then the averaged input current can be found as

$$i_{1,avg}(t) = \frac{1}{T_s} \cdot \frac{1}{2} \cdot D_1 T_s \cdot \frac{v_1(t)}{L_1} DT_s \tag{6}$$

$$= \frac{D^2 T_s}{2L_1} v_1(t) + I_o D$$



(a) Typical current waveforms of Cuk converter



(b) Input V-I Characteristics

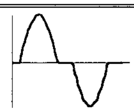
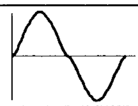
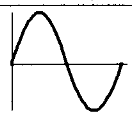
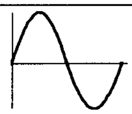
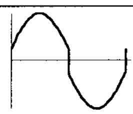
Fig. 7 Input V-I Characteristic of basic Cuk converter operating in DCM input

From Eq.(6), the input V-I characteristic of Cuk converter is plotted in Fig. 7(b). According to this input V-I chart, the input current waveform corresponding to a sinusoidal input voltage is sketched. As we can see that the input current waveform is a distorted one. Therefore, Cuk converter does not have a good self-PFC property. This conclusion can be also extended to the Sepic and Zeta converters.

III. Conclusions

According to the above discussion, we may conclude that the basic boost converter, flyback converter and buck-boost converter have excellent self-PFC capability naturally. Among them, boost converter and flyback converter are especially suitable for DCM PFC usage. Hence, these two converters are most preferable by the designers for power factor correction purpose. Other converters may be used only if their input V-I characteristics have been modified (linearized), or when they operate in continuous conduction mode. The characteristics of the above eight basic converter topologies are summarized as in Table I.

Table I

Basic converter	Line current waveform	DCM self-PFC	Power level
Buck		Poor	Low to medium
Boost		Good	Low to medium
Buck-Boost		Excellent	Low to medium
Flyback		Excellent	Low
Forward	-	No	-
Cuk, Sepic, Zeta		Poor	Low to medium

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