Boundary Conduction Mode Modified Buck Converter with Low Input Current Total Harmonic Distortion

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Abstract

Buck Power Factor Correction (PFC) converter is widely used for a broad range of AC/DC applications because of its many advantages like protection against short circuit, high efficiency at universal input voltage, low output voltage, less voltage stress on the switch, low inrush current and low component count. However, the inherent dead zone introduces a large harmonic distortion in the average input current, resulting in a low Power Factor (PF) and high Total Harmonic Distortion (THD). A constant on-time controlled Boundary Conduction Mode (BCM) buck-flyback converter is introduced in this paper. It can achieve low input current THD and high PF. The operating principle of the traditional and proposed converter is discussed and the effectiveness of proposed topology is evaluated by simulation results.

Keywords: Boundary Conduction Mode (BCM), Buck Converter, Power Factor (PF), Total Harmonic Distortion (THD)

1. Introduction

Nowadays power electronic technology has bought the revolution in the field of electrical/electronic engineering due to which it is being widely used in various types of modern equipment's which has made our life easier, simpler and luxurious. However, this technology is based on the solid state devices due to which the shape of input current is distorted. So the industries have built various standards such as IEC61000-3-2 limit and IEEE 519-4. Therefore, various types of Power Factor Correction (PFC) converters are put forward in the literature to improve the shape of distorted current and the buck converter is one of them. It has the major advantage of maintaining high efficiency in universal input voltage range. However, its input Power Factor (PF) is low due to dead zone in the average input current as shown in Figure 1. Thus, it is necessary for the buck converter to propose the technique or topology which can improve its PF.

For modifying the performance of traditional buck converter, various researches have proposed various techniques and control schemes.

A high PF buck converter is introduced in6. The work in6 has discussed modeling, analysis, and applications of buck converter in discontinuous input voltage mode operation. In7, a new topology is proposed for reducing the input current harmonics. The performance evaluation on a clamped-current buck PFC converter is presented in8. A bridgeless buck PFC converter that substantially improves the efficiency at low line is introduced in9. The study in10 has presented soft switched buck PFC converter operating with constant on-time control. A tapped-inductor high-brightness light-emitting diode (HB-LED) AC/DC driver operating in Boundary Conduction Mode (BCM) for replacing incandescent bulb lamps is presented11. In12 variable on-time control strategy is put forward to enhance the PF of buck converter. The study in13 has presented a solution to attain high PF.

In this paper, a BCM flyback converter is introduced to work with buck converter during dead zone time period to eliminate the dead zone. It can achieve low input current Total Harmonic Distortion (THD) and high PF.

This paper is divided into six sections. In section 2, the operation states of BCM buck PFC converter are analyzed. A BCM flyback converter to work during dead zone time is introduced in section 3. Then the comparative analysis is discussed in section 4 in terms of input PF and contents of input current harmonics. In section 4, the effectiveness
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The instantaneous and rectified input voltage during half line cycle can be given as:

\[ v_{in} = v_a = V_m \sin \theta \]  

(1)

While \( Q_b \) is ON, current flows through \( L_s, C_o, \) and \( R_{Ld} \). The rising slope of buck inductor is:

\[ \frac{di_{ls}}{dt} = \frac{V_m \sin \theta - V_o}{L_s} \quad \theta_0 \leq \theta \leq \pi - \theta_0 \]  

(2)

where \( \theta_0 = \arcsin \frac{V_{boundary}}{V_m} \).

The maximum value of inductor current is:

\[ i_{ls\_pk} = \frac{V_m \sin \theta - V_o}{L_s} t_{on} \]  

(3)

When, \( Q_b \) is OFF, the path of current is through \( L_s, C_o, R_{Ld}, \) and \( D_{fw} \). The falling time of buck inductor is determined as:

\[ t_{off} = \frac{L_s}{V_o} i_{ls\_pk} \]  

(4)

2. Operation Analysis of BCM Buck PFC Converter

Figure 1 and 2 illustrates the schematic diagram of a BCM buck PFC converter.

![Figure 1. Waveforms for traditional buck converter.](image)

![Figure 2. Schematic diagram of a BCM buck PFC converter.](image)
By substituting the value of $i_{Ls.pk}$ in eq. (4), we get:

$$t_{off} = t_{on} \frac{V_a \sin \theta - V_o}{V_a}$$

(5)

The total time is:

$$t_s = t_{on} + t_{off}$$

(6)

By putting the (5) into (6) results in:

$$t_s = \frac{V_a \sin \theta}{V_o} t_{on}$$

(7)

The formula to calculate the average input current of buck converter ($i_{in.b}$) is:

$$i_{in.b} = \frac{i_{Ls.pk} t_{on}}{2 t_s} = \frac{V_a \left(V_a \sin \theta - V_o\right) t_{on}}{2L V_o \sin \theta} \quad \left(\theta_0 \leq \theta \leq \pi - \theta_0\right)$$

(8)

By Fourier analysis, the harmonics of the input current is calculated as:

$$I_n = \frac{2}{\pi} \int_0^\pi i_{in.b} \sin n \theta d\theta \quad \left(n = 1, 3, 5 \cdots\right)$$

(9)

The average input power can be calculated from (1) and (8) as:

$$P_{in.b} = \frac{1}{\pi} \int_0^\pi V_a t_{on} d\theta = \frac{t_{on}}{2\pi L} \int_{\theta_0}^{\pi-\theta_0} V_a \left(V_a \sin \theta - V_o\right) d\theta$$

(10)

From (10), $t_{on}$ can be determined by assuming the efficiency to be 100% as:

$$t_{on} = \frac{2 \pi P_L}{\int_{\theta_0}^{\pi-\theta_0} V_a \left(V_a \sin \theta - V_o\right) d\theta}$$

(11)

According to (8), (11) and the specification of the buck converter that are mentioned in section 5, the input current waveforms regarding the input voltage at 90VAC is depicted in Figure 3. It can be observed that input current has dead zone. Therefore, its PF will be low.

From (9), the relative harmonic content of the 3rd, 5th, and 7th harmonic along with IEC61000-3-2 class C limit are illustrated in Figure 4, from which it can be observed that input current does not pass the Class C limits.

The input PF of BCM buck converter can be determined as:

$$PF_{COTC} = \frac{P_{in}}{V_m \sqrt{2} I_{rms}}$$

(12)

According to (12), the curve of the input PF with respect to universal input voltage range is drawn, which shows that input PF is low for BCM buck converter. It is low particularly at low input voltage (Figure 5).
3. Operation analysis of BCM buck-flyback converter to improve input PF

Figure 6 illustrates the schematic diagram of a BCM buck-flyback PFC converter.

The operating time period between buck and flyback converter depends on the boundary voltage, whose value is little more as compared to output voltage ($V_o$). The introduced converter operates in flyback mode as the input voltage ($v_i$) is lower than $V_o$ and in buck mode for opposite condition (i.e. $v_i > V_{boundary}$) as shown in Figure 7. Thus, the operating principle of the converter operating in Boundary Conduction Mode (BCM) can be divided into two cases.

The converter is operating in buck mode when $v_i > V_{boundary}$. The buck switch ($Q_b$) keeps switching, while flyback switch ($Q_f$) remains closed. The operation analysis is same as discussed in section 2.

The converter is operating in flyback mode when $v_i < V_{boundary}$. The flyback switch ($Q_f$) keeps switching, while buck switch ($Q_b$) remains closed.

When $Q_f$ is ON, the current flows through primary inductor $L_p$ and the values of inductor's rising slope and peak current are:

$$
\frac{di_{ip}}{dt} = \frac{V_m \sin \theta}{L_p} \quad 0 \leq \theta < \theta_0 \& \pi - \theta_0 \leq \pi
$$

(13)

$$
i_{ip \_pk} = \frac{V_m \sin \theta}{L_p}
$$

(14)

While, $Q_f$ is OFF, $L_s$, $C_o$, $R_{Ld}$, $D_{fw}$ conducts and the falling slope is:

$$
\frac{di_{ip}}{dt} = -\frac{V_o}{L}
$$

(15)

Based on volt–second balance, we can get the resulting equation as:

$$
t_{off} = \sqrt{\frac{L_s V_m \sin \theta}{L_p V_o}} t_{on}
$$

(16)

Figure 6. Schematic diagram of a BCM buck-flyback PFC converter.
From (16) and (6), following relation is obtained.

$$t_s = t_{on} \left(1 + \frac{\sqrt{L_s V_m}}{\sqrt{L_p V_o}} \sin \theta \right)$$

(17)

The input current of flyback converter is:

$$i_{in, f} = \frac{V_m \sin \theta}{2L_p} \left(1 + \frac{\sqrt{L_s V_m}}{\sqrt{L_p V_o}} \sin \theta \right) t_{on}$$

(18)

By combining (8) and (18), the input current of the put forward converter is expressed as:

$$i_{in, f} = \begin{cases} \frac{t_{on} V_m \sin \theta}{2L_p} & (0 \leq \theta < \theta_b) \&(\pi - \theta_b \leq \theta < \pi) \\ \frac{t_{on} V_m (\theta - \theta_b)}{2L_p} & (\theta_b \leq \theta \leq \pi - \theta_b) \end{cases}$$

(19)

The average input power can be calculated from (1) and (19) as:

$$P_{in, f} = \frac{1}{\pi} \int_{\theta_b}^{\pi} V_m \sin \theta \, d\theta + \frac{1}{\pi} \int_{0}^{\pi} V_m \sin \theta \, d\theta + \frac{1}{\pi} \int_{\pi}^{\pi - \theta_b} V_m (\theta - \theta_b) \, d\theta$$

$$= \frac{2\pi P_o}{\pi} \left( \frac{V_m \sin \theta}{2L_p} \left(1 + \frac{\sqrt{L_s V_m}}{\sqrt{L_p V_o}} \sin \theta \right) \right)$$

(20)

From (20), $t_{on}$ can be determined by assuming the efficiency to be 100% as:

$$t_{on} = \frac{2\pi P_o}{\pi} \left( \frac{V_m \sin \theta}{2L_p} \left(1 + \frac{\sqrt{L_s V_m}}{\sqrt{L_p V_o}} \sin \theta \right) \right)$$

(21)

The input PF of the converter can be determined as:

$$PF_{in, f} = \frac{P_{in, f}}{\sqrt{2} I_{rms}}$$

(22)

According to (22), the curve of the input PF with respect to universal input voltage range for $n=1, 2, 3$ and 100 is
drawn, which shows that input PF with \( n=2 \) is more as compared to other turns ratio. Thus \( n=2 \) is finally selected for the converter (Figure 8).

By Fourier analysis, the harmonics of the input current is calculated as:

\[
I_n = \frac{2}{\pi} \int_0^\pi i_{\text{in},n} \sin n\theta d\theta \quad (n = 1, 3, 5, \ldots)
\]  

(23)

From (23), the relative harmonic content of the 3rd, 5th, and 7th harmonic along with IEC class C limits are illustrated in Figure 9, from which it can be observed that input current passes Class C limits very easily in case of the proposed converter.

4. Comparative analysis

The comparative analysis between input PF and contents of input current harmonics between the buck converter and proposed converter is given in Figure 10 and 11 respectively. It can be observed that input PF and contents of input current harmonics are improved in case of proposed converter as compared to traditional converter.

5. Simulation Results

For verifying the effectiveness of proposed topology, simulations are carried out. The input voltage range is 90-264VAC, and the output is 80V. For ensuring the current to be in BCM, L6561 IC is used. All the components in the circuit are selected as idea.

Figure 12 and 13 show the simulation waveforms of \( v_{\text{in}} \), \( i_{\text{in}} \), and \( v_{\text{o}} \) of the buck converter and proposed converter at 110VAC. It can be observed that the buck converter has dead zone as compared to introduced converter. Thus its input PF will be more as compared to traditional converter.
Figure 10. Input PF comparison: (a) buck converter, (b) buck-flyback converter.

Figure 11. Input PF comparison: (a) traditional converter, (b) proposed converter.

Figure 12. $v_{in}$, $i_{in}$, and $v_o$ for buck converter.
Figure 13. $v_{in}$, $i_{in}$, and $v_o$ for buck-flyback converter.

Figure 14. Primary and secondary inductor current.
Figure 14 and 15 shows the inductor current waveform, from which it can be seen that inductor current is in boundary conduction mode.

6. Conclusion

Due to dead zone, input power factor of boundary conduction mode buck converter is low and input current cannot pass the class C limits. Therefore flyback converter is introduced to work with buck converter during dead zone time period to eliminate the dead zone. It can achieve low input current total harmonic distortion and high power factor. Simulation results are presented for the verification of the analysis.

7. References

1. Limits-Limits for harmonic current emissions (Equipment input current ≤ 16 A per Phase), IEC. 2014; 61000:3–2.


