DISCONTINUOUS CONDUCTION MODE BUCK CONVERTER WITH HIGH EFFICIENCY

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ABSTRACT

Electronic devices require AC to DC converter (rectifier) to convert AC voltage from the grid to DC voltage for the electronics and its result is low power factor (PF) and harmonic current injection into the system. Nowadays, power factor correction (PFC) converters are being widely used which can achieve high power factor (PF) and reduce the harmonics caused during AC to DC conversion and buck PFC converter is one of mostly used converter. On the other hand, if this converter works with constant duty-cycle (CDC) control scheme, the overall losses are more and efficiency is less. In order to increase the efficiency of buck converter operating in discontinuous conduction mode (DCM), a variable duty-cycle (VDC) control scheme is proposed. The method of fitting VDC control scheme is given for making implementation of circuit simpler. The performance of buck converter is compared with CDC and VDC control scheme in terms of efficiency. For verifying the validity of proposed technique, the simulation results are carried out. The object of the research paper is to propose the control scheme to achieve high PF for DCM buck converter by only modulating the duty-cycle of buck switch.

KEYWORDS

Variable Duty-Cycle (VDC), Constant Duty-Cycle (CDC), Discontinuous Conduction Mode (DCM), Electromagnetic Interference (EMI), Duty-Cycle, Buck Converter.
1. INTRODUCTION

Electronic devices require AC to DC converter (rectifier) to convert AC voltage from the grid to DC voltage for the electronics and its result is low power factor (PF) and harmonic current injection into the system. Nowadays, power factor correction (PFC) converters are being widely used which can achieve high power factor (PF) and reduce the harmonics caused during AC to DC conversion (Praneeth & Williamson, 2018; Williamson, Rathore & Musavi, 2015; Nussbaumer et al., 2019; Anwar et al., 2017; Al Gabri, Fardoun & Ismail, 2015; Badawy, Sozer & De Abreu-Garcia, 2016; Memon et al., 2019a, 2019b, 2019c, 2019d, 2019e).

Power factor correction can be of two types: active PFC and passive PFC. Active PFC can be achieved by using passive elements like inductors, capacitors and inductors and passive PFC can be achieved by using electronic circuits with active switches like insulated gate bipolar junction transistor (IGBT) and metal oxide semiconductor field effect transistor (MOSFET), etc. To obtain the good value of power factor and meet the standards like IEC61000-3-2 and IEEE 519, active power factor correction (PFC) techniques are used. DC to DC converters used as power factor correction circuits with the help of active switches shape the value of supply current which not only improves the PF, but also reduce the harmonics. Among DC-DC converters, DCM buck PFC is generally utilized in many applications because of various advantages like maintaining high efficiency for the wide range of input voltage, cost reduction, low output voltage, protection against inrush current lifetime improvement and easy design of electromagnetic interference (EMI) filter. The major drawback of the buck converter is its PF is low and efficiency is also low, especially when operated with constant duty-cycle control scheme (CDCCS).

For modifying the performance of traditional buck converter, various research has proposed various topologies and control schemes (Endo, Yamashita & Sugiura, 1992; Lee, Wang & Hui, 1997; Spiazzi & Buso, 2000; Huber, Gang & Jovanovic, 2011; Jang & Jovanović, 2011; Lamar et al., 2012; Ki & Lu, 2013; Al Gabri, Fardoun & Ismail, 2015; Memon et al., 2016; Memon et al., 2017; Memon et al., 2018a, 2018b; Memon et al., 2019a, 2019b, 2019c, 2019d, 2019e; Liu et al., 2020).
Most of the work in the literature is done to improve the PF of the buck converter. The purpose of this paper is to introduce the control scheme which can improve the efficiency of DCM buck converter.

In this paper, a variable duty-cycle control scheme (VDCCS) is introduced for DCM buck converter to reduce peak and rms current of inductor and hence ultimately enhancing its efficiency.

This paper is divided into six sections. In section 2, the operation states of DCM buck converter are analyzed with traditional CDCCS strategy. The introduced VDCCS is discussed in section 3. Then the comparative analysis is discussed in section 4 in terms of efficiency. In section 5, the effectiveness of proposed topology is evaluated by simulation results. Finally, some conclusions are drawn in section 6.

2. RESEARCH METHODOLOGY

The research methodology is based on:

1. Mathematical analysis of the operating principle of the control schemes for DCM Buck converter with the help of MATHCAD converter.
2. Introducing the proposed control scheme to obtain high efficiency
3. Realization of control scheme through control blocks.
4. Comparative analysis of the converter for CDCC and VDCC strategy
5. Developing the simulation model of DCM Buck converter with the help of MATLAB software
6. Confirming the results.

3. CONVENTIONAL CDC CONTROL SCHEME FOR BUCK CONVERTER

Figure 1(b) shows the main circuit of a buck converter with CDC control scheme.

The input voltage before and after the bridge are given as
Where $V_{rms}$ is the rms value.

There are three switching cycles when buck converter works in discontinuous conduction mode (DCM).

When $Q_b$ conducts, the inductor is getting charge from supply voltage in first switching cycle as depicted in Figure 2.

The peak current of inductor $i_{L_{pk}}$ is given as

$$i_{L_{pk}} = \frac{\sqrt{2} V_{rms} \sin \theta - V_o}{D_{on} T_s}$$  \hspace{1cm} (2)

Where $D_{on}$ is the duty-cycle of during turn on time of switch

When $Q_b$ is off, inductor is discharging through load and output capacitor, as shown in in Figure 3. It occurs in second switching cycle
Figure 3. Buck converter during second switching cycle.  
**Source:** (Yao *et al.*, 2017).

The peak current of inductor $i_{L, pk}$ is

$$i_{L, pk} = \frac{V_o}{L_s} D_{on} T_s \tag{3}$$

By using the information of volt-second balance, following expression is obtained

$$(\sqrt{2}V_{rms} \sin \theta - V_o)D_{on} T_s = V_o D_{off} T_s \tag{4}$$

From (2) and (4), the following relation is obtained

$$D_{off} = \frac{\sqrt{2}V_{rms} \sin \theta - V_o}{V_o} D_{on} \tag{5}$$

During third switching cycle, output capacitor is discharged through load as shown in Figure 4.

Figure 4. Buck converter during third switching cycle.  
**Source:** (Yao *et al.*, 2017).

The value of average input current for buck converter is got as

$$i_{\text{ave, in}} = \frac{D_{on}^2 (\sqrt{2}V_{rms} \sin \theta - V_o)}{2L_s f_s} \tag{6}$$

For complete half cycle, input current is expressed as
Based on (1) and (7), the input power of the buck converter is expressed as

\[ P_{in \_vdcx} = \frac{\sqrt{2} V_{m} D_{in}^{2}}{2 \pi L_{s} f_{s}} \int_{\theta_{0}}^{\pi - \theta_{0}} \sin \theta (\sqrt{2} V_{m} \sin \theta - V_{o}) d\theta \]  

(8)

Now \( D_{in} \) can be calculated by assuming the efficiency of buck converter as 100%.

\[ D_{in} = \frac{2 \pi L_{s} f_{s} P_{o} \sqrt{2 V_{m} V_{o} \sin \theta - V_{o}}} {\sqrt{2 V_{m} \int_{\theta_{0}}^{\pi - \theta_{0}} \sin \theta (\sqrt{2} V_{m} \sin \theta - V_{o}) d\theta}} \]  

(9)

4. PROPOSED VDC CONTROL SCHEME FOR BUCK CONVERTER FOR EFFICIENCY IMPROVEMENT

4.1. VDC CONTROL SCHEME FOR EFFICIENCY IMPROVEMENT

For obtaining, high efficiency, the variation rule for duty-cycle must be

\[ D_{om \_vdcx} = \sqrt{\frac{D_{in} V_{m} \sin \theta}{\sqrt{2 V_{m} \sin \theta - V_{o}}}} \]  

(10)

Where Dc is a co-efficient,

By substituting the value of \( D_{om} \) in (6), we obtain

\[ i_{in \_b \_vdcx} = \frac{\sqrt{2} V_{m} \sin \theta D_{in} T_{s}}{2 L_{s}} \]  

(11)

The average value of input power with VDC control scheme is expressed as

\[ P_{in \_b \_vdcx} = \frac{1}{\pi} \int_{\theta_{0}}^{\pi - \theta_{0}} D_{in} T_{s} \left(\sqrt{2} V_{m} \sin \theta\right)^{2} d\theta = P_{o} \]  

(12)

The value of \( D_{c} \) is got from (12) as

\[ D_{c} = \frac{4 \pi L_{s} P_{o}}{(\sqrt{2} V_{m})^{2} (\pi - 2 \theta_{0} + \sin 2 \theta_{0}) T_{s}} \]  

(13)

By substituting the value of \( D_{c} \) in (11), we get

\[ D_{om \_vdcx} = \sqrt{\frac{4 \pi P_{o} L_{s} \sin \theta}{(\pi - 2 \theta_{0} + \sin 2 \theta_{0}) (\sqrt{2} V_{m} \sin \theta - V_{o}) \sqrt{2} V_{m}} T_{s}} \]  

(14)
4.2. FITTING VDC CONTROL SCHEME

For the implementation of Don_vdccs, it is essential to remove square root term from (14). Because it is difficult to realize to it by using analogue circuits.

Defining $a = \frac{V_m}{V_o}$, $y = \sin \theta$, eq. (14) can be simplified as

$$D_{on, fit} = D_l \left(1 - \frac{y}{2ay_0^2 - y_0}\right)$$

where

$$D_l = \frac{D_0 ay_0}{\sqrt{ay_0 - 1} \left(2(ay_0 - 1)\right)}.$$

$y_0 = 0.75$

Eq. 15 can be rewritten as

$$D_{on, fit} = D_l \frac{1.125V_m - 0.75V_o - V_o \sin \theta}{1.125V_m - 0.75V_o}$$

The average input current with VDCCS is given as

$$i_{a, VDCCS} = \frac{(\sqrt{2} \cdot \frac{V_m \sin \theta - V_o}{2L_1 f_s}) D_{on, fit}^2}{V_{FD} I_{in, avg}(vdccs)}$$

5. EFFICIENCY COMPARISON

5.1. LOSS DUE TO BRIDGE DIODE RECTIFIER

The loss caused by bridge diode rectifier is calculated as below

$$P_{con, bridge(vdcs)} = 2V_{FD} I_{in, avg}(vdccs)$$

KBL10 is adopted as the rectifier bridge, whose forward voltage drop VFD is 0.9 V.

The input current with CDC control scheme and VDC control scheme is given as

$$i_{a, SDCS} = \frac{2\pi L_1 f_s P_o \left(\sqrt{2} \cdot \frac{V_m \sin \theta - V_o}{V_m \sin \theta - V_o}\right)}{2\sqrt{2} L_1 f_s V_m \int_{\theta_0}^{\pi - \theta_0} \sin \theta (\sqrt{2} \cdot \frac{V_m \sin \theta - V_o}) d\theta}$$
5.2. CONDUCTION LOSSES OF THE SWITCHES

The rms current of the on time period, i.e., the rms current of switch $Q_b$ can be got as

$$I_{\text{rms}(Q_b\text{-on})} = \sqrt{\frac{\int_{\theta_0}^{\pi-\theta_0} i_{r-pk}^2 D_{\text{on}} \, d\theta}{3\pi}}$$

(20)

The rms current of the off time period can be determined as

$$I_{\text{rms}(Q_b\text{-off})} = \sqrt{\frac{\int_{\theta_0}^{\pi-\theta_0} i_{r-pk}^2 D_{\text{off}} \, d\theta}{3\pi}}$$

(21)

While $Q_b$ is on and off, the current flows through the winding of the inductor, whose rms current is

$$I_{\text{rms}(\text{adccs})} = \sqrt{I_{\text{rms}(Q_b\text{-on\_adccs})}^2 + I_{\text{rms}(Q_b\text{-off\_adccs})}^2}$$

(22(a))

$$I_{\text{rms}(\text{vadccs})} = \sqrt{I_{\text{rms}(Q_b\text{-on\_vadccs})}^2 + I_{\text{rms}(Q_b\text{-off\_vadccs})}^2}$$

(22(b))

The losses due to conduction of switches can be got as

$$P_{\text{con\_switches\(adccs\)}} = I_{\text{rms}(Q_b\text{-on\_adccs})}^2 R_{DS(\text{on\_S})}$$

(23(a))

$$P_{\text{con\_switches\(vadccs\)}} = I_{\text{rms}(Q_b\text{-on\_vadccs})}^2 R_{DS(\text{on\_S})}$$

(23(b))

The value of $R_{DS(\text{On})}$ 0.19 Ω which is found from datasheet of 20N60C3.

5.3. LOSSES DUE TURN OFF SWITCHES

The loss caused by turning off the switch with CDC control scheme and VDC control scheme is calculated as

$$P_{\text{off\_switches\(adccs\)}} = \frac{T_i}{2\pi} \int_0^{\pi} i_{r-pk\_adccs} (V_m \sin \theta) \, d\theta$$

(24(a))
\[ P_{\text{off-switches}(v)} = \frac{T_s t_f}{2\pi} \int_0^\pi i_{L_{pk-v}} (V_m \sin \theta) \, d\theta \]  

(24(b))

Where \( t_f \) value is 12ns for CMOS 20N60C.

5.4. THE LOSS CAUSED BY COPPER OF THE INDUCTOR

The inductor’s copper loss with CDCCS and VDCCS can be found below as

\[ P_{\text{copper}(v)} = I_{\text{rms}(v)}^2 R_{\text{copper}(f)} + I_{\text{rms}(v)}^2 R_{\text{copper}(Hf)} \]  

(25(a))

\[ P_{\text{copper}(v)} = I_{\text{rms}(v)}^2 R_{\text{copper}(f)} + I_{\text{rms}(v)}^2 R_{\text{copper}(Hf)} \]  

(25(b))

Where \( R_{\text{copper}(f)} \) is 0.16 and \( R_{\text{copper}(Hf)} \) is 0.23.

The low frequency and high frequency of rms current can be found out by using below formula

\[ I_{\text{rms-f}} = \sqrt{\frac{1}{\pi} \int_0^\pi i_{L_{ave}}^2 d\theta} = \sqrt{\frac{1}{\pi} \int_0^\pi \left[ \frac{D^2 T_s v_g (v_g - V_o)}{2L_o V_o} \right]^2 d\theta} \]  

(26(a))

\[ i_{\text{rms-f}} = \sqrt{I_s \int_0^{T_s} (i_L(t) - i_{L_{ave}})^2 dt} \]  

(26(b))

\[ I_{\text{rms-Hf}} = \sqrt{\frac{1}{\pi} \int_0^\pi i_{\text{rms-Hf}}^2 d\theta} \]  

(26(c))

5.5. LOSS DUE TO CORE OF THE INDUCTOR

The loss caused by core of inductor with CDCCS and VDCCS is calculated as

\[ P_{\text{core}(v)} = \left[ \int_0^\pi C_m f_s(v) x B_{ac(v)} (ct_0 - ct_a T_a - ct_2 T_a^2) d\theta \right] \frac{10^3 V_e}{\pi} \]  

(27(a))

\[ B_{ac(v)} = \frac{L_{iL_{pk-v}}}{2NA_v} \]  

(27(b))
The value of core parameters can be found from [24].

5.6. THE LOSS DUE TO CONDUCTION OF THE FREEWHEELING DIODE

The conduction loss due to freewheeling diode with CDC and VDC control scheme is

\[
P_{\text{con\_freewheelingdiode}} = \frac{V_{FD_{dc}}}{\pi} \int_{0}^{\pi} \frac{i_{pk(\text{dc LCS})}}{2} D_{\text{off}} \, d\theta \tag{28(a)}
\]

\[
P_{\text{con\_freewheelingdiode}} = \frac{V_{FD_{dc}}}{\pi} \int_{0}^{\pi} \frac{i_{pk(\text{dc LCS})}}{2} D_{\text{off}} \, d\theta \tag{28(b)}
\]

The value of VFD is 0.67 for MUR 860 diode.

5.7. THE EFFICIENCY COMPARISON

The efficiency of DCM buck converter with CDC and VDC control scheme can be calculated as

\[
\eta_{(\text{dc LCS})} = \frac{P_{o}}{P_{o} + P_{\text{con\_bridge(\text{dc LCS})}} + P_{\text{con\_switcher(\text{dc LCS})}} + P_{\text{off\_switches(\text{dc LCS})}}} + P_{\text{copper(\text{dc LCS})}} + P_{\text{core(\text{dc LCS})}} + P_{\text{con\_freewheelingdiode(\text{dc LCS})}} \tag{29(a)}
\]

\[
\eta_{(\text{dc LCS})} = \frac{P_{o}}{P_{o} + P_{\text{con\_bridge(\text{dc LCS})}} + P_{\text{con\_switcher(\text{dc LCS})}} + P_{\text{off\_switches(\text{dc LCS})}}} + P_{\text{copper(\text{dc LCS})}} + P_{\text{core(\text{dc LCS})}} + P_{\text{con\_freewheelingdiode(\text{dc LCS})}} \tag{29(b)}
\]

From above equations and parameters of converter, the theoretical efficiency of converter with CDC and VDC control scheme is calculated and compared as shown in Figure 5. It can be concluded that efficiency of DCM buck converter has improved in case of VDC control scheme.
6. SIMULATION RESULTS

For verifying the effectiveness of VDCCS strategy, simulations are carried out. The input voltage range is 90-264VAC, and the output is 80V. For ensuring the current to be in DCM, UC3525A IC is used. All the components in the circuit are selected as idea.

Figure 6 and Figure 7 show the simulation waveforms of input voltage, input current and output voltage of DCM buck converter with CDCCS and VDCCS at 220VAC inputs, respectively. It can be seen that the input current with VDCCS has less peaks as compared to input current with CDCCS is more sinusoidal as compared with CDCC.
7. CONCLUSIONS

Electronic devices require AC to DC converter (rectifier) to convert AC voltage from the grid to DC voltage for the electronics and its result is low power factor (PF) and harmonic current injection into the system. Nowadays, power factor correction (PFC) converters are being widely used which can achieve high power factor (PF) and reduce the harmonics caused during AC to DC conversion and discontinuous conduction mode (DCM) buck PFC converter is one of mostly used converter. The DCM buck converter is generally utilized in many applications because of various advantages like maintaining high efficiency for the wide range of input voltage, cost reduction, low output voltage, protection against inrush current and life time improvement. However, its efficiency is low when operated with constant duty-cycle control scheme. For increasing the efficiency and ultimately reducing the losses of the DCM buck converter, a variable duty-cycle control scheme has been introduced. Fitting duty-cycle method is also discussed to make circuit implementation easier. For verifying the validity of proposed technique, the simulation results are carried out.

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