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A High Power Factor Rectifier Based on Buck Converter Operating in Discontinuous Inductor Current Mode*

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ABSTRACT

By adding a suitable LC filter to the input of a Buck converter, a high-power-factor buck converter is proposed. The converter can operate in the discontinuous-output-current mode operation. A Buck converter in this operation mode features simple control as the constant duty cycle PWM used. The operation condition of the converter is studied. The validity of analysis is verified by Simulation and Experimental results.

Keywords: Discontinuous-output-current; Buck Converter; Power Factor Correction

1. Introduction

Intensive research has been carried out to improve the power factor of AC/DC converters [1]-[4]. Among the research, it has been reported that by adding a suitable LC filter to the input of a Buck converter to make the converter operate as power factor correction circuit [5] [6]. An example of the converter is presented in Fig. 1. The input capacitor C_1 usually has a low enough value and the voltage across it can be discontinuous. Then a high-power-factor can be obtained by a simple constant duty ratio PWM control. However, the voltage stress across switch(S in **Figure 1**) and diode (D in **Figure 1**) imposes major restrictions as the peak value of V_{c1} is very high when V_{c1} becomes zero for part of the switching cycle. In this paper, the Buck converter with LC input filter operates in a “discontinuous-output-current” mode. The current of output inductor (L_2 in **Figure 1**) falls to zero for part of the switching cycle and the voltage of the input capacitor (C_1) becomes continuous. Thus, the peak value of V_{c1} is reduced substantially and switch voltage stress will be no longer a restriction. Besides the reverse recovery loss of the freewheeling diode (D) is reduced.

The goal of this paper is to give a more comprehensive analysis of Buck converter with the LC input filter operating in DICM. In section 2 of this paper, the principle of DICM is analyzed. Based on the analysis, the characteristics of the converter and the conditions for power factor

correction are studied in section 3. In section 4, the simulation and experimental verifications are given.

2. Operation Principles of DICM

2.1. Operation with Constant Input

As shown in **Figure 1**, if C_1 has large enough value, it will operate in CCVM and the voltage across C_1 can be considered constant during one switching cycle. L_1 has large value so that the input current I_i can be considered as constant. Inductor L_2 has low enough value and operates in DICM. With these assumptions, the converter is the same as the Buck DC/DC converter operating in DCM and the characteristic waveform are presented in **Figure 2**. The operation over one switch cycle is as follows:

1) $0 < t < DT_s$: at $t = 0$, S is turned on. The current through C_1 is $I_i - I_o$. L_2 is charging under constant voltage ($V_i - V_o$). The current through L_2 increases linearly from zero. Accordingly, the current through C_1 decreases linearly. When $I_2 < I_i$, i_{c1} is positive, C_1 is charging. And when $I_2 > I_i$, i_{c1} is turned to negative, C_1 is discharging.

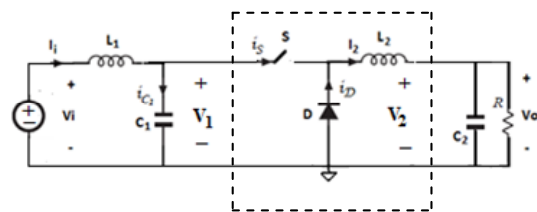


Figure 1. Buck AC/DC converter with LC input filter.

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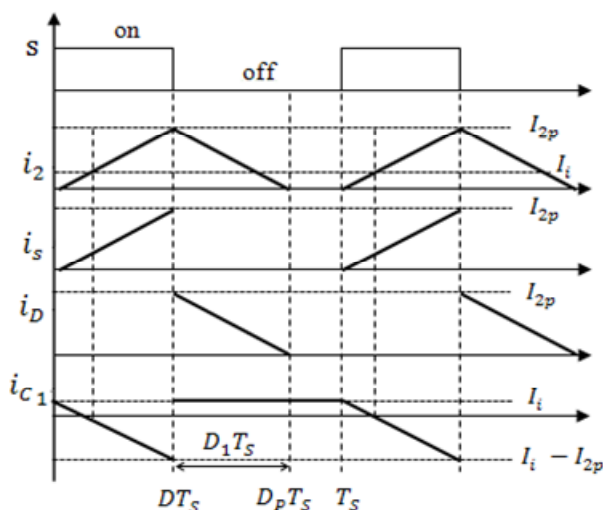


Figure 2. Waveforms for buck converter in DICM.

2) $DT_s < t < D_pT_s$: at $t = DT_s$, S is turned off. D starts to conduct. L_2 is discharging under output voltage. The current through L_2 decreases to zero. C_1 is charging with input current.

3) $D_pT_s < t < T_s$: the current through L_2 maintains zero. The output is supported by C_2 . C_1 is still charging by the input current.

The average voltage across inductor L_1 , over one switch cycle, is zero in stationary state. Therefore, the average voltage across capacitor C_1 is equal to the input voltage. As C_1 is large enough the changes of voltage across it during a switch cycle can be disregarded. Thus, the instantaneous voltage across C_1 can be considered the same as the average voltage across it. As a result, the voltage across C_1 is the input voltage.

Based on the analysis above, the maximum current through L_2 is,

$$I_{2p} = \frac{(V_i - V_o)DT_s}{L_2} \tag{1}$$

The average current through capacitor C_1 , over one switching cycle, is zero in steady state. The input current equals to the average switch current I_s over one switch cycle.

$$I_i = \frac{I_{2p}}{2} D \tag{2}$$

Substitution of (1) into (2) gives

$$I_i = \frac{(V_i - V_o)D^2T_s}{2L_2} \tag{3}$$

The conversion ratio can be defined as $k = \frac{V_o}{V_i}$

Then an equivalent input resistance R_i as the ratio between input voltage and input current is obtained,

$$R_i = \frac{2L_2}{(1-k)D^2T_s} \tag{4}$$

The equivalent input resistance R_i is proportional to L_2 and inversely proportional to switching cycle T_s and duty ratio D .

2.2. Operation with Sinusoid Input

The input voltage of the off-line Buck AC/DC converter is a rectified sinusoid voltage.

$$v_i(t) = V_p |\sin w_i t| \tag{5}$$

where $w_i = 2\pi/T_i$ and T_i is the input cycle.

The switching cycle T_s is usually much smaller than the input cycle T_i . Thus, the input voltage can be considered constant over one switching cycle. Thus, the analysis of the converter with rectified sinusoid input over one switching cycle is the same as the converter with constant input. Simply substitution of (5) into (3), the input current is then

$$i_i(t) = \frac{(V_p |\sin w_i t| - V_o)D^2T_s}{2L_2} \tag{6}$$

If $V_p |\sin w_i t| \gg V_o$, the input current can be simplified as,

$$i_i(t) = \frac{V_p |\sin w_i t| D^2T_s}{2L_2} \tag{7}$$

Thus, the input current is proportional to the input voltage when the duty ratio is constant.

Buck converter operates only when the input voltage is higher than the output voltage. Therefore, (6) is valid only for $V_i |\sin w_i t| > V_o$. When the input rectified voltage equals to the output voltage,

$$t_1 = \frac{1}{w_i} \arcsin \frac{V_o}{V_i} = \frac{1}{w_i} \arcsin \alpha \tag{8}$$

$\alpha = \frac{V_o}{V_p}$. Thus, over half input line cycle, operation is possible only for $t \in (t_1, \frac{T_i}{2} - t_1)$ as shown in Figure 3. As

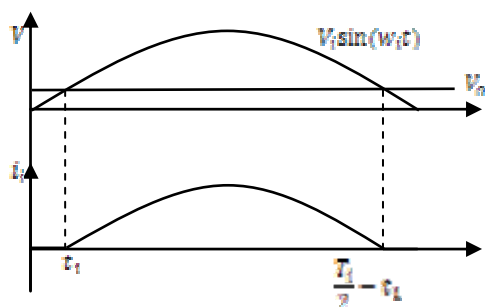


Figure 3. Operation waveforms during half input cycle.

shown in **Figure 3**, the input current is zero outside the Interval $(t_1, \frac{T_i}{2} - t_1)$. This introduces the crossover distortion in the input current. However, the distortion can be accepted if the output voltage is much lower than the peak input voltage.

3. DICM Operation Boundary

The average voltage across inductor L_2 is zero over a switching cycle in steady state. Thus, according to **Figure 2**,

$$(V_i - V_o)D = V_o(D_p - D) \tag{9}$$

Then the conversion ratio can be obtained as,

$$\frac{V_o}{V_i} = \frac{D}{D_p} \tag{10}$$

As depicted in **Figure 2**, for Buck converter under DICM $D_p < 1$. Thus $(V_o/V_i) > D$. The conversion ratio has to be larger than duty cycle D to maintain the converter operates under DICM. This restriction is also valid for rectified input voltage. Therefore, with rectified input voltage, the conversion ratio is,

$$\frac{V_o}{V_p |\sin w_i t|} > D \tag{11}$$

Then,

$$|\sin w_i t| < \frac{\alpha}{D} \tag{12}$$

As the maximum value of sinusoid waveform is 1, α/D must be larger than 1 to maintain the converter operates under DICM. When α/D smaller than 1, thus for

$$t \in (t_2, \frac{T_i}{2} - t_2) \tag{13}$$

where,

$$t_2 = \frac{1}{w_i} \arcsin \frac{\alpha}{D} \tag{14}$$

the converter operates in DCVM [6].

A summarization can be given So far for the operation of the converter. The converter will operate in DICM during the entire input cycle (half-line cycle) when $\alpha/D > 1$.

If $\alpha/D < 1$, the converter will operate in DCVM for $t \in (t_2, \frac{T_i}{2} - t_2)$ where $t_2 > t_1$ t_1 is given by (8). During the

intervals $(t_1, t_2) \cup (\frac{T_i}{2} - t_2, \frac{T_i}{2} - t_1)$, the converter operates in DICM. Thus, when $\alpha/D < 1$, the operation of the converter switches between DICM and DCVM. These

intervals are presented in **Figure 4**.

The conversion ratio α can be obtained as a function of duty ratio D from the energy balance over half input cycle. The input energy can be calculated as,

$$W_i = \int_{t_1}^{\frac{T_i}{2} - t_1} v_i i_i dt \tag{15}$$

Substitution of (5), (6), (8) into (15), the input energy is obtained as,

$$W_i = \frac{V_i^2 D^2 T_i T_s}{8L_2} (1 - \frac{2}{\pi} \arcsin \alpha - \frac{2\alpha\sqrt{1-\alpha^2}}{\pi}) \tag{16}$$

The output energy over half input cycle is

$$W_o = \frac{T_i V_o^2}{2 R} \tag{17}$$

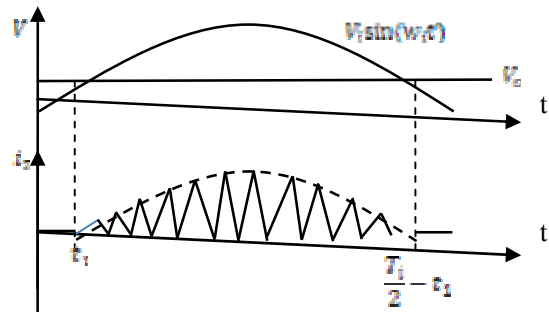
R is load in **Figure 1**. With consideration of efficiency η , the energy balance is,

$$W_o = \eta W_i \tag{18}$$

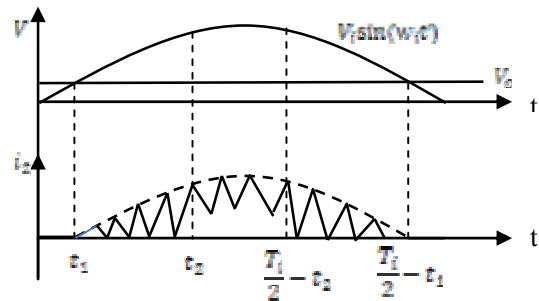
Substitution of (16) and (17) into (18), a quadratic equation of α can be obtained as,

$$\alpha^2 \frac{2k_1}{D^2} - \eta(1 - \frac{2}{\pi} \arcsin \alpha - \frac{2\alpha\sqrt{1-\alpha^2}}{\pi}) = 0 \tag{19}$$

where $k_1 = \frac{2L_2}{RT_s}$.



(a) $\alpha/D > 1$, DICM



(b) $\alpha/D < 1$, switching between DICM and DCVM

Figure 4. Operation modes with different α/D .

Matlab can be used to solve (19) and to plot the conversion ratio α as a function of duty ratio D with different parameters k_1 . The plot is depicted in **Figure 5**. The efficiency η is assumed to be 0.8. The results in **Figure 5** show the boundary $\alpha/D=1$. When the parts of the curves lie in the area above the boundary, it means $\alpha/D < 1$ and the converter operates in DICM. When the remainders of the curves are under the boundary, it means that the converter operates between DICM and DCVM. When k_1 is smaller, the more parts of the curves are above the boundary. As k_1 is proportional to the L_2 , it is in accordance with our sense that the smaller L_2 operates in DCM more possibly with constant duty cycle.

4. Results

4.1. Simulations

Simulations were carried out by Psim to verify the discontinuous inductor current operation of the circuit. The components used are: $L_1 = 500\mu$, $L_2 = 20\mu$, $C_1 = 220n$, $C_2 = 2000\mu$ $D = 0.1$, $R = 13$. The input voltage is

220VAC and the output voltage is 36V. According to the parameters, $\alpha/D > 1$. The converter will operate in DICM during the entire half-line cycle base on the analysis in section 3. The simulation results verify the theoretical analysis and show that input current will follow the input voltage automatically when Buck converter with an input LC filter operates in DICM with a constant the duty cycle.

4.2. Experiments

An experiment circuit was also built and the parameters and the components used is the same as the simulations. The control chip was UC3854AN. The experimental results are in accordance with the simulations. The input power is 125w and the output power is 100w. The efficiency is about 80%. The power factor is 0.98.

Figures 6 to 15 verify the boundary condition of the converter operating in DICM. The experiments also prove that the duty cycle D can be a simple constant value to gain a high power factor when the converter operating in DICM.

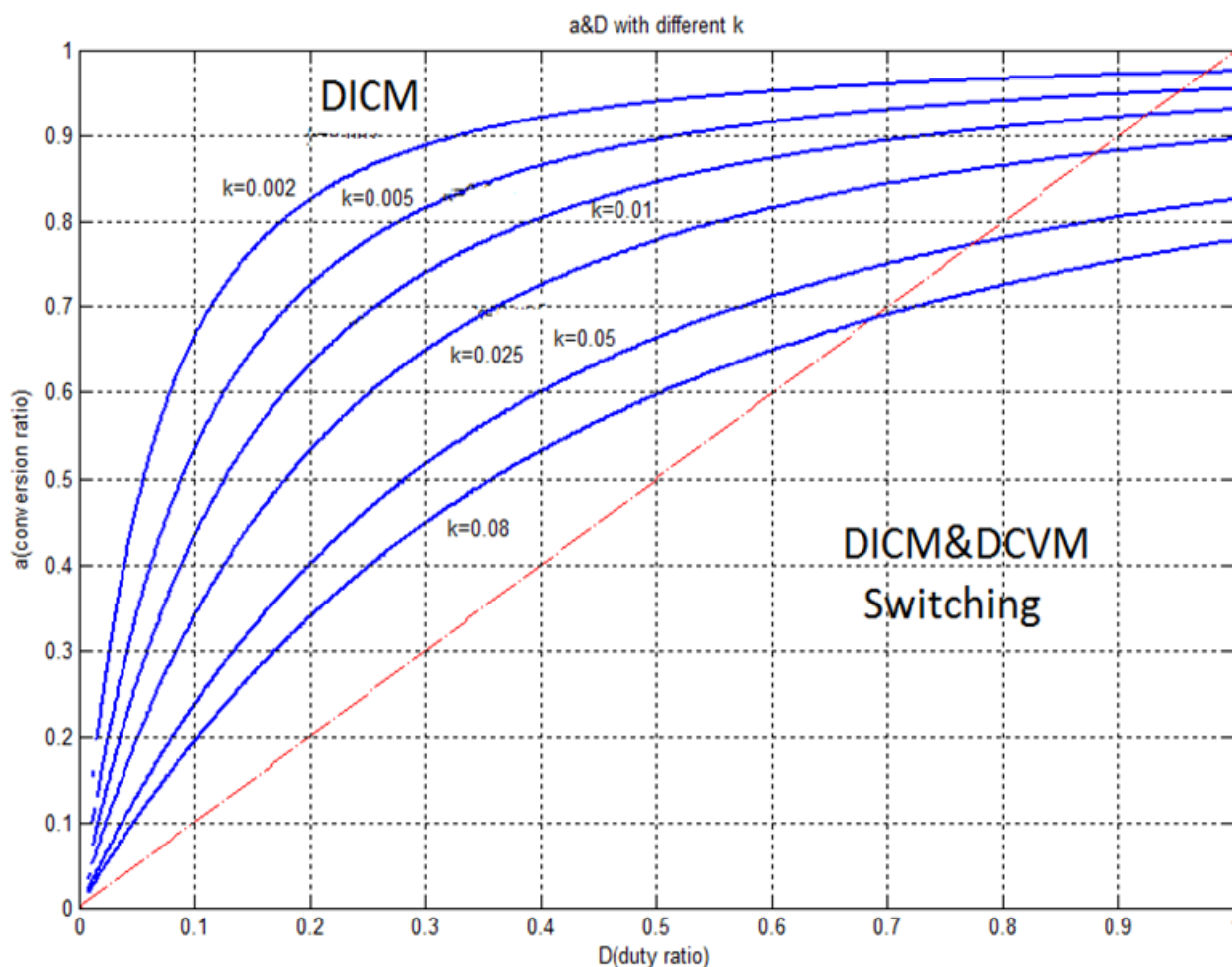


Figure 5. Conversion ratio α with different duty ratio D and k_1 from (19).

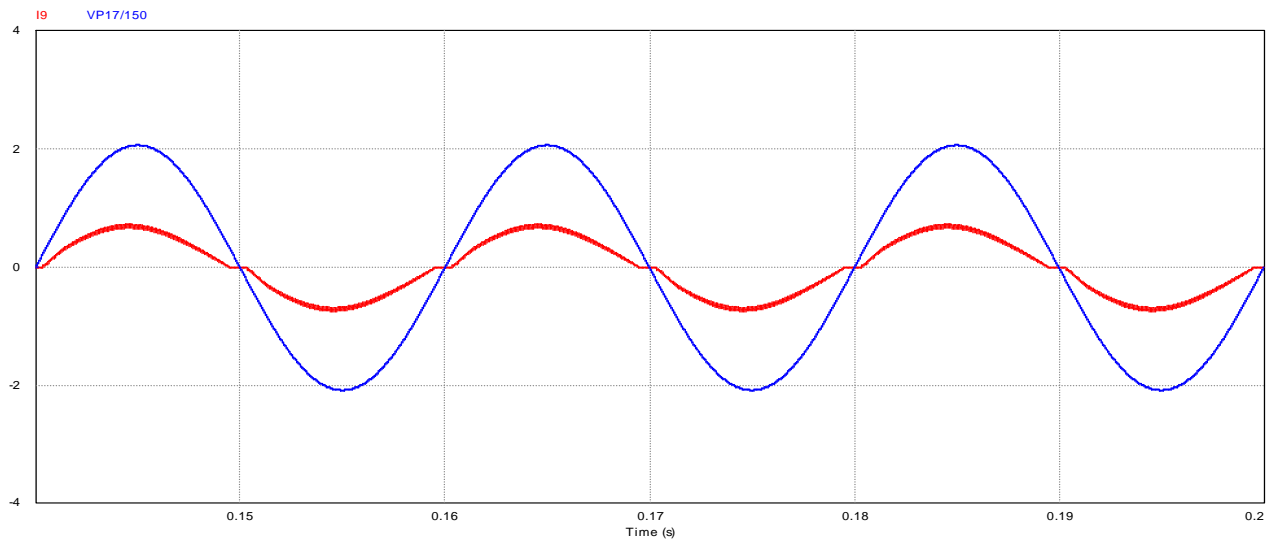


Figure 6. Input voltage and input current (220Vac; 0.52A).

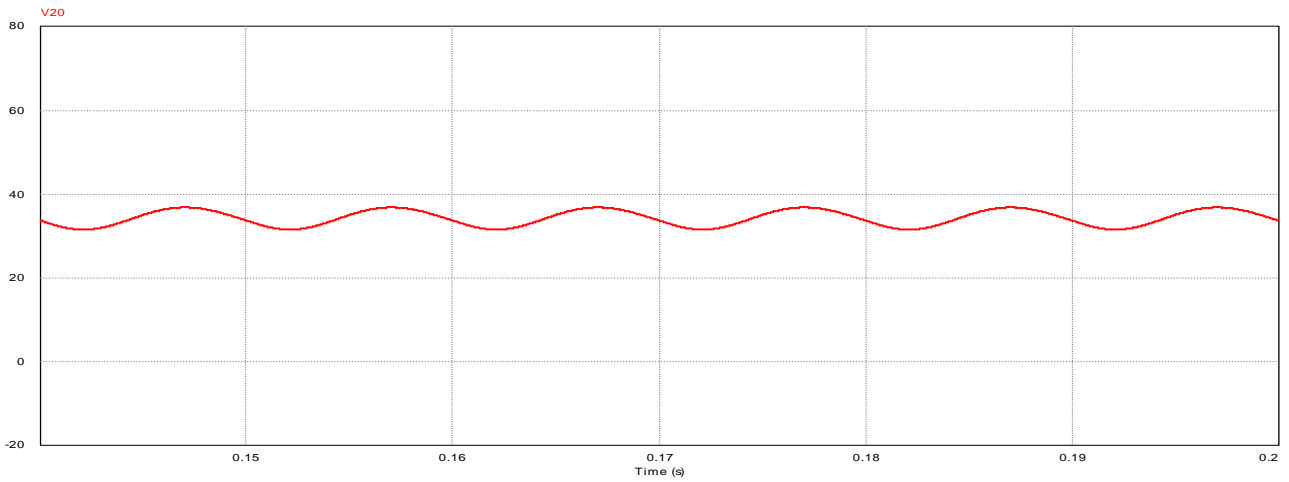


Figure 7. Output voltage: 36v (ripple: 5v).

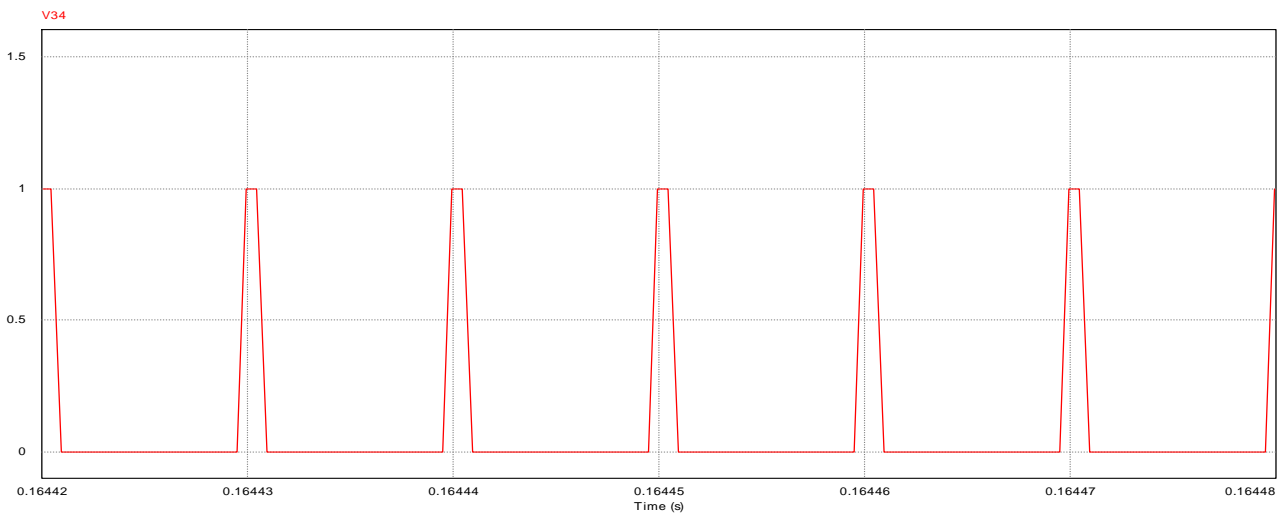


Figure 8. Constant duty cycle (0.15).

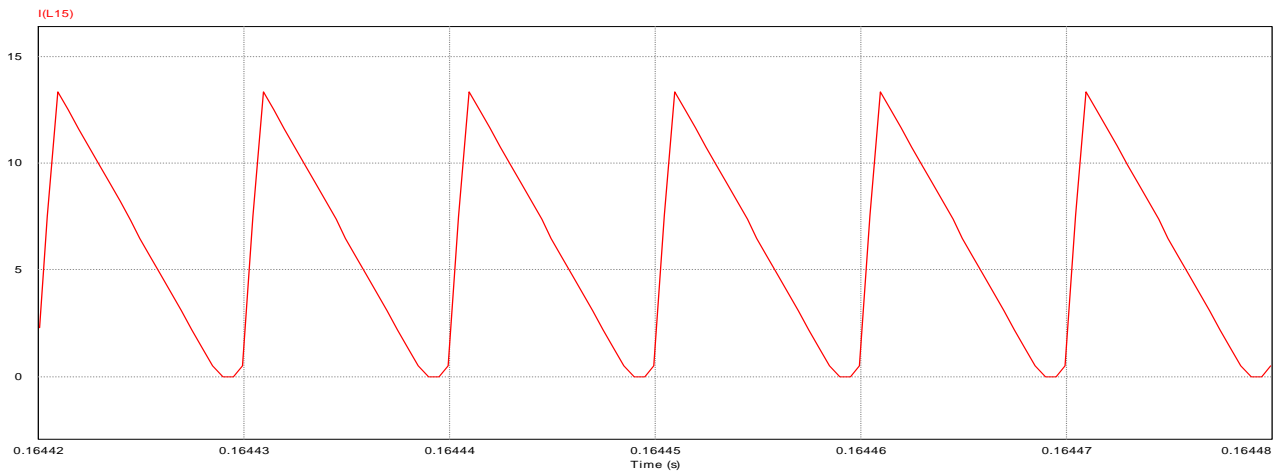


Figure 9. Output inductor current (L2 in Figure 1: DCM).

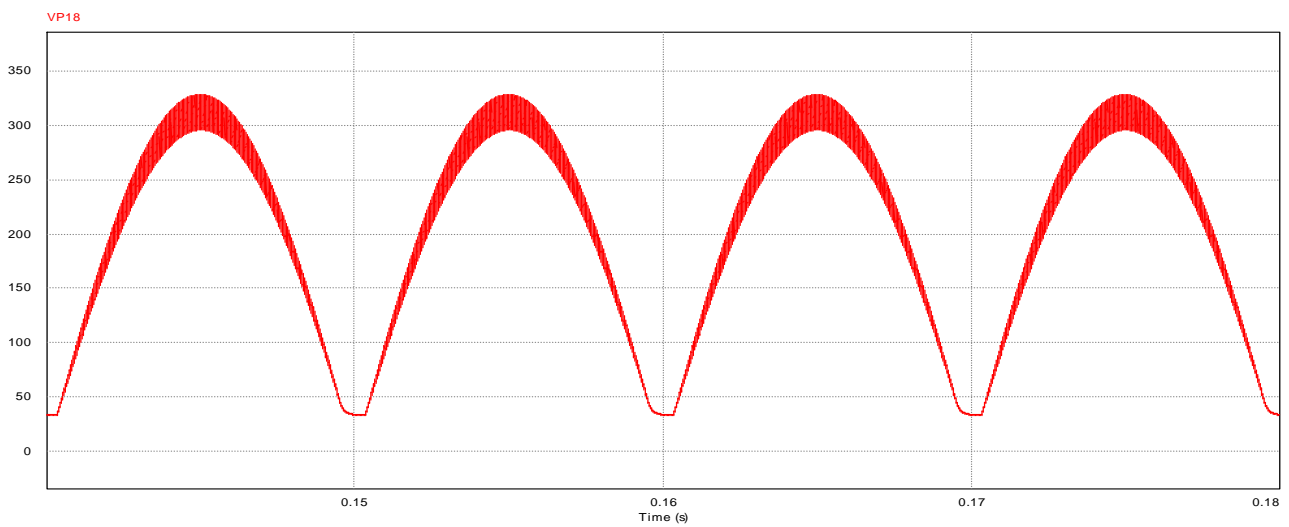


Figure 10. Input capacitor voltage (C1 in Figure 1: CCM).

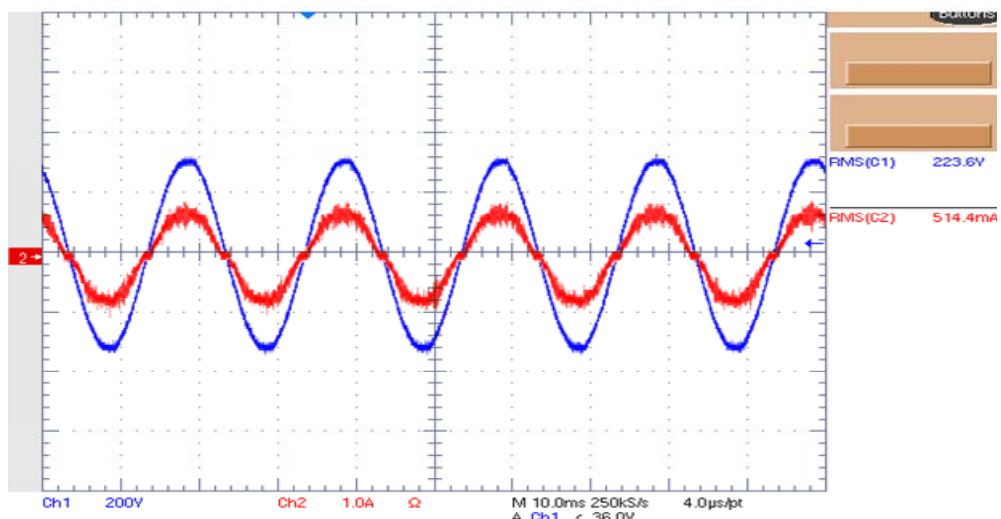


Figure 11. Input Voltage: 220vac Input Current: 0.54mA).

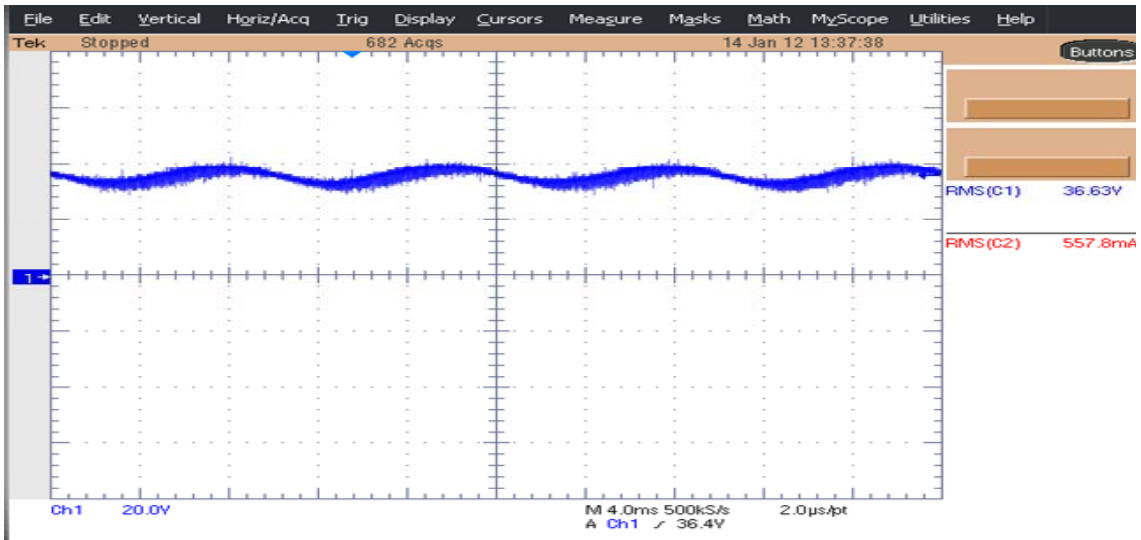


Figure 12. Output voltage: 36VDC (ripple: 5v).

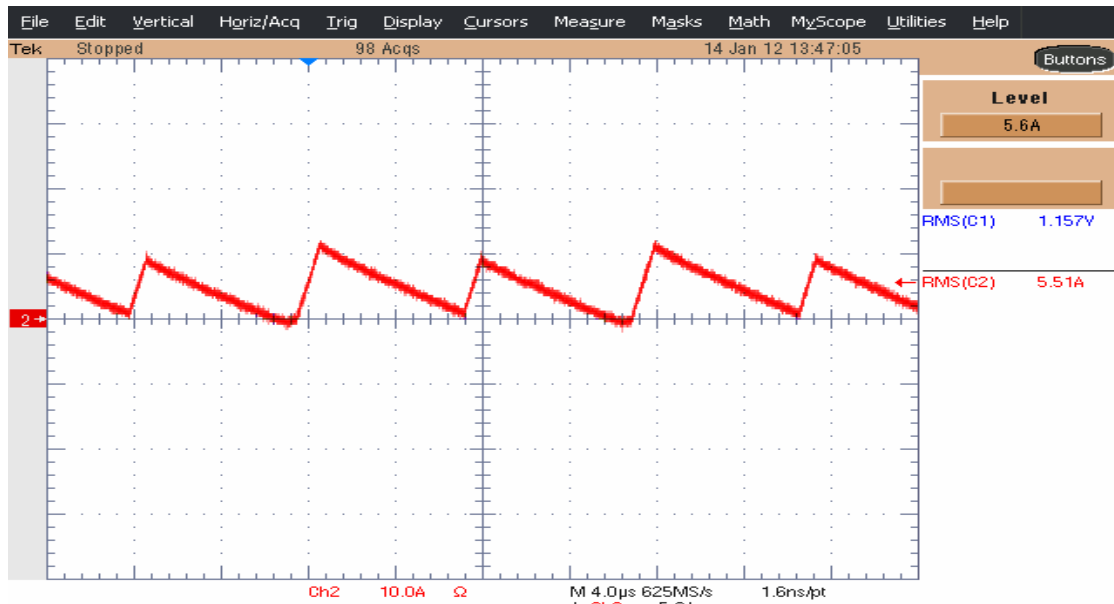


Figure 13. Output inductor current (L2 in Figure 1) DCM.

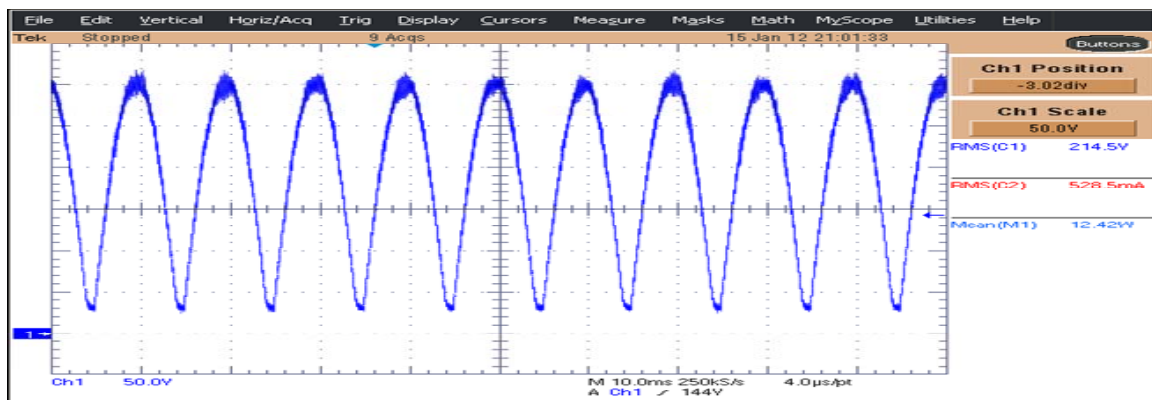


Figure 14. Input capacitor voltage (C1 in Figure 1) CCM.

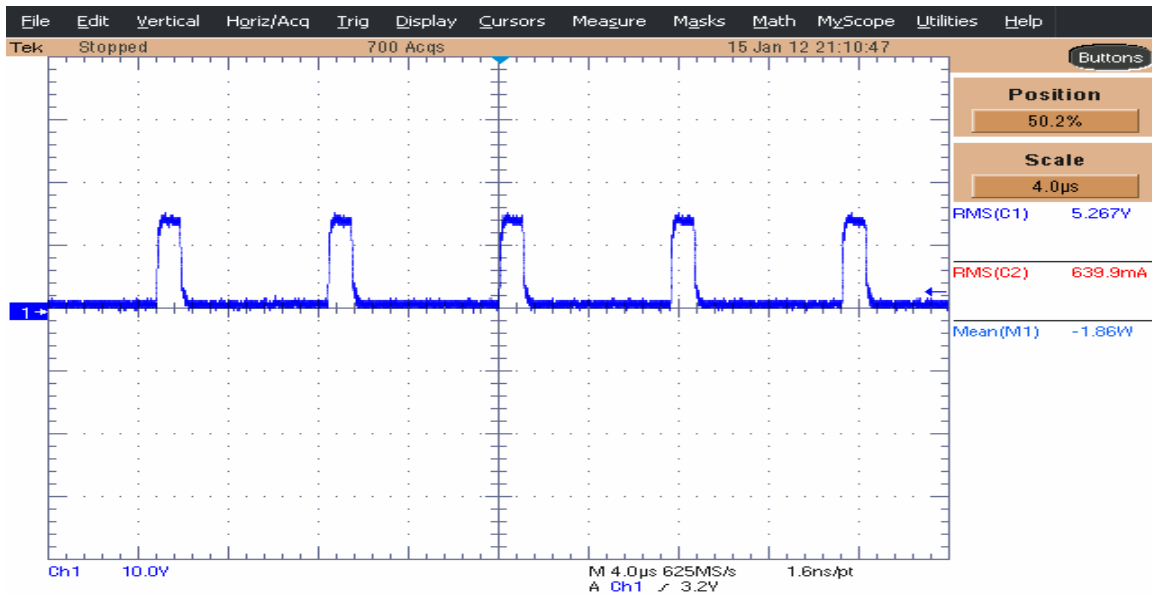


Figure 15. Constant duty cycle (0.15).

5. Conclusions

The Buck converter with LC input filter operating in DICM can gain a high power factor when the duty ratio maintain constant. Composed to the BOOST PFC converter, the Buck PFC converter can obtain an output voltage lower than the peak of the input voltage, which is suitable for the low DC voltage application. The detailed analysis presented in the paper suggested that the Buck converter may switch between DICM and DVCM if $\alpha/D < 1$. When $k_1 = \frac{2L_2}{RT_s}$ is constant, the duty ratio is

proportional to the conversation ratio α . As the output voltage is constant, thus, the duty ratio is actually reversely proportional to the input voltage.

A 100 w prototype has been built and the results verified the theoretical analysis in this paper

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Nomenclature

- DICM Discontinuous Inductor Current Mode
- DCVM Discontinuous Capacitor Voltage Mode

- CCVM Continuous Capacitor Voltage Mode
- CICM Continuous Inductor Voltage Mode [6]