A Novel Control Scheme to Reduce Storage Capacitor of Flyback PFC Converter

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***Abstract*—DCM Flyback PFC converter is mainly used in medium and low power applications, having such advantages as zero-current turning on of switch, no reverse recovery of diode and high PF. At the time power electronics widely used today, passive components volume limits the improvement of power density. This paper derives the expressions of the switching turn-on time and the input current of DCM Flyback PFC converter, and based on which, a variable duty control is proposed so as to make the energy storage capacitor reduce to the original 65.6% at the same voltage ripple level while PF is not less than 0.9. The simulation results from a 200W universal input prototype are given to verify the effectiveness of the analysis.**

***Index Terms*—power factor correction, energy storage capacitor, variable duty control, power density**

I. INTRODUCTION

[1]Power Factor Correction (PFC) converters have been widely used in ac-dc power conversions to achieve high power factor (PF) and low harmonic distortion. With the development of the power electronics, high frequency, miniaturization is the trend. In the process of power electronic devices running, it brings a lot of harmonic injection public grid, seriously affected the normal operation of the grid power quality and other devices. In order to reduce the harmonic pollution power electronic devices on the grid to meet the harmonic standard IEC61000-3-2 constitute by international organizations, we need a power factor correction (PFC) converter to suppress it. [1], [2]

Flyback PFC Converter compared with the same type of PFC converter has the advantage of isolated input and output devices, simple structure, low cost, is one of the most common active power factor correction (PFC) converter. According to the current of the inductor at the primary side of the converter is continuous or not, the operating mode can be divided into Continuous Conduction Mode (CCM), Critical Conduction Mode (CRM), Discontinuous Conduction Mode (DCM).

DCM Flyback PFC converter which has the advantage of simple control, unity power factor correction, no reverse recovery current, feedback loop stability and fast response, etc., is generally suitable for small and medium occasions. [3], [4]

II. ANAYSIS OF DCM FLYBACK PFC

Fig. 1 is the main circuit of Flyback PFC Converter. In order to facilitate analysis, make the following assumptions: 1) All devices are ideal components; 2) The output voltage ripple is small compared to its direct flow; 3) The switching frequency is much higher than the input voltage frequency.

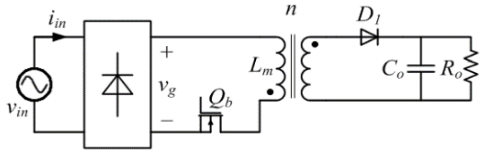

Figure 1. Main circuit of flyback PFC Converter

Fig. 2 is the waveform change of the inductor current and the flux of the DCM Flyback PFC Converter at one period.

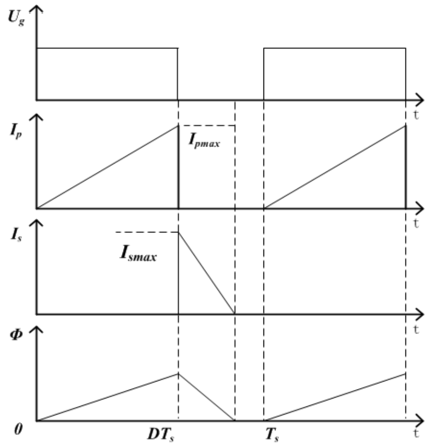

Figure 2. The inductor current and the flux in one period

When Q_b is on, the secondary side is not conductive because of the diode D_1. The voltage between the primary sides of the transformer is v_g, and its current i_p rise from

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zero in the slope of v_g/L_m, the flux increases linearly, and the energy stored in the transformer. When Q_b is off, the voltage of the secondary side increases linearly, until its voltage is bigger than the voltage of the storage capacitor, the secondary side is conductive. The current of the secondary I_s down to zero and the energy is transferred to the secondary side at the same time.

In the frequency of positive half cycle, assume that the input voltage is $v_g(t)=V_m\left|\sin(\omega t)\right|$, then the input peak current in a period can be expressed as:

$$i_{in\_pk}=\frac{V_m\cdot\left|\sin(\omega t)\right|}{L_p}\cdot D\cdot T_s \tag{1}$$

And the input average current can be expressed as:

$$i_{in\_av}=\frac{1}{2}\cdot i_{in\_pk}\cdot D=\frac{V_m\cdot D^2\cdot\left|\sin(\omega t)\right|}{2\cdot L_p\cdot f_s} \tag{2}$$

The input power in half frequency period can be expressed as:

$$P_{in}=\frac{1}{\frac{T}{2}}\cdot\int_0^{\frac{T}{2}}v_{in}(t)\cdot i_{in}(t)dt=\frac{D^2\cdot V_m^2}{4\cdot L_p\cdot f_s} \tag{3}$$

The Power Factor in ideal can be expressed as:

$$PF=\frac{P_{in}}{\frac{1}{\sqrt{2}}\cdot V_m\cdot I_{m\_rms}}=1 \tag{4}$$

So the conclusion we can get is that the PF of Flyback PFC is 1 in ideal and it's very suitable to sacrifice some PF in exchange of reducing the storage capacitor.

III. ANAYSIS OF RELATIONSHIP BETWEEN THE STORAGE CAPACITOR AND PF

Because of the input power of PFC converter is pulsed. In one period, the average input and output power is balanced with the unbalanced instantaneous power. So it is necessary to balance the pulsation power by using the power storage capacitor. [5]

On the other hand, if the instantaneous power of the input and output are balanced, there is no need of power storage capacitor, and the input current can be expressed as:

$$i_{in}(t)=\frac{P_o}{V_m\cdot\sin(\omega t)} \tag{5}$$

Fig. 3 shows the input current in one period.

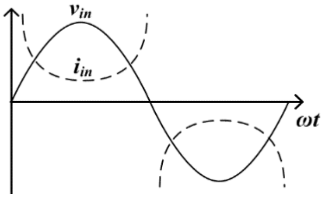


Figure 3. The current and voltage without the storage capacitor

By Fourier decomposition of the input current, it can be seen in the Fig. 3, we can conclude that when the input and output instantaneous power balance, input current contains a large number of odd harmonics and PF is almost zero. In order to achieve the effect to reduce the storage capacitor, we can inject appropriate odd harmonics to the input current.

IV. THE IMPACT OF INJECT THE THIRD HARMONIC TO THE INPUT POWER

When the input voltage is $V_m\cdot\sin(\omega t)$, the input current fundamental can be expressed as:

$$i_{in1}=I_1\sin(\omega t) \tag{6}$$

The instantaneous input power of fundamental current can be expressed as:

$$p_{in1}=V_mI_1\sin^2(\omega t) \tag{7}$$

If the input current have the same initial phase as the third harmonic,

$$i_{in3}=I_3\sin(3\omega t) \tag{8}$$

$$p_{in3}=V_mI_3\sin(\omega t)\sin(3\omega t) \tag{9}$$

Injecting a certain amount of third harmonic current which has the same phase as the fundamental, controlled by a certain way, the input current is expressed as:

$$i_{in}(t)=I_1\sin(\omega t)+I_3\sin(3\omega t)=I_1(\sin(\omega t)+I_3^*\sin(3\omega t)) \tag{10}$$

I_3^* is the input current per unit on the third harmonic of the fundamental.

In this case the input power factor of the converter:

$$PF=\frac{1}{\sqrt{1+I_3^*}} \tag{11}$$

According to Energy Star standards of commercial lighting, the power factor of the powered devices are not less than 0.9. In this case, the amplitude of third harmonic of the fundamental is 48.4%.

Assuming the efficiency of the converter is 100%, then:

$$\begin{aligned}P_{in}'=P_o'&=\frac{2}{T_l}\int_0^{\frac{T_l}{2}}v_{in}(t)i_{in}(t)d\omega t\\&=\frac{1}{\pi}\int_0^{\pi}(V_m\sin(\omega t)\cdot I_1(\sin(\omega t)+I_3^*\sin(3\omega t)))d\omega t\\&=\frac{V_mI_1}{2}\end{aligned} \tag{12}$$

Instantaneous power per unit value (reference the value of output power) is:

$$\begin{aligned}p_{in3}^*&=\frac{v_{in}(t)i_{in3}(t)}{P_o'}=\frac{V_m\sin(\omega t)\cdot I_1(\sin(\omega t)+I_3^*\sin(3\omega t))}{V_mI_1/2}\\&=2\sin(\omega t)\cdot(\sin(\omega t)+I_3^*\sin(3\omega t))\end{aligned} \tag{13}$$

When using fixed duty cycle control, the instantaneous input power per unit of DCM FLYBACK PFC converter can be expressed as,

$$p_{in1}^*(t)=\frac{v_{in}(t)i_{in}(t)}{P_o'}=2\sin^2(\omega t) \tag{14}$$

As it is shown in the Fig. 4, the storage capacitor C_o is charging when $p_{in}^*(t)>1$. The storage capacitor C_o is discharging when $p_{in}^*(t)<1$. Assuming start from $\omega t=0$, under the control of fix duty cycle and variable duty cycle, the waveform of $p_{in}^{*}(t)$ intersection with 1 corresponding the axis at ωt_1 and ωt_2. The energy storage by C_o in frequency of half period can be expressed as,

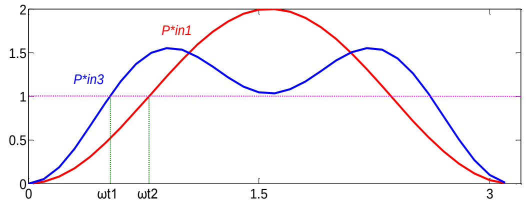


Figure 4. The instantaneous input power per unit

$$\Delta E_1 = \frac{2}{T_l} \cdot 2\int_0^{t_1} [1 - p_{in1}^{*}(t)]dt \tag{15}$$

$$\Delta E_3 = \frac{2}{T_l} \cdot 2\int_0^{t_2} [1 - p_{in3}^{*}(t)]dt \tag{16}$$

According to the formula of the energy storage capacitor, the maximum energy per unit and can be expressed as:

$$\Delta E_1 \approx \frac{\frac{1}{2}C_{o1}(V_o + \frac{\Delta V_{o1}}{2})^2 - \frac{1}{2}C_{o1}(V_o - \frac{\Delta V_{o1}}{2})^2}{P_o T_l / 2} = \frac{2C_{o1}V_o \Delta V_{o1}}{P_o T_l} \tag{17}$$

$$\Delta E_3 \approx \frac{\frac{1}{2}C_{o3}(V_o + \frac{\Delta V_{o3}}{2})^2 - \frac{1}{2}C_{o3}(V_o - \frac{\Delta V_{o3}}{2})^2}{P_o T_l / 2} = \frac{2C_{o3}V_o \Delta V_{o3}}{P_o T_l} \tag{18}$$

Lead to:

$$\Delta V_{o1} = \frac{2P_o}{C_{o1}V_o}\int_0^{t_1} [1 - p_{in1}^{*}(t)]dt \tag{19}$$

$$\Delta V_{o3} = \frac{2P_o}{C_{o3}V_o}\int_0^{t_2} [1 - p_{in3}^{*}(t)]dt \tag{20}$$

With the same requirement of the ripple,

$$\frac{C_{o1}}{C_{o3}} = \frac{\int_0^{\frac{\pi}{4}} [1 - 2\sin^2(\omega t)]d\omega t}{\int_0^{\frac{\pi}{6}} [1 - 2\sin^2(\omega t) - 2 \cdot 0.484\sin(\omega t) \cdot \sin(3\omega t)]d\omega t} = 1.52 \tag{21}$$

By the method of injecting the third harmonic, with the same requirement of the ripple, the storage capacitance can be 65.6% as the original.

V. THE CONTROL CIRCUIT

After injecting the third harmonic, the input current following the equation:

$$i_{in}(t) = \frac{2 \cdot P_o}{V_m}(\sin(\omega t) + I_3^{*}\sin(3\omega t)) \tag{22}$$

Lead (22) into (2),

$$D = \sqrt{\frac{2L_p f_s \cdot 2P_o \cdot (\sin(\omega t) + I_3^{*} \cdot \sin(3\omega t))}{V_m^2 \sin(\omega t)}} \tag{23}$$

Assume that:

$$D_o = \frac{2\sqrt{L_p f_s P_o}}{V_m} \tag{24}$$

Then:

$$D = D_0 \cdot \sqrt{1 + I_3^{*}(3 - 4\sin^2(\omega t))} \tag{25}$$

To achieve the duty is difficult because of the complex formula, so it's necessary to simplify the formula.

For convenient, set $y = |\sin(\omega t)|$, then:

$$D_y = D_0 \cdot \sqrt{1 + I_3^{*}(3 - 4y^2)} \tag{26}$$

According to the Taylor series expansion formula, expand the function at $y = y_0$:

$$D_y = D_0 \left\{ \sqrt{1 + I_3^{*}(3 - 4y_0^2)} - \frac{4I_3^{*}y_0}{\sqrt{1 + I_3^{*}(3 - 4y_0^2)}}(y - y_0) + \ldots \right\} \tag{27}$$

Ignore higher order terms, take only the formula of the first two to fit, then:

$$D_y = D_0 \left\{ \sqrt{1 + I_3^{*}(3 - 4y_0^2)} - \frac{4I_3^{*}y_0\sqrt{1 + I_3^{*}(3 - 4y_0^2)}}{1 + I_3^{*}(3 - 4y_0^2)}(y - y_0) \right\} = D_1(1 + 3I_3^{*} - 4I_3^{*}y_0 y) \tag{28}$$

Among them $D_1 = D_0 \cdot \frac{1}{\sqrt{1 + I_3^{*}(3 - 4y_0^2)}}$

Next we discuss the suitable point of y_0 to make sure the PF is not less than 0.9. The above analysis already has $I_3^{*} = 0.484$, then (28) lead to:

$$D_{y\_fit} = D_1 \cdot \{2.452 - 1.936 y_0 y\} \tag{29}$$

Bring (29) into (2), then:

$$i_{in} = \frac{V_m|\sin(\omega t)|}{2L_p f_s} \cdot D_1^2 \cdot \{2.452 - 1.936 y_0 y\}^2 \tag{30}$$

Assume that the efficiency of the converter is 100%, then the average input power can be expressed as:

$$P_{in}" = P_o" = \frac{2}{T_l}\int_0^{\frac{T_l}{2}} v_{in}(t) i_{in}(t) d\omega t = \frac{1}{\pi}\int_0^{\pi} \frac{V_m^2 \sin^2(\omega t)}{2L_p f_s} \cdot D_1^2 \cdot (2.452 - 1.936 y_0 y)^2 d\omega t \tag{31}$$

Then:

$$PF = \frac{P_{in}}{V_{in\_rms} I_{in\_rms}} = \frac{P_{in}}{\frac{1}{\sqrt{2}} V_m \sqrt{\frac{1}{\pi}\int_0^{\pi} (i_{in}(t))^2 d\omega t}} = \sqrt{\frac{2}{\pi}} \cdot \frac{\int_0^{\pi} \sin^2(\omega t) \cdot (2.452 - 1.936 y_0 \sin(\omega t))^2 d\omega t}{\sqrt{\int_0^{\pi} \sin^2(\omega t) \cdot (2.452 - 1.936 y_0 \sin(\omega t))^4 d\omega t}} \tag{32}$$

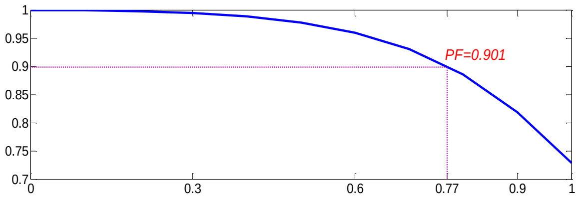


Figure 5. The relationship between the PF and y_0

The size of PF is associated with the y_0, so it's easy to find y_0=0.77 and PF=0.091 in Fig. 5.

Lead to:

$$\begin{aligned} D_{y\_fit} &= D_1 \cdot (2.452 - 1.936 \cdot 0.77\left|\sin(\omega t)\right|) \\ &= \frac{1.752\sqrt{L_p f_s P_o}}{V_m} \cdot (2.452 - 1.491\left|\sin(\omega t)\right|) \end{aligned} \tag{33}$$

VI. DESIGN AND SIMULATION RESULT

The Fig. 6 shows the control circuit basis of formula (33).

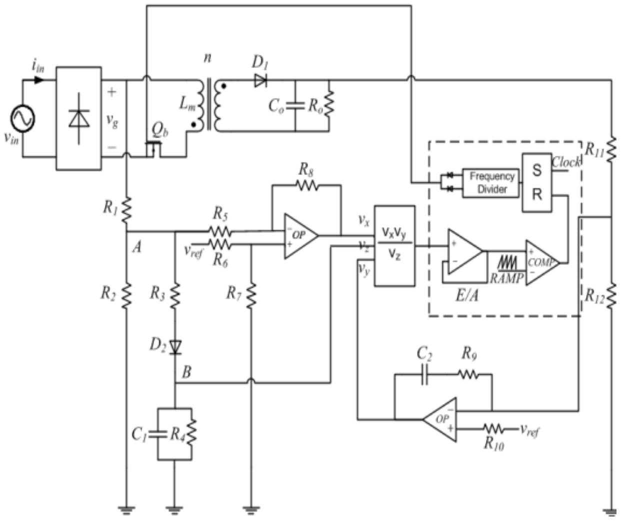


Figure 6. The control circuit

Among them the input voltage is divided by R_1 and R_2 and $v_A = k_1 \cdot V_m \cdot \left|\sin(\omega t)\right|$; R_3 , R_4 , D_2 , C_1 constitute of peak sampling circuit, then $v_z = v_B = k_2 \cdot V_m$; After the op amp, $v_x = k_3 v_{ref} - k_4 v_A$; The output voltage is divided by R_{11} and R_{12} , the voltage through PI adjustment and obtain v_y ; Through the Multiplier the Electric signal can be expressed as

$$v_{EA} = \frac{v_y \cdot (k_3 v_{ref} - k_1 k_4 V_m \sin(\omega t))}{k_2 \cdot V_m} \tag{34}$$

v_{EA} intersects with the sawtooth wave and obtain the PWM signal.

Design and simulation by the formula (31).

In order to verify the validity of the proposed variable duty cycle control, a prototype has been built and simulate in Saber. The parameters of the prototype are as follows:

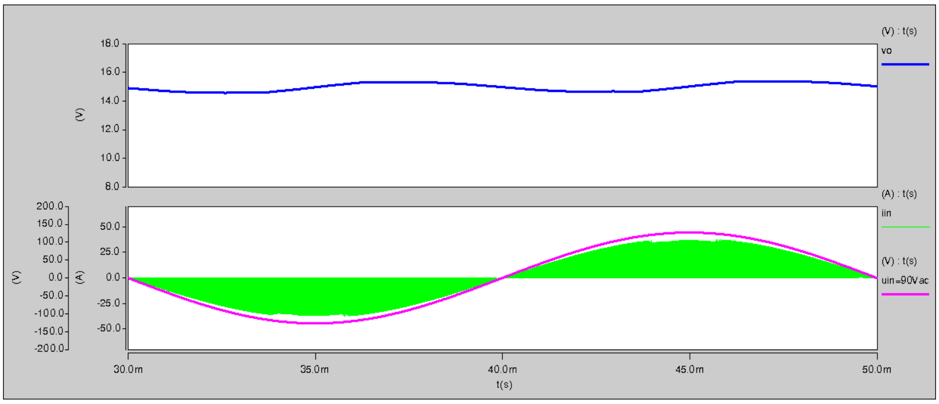
1) Input voltage: $v_{in} = 90 \sim 264 Vac / 50Hz$;
2) Output voltage: $v_o = 15 \pm 0.75 Vdc$;
3) Output power: $P_o = 100W$;
4) Switching frequency of the converter: $100kHz$

The parameters of the PFC stage are as follows:

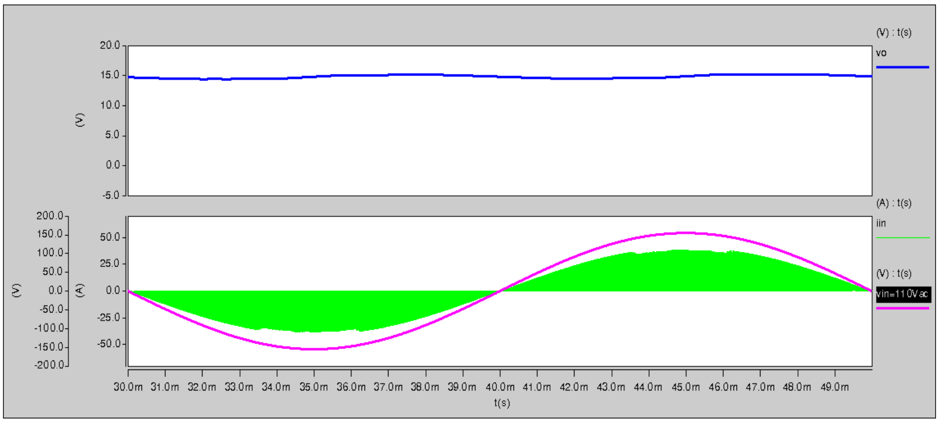
1) Magnetizing inductance: $L_p = 3.6uH$;
2) Turns ratio: $n = 1$;
3) Storage capacitor:

$C_o = 7.07mF$ (constant duty cycle)

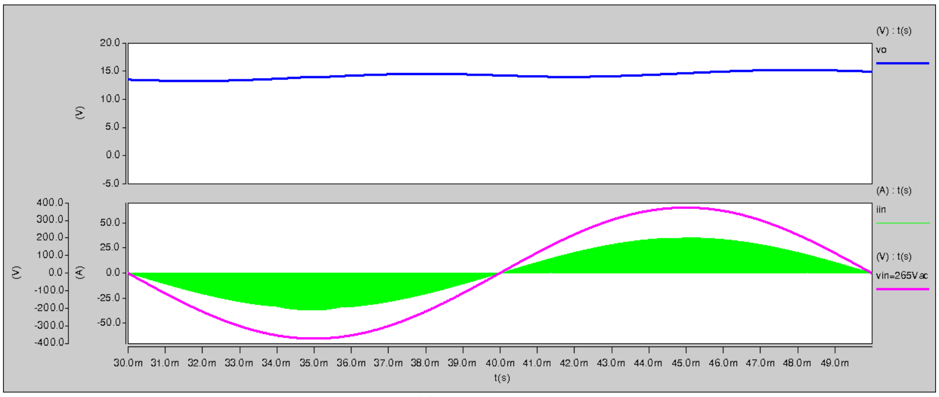
$C_o = 4.638mF$ (variable duty cycle)



(a) 90Vac

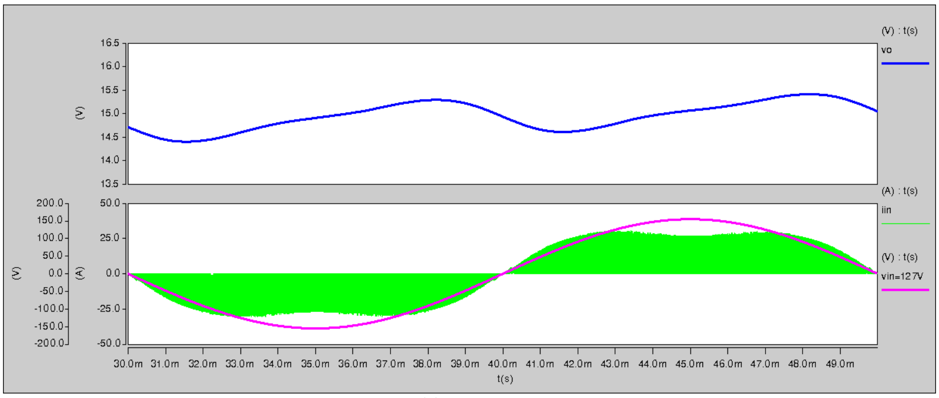


(b) 115Vac

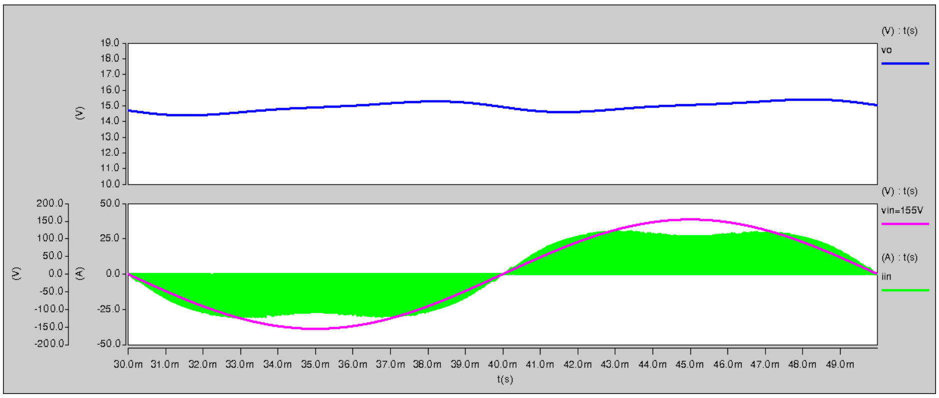


(c) 265Vac

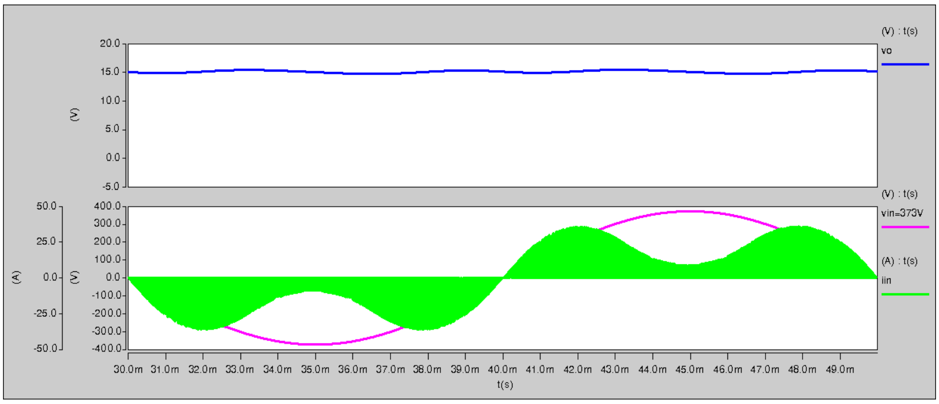
Figure 7. Simulation waveforms of output voltage, input current and voltage with constant duty cycle



(a) 90Vac



(b) 115Vac



(c) 265Vac

Figure 8. Simulation waveforms of output voltage, input current and voltage with variable duty cycle

Fig. 7 and Fig. 8 show the waveforms of the output voltage, input voltage and input current with constant duty cycle and variable duty cycle at 90Vac, 110Vac, 264Vac input, respectively, it can be seen that, the input current has some distortion due to DCM operation and it mainly contain 3rd harmonic which has a phase difference of π and 0 with fundamental component, especially at high input voltage.

And because of the peak input current is decreased by injecting the 3rd harmonic, the efficiency is improved, particularly at low input voltage.

VII. CONCLUSIONS

DCM Flyback PFC Converter has the advantage of topology simple and efficient, widely used in small and medium power applications while the volume of passive components constraint its further improve of the power density. With variable duty cycle control of DCM Flyback PFC Converter the storage capacitance is reduced to the original 65.6% at the same ripple level. Over a wide input voltage rage make the topology of the power density further improved, more in line with small, modular trends.

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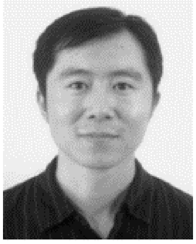

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