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SINGLE-INDUCTOR TWO-STAGE PFC CONVERTER

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Abstract. *A topological structure of a single-inductor two-stage power factor correction (PFC) with high power factor (PF) and little ripple of the output voltage is proposed in this paper, while a corresponding control strategy is proposed for this topology. Introducing the concept of multiplexing a single inductor, compared to the traditional two-stage PFC can reduce an inductor. The control strategy and characteristics of the proposed converter are analyzed. The experimental results show that the single-inductor two-stage PFC can reduce an inductor compared with traditional two-stage PFC and have less performance sacrifices than the traditional two-stage PFC.*

Keywords: Power factor corrector (PFC), Discontinuous current mode (DCM), Multiplexing inductor

1. **Introduction.** In order to reduce the harmonic pollution of the power electronics, the IEC 61000-3-2 limits the harmonic current injected into the AC-DC converter. For some special industrial products, such as lighting equipment, they need to meet the more stringent 61000-3-2 C class harmonics requirements. Therefore, AC-DC converters need to have power factor correction (PFC) function [1-3]. The traditional method is to cascade multiple DC-DC converters behind the single-stage PFC converter. That is, the single-stage PFC converter provides DC bus voltage, DC-DC converter to achieve the required output function, thus forming a multi-stage PFC.

Two-stage PFC is a cascade of DC-DC converters behind a single-stage PFC. Two-stage PFCs can achieve better output voltage characteristics, such as smaller output voltage ripple, and faster output voltage dynamic response, while achieving high power factor and low input current harmonics. However, the circuit is more complex. As the energy transferred to be processed twice, the whole efficiency is low. Because of the need for two sets of control circuit, the cost is higher. As the device more, the volume is also larger. Its applications are: the higher requirements of the PFC circuit output voltage characteristics or the input current quality.

[4] pointed out that if the PFC converter input power factor is 1, the output voltage is constant, and the input power is like a rectified sine wave, and the PFC converter needs an intermediate capacitor. The intermediate capacitor acts as a filter for low frequency harmonics and stores second harmonic. So it is necessary to add an intermediate capacitor. The common two-stage PFC structure is the direct connection of two DC-DC converters. The typical structure of a non-isolated two-stage PFC is a cascade of a BOOST with a BUCK.

This paper proposes a topology that reduces an inductor with respect to the structure of the traditional BOOST converter and the BUCK converter that is directly cascaded. This topology can operate in BOOST state and BUCK state, respectively. However, compared to the traditional BOOST BUCK two-stage PFC converter, this proposed converter reduces an inductor and can save cost and volume. [5] proposed a control method of fitting the duty ratio to make PF 1, but it is too complicated to implement, so this article is not yet used. In this paper, a method of peak current control is proposed. For the two sets of control circuits of the traditional two-stage PFC converter, only one set of control circuit is used to reduce the cost.

Section 1 points out the problem of traditional two-stage PFC converter and puts forward a single-inductor two-stage PFC converter. Section 2 analyzes the traditional two-stage PFC converter. Section 3 is single-inductor two-stage PFC converter and its theoretical analysis. In Section 4, the simulation results verify the feasibility and performance of single-inductor two-stage PFC to meet the basic industrial requirements. To reduce the size of the converter and to meet the requirements of high power density and high integration, single-inductor two-stage PFC has a great research value. Finally, Section 5 concludes the paper.

2. Analysis of Traditional Two-Stage PFC Converter.

Figure 1 shows a two-stage PFC converter with a conventional pre-BOOST post-BUCK. AC source and diodes D1-D4 output rectified sine wave. L1, T1, D5 and C1 form a BOOST circuit, which output 400V. L2, T2, D6 and C2 constituting a BUCK circuit will convert the 400V to 48V. It can be seen that the circuit above contains two inductors, so the volume is large. Pre-BOOST circuit and post-BUCK circuit, under meeting the energy conservation, could have a separate control that is more flexible [6]. The pre-BOOST circuit can make the power factor PF reach 1 and convert 220v AC to 400v DC. Post-BUCK circuit will convert the 400V DC to 48V DC for industrial production use.

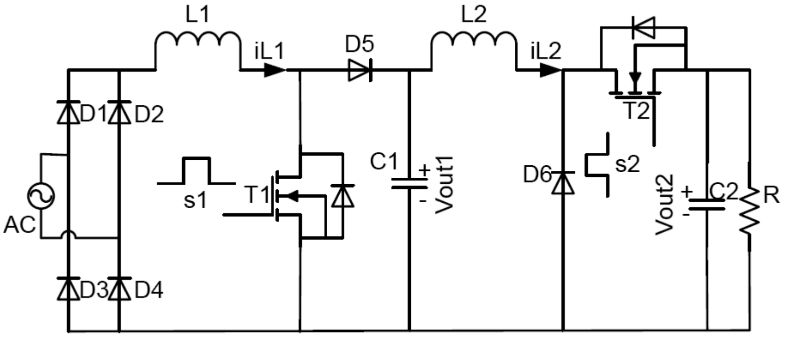


Figure 1. Traditional two-stage PFC converter

3. Single-Inductor Two-Stage PFC Converter.

3.1. Topology.

Think about how to use an inductor to achieve a two-stage PFC converter, that is, how to make a part of the time of the inductor work in the BOOST state, while the other part of the time work in the BUCK state. [7-10] proposed multiplexing a single inductor, but for an output only one capacitor. In order to meet the needs that PF of the PFC converter is 1 and the output voltage is constant, the converter must need an intermediate capacitor to store low-frequency energy [4]. Imagine that in one cycle, the converter first converts the energy through the inductor to the intermediate capacitance in the state of BOOST, and the converter needs to use the same inductor again to convert the energy on the intermediate capacitor to the output capacitor in the state of BUCK. This achieves the same energy transfer of the traditional two-stage PFC, but only uses one inductor. In order to achieve such an idea, using an inductor, two capacitors and multiple switch, put forward a topology as shown in Figure 2.

In order to prevent the current from flowing back to the AC input, it is necessary to add the diode D5. In order to prevent the output current from flowing into the other part of the circuit, it is necessary to add the diode D6.

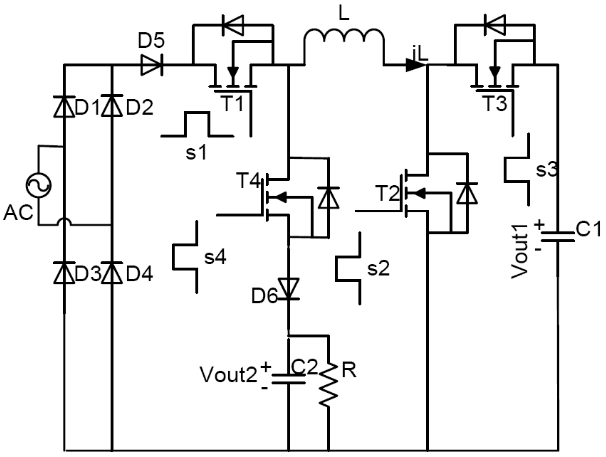


Figure 2. Single-inductor two-stage converter circuit signals

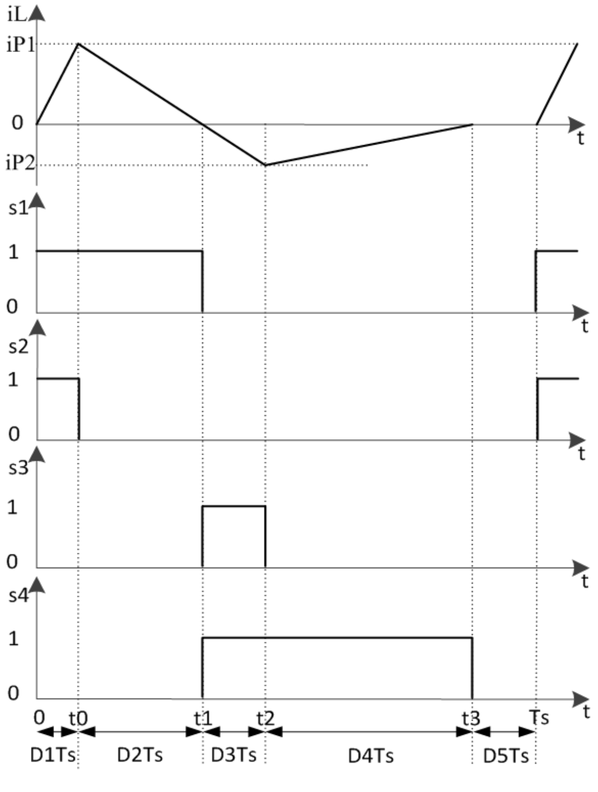


Figure 3. The relationship between current of inductor iL and driven signals

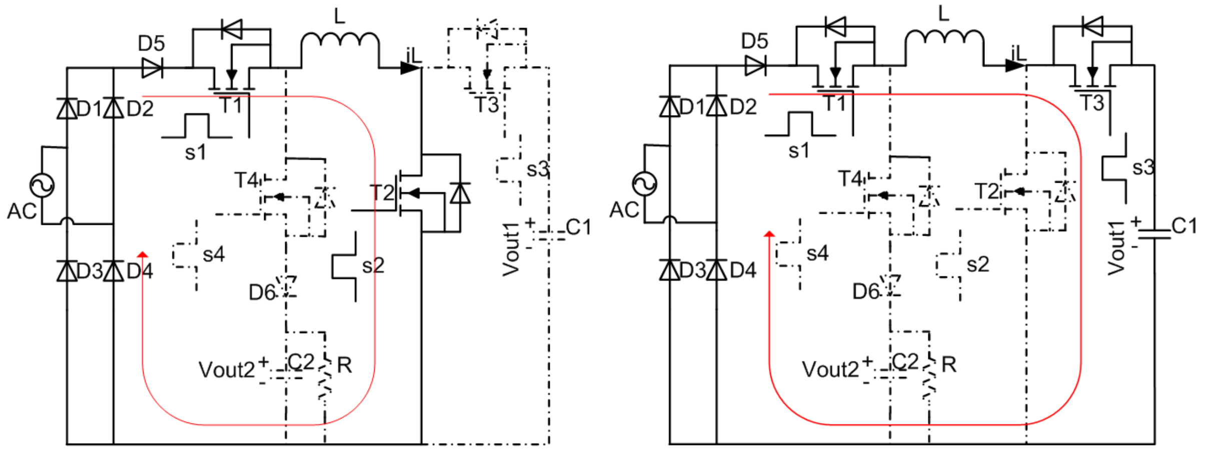
3.2. **Control logic.** Single-inductor two-stage PFC converter operates in a total of five phases. Phases I and II correspond to BOOST circuit working state, and Phases III and IV correspond to working state of the BUCK circuit, respectively. Phase V turns off all switches for the inductor current. The relationship between the current of inductor iL and driven signals is shown in Figure 3. In Figure 3, s1, s2, s3 and s4 are the driven signals of MOS tub T1, T2, T3 and T4. The relationship between the current of inductor iL and driven signal is described in detail in the description of phases I, II, III, IV, V as follows.

Phase I is time 0 to t0, MOS tube T1 and MOS tube T2 conduction. The inductor current rises from zero, when the current rises to the peak iP1, current peak signal P1 is produced and then make MOS tube T2 turn off, the converter working state enters the phase II. Phase I of the conduction circuit is shown in Figure 4(a).

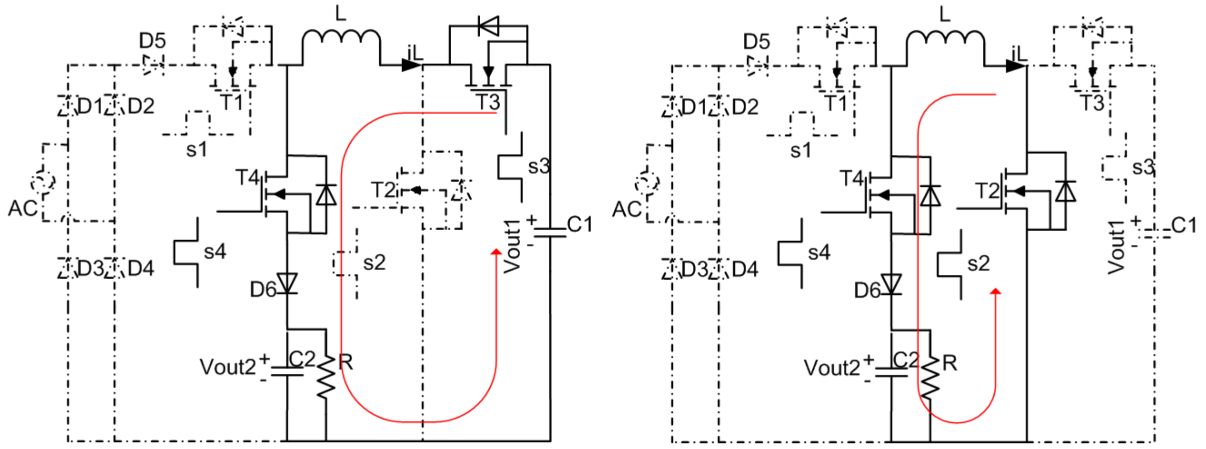
Phase II is time t0 to t1. The inductor current flows through the bypass diode of the MOS tube T3 until the current on the inductor is zero, then zero crossing signal Z1 is produced and make MOS transistor T1 turn off. Phase II of the conduction circuit is shown in Figure 4(b).

Phase III is the time t1 to t2, MOS tube T3 and MOS tube T4 conduction. The inductor current increases from zero to the negative direction, when the current reaches the peak iP2, current peak signal P2 is produced and make MOS tube T3 disconnect, the converter working state into the Phase IV. Phase III of the conduction circuit is shown in Figure 4(c).

Phase IV for the time t2 to t3, MOS tube T3 disconnected. The inductor current flows through the bypass diode of the MOS tube T2 until the current on the inductor is zero, then zero crossing signal Z2 is produced and make all MOS tubes disconnect. Phase IV of the conduction circuit is shown in Figure 4(d).



(a) Phase I (b) Phase II



(c) Phase III (d) Phase IV

FIGURE 4. The working state diagram of single-inductor two-stage PFC converter

Phase V for time t3 to TS, all MOS tubes are kept off. The current on the inductor remains zero until the next cycle begins.

For single-inductor two-stage PFC converter, its BOOST state and BUCK state use peak current control. The trigger signals P1, P2, Z1, and Z2 which are mentioned above and the control logic of the four switches which is obtained by four SR flip-flops are shown in Figure 5.

3.3. Single-inductor two-stage PFC converter operating characteristics analysis.

Due to the characteristics of this topology, both the BOOST state and BUCK state are in DCM mode. In the same cycle, BOOST stage and BUCK stage can be controlled by controlling their turn-on time.

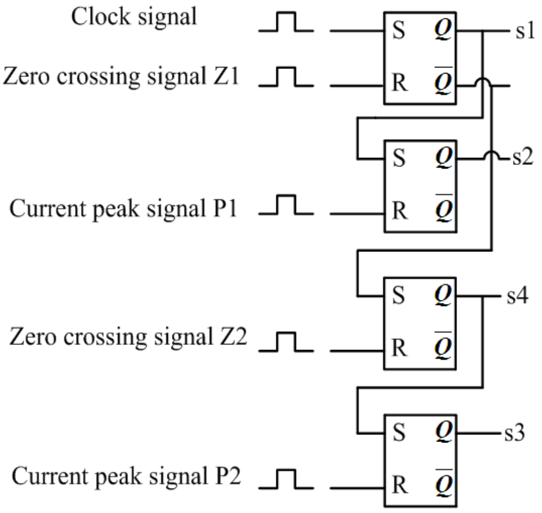


Figure 5. The relationship between trigger signals and driven signals

For the BOOST stage, in order to facilitate the analysis, make the following assumptions.

a) All components are ideal components.

b) The voltage ripple on the intermediate capacitor is much smaller than its DC.

c) The switching frequency is much greater than the input voltage frequency.

The input voltage is expressed as:

$$U_{in}(t) = U_m \sin \omega t \tag{1}$$

In (1), U_m is the amplitude of the input AC voltage and ω is the angular frequency of the input AC voltage.

After the diode rectified the voltage $U_{in\_r}(t)$ becomes:

$$U_{in\_r}(t) = U_m |\sin \omega t| \tag{2}$$

In a switching cycle, the current peak $I_{p1}(t)$ in the BOOST state is:

$$I_{p1}(t) = \frac{U_{in\_r}(t)}{L} D_1 T_S \tag{3}$$

In (3), L is the inductance of inductor, T_S is the time of a switching cycle. In addition, f_S is the frequency of a switching cycle.

In a switching cycle, because of the volt-second balance principle, Equation (4) can be obtained. The duty cycle D_2 can be obtained by Equation (4).

$$U_{in\_r}(t) D_1 T_S = \left[U_{out1} - U_{in\_r}(t)\right] D_2 T_S \tag{4}$$

$$D_2 = \frac{U_m |\sin \omega t|}{U_{out1} - U_m |\sin \omega t|} D_1 \tag{5}$$

The average current $I_{avr1}(t)$ in a switching cycle on inductor and input current $I_{in}(t)$ could be got:

$$I_{in}(t) = I_{avr1}(t) = \frac{1}{2} I_{p1}(t)(D_1 + D_2) = \frac{U_m D_1^2}{2Lf_S} \frac{|\sin \omega t|}{1 - \frac{U_m}{U_{out1}} |\sin \omega t|} \tag{6}$$

Equations (1) and (6) can be used to get the input power of the converter P_{in} in half a line cycle. In (7), T_{line} is the time of a cycle of input AC voltage.

$$P_{in} = \frac{1}{T_{line}/2} \int_0^{T_{line}/2} U_{in}(t) I_{in}(t) dt = \frac{U_m^2 D_1^2}{2\pi L f_S} \int_0^{\pi} \frac{|\sin \omega t|}{1 - \frac{U_m}{U_{out1}} |\sin \omega t|} d(\omega t) \tag{7}$$

Assuming the conversion efficiency is 100%, then there is $P_{in} = P_o$, and by (7) duty cycle D_1 could be got:

$$D_1 = \frac{1}{U_m}\sqrt{\frac{2\pi L f_S P_o}{\int_0^{\pi} \frac{|\sin\omega t|}{1-\frac{U_m}{U_{out1}}|\sin\omega t|} d(\omega t)}} \tag{8}$$

Input current effective value I_{in_avr}:

$$I_{in\_avr} = \sqrt{\frac{1}{\pi}\int_0^{\pi} i_{in}^2(t) d(\omega t)} \tag{9}$$

According to Equations (7) and (9), power factor (PF) is available

$$PF = \frac{P_{in}}{\frac{1}{\sqrt{2}}U_m I_{in\_avr}} = \frac{P_{in}}{\frac{1}{\sqrt{2}}U_m\sqrt{\frac{1}{\pi}\int_0^{\pi} i_{in}^2(t)d(\omega t)}} = \frac{\sqrt{\frac{2}{\pi}}\int_0^{\pi}\frac{|\sin\omega t|}{1-\frac{U_m}{U_{out1}}|\sin\omega t|}d(\omega t)}{\sqrt{\int_0^{\pi}\left(\frac{|\sin\omega t|}{1-\frac{U_m}{U_{out1}}|\sin\omega t|}\right)^2 d(\omega t)}} \tag{10}$$

As you can see, $\frac{U_m}{U_{out1}}$ will affect PF value and the value of $\frac{U_m}{U_{out1}}$ smaller, the PF value is greater. The voltage above the intermediate capacitor can be taken to a relatively large value to make the PF value relatively high. From Formula (8) we can see that when the output power P_o is determined, D_1 can determine the value of the intermediate capacitor voltage U_{out1}.

For converters under the BUCK stage, the energy on the intermediate capacitor is switched to the load. It can be seen from [11], in the DCM mode the conversion ratio $\frac{U_{out2}}{U_{out1}}$ and duty cycle D_4 on which current drops from the peak down to zero are as follows, where $K = \frac{2L}{RT_s}$ and R is the load resistance.

$$\frac{U_{out2}}{U_{out1}} = \frac{2}{1+\sqrt{1+4K/D_3^2}} \tag{11}$$

$$D_4 = \frac{K}{D_3}\frac{2}{1+\sqrt{1+4K/D_3^2}} \tag{12}$$

In a switching cycle, the current peak in the BUCK state $I_{p2}(t)$ is:

$$I_{p2} = \frac{U_{out2}-U_{out1}}{L}D_3T_S \tag{13}$$

It is available to obtain the current average I_{avr2} and the output current I_{out} through the inductance in the BUCK state in one cycle.

$$I_{out} = I_{avr2} = \frac{1}{2}I_{p2}(D_3+D_4) = \frac{U_{out2}-U_{out1}}{2L}D_3T_S\left(D_3+\frac{K}{D_3}\frac{2}{1+\sqrt{1+4K/D_3^2}}\right) \tag{14}$$

The output power P_o can be got by Equation (14)

$$P_o = U_{out2}I_{out} = \frac{U_{out2}-U_{out1}}{2L}U_{out2}D_3T_S\left(D_3+\frac{K}{D_3}\frac{2}{1+\sqrt{1+4K/D_3^2}}\right) \tag{15}$$

From Equations (8), (10), (11), and (15), if the circuit parameters such as inductance and resistance in Figure 2 are determined, the duty cycle D_1 determines the intermediate capacitor voltage U_{out1} and power factor PF. The duty cycle D_3 determines the output voltage U_{out2} and output power P_o. So it is necessary to control D_1 and D_3 in the closed-loop control of the circuit in Figure 2.

Using peak current control method for BOOST state and BUCK state is to control the duty cycle D_1 and duty cycle D_3. In order to facilitate the control, this paper for the BOOST state control uses constant conduction time control.

4. **Simulation Analysis.** To verify the analysis results given earlier, the parameters of the circuit in Figure 2 are: input voltage is 220V AC; output voltage is 48V; inductance of L is 60uH; output power is 120W, so the R is 19.2 ohm; the intermediate capacitor C1 and output capacitor C2 are both 100μF. Figure 6 shows the relationship between the power factor and the intermediate voltage, and verifies the theoretical analysis of Equation (10). The greater the intermediate voltage is, the greater the power factor is. However, the voltage which capacitor could hold is limited, so the selection is 400V.

After the intermediate voltage Vout1 is selected 400V, the input current and input voltage are shown in Figure 7. The phase difference between the input current and the input voltage is close to zero, and the input current shape is approximately sinusoidal, which is the shape of the input current in typical DCM mode. The power factor PF is 0.94.

As shown in Figure 8, the output voltage ripple is 5%, and the ripple of the intermediate voltage is 3%, where the proportion of the second harmonic in the ripple of the output

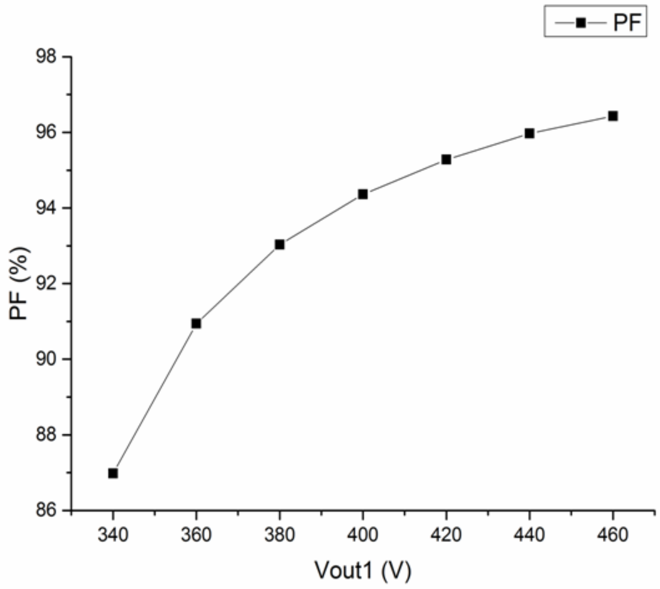


FIGURE 6. The relationship between power factor and intermediate voltage

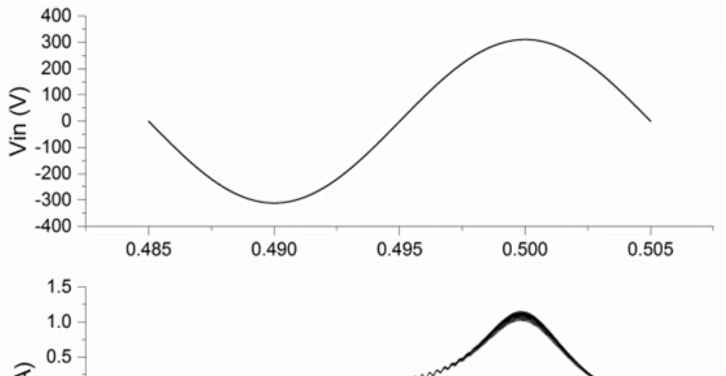


FIGURE 7. Input current and input voltage

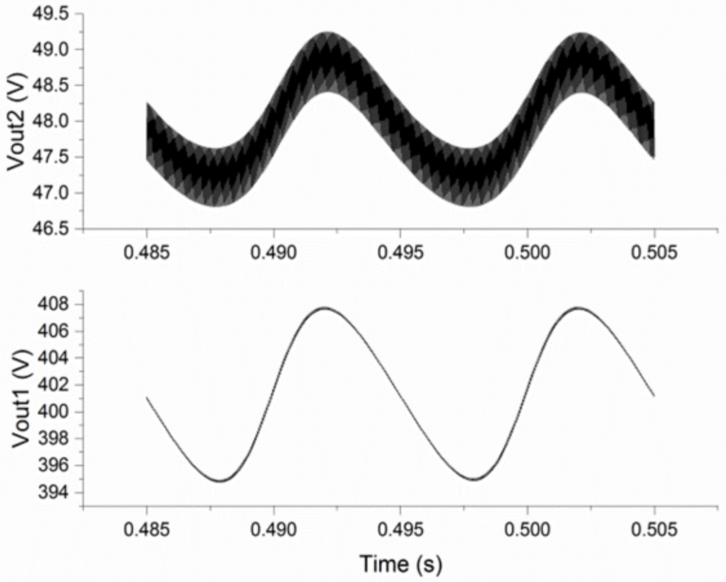


Figure 8. The output voltage and the intermediate voltage

voltage is large. While that PF is above 0.9 and output voltage ripple is below 5% is ok in the common industry standard, single-inductor two-stage PFC converter performs good with 0.94 PF and 5% output voltage ripple.

5. Conclusions.

1) The traditional two-stage PFC converter requires two inductors, taking up more space.

2) Propose a single-inductor two-stage PFC converter, and a basic control method.

3) The study shows that the performance of the single-inductor two-stage PFC converter is lost to performance of traditional two-stage PFC converter, but reducing an inductor and reducing the volume of the converter.

4) In [5], the control method of fitting the duty ratio is put forward, and the PF value can be theoretically 1. It is valuable that the control method of fitting the duty ratio is used into single-inductor two-stage PFC. More control method should be proposed to make single-inductor two-stage PFC work effectively and practically.

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REFERENCES

[1] T. Yan, J. Xu, F. Zhang, J. Sha and Z. Dong, Variable-on-time-controlled critical-conduction-mode flyback PFC converter, *IEEE Trans. Industrial Electronics*, vol.61, no.11, pp.6091-6099, 2014.

[2] O. Garcia, J. A. Cobos, R. Prieto, P. Alou and J. Uceda, Single phase power factor correction: A survey, *IEEE Trans. Power Electronics*, vol.18, no.3, pp.749-755, 2003.

[3] T. Yan, J. Xu, X. Liu, G. Zhou and J. Gao, Flicker-free transformerless LED driving circuit based on quadratic buck PFC converter, *Electronics Letters*, vol.50, no.25, pp.1972-1974, 2014.

[4] C. K. Tse, M. H. L. Chow and M. K. H. Cheung, A family of PFC voltage regulator configurations with reduced redundant power processing, *IEEE Trans. Power Electronics*, vol.16, no.6, pp.794-802, 2001.

[5] K. Yao, X. Ruan, X. Mao and Z. Ye, Variable-duty-cycle control to achieve high input power factor for DCM boost PFC converter, *IEEE Trans. Industrial Electronics*, vol.58, no.5, pp.1856-1865, 2011.

[6] J. Zhang, M. M. Jovanovic and F. C. Lee, Comparison between CCM single-stage and two-stage boost PFC converters, *The 14th Applied Power Electronics Conference and Exposition*, vol.1, pp.335-341, 1999.

[7] X. Liu, J. Xu, Z. Chen and N. Wang, Single-inductor dual-output Buck-Boost power factor correction converter, *IEEE Trans. Industrial Electronics*, vol.62, no.2, pp.943-952, 2015.

[8] H. P. Le, C. S. Chae, K. C. Lee, S. W. Wang, G. H. Cho and G. H. Cho, A single-inductor switching DC-DC converter with five outputs and ordered power-distributive control, *IEEE Journal of Solid-State Circuits*, vol.42, no.12, pp.2706-2714, 2007.

[9] D. Ma, W.-H. Ki, C.-Y. Tsui and P. K. T. Mok, Single-inductor multiple-output switching converters with time-multiplexing control in discontinuous conduction mode, *IEEE Journal of Solid-State Circuits*, vol.38, no.1, pp.89-100, 2003.

[10] C. S. Chae, H. P. Le, K. C. Lee, G. H. Cho and G. H. Cho, A single-inductor step-up DC-DC switching converter with bipolar outputs for active matrix OLED mobile display panels, *IEEE Journal of Solid-State Circuits*, vol.44, no.2, pp.509-524, 2009.

[11] R. W. Erickson, *Fundamentals of Power Electronics*, Kluwer Academic Publishers, 2001.