Research on Output Voltage Ripple of Boost DC/DC Converters

Shu-lin Liu, Jian Liu, *Senior Member*, *IEEE*, Jing Zhang

Abstract: **According to the minimum inductor-current of Boost DC/DC converters, the energy transmission mode (ETM) can be divided into two types, i.e., the Complete Inductor Supply Mode (CISM) and the Incomplete Inductor Supply Mode (IISM). Based on the classification, three operating modes can be defined, i.e., CISM, IISM as well as Continuous Conduction Mode (IISM-CCM) and IISM as well as Discontinuous Conduction Mode (IISM-DCM). The Output Voltage Ripples (OVR) in three modes are analyzed, respectively. It is pointed out that the converter in CISM has the smallest output voltage ripple independent of the inductance, while that in IISM-CCM and IISM-DCM has rather larger output voltage ripple that is increasing with the decrease of inductance. The maximum of output voltage ripple in various operating mode is obtained. It is also pointed out that the minimum inductance to guarantee the lowest output voltage ripple is the critical inductance of CISM and IISM.**

Key words: **Boost DC/DC converters, energy transmission mode, output voltage ripple.**

I. INTRODUCTION

With the development of the electronic technology, low cost and convenient electronic equipments are springing up, in which batteries or a low voltage power source is widely applied, however, the voltage grades of the system are various.. Therefore, there is no doubt that Boost converter will be widely used in these systems[1~2].

In the existing literatures, the operating mode of a Boost converter is usually divided into Continuous Conduction Mode (CCM) and Discontinuous Conduction Mode (DCM) [3~9], and the output voltage ripple is independent of the inductance of the inductor when a Boost converter works in the CCM[9]. However, many experiment results indicate that the output voltage ripple of a Boost converter in CCM increases with the decreasing of the inductance in the case of small inductance. Thus, to design the inductance according to traditional knowledge can't ensure the converter to meet the desired requirements.

In fact, since the inductor of a Boost converter is in the input part, the energy transmission process from the input to the output becomes more complicated than the published knowledge. Therefore, it is also necessary to further study the energy transmission mode of a Boost converter.

As for an optimal design of Boost DC-DC converter, especially the design of intrinsically safe switching power supply applied in flammable and explosive conditions (to

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reduce the electric sparks energy from the output short-circuit and the inductor being disconnected, the values of capacitor and inductor of this kind of power supply should be as small as possible[10~11].), it is highly important that the minimum inductance to guarantee the lowest output voltage ripple is obtained by analyzed the energy transmission process of the output voltage ripple of a Boost converter.

II. CRITICAL INDUCTANCE AND OPERATING MODES

A basic Boost converter is shown in Fig.1. The Boost DC-DC converter can operates in two modes: Continuous Conduction Mode (CCM) and discontinuous Conduction Mode (DCM). If the converter works in CCM, the relationship between the input voltage V_i the output voltage V_O and the conducting ratio d is $\dfrac{V_O}{V_i} = \dfrac{1}{1-d}$, the minimum inductor-current I_{LV} is

$$I_{LV} = I_O \left[\frac{1}{1-d} - \frac{R_L}{2Lf} d(1-d) \right] \qquad (1)$$

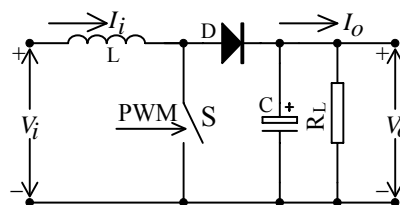Where R_L is the load resistance, f is the switching frequency.

Fig.1 A Boost DC-DC converter

Comparing the minimum inductor-current I_{LV} with the output current I_O of a Boost converter, the Energy Transmission Mode (ETM) can be divided into Complete Inductor Supplying Mode (CISM) in case of $I_{LV} > I_O$ and Incomplete Inductor Supplying Mode (IISM) in case of $I_{LV} < I_O$ during turn-off period of the power switch. Obviously, the critical condition of CISM and IISM is $I_{LV} = I_O$, so we can obtain that the critical inductance L_K is

$$L_K = \frac{(1-d)^2 R_L}{2f} = \frac{R_L V_i^2}{2fV_o^2} \qquad (2)$$

When $L > L_K$, the converters works in CISM; when $L < L_k$, the converters works in IISM.

As for a Boost converter, the critical condition of the Continuous Conduction Mode (CCM) and the

Discontinuous Conduction Mode (DCM) is $I_{LV}=0$, the critical inductance L_C is[5, 9]

$$L_C = \frac{R_L d(1-d)^2}{2f} \qquad (3)$$

According to Eq.(2) and (3), it is obvious that $L_K > L_C$ because of $d<1$. Therefore, if a Boost converter is in CISM, it must be working in CCM. But if a Boost converter is in IISM, it may be working in CCM. or DCM.

Based on the above analysis, a Boost converter can be divided into three operating modes: CISM, IISM as well as Continuous Conduction Mode (IISM-CCM) and IISM as well as Discontinuous Conduction Mode (IISM-DCM), which are shown in Fig.2, respectively.
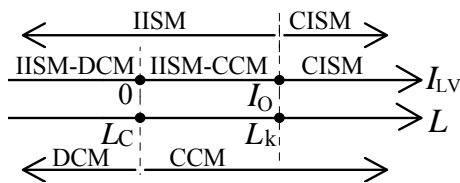

Fig.2 Three operating modes and the critical conditions

The waveforms of the inductor-current, inductor-current and the output voltage of Boost converters operating in CISM, IISM-CCM and IISM-DCM are shown in Fig.3(a)，(b), and (c), respectively.

CISM ($I_{LV}>I_O$): The inductor is not only supplying energy for the load, but also charging the capacitor. The waveforms of the inductor-current and capacitor-voltage in CISM are shown in Fig.3(a), where I_{LP} is the peak inductor-current, T_{on} and T_{off} are the turn-on and turn-off time of the power switch, V_{CP} and V_{CV} are the peak and minimum capacitor-voltage, respectively.

IISM-CCM($0<I_{LV}<I_O$):The waveforms of the inductor-current and capacitor-voltage are shown in Fig.3(b). It can be seen from Fig.3(b) that the energy transfer process during the turn-off period of the switch can be divided into two stages.

The first stage is that only the inductor is being discharged, the equivalent circuit of which is shown in Fig.3(a). In this case, the inductor-current $i_L>I_O$, which is not only supplying energy for the load, but also charging the capacitor. The capacitor-voltage increases during t_1 to t_2 as illustrated in Fig.3(b).

The second stage is that both the inductor and the capacitor provide energy for the load. In this case, $i_L<I_O$, and the capacitor-voltage decreases from t_2 to t_3 as illustrated in Fig.3(b).
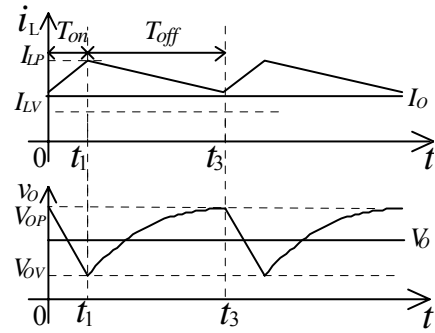
IISM-DCM ($I_{LV}=0$): The waveforms of the inductor-current and capacitor-voltage in DCM are shown in Fig.3(c). The energy transfer process can be divided into three stages:

The first stage is that only the inductor discharges energy. The inductor-current $i_L>I_O$, which is not only supplying energy for the load, but also charging the capacitor. The capacitor-voltage increases. This process is from t_1 to t_2.

The second stage is that both the inductor and the capacitor supply energy for the load simultaneously. The inductor-current $i_L<I_O$, and the capacitor-voltage keeps on

decreasing until the inductor-current reaches zero. This process lasts from t_2 to t_{2a}.
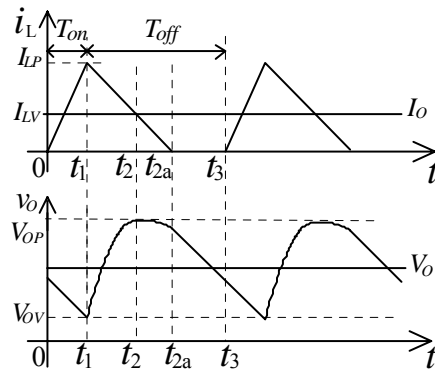
The third stage is that only the capacitor discharges energy, and the diode D turns off due to $i_L=0$. The capacitor-voltage keeps on decreasing until the transistor stops conducting in the next cycle.

(a) CISM
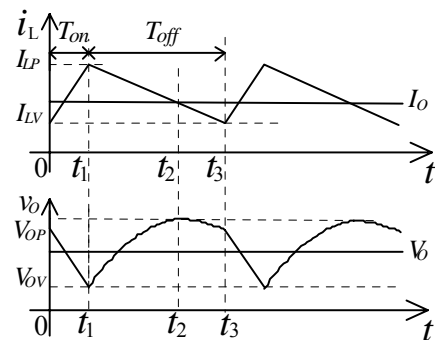
(b) IISM-CCM

(c) IISM-DCM

Fig.3 Waveforms of current and output voltage

III. THE OUTPUT RIPPLE VOLTAGE OF A BOOST CONVERTER

When a Boost converter works in CISM, the waveforms of the inductor-current and the output voltage are shown in Fig.3(a), from which we can obtain that the output voltage ripple V_{PP1} is

$$V_{PP1} = \frac{dTI_O}{C} = \frac{dV_O}{R_L Cf} = \frac{V_O - V_i}{R_L Cf} \qquad (4)$$

Where, T is the switch cycle($T=1/f$). C is the capacitance of the output capacitor. Obviously, V_{PP1} is independent of the inductance.

When a Boost converter works in IISM-CCM, the waveforms of the inductor-current and the output voltage are shown in Fig.3(b), from which we can obtain that the output voltage ripple V_{PP2} is

$$V_{PP\,2} = \frac{V_O - V_i}{2CV_O}\left(\frac{LV_O^3}{R_L^2 V_i^2} + \frac{V_i^2}{4Lf^2 V_O} + \frac{V_O}{R_L f}\right) \quad (5)$$

Obviously, V_{PP2} is dependent on the inductance L and decreases with the increasing of L, then the minimum and maximum values of V_{PP2} are given in Eq.(6-a) and (6-b), respectively

$$V_{PP2,min} = \frac{V_O - V_i}{R_L Cf} = V_{PP1} \quad (6\text{-}a)$$

$$V_{PP2,max} = \frac{V_O}{R_L Cf}(1 - \frac{V_i}{2V_O})^2 \quad (6\text{-}b)$$

When a Boost converter works in IISM-DCM, from Fig.3(b), we can obtain that the output voltage ripple is

$$V_{PP3} = \frac{V_O}{CfR_L} + \frac{LV_O^2}{2C(V_O - V_i)R_L^2}$$

$$- \frac{V_O\sqrt{2LfV_O(V_O - V_i)}}{Cf(V_O - V_i)}R_L^{-\frac{3}{2}} \quad (7)$$

It is obvious that V_{PP3} is also a function of the inductance and decreases with increasing of inductance. The minimum value of V_{PP3} is

$$V_{PP3,min} = \frac{V_O}{R_L Cf}(1 - \frac{V_i}{2V_O})^2 = V_{PP2,max} \quad (8)$$

According to the above analysis, the curve of output voltage ripple versus the inductance with given load, capacitance and switching frequency can be drawn, which is shown in Fig.4 .
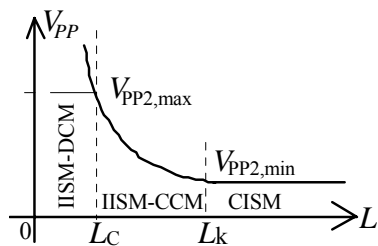

Fig.4 OVR vs. L of Boost converter with certain R_L, C and f

It can be seen from Fig.4 that as for a Boost DC-DC converter with given load, capacitance and switching frequency, if it works in CISM, it has the smallest output voltage ripple independent of the inductance, if it works in IISM-CCM, it has larger output voltage ripple being dependent on the inductance than that in CISM, if it works in IISM-DCM, it has larger output voltage ripple being dependent on the inductance than that in IISM-CCM.

Therefore, if we want to obtain the minimum value of output voltage ripple, the inductance of the inductor should be designed to be larger than L_K, which is a value much larger than L_C described in the existing literatures.

IV. EXAMPLES AND VERIFICATION

As for a Boost DC-DC converter with the parameters as: input voltage V_i=12V, output voltage V_O=18V, output current I_O =0.5A (R_L =36Ω), C=15μF, f =100kHz, we can get L_C=27μH, L_K=80μH, according to Eq. (2) and (3).
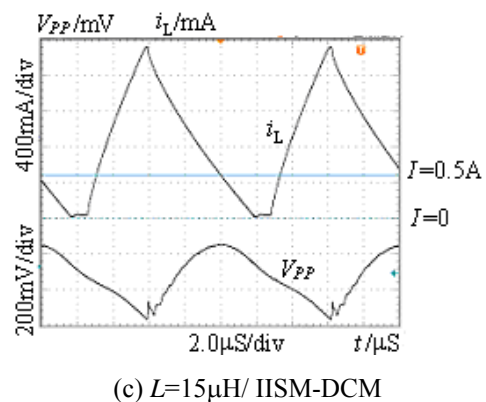
The experimental waveforms of output voltage ripple (V_{PP}) and inductor-current (i_L) in the case of L=100μH, L=30μH and L=15μH are shown in Fig.5(a), (b) and (c) corresponding to CISM, IISM-CCM and IISM-DCM, respectively.

(a) L=100μH/ CISM
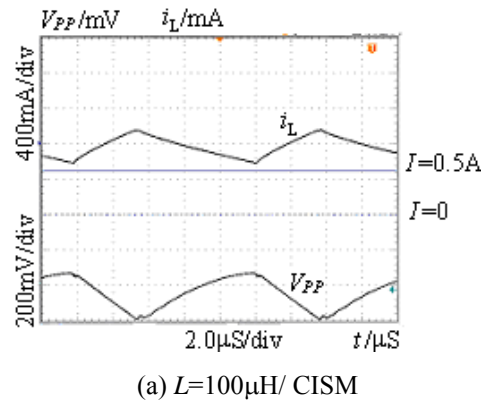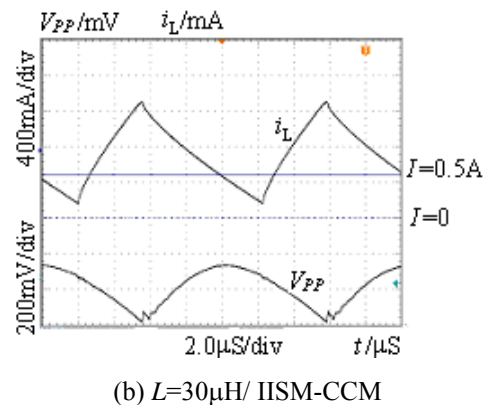
(b) L=30μH/ IISM-CCM

(c) L=15μH/ IISM-DCM

Fig.5 Inductor-current (i_L) and output voltage ripple (V_{PP})

From Fig.5, we can see that the converter will work in different modes with the various inductances with the given load, capacitance and switching frequency, and the output voltage ripple level will be different obviously.

From Fig.5(a), when the converter is in CISM in the case of L=100µH, since the inductor-current I_L is always larger than 0.5A (the output current I_O) during the period of turn-off of the switch, the capacitor is charged by the inductor and the capacitor-voltage is rising until the beginning of next turn-on period. In the turn-on period, the capacitor-voltage is decreasing with a magnitude (that is the ORV) only dependent on the capacitance. Thus, the ORV is independent of the inductance.

From Fig.5(b), when the converter works in IISM-CCM in the case of L=30µH, the capacitor-voltage starts decreasing in the case of I_L<I_O=0.5A during the period of turn-off of the switch, and the decreasing magnitude of the capacitor-voltage becomes larger than that in CISM.

From Fig.5(c), when the converter is in IISM-DCM in the case of L=15µH, the capacitor-voltage also starts dropping in case of I_L<I_O=0.5A during the period of turn-off of the switch, but it experiences two periods: corresponding to i_L<0.5A and i_L=0, respectively. Thus, the decreasing magnitude, i.e., the ORV is the largest.

The experimental results of output voltage ripple with various inductances are shown in Table1. It can be seen that the experiment results are in positive with theoretical ones perfectly, that is the OVR is the smallest and independent of the inductance in CISM, and that is larger and increases with the decrease of inductance in IISM-CCM and IISM-DCM, moreover, the minimum inductance to guarantee the lowest output voltage ripple is the critical inductance of CISM and IISM. But the experimental results of output voltage ripple are somewhat different from the theoretical values. The main reason is that the current through the inductor is nonlinear and the influences of some parasitical parameter in the components are not considered.

Table Ⅰ The output voltage ripple with various values of L

Operating mode	CISM			IISM-CCM			IISM-DCM		
L(µH)	400	200	100	70	50	30	20	15	10
V_{PP}(mV) (Experimental)	278	278	279	282	298	356	411	452	512
V_{PP}(mV) (Theoretical)	245	245	245	246	259	309	372	414	466

Ⅴ CONCLUSIONS

The energy transmission mode of a Boost converter can be divided into CISM and IISM, its operating modes can be divided into three types, that is CISM, IISM-CCM and IISM-DCM. A Boost converter in CISM must work in CCM while that in IISM may be in DCM or CCM. As for a Boost DC-DC converter with given load, capacitance and switching frequency, the converter in CISM has the smallest output voltage ripple independent of the inductance. The converter in IISM has rather larger output voltage ripple that is related with the inductance. The minimum inductance to guarantee the lowest output voltage ripple is the critical inductance of CISM and IISM, which is a value much larger than the critical inductance of CCM and DCM described in the existing literatures.

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