Power Efficiency Analysis of a Multi-Oscillated Current Resonant Type DC-DC Converter

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Abstract— **This paper deals with an analysis of the power efficiency of a multi-oscillated current resonant type DC-DC converter. The current resonant type converter employs generally the pulse frequency modulation. For this reason, the magnetizing current through the converter causes not only a power loss under a light load, but also a loss during stand-by. In order to solve these problems, a multi-oscillated current resonant type DC-DC converter has been proposed, and revealed the advantage of its control method which can reduce power loss under light load and keep low switching noise. An analytical relationship of among states, operating mode and efficiency characteristics of this converter are defined. As a result, it was confirmed that for this converter, the output power depends on the voltage of resonant capacitor, and consequently, it is important to determine constants of resonant capacitor and inductance of transformer. The maximum efficiency is 95.4% with the magnetizing inductance 1.8mH.**

I. Introduction

A switching power supply system with the high efficiency, small size, low noise and low cost, is requested in many areas of portable electronics systems such as personal computers, cellular phones, flat panel displays and so forth. In switching power supply systems, generally the pulse frequency modulation has been applied to current resonant type converters [1, 2].

However, these types of converter have problems, in which a magnetizing current through the converter causes a loss of power under the light load and stand-by conditions. Consequently, the small size required for this type of converter cannot be achieved, because an auxiliary source is necessary in the stand-by mode.

In order to solve these problems, a multi-oscillated current resonant type DC-DC converter has been proposed, and revealed the advantage of its control method which can reduce the power loss under light load and standby conditions, and keep low noise by using both pulse width modulation (PWM) and pulse frequency modulation (PFM) control modes [3-5].

This paper defines an analytical relationship among states, operating mode and efficiency characteristics of this proposed converter by considering to the currents of primary and secondary sides. Furthermore, the influence of a magnetizing inductance is clarified.

II. Circuit Configuration and Operating Principle

Figures 1 and 2 show the proposed multi-oscillated current resonant DC-DC converter and the timing chart, respectively. This converter consists of a half-bridge circuit, whose switches Q_1 and Q_2 are operated by a multi-oscillated current resonant driven by an IC with pulse-width modulation (PWM), and an auxiliary winding N_{P2} of the transformer, respectively.

By applying a gate voltage to Q_1 and Q_2 at turn-on and turn-off, switching power losses are reduced due to the zero-voltage switching (ZVS) and zero-current switching (ZCS). In the isolated transformer T_r, the primary winding N_{P1} is loosely coupled to the secondary windings N_{S1} and N_{S2}, for in which the voltage of the leakage inductance is relatively large. Because of the resonant circuit with this leakage inductance and the resonant capacitor, the switching power losses of Q_1 and Q_2 are reduced.

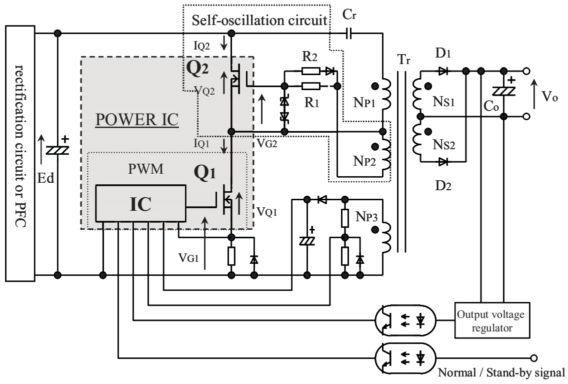

Figure 1. Circuit configuration

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III. Analysis of States and Operating Modes

Figure 3 shows the equivalent circuits of the converter shown in Fig.1, which is divided into eight behavior states. Taking into account the combination of the eight states of behavior, they are further divided into four operating modes [5-7].

Figure 4 shows the simulated waveforms of the current and voltage for the four operating modes. From the results, the operating modes appear in the order of I, II, III and IV when the load current is varied from a light load to the heavy load.

The operating modes I and II mainly appear at light load. The energy in C_r is discharged when the Q_1 turns off and Q_2 turns on, and charged by applying the output voltage E_d of the PFC when the Q_1 turns on and Q_2 turn off. Therefore, the energy is discharged to the secondary side through the transformer. However, because of the magnetizing inductance L_m is set relatively large when there is shortage of the energy discharged from C_r, operating state 7 appears, in which there is no discharging interval to the secondary side.

In mode III, a ripple is reduced and smoothed by the leakage inductance L_{l2} of the secondary winding and the output capacitor C_o because the current flows continuously through D_1 and D_2, alternately.

The Mode IV appears when the duty ratio is almost over 50 %. In this mode, the state 8 appear where the power is not applied to the secondary side even when Q_1 turns on.

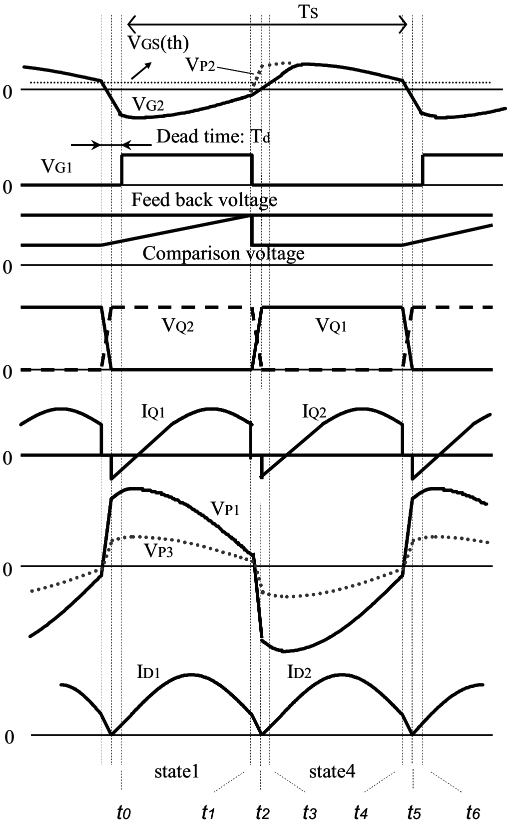
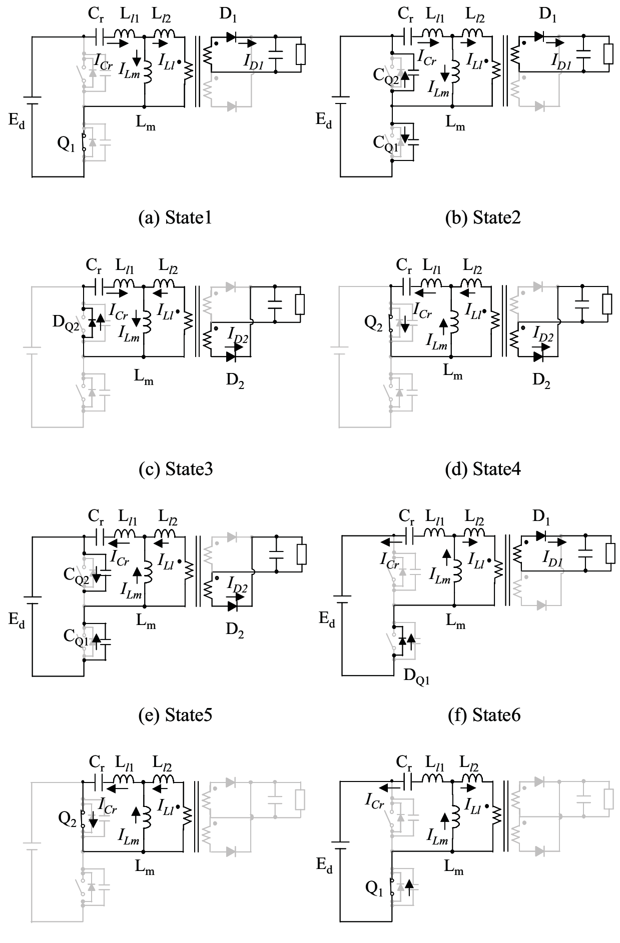


Figure 2. Timing chart



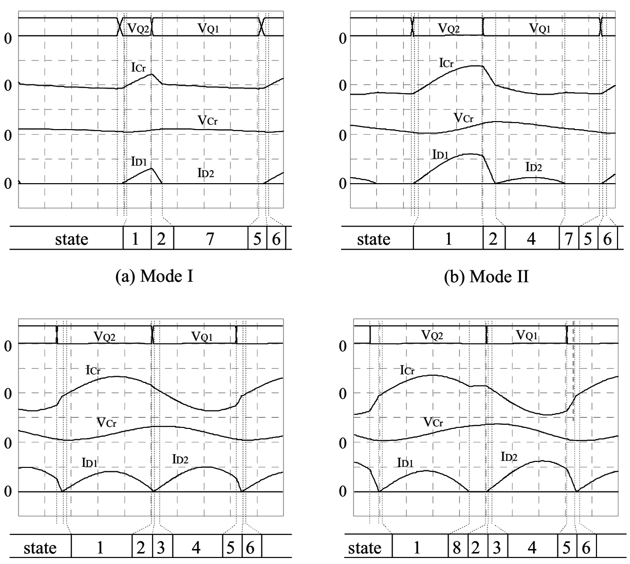
(a) State1 (b) State2

(c) State3 (d) State4

(e) State5 (f) State6

(g) State7 (h) State8

Figure 3. Equivalent circuits and operation states



(a) Mode I (b) Mode II

(c) Mode III (d) Mode IV

Figure 4. Operation modes

IV. RESULT OF POWER EFFICIENCY ANALYSIS

In this converter, the output power is controlled by transmitting the energy stored in the resonant capacitor. It has been clarified in the recent papers that voltage amplitude of C_r is important to determine the output power [5-7]. In the Mode III, assuming that the voltage amplitude of C_r is equal to the output voltage E_d of the PFC when the maximum output power is received from C_r in the converter, the maximum output can be approximated by E_d.

$$P(C_r) = C_r \cdot E_d^2 \cdot f_r \tag{1}$$

where f_r is the resonant frequency, given by

$$f_r = \frac{1}{2\pi\sqrt{C_r \cdot L_r}} \tag{2}$$

where L_r is the inductance of primary side at the short-circuit of the secondary winding, given by

$$L_r = L_{l1} + \frac{L_{l2} \cdot L_m}{L_{l2} + L_m} \tag{3}$$

Therefore, it is important to determine the parameters E_d, C_r and L_r for realizing the maximum power from C_r. In addition, a magnetizing inductance L_m is supposed to be sufficiently large.

The relations between the power efficiency and each circuit parameters are investigated as follows.

A. Power Efficiency Analysis with Effective Currents

Fig.5 (a), (b) and (c) show the power efficiency and a duty ratio of switch Q_1, taking E_d, C_r and L_r as parameters, respectively. The experimental conditions are as follows: E_d=350V, 360V, 380V, C_r,=12nF, 15nF, 18nF, L_r=180μH, 320μH, 220μH 400μH, L_m=13mH, 18mH, a output current of I_o=1A - 7A.

It is seen in Fig.5 that the power efficiency becomes max when duty is 50 % even if E_d, C_r and L_r varied. Fig.6 shows the switching frequency characteristics, taking E_d, C_r and L_r as parameters. The experimental conditions are same as in Fig.5. In Fig6, the switching frequency is almost constant in the current range of 3A or more. In this case, the duty is over 35%. Therefore, this converter achieves high efficiency when duty is 50 %. And the influence of the switching loss can be disregarded because the switching frequency becomes constant at the mode III where duty is approximately 50 %.

Then, as follows discussing the conduction loss, the stored energy in C_r is composed of the current transmitted to the secondary side I_o and the current circulated through the only primary side I_{CP}. These relations are

$$n \cdot (I_{Cr} - I_{CP}) = I_o \tag{4}$$

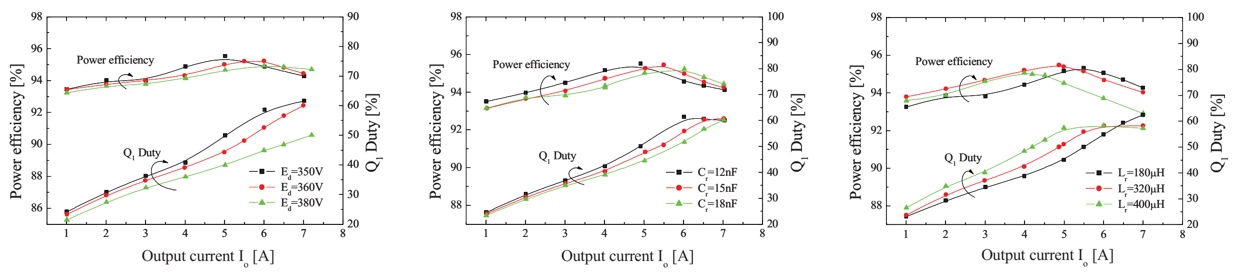
where n is the winding ratio of the primary side and the secondary side,

$$n = T_{NP} / T_{NS} \tag{5}$$

where, T_{NP} is the winding number of primary side, and T_{NS} is the winding number of secondary side.

Fig.7 shows an analysis of the effective currents $I_{CP(RMS)}$, $I_{o(RMS)}$. These currents in Fig.7 are normalized by the output current I_o. It is seen in Fig.7 that the circulated current of primary side is almost constant and comparatively small even when duty is changed. The effective current of secondary side is minimized when duty is almost 50%, in which the proposed converter is able to minimize the consumption loss.

As a result, it is confirmed that the maximum power efficiency is achieved when duty is about 50%.

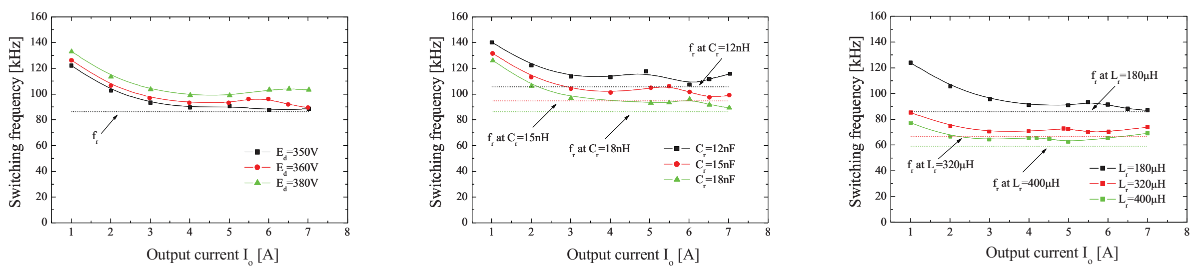


L_m=1.3mH, L_r=180μH, C_r=18nF — (a) E_d

L_m= 1.3mH, L_r=180μH, E_d=360V — (b) C_r

L_m=1.8mH, C_r=18nF, E_d=360V — (c) L_r

Figure 5. Power efficiency and duty cycle characteristics



L_m= 1.3mH , L_r=180μH, C_r=18nF — (a) E_d

L_m= 1.3mH, L_r=180μH, E_d=360V — (b) C_r

L_m=1.8mH, C_r=18nF, E_d=360V — (c) L_r

Figure 6. Switching frequency characteristics

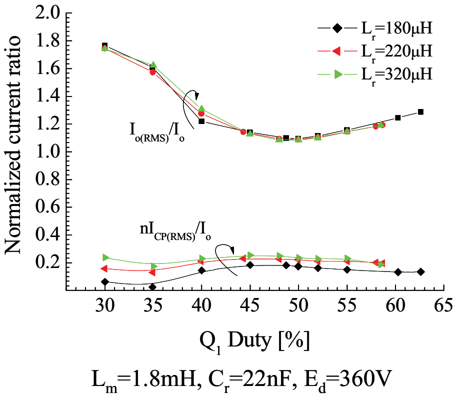


Figure 7. Q_1 duty-normalized current ratio

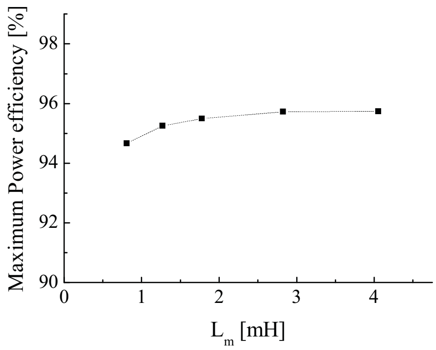


Figure 8. L_m vs. maximum power efficiency

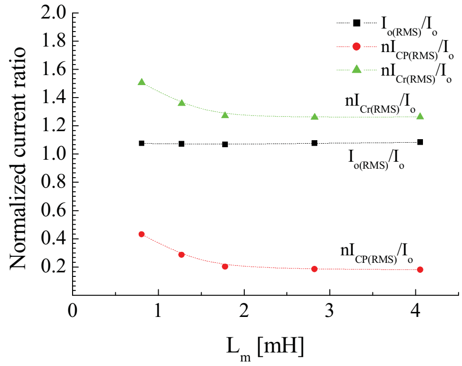


Figure 9. L_m vs. normalized current ratio

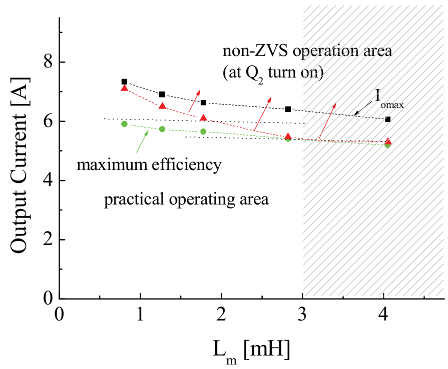


Figure 10. L_m vs. normalized current ratio

B. The Design of Magnetizing Inductance L_m

A feature of this converter is able to suppress the rise of the frequency at light load because of the proposed control method.

Therefore, L_m can be designed relatively large compared with PFM controlled current resonant type converter.

In equation (1), a magnetizing inductance L_m is assuming that it is sufficiently large. Then the relation between L_m and power efficiency is investigated.

Figure 8 shows a power efficiency characteristics at duty is 50% when L_m is changed. It is found that the maximum power efficiency improves when L_m is enlarged.

Figure 9 shows an analysis of the effective currents $I_{CP(RMS)}$ and $I_{o(RMS)}$ at the duty 50%. In a word, it is the load at the maximum efficiency point. These currents in Fig.9 are also normalized by the output current I_o same as Fig.7.

It can be seen in Fig.9 that the circulated current of primary side can be decreased with keeping the effective currents of secondary side is almost constant when L_m is increased.

However, at heavy load, the switch Q2 is not able to achieve ZVS when L_m becomes large.

Figure 10 shows maximum output current I_{omax} and a range where Q_2 is able to achieve ZVS. The experimental conditions are as follows:

E_d=360V, output voltage V_o=24V, output current I_o=1A-7A, C_r=22nF, L_r=320μH, L_m=0.8mH, 1.3mH, 1.8mH, 4.1mH and C_{Q1}=C_{Q2}=170pF.

Non-ZVS is observed in the area of L_m=3mH or more from figure 10. It is found that L_m=3mH or less is preferable to achieve a ZVS at the maximum efficiency in the rated load. And L_m=2mH or less is preferable to achieve ZVS at maximum power, if it is defined as 110% from rated load.

Therefore the preferable design of L_m is about 2mH or less from the viewpoint of ZVS operation, maximum power efficiency and maximum output power. It can be seen in Fig10 that the maximum power efficiency is 95.4% with L_m is 1.8mH.

V. CONCLUSION

This paper is conclude as follows,

(1) This converter is controlled by a combination of self-oscillation and a separated oscillation.

(2) This converter has eight states and four operating modes.

(3) This opposed converter is able to achieve high efficiency at duty of switch Q_1 is 50%.

(4) Power efficiency improves when L_m becomes large.

(5) It is necessary to select L_m within the range where Q_2 is able to achieve ZVS.

(6) It is necessary to select L_m about 2mH from the viewpoint of ZVS operation, maximum power efficiency and maximum output power.

(7) The maximum power efficiency is 95.4% with the magnetizing inductance 1.8mH.

REFERENCES

[1] M. Gekinozu, K. Kuroki, K. Mori, T. Fujita "Self-oscillated type current resonant DC/DC converter", IEICE Technical Report, EE99-58, pp.33-38. 2002.

[2] Y. Nishikawa, T. Nozawa, S. Igarashi, K. Kuwahara, N. terasawa "Multi-oscillated Current Resonant Converter", Annual Conference Record of EEEJ, Vol.4, pp.157-158, 2002.

[3] Y. Nishikawa, T. Nozawa, S. Igarashi, K. Kuwahara, N. Nozawa, H. Ota "A control method that reduce the conversion loss at a light load", Annual Conference of Japan, Industry Application Society, pp.631-632, 2002.

[4] K. Kuwahara, H. Ota "On the Output Increase of a Series Resonant DC-DC Converter", IEICE Technical Report, Vol.105, no.45, EE2005, pp.35-40, 2005.

[5] R.Araki, O. Matsuo, H. Ota, M. Tuji, Y. Ishizuka, H. Matsuo "Static Analysis of Multi-Oscillated Current Resonant Type DC-DC Converter", IEICE Technical Report, EE2006-31, pp13-18, 2006.

[6] N. Higashi, R. Araki, O. Matsuo, H. Ota, Y. Ishizuka, H. Matsuo "Multi-Oscillated Current Resonant Type DC-DC Converter", IEICE General Conference, pp.S-45-46, 2007.

[7] O. Matsuo, H. Matsuo, Y. Ishizuka, H. Ota "Analysis of a New Multi-Oscillated Current Resonant Type DC-DC Converter", IEEE INTELEC'07, pp.348-354, 2007.