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

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Abstract — This paper deals with an improvement of a power efficiency of a multi-oscillated current resonant type DC-DC converter. The current resonant type converter employs generally the pulse frequency modulation and its magnetizing inductance is set relatively low. For this reason, the magnetizing current through the converter causes a power loss under a light load. In order to solve this problem, 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. In this topology, output power is controlled by duty ratio and operating frequency is determined by resonant condition.

In this paper, an analysis of power loss by focusing on switching devices in this converter to improve power efficiency was given. As a result, it was confirmed that the loss of diodes in secondary side occupies main loss. Adopting the synchronous rectifier in the secondary side, the maximum power efficiency is improved to 96.3%, and the average efficiency, which is averaged efficiency at 25%, 50%, 75% and 100% of the rated load, reached 95.5%.

I. INTRODUCTION

A switching power supply system with the high efficiency, small size, low noise and low cost, is required in many areas of not only consumer electronics but also telecommunication systems such as personal computers, cellular phones, flat panel displays and so forth. Recently, keeping to high efficiency from the light load to the rated load is more important from the point of energy savings considering actual operating condition of the power supply.

The current resonant type converters make practicable because of high efficiency and low noise. Generally the pulse frequency modulation (PFM) is applied to the current resonant type converters [1, 2]. However, this type of converter has problem, in which a magnetizing current through the converter causes a loss of power under the light load. Consequently, it is hard to improve average efficiency from the light load to the rated load.

In order to solve these problems, a multi-oscillated current resonant type DC-DC converter has been proposed [3, 4].

It has been clarified in recent investigation that maximum output power is depend on the energy charged in resonant capacitor [5, 6]. In addition, as an analysis of power efficiency, analyzed from the viewpoint of the duty ratio and a through current in primary and secondary sides [7].

This paper presents an analysis of power loss by focusing on switching devices in a Multi-Oscillated Current Resonant Type DC-DC Converter, and an improvement of power efficiency by using synchronous rectifier on the secondary side.

II. CIRCUIT CONFIGURATION AND OPERATING PRINCIPLE

Fig. 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 which consist of MOSFET, 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.

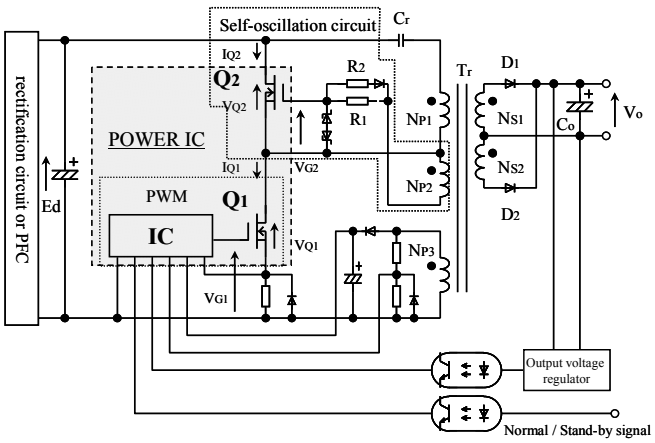

Fig. 1 Circuit configuration

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III. ANALYSIS OF STATES AND OPERATING MODES

Fig. 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].

Fig.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.

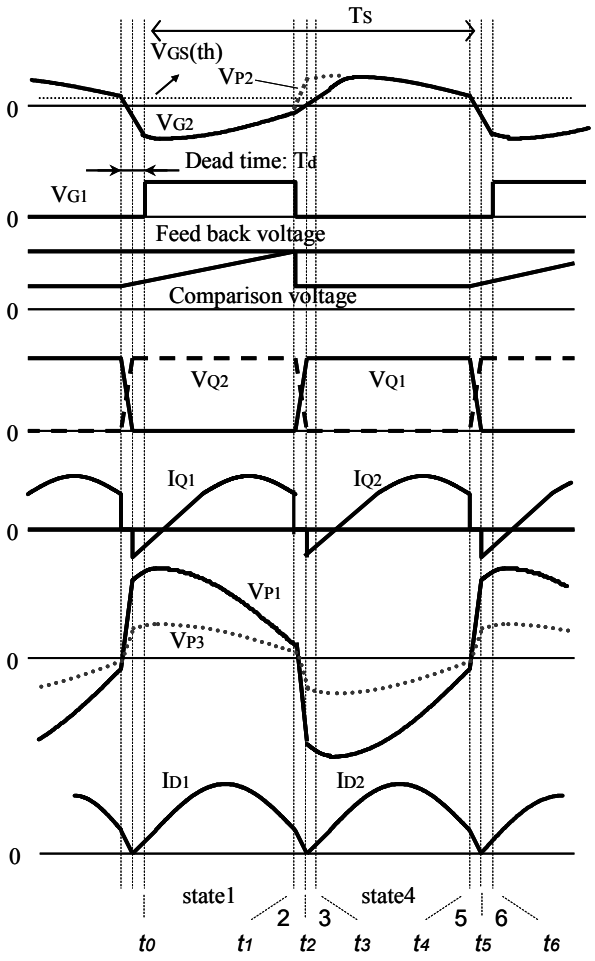


Fig. 2 Timing chart

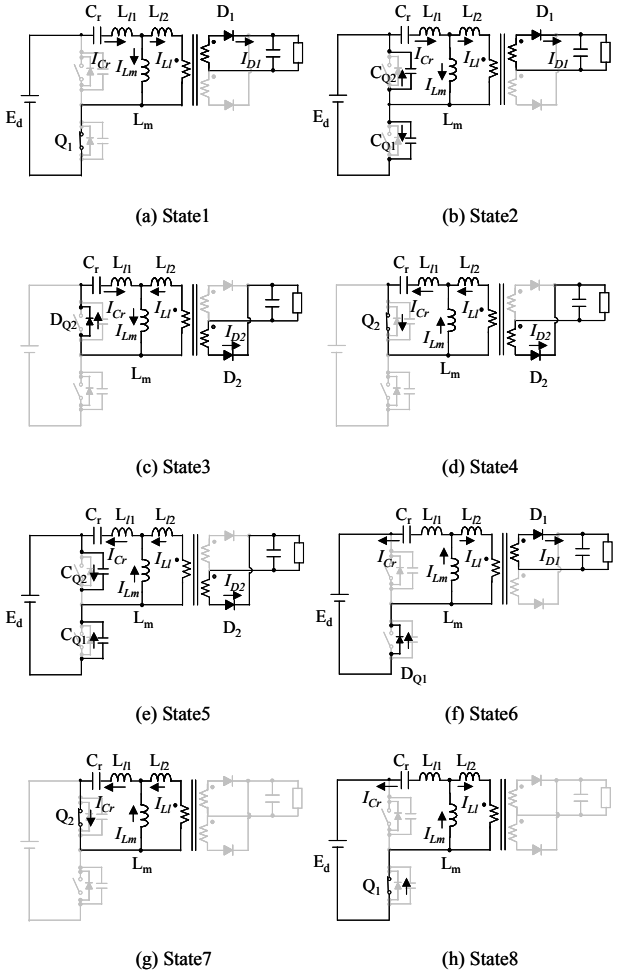


Fig. 3 Equivalent circuits and operation states

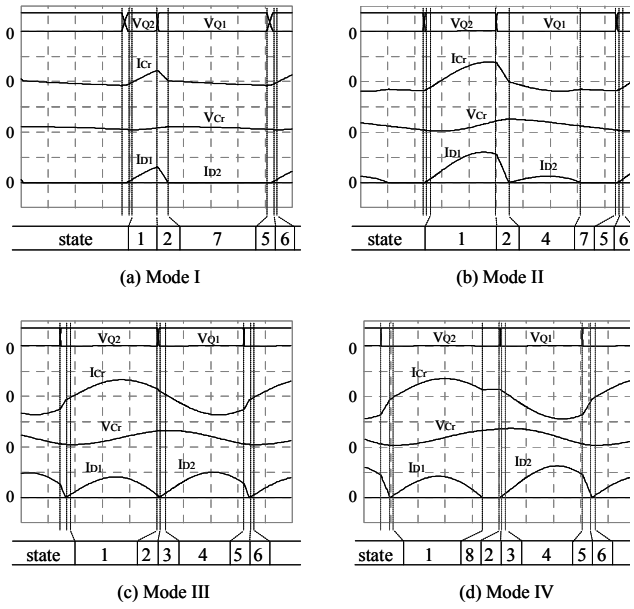


Fig. 4 Operation modes

IV. POWER EFFICIENCY IMPROVEMENT

A. Power loss analysis by focusing on the switching devices

Fig. 5 shows the power efficiency characteristic of this converter. The experimental conditions are as follows:
Output voltage E_d of PFC= 360V, Output voltage V_o=24V, Output current I_o=0.5A-6.2A, Output Rating P_o (typ.) =144W, Resonant Capacitor C_r=22nF, Resonant Inductance L_r= 320uH, Magnetizing Inductance L_m=1.8mH, Winding ratio of T_r N_{P1}: N_{S1} (=N_{S2}): N_{P2}: N_{P3}= 59: 8: 5: 6

To improve power efficiency from the light load to the rated load, power losses in the switching devices at 25%, 50%, 75% and 100% of the rated load are analyzed.

At first, loss E_{Dn} (n=1, 2) of diode D_1 and D_2 consist of conductive loss E_{conDn} (n=1, 2) of diode and switching loss E_{swDn} (n=1, 2) of diode. And they are given as:

$$E_{Dn}=E_{conDn}+E_{swDn} \quad (1)$$

$$E_{conDn}=V_{FDn}\cdot I_{Dn} \quad (2)$$

$$E_{swDn}=E_{onDn}+E_{trrDn} \quad (3)$$

where, V_{FDn} and I_{Dn} (n=1, 2) are forward voltage and forward current respectively, and assumed for estimate that V_{FDn} are 0.4V and I_{Dn} use the effective current of D_n (n=1, 2).

E_{onDn} and E_{trrDn} are turn-on loss and reverse recovery loss respectively.

Next, loss E_{Qn} (n=1,2) of switch Q_1 and Q_2 are given as:

$$E_{Qn}=(I_{Qn})^2\cdot R_{DSonQn}+E_{swQn} \quad (4)$$

where, R_{DSonQn} are resistance of MOSFET during turn on and assumed 0.5 Ω. I_{Qn} use the effective current of Q_n. The switching loss E_{swQn} of MOSFET which consists of loss E_{onQn} at turn-on and loss E_{offQn} at turn-off are given as:

$$E_{swQn}=E_{onQn}+E_{offQn} \quad (5)$$

Because of this converter achieves ZVS and ZCS at the point of turn-on of Q_1 and Q_2, E_{onQn} are negligible. Therefore, (5) is simplified as:

$$E_{swQn}=E_{offQn} \quad (6)$$

In addition, the period of state 3 and state 6 in Fig. 2, although current through the body-diode of MOSFET generates the loss before Q_1 or Q_2 turns-on, these periods are short so this loss is assumed negligible.

Fig. 6 shows the estimated power loss and the power loss ratio of the switching devices. In this figure, an item of "Other" consists of other loss (e.g. loss of transformer, conductive loss of PC board) except for switching device.

It can be seen in Fig. 6 that the loss of diodes in secondary side occupies over 50% of total loss under all load condition.

Fig. 7 shows the specifics of power loss in diodes. It is found that the main loss of diodes is almost conductive loss.

Furthermore, in Fig. 6 and 7, it is confirmed that the loss of D_1 is the most significant under the load condition from 25% to 75% of the rated load.

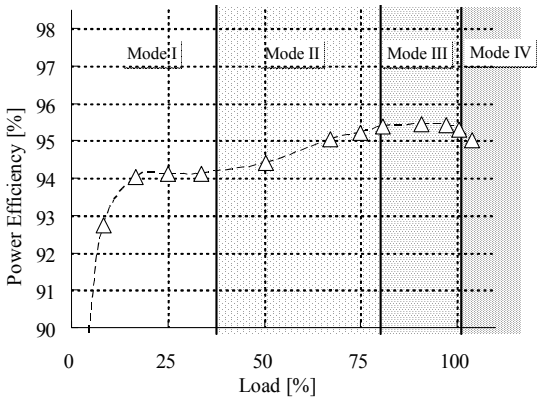
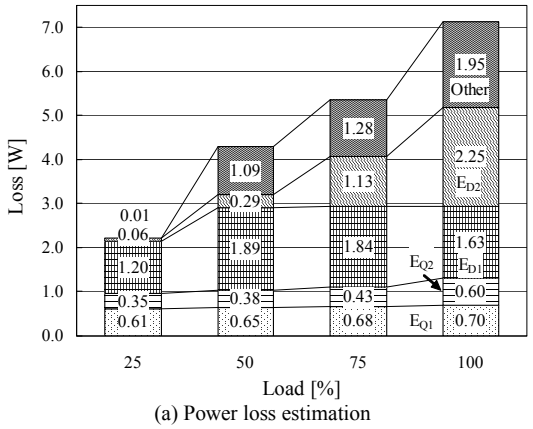
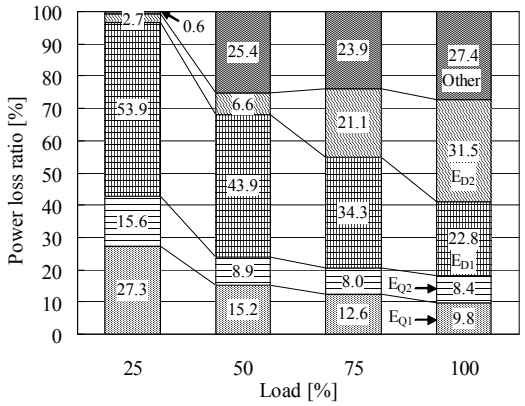


Fig. 5 Power efficiency characteristic



(a) Power loss estimation



(b) Power loss ratio

Fig. 6 Power loss

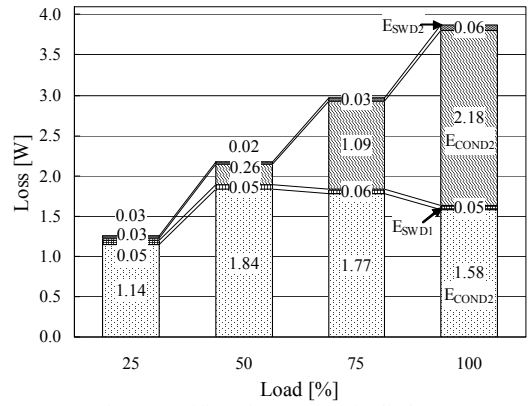


Fig. 7 Specifics of power loss in diodes

B. *Power efficiency improvement using synchronous rectifier*

Generally, current resonant type DC-DC converter employs PFM control and the duty ratio of switch is 50% regardless of load condition. Therefore the current of diodes in the secondary sides are symmetric. On the other hand, in this proposed converter, the duty ratio of switch Q1 is varied with the load condition. Because of this reason, the current in the secondary sides through D_1 and D_2 becomes asymmetric. In Fig. 8, during Mode I and Mode II, the current through D_1 is higher than that of D_2. Meanwhile the current through D_2 is higher during Mode IV. By reducing the power loss of D_1, improvement of power efficiency in wide range of load is expected.

It is known that adopting synchronous rectifier to reduce power loss of diodes.

Fig.9 shows circuit configuration of synchronous rectifier. In this circuit, diode D_1 is replaced with MOSFET Q_{S1}. Comparator detects direction of the current by sensing voltage between Drain and Source of Q_{S1}. The same circuit configuration is applied to replace D_2 with Q_{S2}. A power for the comparator and the driver in this circuit is supplied from additional winding on secondary side.

Fig.10 shows power loss characteristics and Fig.11 shows improved power efficiency characteristics. In these figures, only one side of D_1 or D_2 was replaced with the synchronous rectifier to confirm its effect. It is confirmed in Fig. 10 that the power loss at the rated load reduces 15% (7.13W to 6.06W) in the case of replacing D_1, and 19% (7.13W to 5.78W) in the case of replacing D_2. And it is found in Fig. 11 that power efficiency at the rated load are 96.0% and 96.2% when replacing D_1 and D_2 respectively. Regarding at the rated load, changing D_2 is effective to improve power efficiency. But considering wide range from the light load to the rated load, changing D_1 is more effective.

As a result, it is seen in Table 1 that maximum power efficiency achieves 96.3% and the average efficiency is 95.5% by adopting the synchronous rectifier to D_1.

The details of control method and optimization of synchronous rectifier will be reported in our next paper.

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) In this converter, the loss of diodes in secondary side occupies over 50% of total loss.

(4) The current in the secondary sides through D_1 and D_2 becomes asymmetric because the duty ratio of switch Q_1 is varied with the load condition.

(5) The power loss at the rated load reduces 15% in case of adopting Q_{S1}, and 19% in the case of adopting Q_{S2}.

(6) Considering wide range from the light load to the rated load, adopting the synchronous rectifier to D1 is more effective and maximum power efficiency achieves 96.3% and the average efficiency is 95.5%.

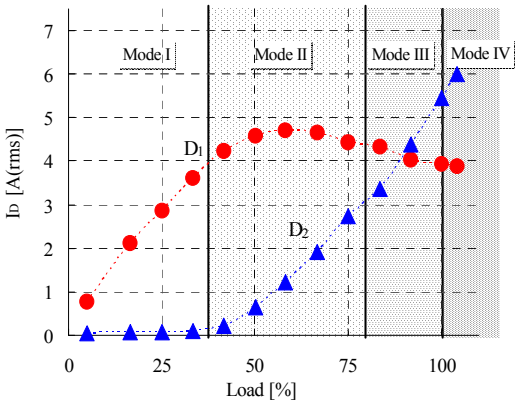


Fig. 8 The current characteristics of Diodes

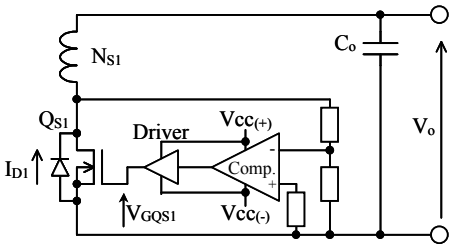


Fig. 9 Circuit configuration of synchronous rectifier

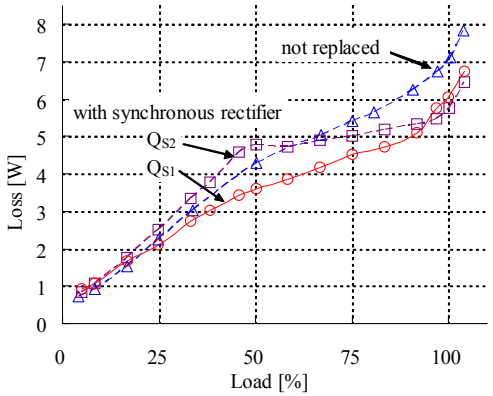


Fig. 10 Power loss characteristics

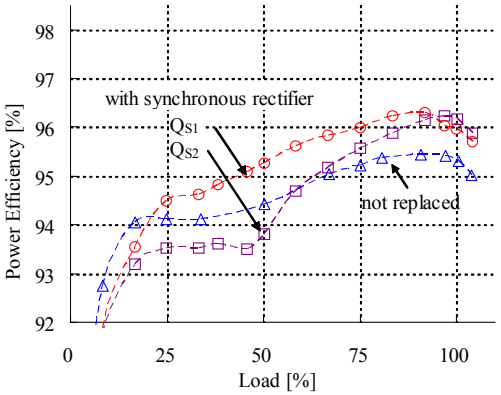


Fig. 11 Improved power efficiency characteristics

Table 1 comparison of power efficiency

	Replaced with synchronous rectifier			
	Load	not replaced	D1	D2
Power Efficiency	25%	94.1%	94.5%	93.5%
	50%	94.4%	95.3%	93.8%
	75%	95.2%	96.0%	95.6%
	100%	95.3%	96.0%	96.2%
	maximum	95.4%	96.3%	96.2%
	average	94.7%	95.5%	94.8%

VI. REFERENCES

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