Light-Load Efficiency Improvement Using Load Adaptive Gate Driving Method

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Abstract— In this paper, a new gate driving method to improve light-load efficiency is proposed for the power conversion system with a standby converter. The proposed method reduces the gate driving voltage of power MOSFETs and operating voltage of controller ICs under light load conditions by adjusting the auxiliary output voltage of the standby converter. Therefore, the gate driving loss on MOSFETs and the loss on controller ICs are significantly reduced without the degradation of performance in the main power stage. To confirm the validity of this study, the DC/DC server power supply with 48V input, 12V/60A output for the DC/DC stage, and 5V/3A output for the standby stage is experimented.

Index Terms—Gate driving method, light load efficiency, server power supply, standby converter

I. INTRODUCTION

Today, energy saving in power supplies is an essential issue in order to suppress global warming. As consumer electronic devices and data-processing equipment have grown rapidly, this environmental concern has prompted manufacturers to minimize power consumption under light load conditions as well as full load condition. For example, the 80 Plus incentive program [1] and Climate Saver Computing Initiative (CSCI) [2] require high efficiency from full load to 10% load condition. Furthermore, many manufacturers for computer, telecom, and network equipment require high efficiency under light load conditions that exceed the latest Energy Star specifications, and these requirements tend to be extended down to even 5% load. Thus, many literatures have been presented to improve the light load efficiency [3]-[26].

Generally, the power converters degrade the conversion efficiency mainly due to the conduction loss on semiconductor devices under heavy load conditions. On the other hand, power consumption under light load conditions is dominated by the switching loss and the gate driving loss on semiconductor devices, the power loss on controller ICs, and the core loss on magnetic components [7]-[9]. Among many methods to improve light-load efficiency, decreasing switching frequency is widely used by using the variable frequency control [10], [11] and burst mode control [9], [12], which reduces the

Fig. 1. Typical gate driving circuit in the power supply

switching loss and gate driving loss. However, they lead to poor dynamic performance because the operating frequency changes over a wide range according to the load variation, and in case of the burst mode operation, poor electromagnetic interference (EMI) and audible noise are other issues [8]. On the other hand, reducing gate driving loss can be an effective method to improve light-load efficiency without the degradation of performance in the main power stage [13]-[26].

Fig. 1 describes the typical gate driving circuit in the power supply with the standby converter. In general, the standby converter provides operating power for controller ICs and gate drivers by using auxiliary output stages. The linear regulator tightly regulates the voltage V_{CC} from the auxiliary output voltage V_{AUX} . Meanwhile, the gate driving loss can be reduced by modifying the main power stage, which means that one power MOSFET with large gate charge is replaced by paralleled several MOSFETs with small gate charge, and some of them are turned off under light load conditions so that total gate charge can be decreased [13]-[15]. However, these methods are suitable for the integrated power stage, but not for the discrete power stage due to the large size of many discrete MOSFETs. Other techniques, the resonant gate driver (RGD) circuit [16]-[22] and adaptive gate driving voltage methods [23]-[25], modify the gate driver circuit. The resonant gate drive circuit can recycle the gate charge by using LC-resonance, and the adaptive gate driving voltage methods can reduce the gate charge by decreasing the gate driving voltage V_G of the gate driver, which results in low power consumption on the gate driver. However, these methods are complex, and especially RGD circuit has a large inductor when the converter operates at low switching frequency. Meanwhile, there is another method

Fig. 2. Standby converter (a) conventional structure (b) proposed structure

to modify the linear regulator circuit in [26], where V_{CC} of linear regulator becomes decreased to reduce V_G under light load conditions. However, it has the adverse effect that the reduced V_{CC} makes large loss on the linear regulator.

This paper presents a simple method to reduce power loss under light load conditions for the power supply with the standby converter. The proposed method can decrease not only V_{CC} but also V_{AUX} in the standby converter under light load conditions so that the gate driving loss as well as the loss on the controller ICs and linear regulator circuit can be reduced significantly.

II. PROPOSED METHOD

The proposed method is based on a simple observation that the gate driving loss P_G , the controller loss P_{CON} , and the loss on linear regulator P_{LR} are related to V_{AUX} and V_{CC} in Fig. 1. Those losses are given by

$$P_G = Q_G V_G f_s = Q_G V_{CC} f_s = C_{iss} V_{CC}^2 f_s \quad (1)$$

$$P_{CON} = V_{CC} I_{CC} \quad (2)$$

$$P_{LR} = (V_{AUX} - V_{CC}) I_{LR}, \quad (3)$$

where Q_G is the gate charge of the MOSFET, C_{iss} is the input capacitance of the MOSFET, f_s is the switching frequency, I_{CC} is the current on the controller, I_{LR} is the current on the linear regulator. Typically, $V_G = V_{CC}$. It is clear from (1) and (2) that decreasing V_{CC} can reduce P_G and P_{CON} . Meanwhile, since low gate driving voltage indicates low gate charge and low current

Fig. 3. Operational principle of the proposed standby converter under (a) heavy load conditions (b) light load conditions

I_G flowing toward the gate node of the MOSFET, I_{LR} can be reduced by decreasing V_{CC} , which results in low P_{LR} . However, we can know from (3) that it is undesirable to reduce V_{CC} only in the linear regulator circuit as P_{LR} increases. On the other hand, if not only V_{CC} but also V_{AUX} decreases in the linear regulator circuit, P_{LR} can be reduced due to decreased I_{LR} . Therefore, in the proposed method, both V_{AUX} and V_{CC} become low level under light load conditions so that P_G , P_{CON} and P_{LR} can be reduced greatly.

The implementation of the proposed method is described in Fig. 2. Generally, the multi-output flyback converter in Fig. 2(a) is widely used for the standby converter due to a simple structure and low cost. The primary switch Q_{STB} controls the main output voltage V_{STB} through the main secondary winding N_S and diode D_S , whereas V_{AUX} is cross-regulated through the auxiliary winding N_{AUX} and diode D_{AUX} . As the cross-regulation characteristic is poor in the flyback converter, the linear regulator is used to tightly regulate V_{CC} from V_{AUX} . On the other hand, in order to reduce both V_{AUX} and V_{CC} under light load conditions of the main power stage, a new structure for the standby converter is proposed as shown in Fig. 2(b). The secondary turns N_{AUX} of the transformer in the conventional structure are divided into N_{AUX1} and N_{AUX2} in the proposed structure so that $N_{AUX} = N_{AUX1} + N_{AUX2}$. In addition, V_{AUX} can be varied according to the load condition in the main power stage, changing a powering path between the path through D_{AUX1} and the path through D_{AUX2} . It can be achieved by turning on or off the auxiliary PMOS switch Q_{AUX} . Moreover, V_{CC} can be varied by turning on or off the NPN transistor Q_{LR} . Under heavy load conditions in the main power stage, Q_{AUX} is ON-state so that the powering current can flow through D_{AUX1} and Q_{AUX} , and D_{AUX2} can be reverse bias as shown in Fig. 3(a). Therefore, V_{AUX} is the same as that of the conventional structure as follows:

Fig. 4. Typical structure of DC/DC server power supply

Fig. 5. Control scheme for the proposed method

$$V_{AUX} = \frac{N_{AUX1} + N_{AUX2}}{N_s} V_{STB} = \frac{N_{AUX}}{N_s} V_{STB}. \quad (4)$$

Furthermore, since Q_{LR} is OFF-state, V_{CC} can be expressed as

$$V_{CC} = V_{REF_LR} \left(1 + \frac{R_2 + R_3}{R_1} \right) \quad (5)$$

where V_{REF_LR} is the reference voltage in the linear regulator. On the other hand, under light load conditions in the main power stage, Q_{AUX} become OFF-state so that the powering current can flow through D_{AUX2} , and D_{AUX1} can be turned off as shown in Fig. 3(b). Therefore, V_{AUX} is reduced as follows:

$$V_{AUX} = \frac{N_{AUX2}}{N_s} V_{STB}. \quad (6)$$

Furthermore, since Q_{LR} is ON-state, V_{CC} is also reduced to the following equation:

$$V_{CC} = V_{REF_LR} \left(1 + \frac{R_2}{R_1} \right). \quad (7)$$

Fig. 6. Measured Efficiency

The proposed standby converter can be effective to improve the light-load efficiency for the power system application with the standby converter such as server computer, PC, LED TV and so on. In addition, the auxiliary winding shown in Fig. 2(b) can be used for the proposed gate driving method in the application without the standby converter where the operating voltage of the controller is served from the auxiliary winding of the main converter.

III. EXPERIMENTAL RESULTS

To confirm the validity of the proposed method, 720W prototype of the DC/DC server power supply is implemented as shown in Fig. 4. The phase-shift full-bridge (PSFB) converter is adopted for the main power stage, and the multi-output flyback converter shown in Fig. 2(b) is adopted for the standby stage. The parameters of the PSFB converter are the input voltage $V_{in}=38\sim75V$, output voltage $V_o=12V$, primary and secondary turns of transformer $N_p:N_s:N_s=5:2:2$, magnetizing inductance $L_{m_DCDC}=158\mu H$, leakage inductance $L_{lk_DCDC}=1\mu H$, switching

Fig. 7. Experimental waveform of the gate driving voltage according to load change in the main power stage

Fig. 8. Loss distribution based on the experimental results under light load conditions

frequency $f_{S_DCDC}=70\text{kHz}$, primary switches $Q_1\sim Q_4$ =IPP041N12N, secondary synchronous rectifier $SR_1\sim SR_2$ =IPP030N10N, output inductor $L_O=1\mu\text{H}$. Meanwhile, the parameters of the flyback converter are the output voltage $V_{STB}=5\text{V}$, $P_{O_STB}=15\text{W}$, primary and secondary turns of transformer $N_P:N_S=30:5$, magnetizing inductance $L_{m_STB}=200\mu\text{H}$, switching frequency $f_{S_STB}=65\text{kHz}$, primary switch Q_{STB} =FQP10N20, main rectifier diode D_S =SBR30A45CT, auxiliary rectifier diode $D_{AUX1}\sim D_{AUX2}$ =015MQ040N, auxiliary switch Q_{AUX} =Si4413DY, linear regulator=LM317. In addition, V_{AUXP} and V_{CCP} in the primary side are designed to be 15V and 13V over 30% load condition, and to be 10V and 8V below 30% load condition, respectively. Thus, $N_{AUX1}=9$, $N_{AUX2}=5$, $R_1=1.2\text{k}\Omega$, $R_2=6.2\text{k}\Omega$, and $R_3=5.1\text{k}\Omega$ is selected by (4), (5), (6), and (7). In the secondary side, V_{AUXS} and V_{CCS} are designed to be 15V and 13V over 30% load condition, and to be 9V and 7V below 30% load condition, respectively. Thus, $N_{AUX1}=10$, $N_{AUX2}=4$, $R_1=1.2\text{k}\Omega$, $R_2=5.6\text{k}\Omega$, and $R_3=5.6\text{k}\Omega$ is selected by (4), (5), (6), and (7). In order to turn on or off Q_{AUX} and Q_{LR} depending on the load condition, the control circuit is implemented as shown in Fig. 5. Under heavy load conditions in the main DC/DC power stage, load information is larger than reference voltage V_{REF} , which means that the output of comparator is high and Q_{AUX} is turned on and Q_{LR} is turned off. On the other hand, under light load conditions, the output of comparator is low so that Q_{AUX} is turned off and Q_{LR} is turned on. Fig. 6 shows the measured efficiency for the DC/DC server

power supply in Fig. 4 by using the conventional gate driving method where $V_{CCP}=V_{CCS}=13\text{V}$ regardless of the load condition and by using the proposed method. It is demonstrated that the efficiency under light load conditions can be improved by using the proposed method. Especially, the efficiency under 10% load condition is greatly improved. Fig. 7 shows the key waveforms of V_{CC} , V_{AUX} and V_G when the output current I_{O_PSFB} in the main power stage is changed from 30A to 3A and vice versa. It is confirmed that the proposed method is operated as expected. Fig. 8 shows the loss distribution calculated by (1), (2), and (3) under light load conditions. As shown in Fig. 8, we can know that the gate driving loss, losses on controller and linear regulator are reduced greatly. Especially, the gate driving loss is significantly reduced because Q_G is 128.7nC for $Q_1\sim Q_4$ and 113nC for $SR_1\sim SR_2$ in the proposed method, whereas Q_G is 191.2nC for $Q_1\sim Q_4$ and 201.4nC for $SR_1\sim SR_2$ in the conventional method.

IV. CONCLUSION

This paper introduces a new load adaptive gate driving method that achieves low power consumption under light load conditions. Compared to the conventional method, the proposed method reduces the gate driving voltage under light load conditions by adjusting the auxiliary output voltage of the standby converter. Therefore, the gate driving loss as well as losses on controller ICs and linear regulator is reduced without the degradation of performance in the main power stage. The validity of this study is confirmed by the experimental results. It is suitable for the power system applications with the standby converter such as server computer, PC, LED TV and so on.

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