A Control IC for an Optocoupler-less DC-DC Converter
with a Current Mirror Detection Circuit

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A control IC has been developed that can provide a small flyback DC-DC converter without an optocoupler. This IC has new detection and control circuits using current mirrors and level-shift circuit technology. It reduces the mounting area of the DC-DC converter by 30%, and the DC-DC converter exhibits constant-voltage characteristics and conversion efficiency comparable to those of conventional converters.

Keywords: Control IC, DC-DC Converter

I. Introduction

Smaller power supplies are needed for electronic equipment, such as mobile PCs (personal computers) and telecommunication devices. Consequently, power-supply components like transformers, inductors, rectifiers, and main switches are being miniaturized or integrated into control circuits[1],[2].

As shown in Fig. 1, a conventional flyback DC-DC converter consists of a transformer, a filter, a control circuit, a main switch, a detection circuit, and an optocoupler. The input voltage, \( V_i \), and the output voltage, \( V_o \), are isolated by the optocoupler. The isolation voltage of the optocoupler between the input side and the output side is several thousand volts. However, the integration of the optocoupler into the monolithic IC is difficult.

Figure 2 shows applications of DC-DC converter used for telecommunications. In this case, the loads are telephones, facsimiles and personal computers. In addition, high-impedance resistors connect a terminal, \( V_+ \) or \( V_- \), with ground. The reason is that if the terminal \( V_+ \) or \( V_- \) is completely floating, the output voltage \( V_+ \) or \( V_- \) increases up to dangerous high voltage. In such applications, high impedance between the terminal \( V_+ \) or \( V_- \) and ground is required, but high voltage isolation is not necessary.

Therefore, the optocoupler can be replaced by a high impedance current mirror circuit. It is noted that this technology cannot be used in the purpose of the high voltage (>300V) isolation. This paper describes a control IC for a flyback DC-DC converter that uses current mirrors and a level-shift circuit instead of an optocoupler.
2. Design Considerations

2.1 New Flyback DC-DC Converter

As shown in Fig. 3, in our flyback DC-DC converter, the optocoupler is replaced with a detection circuit and a level-shift circuit using current mirror technology. The output voltage and current of the converter are detected by current mirror circuits, and the standard level of output voltage $V_o$ is changed to that of input voltage $V_i$ by the level-shift circuit. An auxiliary power supply consists of a basic step-down switching regulator with a series reactor. The current mirror detection circuit, the level-shift circuit, the control circuit, the auxiliary power supply and the driver circuit are integrated on one chip, thereby reducing the mounting area of the converter.

![Fig. 3. Schematic diagram of a new flyback DC-DC converter.](image)

The principle of the detection circuit is illustrated in Fig. 4. The output voltage of the auxiliary power supply, $V_{dd}$, is generated on the input side of the DC-DC converter. The voltage of $V_{dd}$ is higher than that of the output terminal $V_o$ because of operating current mirror circuits $CM_1$ and $CM_2$. Current mirror circuit $CM_1$ consists of $Q_1$ and $Q_2$, and $CM_2$ consists of $Q_3$ and $Q_4$. The output voltage of the DC-DC converter, which appears on a floating level, is transformed into current $I_{d1}$. Current $I_{d1}$ flows to resistor $R$ through $CM_1$ and $CM_2$. If $h_{FE}$ of $Q_1$, $Q_2$, $Q_3$ and $Q_4$ are very large, the collector current of $Q_2$ and $Q_4$, $I_{d2}$ and $I_{d4}$, are almost same as $I_{d1}$. Consequently, detection voltage $V_d (= I_d \times R)$ appears on ground level. Detection voltage $V_d$ passes into the DC-DC control circuit. We estimate the output impedance of current mirror circuit. In the current mirror circuit, the following basic equations are obtained:

$$I_{d1} - I_b = I_{d2} \cdot h_{FE} \cdot \cdot \cdot \cdot \cdot (1)$$

$$I_b = I_{d2} \cdot h_{FE} \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot (2)$$

$$h_{FE} = h_{FE} \cdot (1 + V_{CE} / V_d) \cdot \cdot \cdot \cdot \cdot (3)$$

where $I_b$ is the base current of $Q_2$, $V_{CE}$ is the voltage between the collector and emitter of $Q_2$, and $V_d$ is the Early voltage of $Q_2$. In the output characteristics of bipolar transistors, the I-V lines intersect the negative axis at approximately one point, which is called Early voltage $[3]$. From (1) and (2), we obtain the following equation:

$$I_{d1} = I_{d2} \cdot (1 + 2 / h_{FE}) \cdot \cdot \cdot \cdot \cdot (4)$$

By using (3), we have the following equation:

$$I_{d1} = (1 + \frac{2}{h_{FE} \cdot (1 + V_{CE} / V_d)}) I_{d2} \cdot \cdot \cdot \cdot \cdot (5)$$

When we differentiate the equation (5), we have the following equation:

$$dV_{CE} / dI_{d2} = \frac{(1 + \frac{2}{h_{FE} \cdot (1 + V_{CE} / V_d)}) I_{d2}^2 \cdot \cdot \cdot \cdot \cdot (6)}{2 I_{d2} \cdot h_{FE} \cdot (1 + V_{CE} / V_d)}$$

Considering that Early voltage $V_d$ is sufficiently large, (6) can be approximated as follows:

$$dV_{CE} / dI_{d2} \approx h_{FE} \cdot V_d / I_{d2} \cdot \cdot \cdot \cdot \cdot (7)$$

Therefore, the output impedance of $CM_1$ is $h_{FE} \cdot V_d / I_{d2}$. If $h_{FE} = 100$, $V_d = 200 \, V$, and $I_{d2} = 20 \, \mu A$, the output impedance is $1 \, \Omega$. This is enough impedance. Because, in the use of telecommunications, the output impedance is almost $200 \, k \, \Omega - 300 \, k \, \Omega$. 

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The output-current detection circuit of the DC-DC converter is illustrated in Fig. 5. The output current \( I_o \) of the converter is shunted by resistors \( R_1 \) and \( R_2 \). Current \( I_{lb} \), which flows to resistor \( R_2 \), is the source current of a shunt circuit. The shunt circuit consists of a basic current mirror circuit and a starter circuit. The current mirror circuit of the shunt circuit starts operating when the starter circuit puts a very small current into the current mirror circuit. The shunt circuit outputs current \( I_{lb} \). The \( I_{lb} \) is almost the same as the \( I_{la} \), because the shunt circuit is composed of current mirror circuit. The \( I_{lb} \) is the source current of current mirror circuit CM3. The CM4 outputs current \( I_{lc} \) and current \( I_{ld} \). The \( I_{lc} \) and the \( I_{ld} \) are almost the same as the \( I_{lb} \).

The \( I_{ld} \) is the source current of current mirror circuit CM4. The CM4 outputs current \( I_{le} \) and current \( I_{lf} \). The \( I_{le} \) and the \( I_{lf} \) are almost the same as the \( I_{ld} \). Then current \( I_{le} \) is transformed into detection voltage \( V_{ld} (V_{ld} \cong I_{le} \times R_1 \cong I_{la} \times R_2) \). The \( I_{lf} \) is the source current of current mirror circuit CM5, and the CM5 outputs current \( I_{lg} \). The CM5 is the current-compensation circuit for canceling \( I_{ld} \) from the CM3 to \( V_c \). \( I_{lg} \cong I_{lf} \approx I_{ld} \). To operate the CM3, the CM4, and the CM5, an auxiliary power supply \( V_{dd} \) is required.

The output-voltage detection circuit of the DC-DC converter is illustrated in Fig. 6. Current \( I_{2a} \) flows to resistor \( R_4 \) with output voltage \( V_o \). The principle of the output-voltage detection circuit is the same as that of the output-current detection circuit. \( I_{2a} \) also flows to resistor \( R_3 \) through CM6 and CM7. \( I_{2d} \) is transformed into detection voltage \( V_{do} \). Current mirror circuit CM6 is a current-compensation circuit like CM5.

2.3 Control Circuit

The control circuit (Fig. 7) is controlled using pulse-width modulation (PWM). It consists of an error amplifier (EA), an comparator (Comp), an oscillator (OSC), etc. The standard voltage of the EA is generated by a band-gap reference circuit. There are two control modes: constant current and constant voltage. Depending on the load of the DC-DC converter, a selector chooses either detection output voltage \( V_{ld} \) or \( V_{do} \). The feedback loop gain of the control circuit is regulated by discrete capacitor \( C_F \) and resistor \( R_F \). When an over-current flows through main switch \( M \), the over-current protection circuit (OCP) stops the driver circuit of main switch \( M \).
Figure 8 shows a time chart of the control circuit. Each waveforms represent the output of the clock, EA, OSC, Comp, and NAND. The clock frequency is about 300 kHz. When the output electric power of the DC-DC converter increases, the output voltage of the EA rises and the pulse width of the NAND output widens. The clock is also entered into the NAND input. For this reason, even when the EA output is raised too much by a rapid load change, the duty cycle of the NAND output does not become more than 50%. Consequently, an over-shoot of the output of the DC-DC converter can be prevented.

Figure 9 shows a photograph of the control IC we developed for a DC-DC converter. The chip size is 3.7 mm × 3.6 mm. It was manufactured using high-voltage bipolar process technology. Bipolar transistors with a breakdown voltage of 15-70 V were used for the PWM control circuit. Bipolar transistors with a breakdown voltage of 150-320 V were used for the current mirror detection circuit and the level shift-circuit. This IC is protected by some varistors, so the breakdown voltage of 150-320 V is enough.

3. Experimental Results

Figure 10 shows the output characteristics of a conventional flyback DC-DC converter and a developed one at room temperature. The input voltage was 40-60 V. The developed converter’s characteristics was generally as good as the conventional one’s. However, the accuracy of developed detection circuit was a little worse than that of conventional one. Because there was parasitic capacitor of 200 - 300pF in the bipolar transistors of developed detection circuit. As the ripple of DC-DC converter brought an inductive current into the parasitic capacitor, the inductive current caused an error of detection. As a results, the developed converter’s characteristics of constant voltage was a little worse than that of conventional ones. In case of reducing the ripple, the accuracy of the detection improved better. Though the parasitic capacitor influenced the stabilization of feedback loop gain and transient characteristics, they could be adjusted by capacitor $C_F$ and resistor $R_F$ which were illustrated in Figure 7. The constant voltage accuracy of the developed converter was ± 5% in an output characteristic, and the constant current accuracy was the same.
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Figure 10 shows the output characteristics of flyback DC-DC converter using developed control IC.

Figure 11 shows the power loss and efficiency of the flyback DC-DC converter. The horizontal axis expresses the output power ($P_o$), and the vertical axis expresses the power loss ($P_L$) and efficiency ($\eta$). The solid circles show the power loss of the new flyback DC-DC converter and the solid squares show its efficiency. The $P_L$ was 0.41 W at the $P_o = 2.25$ W. The $\eta$ is $100 \times P_o / P_i = 100 \times P_o / (P_o + P_L)$, where $P_i$ is an input power of DC-DC converter. So the $\eta$ is about 85% at $P_o = 2.25$ W. The open circle shows the power loss of a conventional flyback DC-DC converter, and the open square shows its efficiency. The difference between the conventional converter's power loss and the new one's is caused by the detection circuit. The new detection circuits can be integrated because it is designed to be a simple circuit of current mirror. As a result, the power loss of new detection circuit was smaller than that of conventional one. The efficiency of the new DC-DC converter was a little higher than that of the conventional one.

Figure 12 shows the mounting area of both flyback DC-DC converters. The mounting area of the new one is 30% less than that of the conventional one. The 20% in the total reduction ratio (30%) is caused by the replacement of the optocoupler in the detection circuit. The rest 10% is caused by the main circuit. In the conventional DC-DC converter, the auxiliary power supply is necessary for the detection circuit. On the other hand, the auxiliary power supply was integrated into the developed IC. So the mounting area of the main circuit was reduced 10%. The part for the detection circuit was reduced considerably.

Fig.12. Mounting area of flyback DC-DC converter.

4. Conclusion
A control IC for optocoupler-less flyback DC-DC converters has been developed. It uses a new detection circuit and a level-shift circuit using a current mirror circuit. A DC-DC converter using this control IC generally exhibited good constant-voltage characteristics. The efficiency of this converter was a little higher than that of a conventional one. The mounting area was reduced 30%.

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References

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