1 kW Full-Bridge DC-DC Converter

Design Guide

RD170-DGUIDE-01

TOSHIBA ELECTRONIC DEVICES & STORAGE CORPORATION

Contents

1. Introduction

This Design Guide describes how to design the various circuitry and layout of 1kW full-bridge DC-DC converter (hereafter referred to as this power supply).

If a component is indicated as “Not Mount” in the bill of materials, then it is not mounted on the PCB, even if the part number is written in the circuit diagram.

Mounting locations are provided on the PCB for value adjustment of various circuit components at the time of circuit design.

1.1. Power MOSFET Used

TPH2R408QM

In the primary-side of the phase-shift full-bridge (PSFB) circuit

V_{DSS} = 80 V, $R_{DS(ON)}$@V_{GS} = 10 V (max) = 2.43 mΩ, SOP Advance package

U-MOSX-H process: the latest process, good FOM for switching applications

TPH1500CNH

In the secondary-side of the phase-shift full-bridge (PSFB) circuit

V_{DSS} = 150 V, $R_{DS(ON)}$@V_{GS} = 10 V (max) = 15.4 mΩ, SOP Advance package

U-MOSⅧ-H process: suitable for switching applications, reduced synchronous rectification loss

2. Circuit Design

This section describes the main points of circuit design of this power supply.

2.1. Phase-Shift Full-Bridge (PSFB) Circuitry Designing

In this power supply, both the primary and secondary sides generate +54 V output in the phase-shifted full-bridge (PSFB) circuit. PSFB circuitry alternately turns on/off the high-side MOSFET and low-side MOSFET of each arm on the primary side at a duty of 50 %, and adjusts the timing (phase) of the on-state between the legs to control the output voltage. When the high-side MOSFET and low-side MOSFET are switched, a dead-time is provided to prevent shoot-through phenomenon. However, MOSFET switching becomes Zero Volt Switching (ZVSs) due to resonance operation during that period. ZVS reduces switching losses and enables a high-efficiency power supply. This power supply uses a controller UCC28951 manufactured by Texas Instruments ("PSFB controller") to configure PSFB circuit. The following describes basic design of PSFB circuit of this power supply. For detailed designs around the controller, refer to UCC28951 datasheets of Texas Instruments and related documents. In addition, refer to RD170-SCHEMATIC-01 for the circuit diagram of this power supply and to RD170-BOM-01 for the bill of materials.

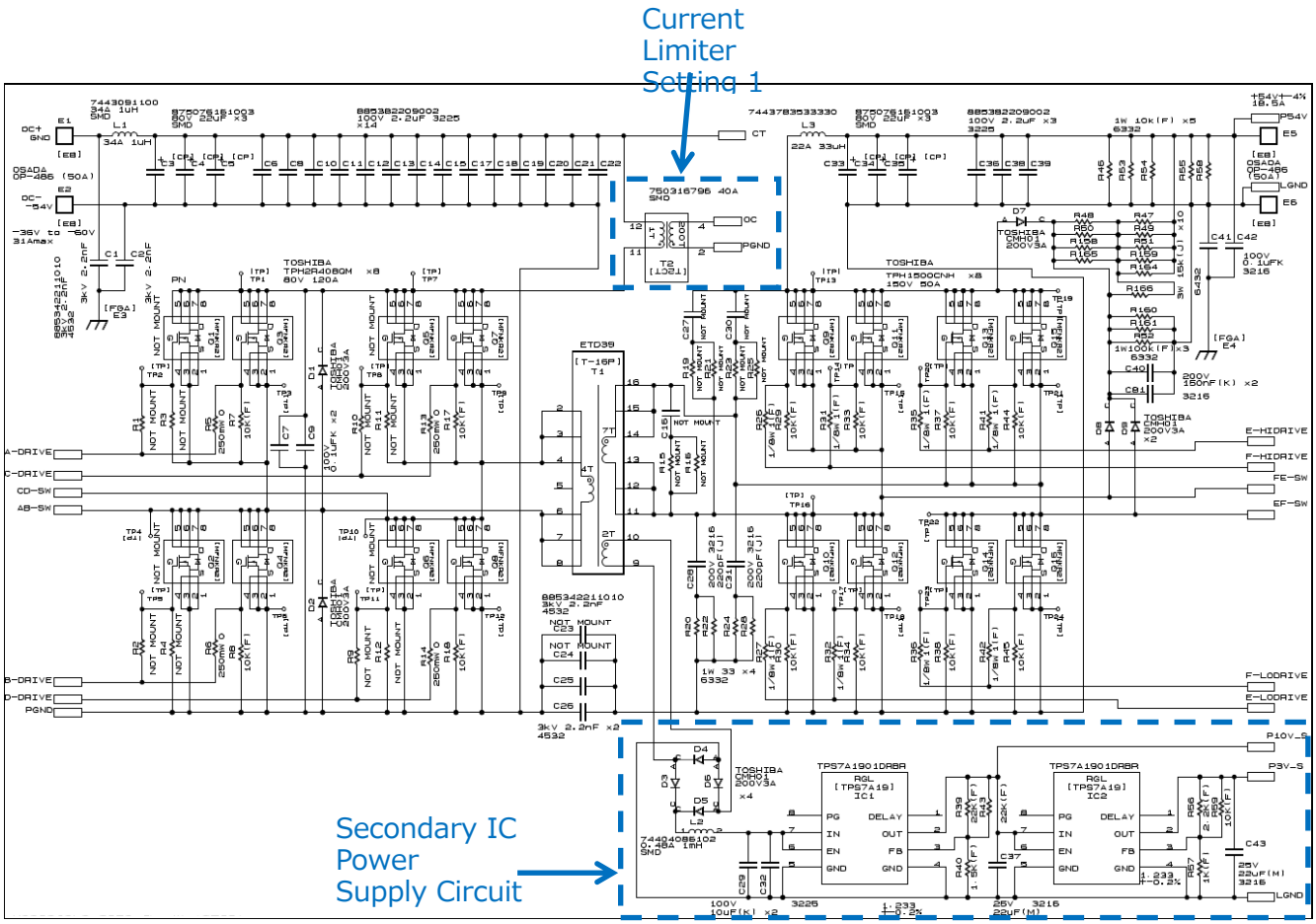

Fig. 2.1 PSFB Circuit/Secondary Side IC Power Supply Circuit

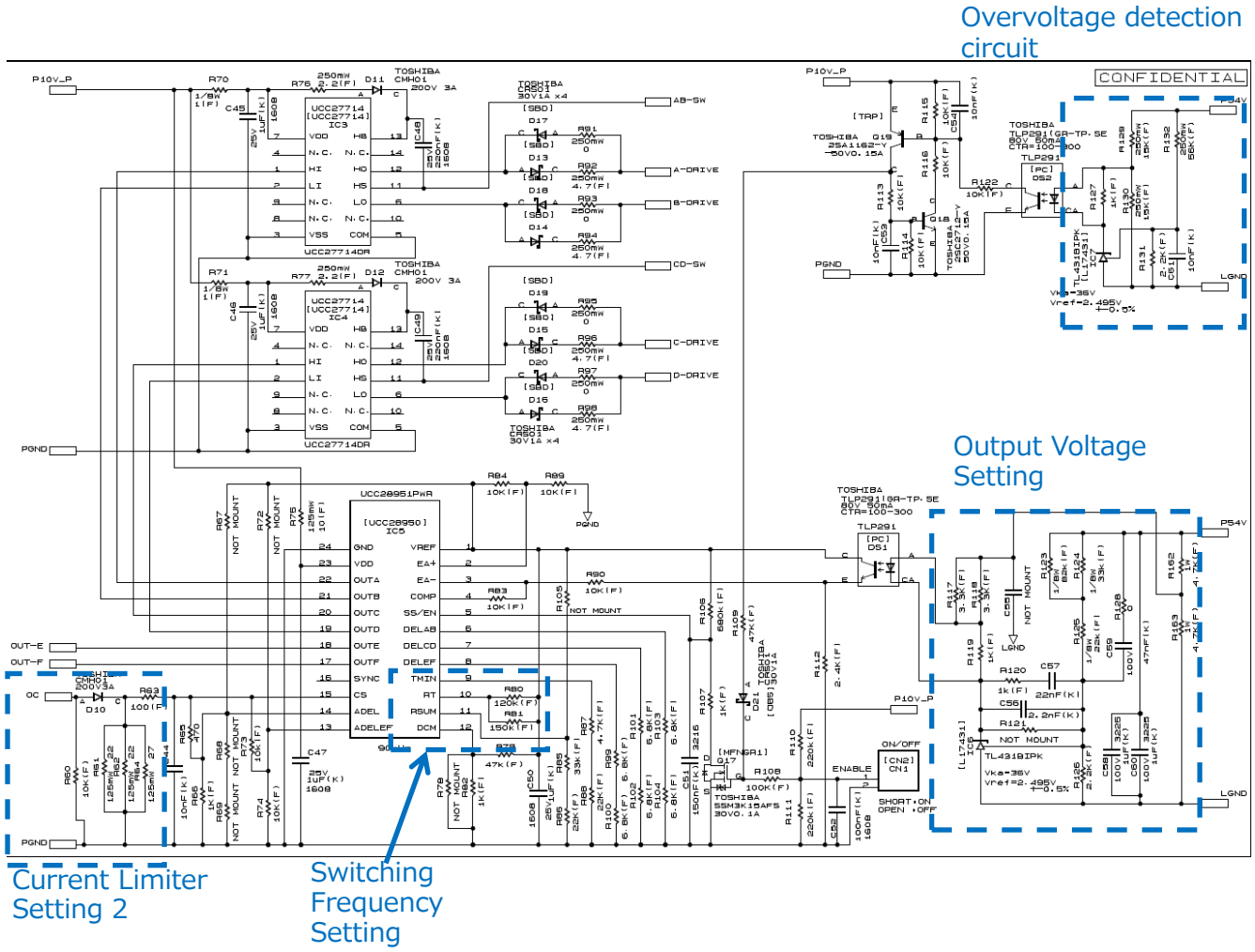

Fig. 2.2 Control IC/Primary Side Gate Drive/Output Control/ Overvoltage Detector Circuit

~~Setting the m~~Minimum ~~i~~Input

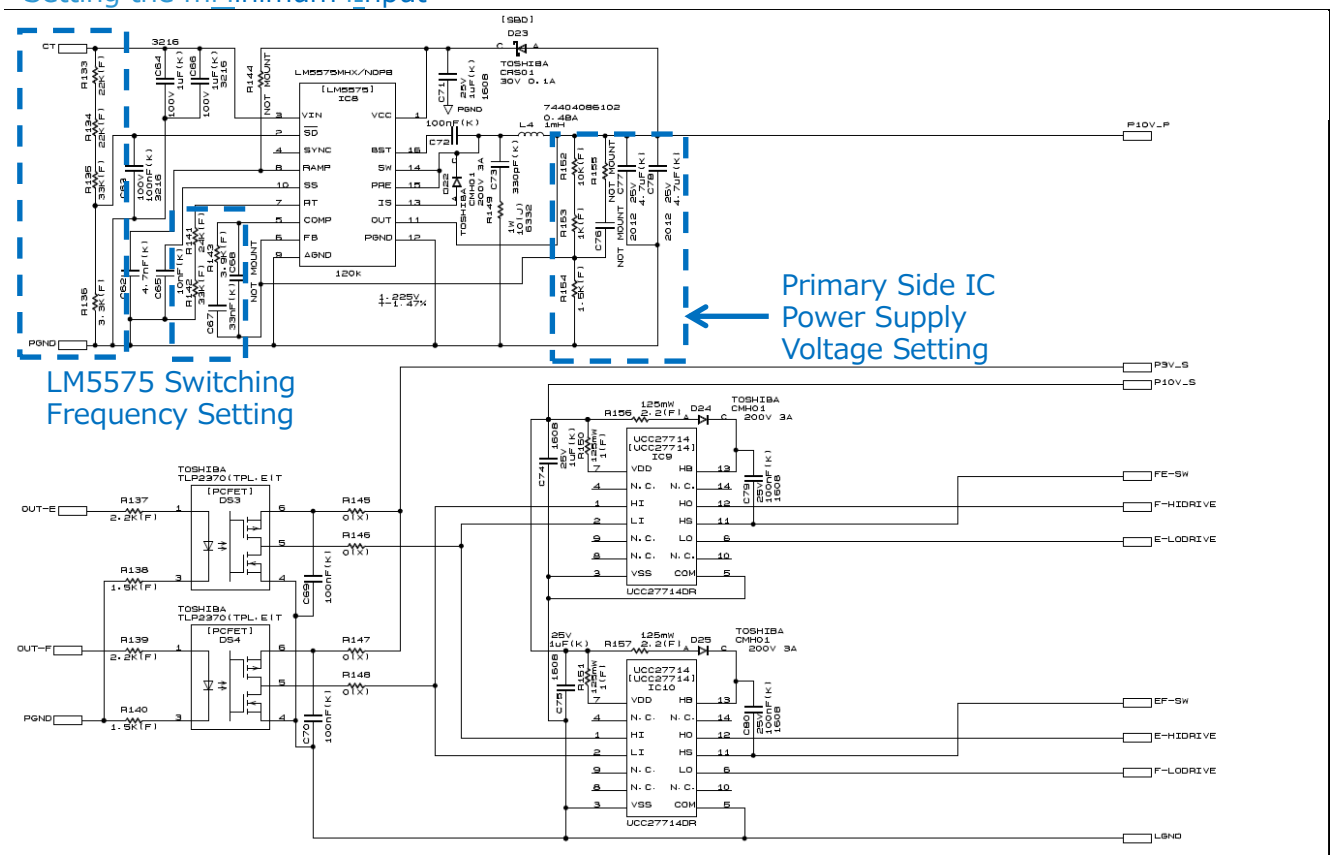

Fig. 2.3 Primary Side IC Power Supply Circuit/Secondary Side Gate Drive

Setting the minimum Input Operating Voltage

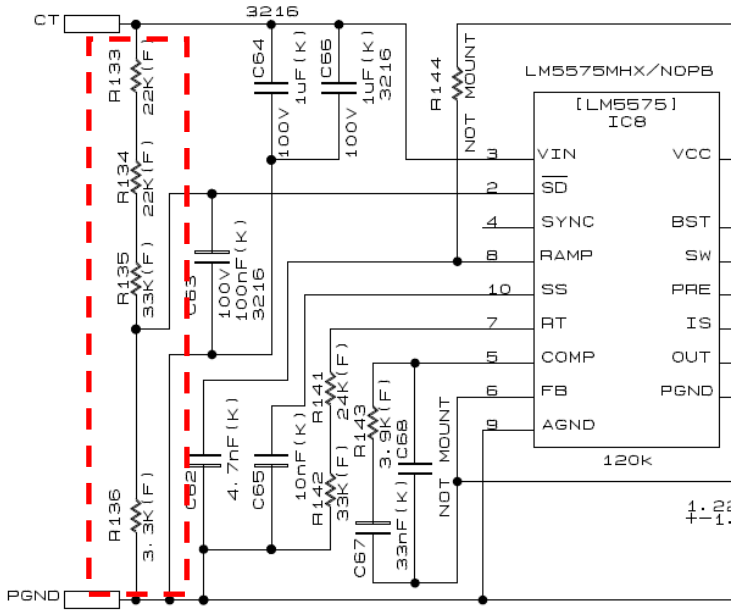

Fig. 2.4 Setting the Minimum Input Operating Voltage

Set the minimum input-voltage at which this power supply operates using the external resistors (R133, R134, R135, R136). The minimum input operating voltage (Vin_min_on) is set by dividing the input voltage Vin by using the resistors (R133, R134, R135, R136) and inputting it to the SD pin of the switching regulator LM5575MHX.

The switching regulator LM5575MHX supplies power to the control IC. Therefore, if LM5575MHX does not operate, the power supply voltage cannot be supplied to the control IC, so this power supply cannot operate. LM5575MHX starts operation when the SD pin voltage exceeds 1.225 V. After the start of operation, the shutdown and the standby thresholds each have a hysteresis of 0.1 V.

The voltage on the SD pin must not exceed 14 V.

Calculate the lower operating-voltage limit (Vin_min_on) using the following equation.

$$Vin\_min\_on = \frac{1.225 \times (R133 + R134 + R135)}{R136} + 1.225$$

In this power supply, Vin_min_on is set to 29.8 V by selecting the value of R133 as 22 kΩ, R134 as 22 kΩ, R135 as 33 kΩ, and R136 as 3.3 kΩ, as shown in Fig. 2.4.

Setting the switching frequency of LM5575MHX

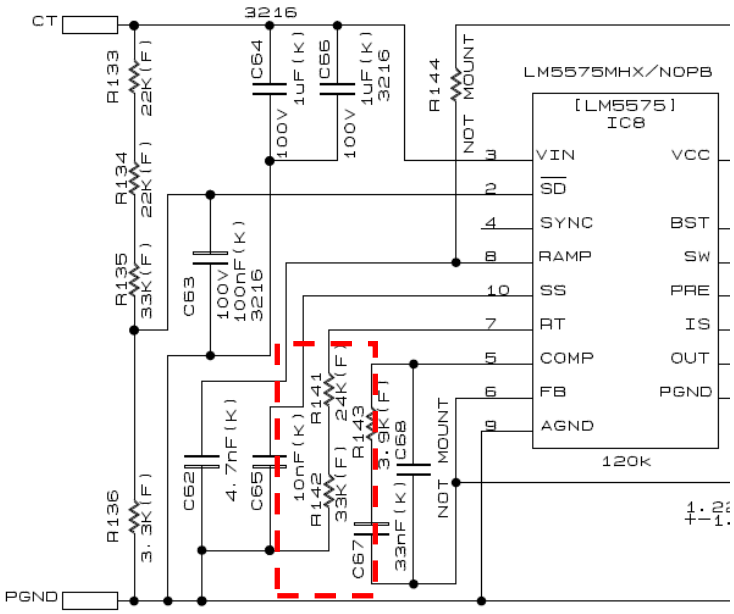

Fig. 2.5 Setting the switching frequency of LM5575MHX

Set the switching frequency (f_{LM5575}) of LM5575MHX using the external resistors (R141 and R142). Calculate the switching frequency (f_{LM5575}) using the following equation.

$$f_{LM5575}(Hz) = \frac{1}{(R141 + R142) \times 135 \times 10^{-12} + 580 \times 10^{-9}}$$

In this power supply, LM5575MHX switching frequency (f_{LM5575}) is set to 120 kHz by selecting the value of R141 as 24 kΩ and R142 as 33 kΩ, as shown in Fig. 2.5.

It is recommended that the switching frequency (f_{LM5575}) of LM5575MHX be at least ±10 % of the switching frequency (f_{PWM}) of the PSFB controller. If the frequency is within ±10%, it may interfere and cause abnormal oscillation.

The frequency can be set within the range: 50 kHz to 500 kHz.

Setting the Primary Side IC Power Supply Voltage (LM5575MHX Output Voltage)

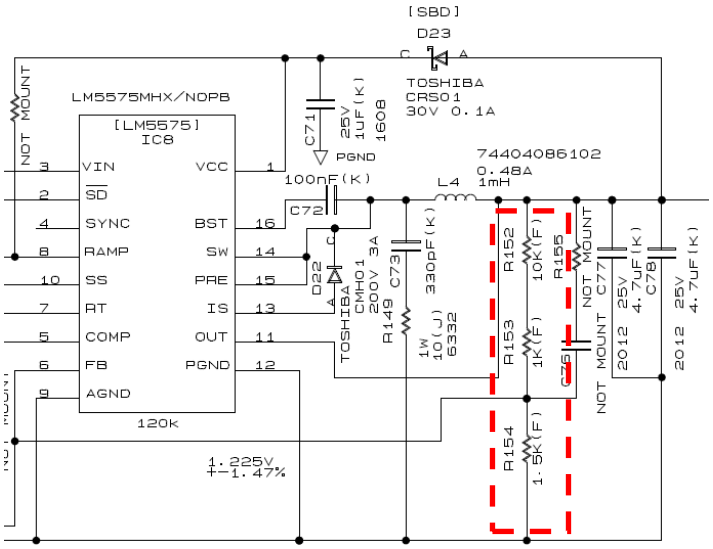

Fig. 2.6 Setting the LM5575MHX Output Voltage

Set the output voltage of LM5575MHX using the external resistors (R152, R153, R154). Adjust the resistors (R152, R153, R154) so that the FB terminal becomes 1.225 V, and set the output voltage (VP10VP).
Calculate the output voltage (VP10VP) using the following equation.

$$V_{P10VP}(V) = \frac{1.225 \times (R152 + R153)}{R154} + 1.225$$

In this power supply, the value of the output voltage of LM5575MHX is set to 10 V by selecting the value of R152 as 10 kΩ, R153 as 1 kΩ, and R154 as 1.5 kΩ, as shown in Fig. 2.6.
The tolerance of 1.225 V of the FB terminal is ±1.5 %.

Setting the Current limiter

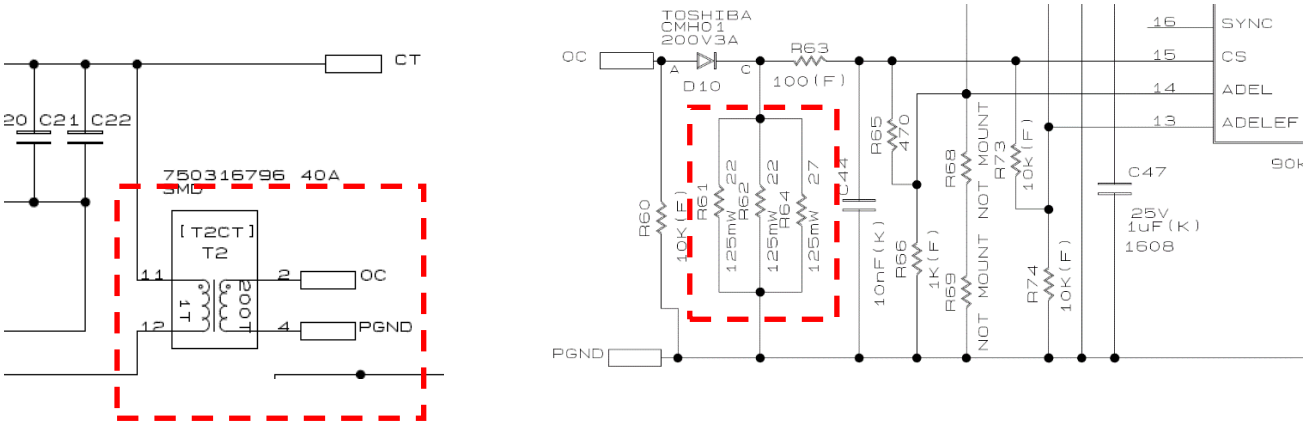

Fig. 2.7 Setting the Current limiter

When the voltage at the CS pin of PSFB PWM controller reaches the current limit threshold value (2.0 V), PSFB controller controls the input-side bridged MOSFET to apply the current limit.

Set the current limiter level (I_limit) by using the current limit threshold value (2.0 V), current detection resistor (R61, R62, R64) value, and the turn ratio (transformer turns ratio) of the current transformer (T2). Calculate the combined resistance value and current limiter level using the following formulas.

RZ is the combined resistance value of R61, R62, and R64

$$Rz(\Omega) = \frac{R61 \times R62 \times R64}{R61 \times R62 + R62 \times R64 + R61 \times R64}$$

Current limiter level (I_limit)

$$I\_limit(A) = \frac{2}{Rz \times (transformer\ \ turns\ \ ratio)}$$

In this power supply, the current limiter level is set to 51.2 A by selecting the value of R61 as 22kΩ, R62 as 22 kΩ and R64 as 27 kΩ, and the turn ratio of current transformer (T2) as 1:200, as shown in Fig. 2.7.

Setting the Switching Frequency

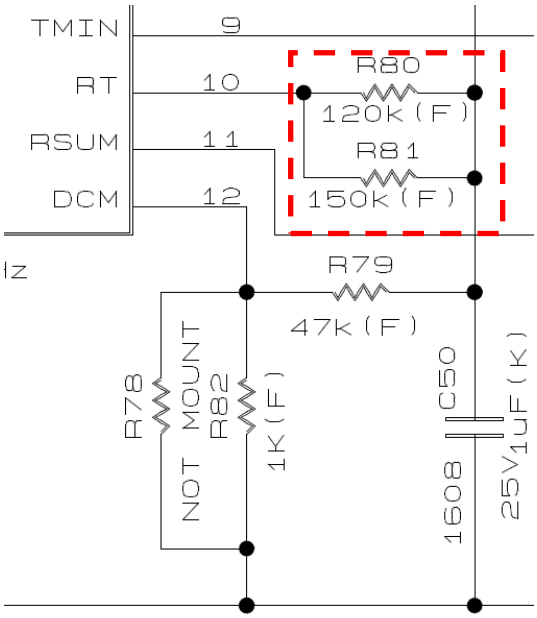

Fig. 2.8 Setting the Switching Frequency

Set the switching frequency (f_{PWM}) of PSFB circuit using the external resistors (R80 and R81). Calculate the switching frequency (f_{PWM}) using the following equation.

Combined resistance R_T of R80 and R81

$$R_T(\Omega) = \frac{R80 \times R81}{R80 + R81}$$

Switching Frequency (f_{PWM})

$$f_{PWM}(kHz) = \frac{2.5 \times 10^3}{(\frac{R_T(k\Omega)}{V_{REF}(V) - 2.5} + 1)}$$

Note. VREF shown above is pin 1 (VREF) of the PSFB controller, and has a voltage of 5.0 V.

In this power supply, the switching frequency (f_{PWM}) is set to 90 kHz by selecting the value of R80 as 120 kΩ, and R81 as 150 kΩ, as shown in Fig. 2.8.

Setting the Output Voltage

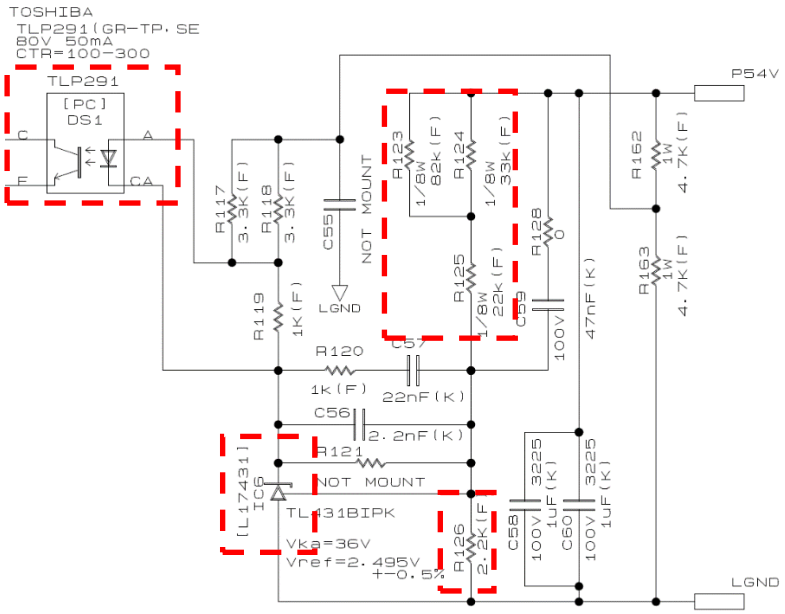

Fig. 2.9 Output Voltage Setting

Set the output voltage (V_{OUT}) of PSFB circuit using the external resistors (R123, R124, R125, R126) and the shunt regulator (IC6). The shunt regulator (TL431BIPK) controls the current of the photocoupler (DS1) so that the voltage obtained by dividing the output voltage of PSFB circuit by resistors (R123, R124, R125, R126) matches the reference voltage (V_{REF} = 2.495). The PSFB controller operates to keep the output voltage (V_{OUT}) constant according to the amount of current fed back from the photocoupler (DS1). Calculate the output voltage (V_{OUT}) by the following equation.

R123, R124, R125 combined resistance R_{VOUT}

$$R_{VOUT}(\Omega) = \frac{R123 \times R124}{R123 + R124} + R125$$

Output Voltage V_{OUT}

$$V_{OUT}(V) = \frac{2.495 \times R_{VOUT}}{R126} + 2.495$$

In this power supply, the output voltage (V_{OUT}) is set to 54.0 V by selecting the value of R123 as 82 kΩ, R124 as 33 kΩ, R125 as 22 kΩ, and R126 as 2.2 kΩ, as shown in Fig. 2.9.

Gate drive circuit

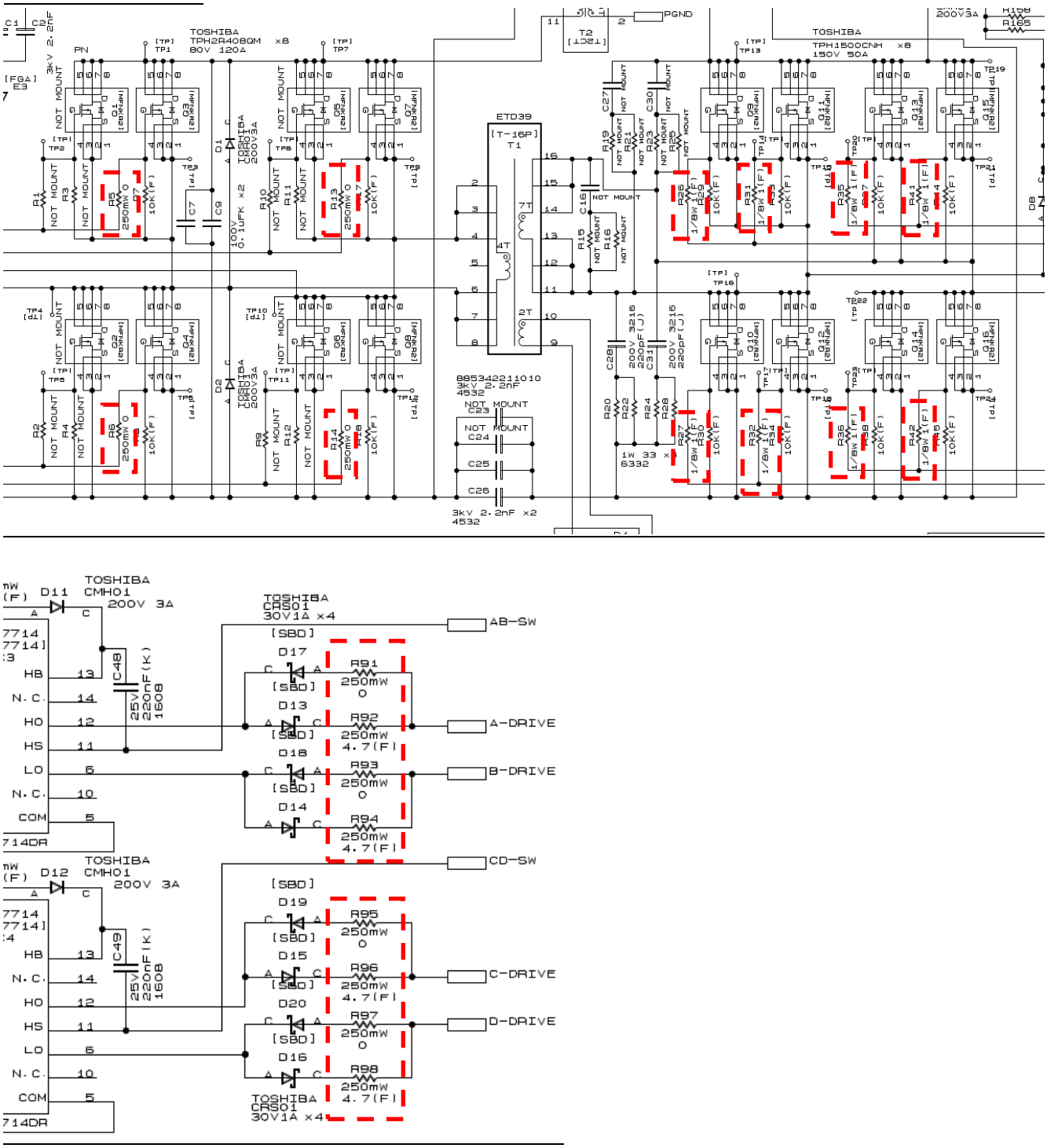

Fig. 2.10 Gate Drive Circuit

The design of the gate drive circuit affects power supply efficiency and EMI. Generally, there is a trade-off between power supply efficiency and EMI, and a balanced design is required for both. Although PSFB circuit has low EMI because of ZVS operation, if the presence of the hard switching area seems to be the cause of EMI, increase the resistance value of the gate series resistors (R5, R6, R13, R14) of the primary MOSFETs (Q3, Q4, Q7, Q8) and increase the resistance value of the gate series resistors (R26, R27, R31, R32, R35, R36, R41, R42) of the secondary MOSFETs (Q9 to

Q16) and then confirm the EMI. The primary MOSFET can be individually adjusted at turn-on and turn-off. As shown in Fig. 2.10, 4.7 Ω is selected as the resistor value (R92, R94, R96, R98) for this power supply.

Transformer

When On Duty of the synchronous rectifier is set to 57 % in the steady-state condition of PSFB circuitry, a square wave of approximately 100 V is required on the secondary side because the output voltage is 54 V. Since the input voltage (standard) of this power supply is -54 V, select 4:7:2 (with auxiliary winding) for the turn ratio of the transformer (T1). This results in a square wave of 94.5 V on the secondary side. In addition, primary-secondary dielectric strength, winding temperature rise, magnetic flux saturation, core loss, etc. must also be considered carefully. Refer to the Bill of Materials (RD170-BOM-01) for the specifications of the transformer used in this power supply.

In addition, this power supply uses the leakage inductance of the transformer to perform ZVS. If the resonance due to the leakage inductance is insufficient, ZVS cannot be realized, and problems such as a decrease in power supply efficiency and an increase in EMI may occur. In such a case, add a coil for resonance and adjust so that the ZVS is achieved over a wide load range.

Output Capacitor

Select the capacitance value (C_{out}) of the output capacitor so that the output ripple voltage (V_{ripple}) is within the required specification. The combined value of the ripple voltage that occurs in each of the following cases becomes the output ripple voltage (V_{ripple}).

1. Ripple voltage (V_{ripple_ESR}) generated by the ripple current (ΔI) and the equivalent series resistance (ESR) of the output capacitor.
2. Ripple voltage (V_{ripple_Cap}) generated by the ripple current (ΔI), the capacitance of the output capacitor (C_{out}), and the switching frequency (f_{PWM}).
3. Ripple voltage (V_{ripple_ESL}) generated by the switching voltage (V_{sw}) and the equivalent series inductance value (ESL) and inductance (L) of the output capacitor.

Calculate each ripple voltage using the following equation.

$$V_{ripple\_ESR}(V) = \Delta I \times ESR$$

$$V_{ripple\_Cap}(V) = \frac{\Delta I}{8 \times C_{OUT} \times f_{PWM} \times 2}$$

$$V_{ripple\_ESL}(V) = \frac{V_{SW} \times ESL}{L}$$

Here,

$$\Delta I(A) = \frac{(V_{SW} - V_{OUT}) \times V_{OUT}}{V_{SW} \times f_{PWM} \times 2 \times L}$$

If the switching voltage (V_{SW}) is 94.5 V, the output voltage (V_{OUT}) is 54.0 V, the switching frequency (f_{PWM}) is 90 kHz, and the inductance (L) is 33 μH, then the ripple current (ΔI) is 3.9 A. If the equivalent series resistance (ESR) is 12.7 mΩ (38 mΩ/3pcs @ 90 kHz), the capacitance (C_{OUT}) of the output capacitor is 66.0 μF (22 μFx3pcs @ 120 Hz,0.25 V), the equivalent series inductance (ESL) of the output capacitor is 2nH (6nH/3pcs), and the inductance (L) is 33μH, then the ripple voltage generated by each is V_{ripple_ESR} = 49.5 mV, V_{ripple_Cap} = 41.0 mV, and V_{ripple_ESL} = 5.7 mV. The ripple voltage generated by V_{ripple_Cap} cannot be simply added because it is out of phase with V_{ripple_ESR} and V_{ripple_ESL}, but because the ripple voltage generated by V_{ripple_Cap} is small, the simplified sum can be used as a reference for the output voltage ripple.

Adjust C_{OUT}, ESR, and ESL of the output capacitor so that the output voltage ripple (V_{ripple}) satisfies the required specifications. Also, check the following:

1. The output terminal's undershoot and overshoot at the time of sudden load change falls within the specified voltage range.
2. The actual ripple current of the output capacitor is within specification.
3. Tolerances and aging of output capacitors are considered.

Output overvoltage detection circuit

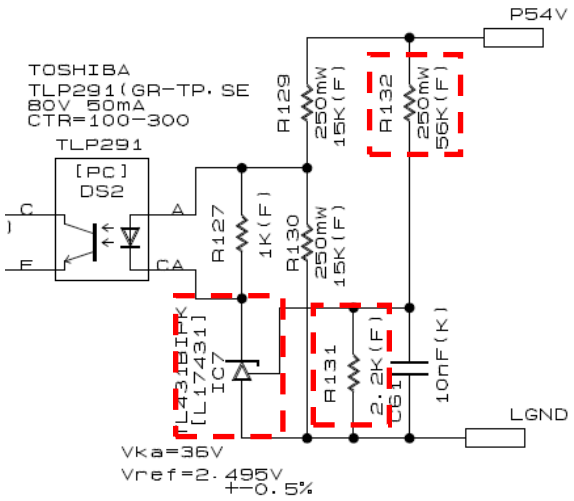

Fig. 2.11 Output Overvoltage Detection Circuit

Set the overvoltage detection value (V_{ovp}) of the output with the reference voltage (Vref = 2.495 V) of the shunt regulator (TL431BIPK) and the external resistors (R131, R132). When the output voltage value reaches the overvoltage detection value (V_{ovp}), the photocoupler DS2 is activated, the SS pin of the PSFB controller is latched to LOW, and the switching operation is stopped. Calculate the output overvoltage detection value (V_{ovp}) using the following equation.

$$Vovp = \frac{2.495 \times R132}{R131} + 2.495$$

In this power supply, the overvoltage detection value (V_{ovp}) is set to 66 V by selecting the value of R131 as 2.2 kΩ, and R132 as 56 kΩ, as shown in Fig. 2.11. To restart the switching operation stopped by overvoltage detection, cut off input and input again.

Setting the secondary IC power supply voltage

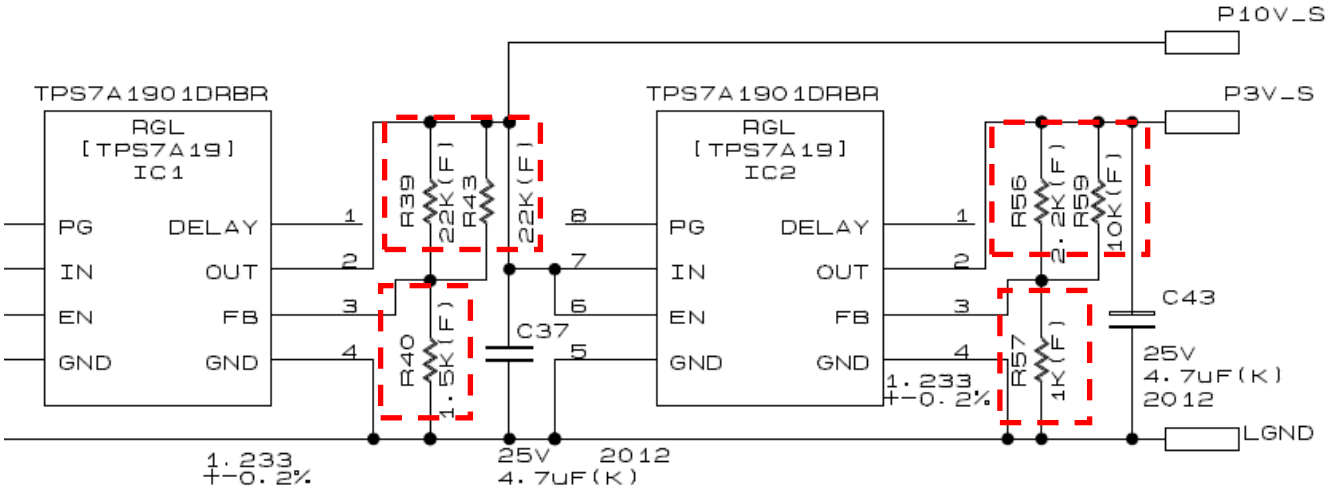

Fig. 2.12 Setting of Secondary IC Power Supply Voltage

As shown in Fig. 2.12, there are two power supplies, one for the power supply (VP10VS) of the secondary driver IC and the other for the power supply (VP3VS) of photocoupler used for transmitting gate signals to the secondary driver IC. Since the same IC is used, the voltage setting method is the same.

Set the output-voltage of TPS7A1901DRBR using the external resistors (R39, R43, R40 (R56, R59, R57)). Adjust the output voltage (using R39, R43, R40 (R56, R59, R57)) so that the FB terminal becomes 1.233 V, and set the output voltages (VP10VS) and (VP3VS). Calculate each output voltage using the following equation.

$$V_{P10VS}(\mathrm{V}) = \frac{1.233 \times (\text{Combined resistance of R39 and R43})}{R40} + 1.233$$

$$V_{P3VS}(\mathrm{V}) = \frac{1.233 \times (\text{Combined resistance of R56 and R59})}{R57} + 1.233$$

In this power supply, the power supply (VP10VS) of the secondary side driver IC is set to 10 V by selecting the value of R39 as 22 kΩ, R43 as 22 kΩ, and R40 as 1.5 kΩ, as shown in Fig. 2.12. In addition, the power supply (VP3VS) of photocoupler used for transmitting the gate signal to the secondary side is set to 3.3 V by selecting the value of R56 as 2.2 kΩ, R59 as 10kΩ, and R57 as 1 kΩ, as shown in Fig. 2.12.

The tolerance of 1.233 V of the FB terminal is ±0.2 %.

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