

For Non-Isolated Off-Line PWM Controllers with Integrated Power MOSFET STR5A450D Series

Description

The STR5A450D Series is power ICs for switching power supplies, incorporating a MOSFET and a current mode PWM controller IC for non-isolated Buck converter and Inverting converter topologies.

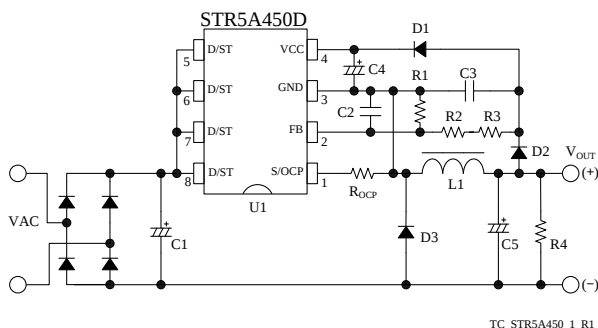
The operation mode is automatically changed, in response to load, to the fixed switching frequency, to the switching frequency control, and to the burst oscillation mode. Thus the power efficiency is improved.

The product achieves high cost-performance power supply systems with few external components.

Features

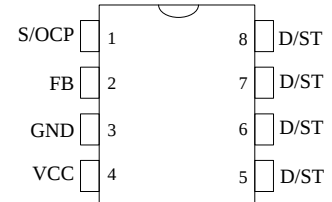
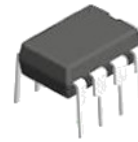
- Buck converter
- Inverting converter
- Current mode type PWM control
- Automatically changed operation mode in response to load conditions
Fixed switching frequency mode, 60 kHz (typ.)
Green mode, 23 kHz (typ.) to 60 kHz (typ.)
Burst oscillation mode
- Built-in Startup Function
reducing power consumption, and shortening the startup time
- Built-in Error Amplifier
- Random Switching Function
- Leading Edge Blanking Function
- Soft Start Function
- Protections
Overcurrent Protection (OCP): adjustable by an external current detection resistor, including OCP input compensation function
Overload Protection (OLP): Auto-restart
Overvoltage Protection (OVP): Auto-restart
Thermal Shutdown with hysteresis (TSD): Auto-restart

Typical Application (Buck Converter)



Package

DIP8



Not to scale

Selection Guide

- Electrical Characteristics
 $f_{OSC(AVG)} = 60 \text{ kHz (typ.)}$
 $V_{D/ST} = 650 \text{ V (max.)}$

Part Number	$R_{DS(ON)}$ (max.)	$I_{OUT(MAX)}^*$ (Universal, open frame, $V_{OUT} = 24 \text{ V}$)
STR5A451D	4.0 Ω	0.7 A
STR5A453D	1.9 Ω	0.9 A

* The output power is actual continues current that is measured at 50 °C ambient. The peak output current can be 120 to 140 % of the value stated here. Thermal design affects the output current. It may be less than the value stated here.

Recommended Operating Condition

Parameter	Buck Converter	Inverting Converter
Input Voltage	AC 85 V to AC 265 V	
D/ST Input Voltage	$\geq 40 \text{ V}$	
Output Voltage Range*	> 11 V < 27.5 V	> - 27.5 V < - 11 V

*Add a zener diode or a regulator to VCC pin when target output voltage is high.

Applications

- White goods
- Auxiliary power supply (lighting equipment with microcomputer, etc.)
- Power supply for motor control (actuator, etc.)
- Telecommunication equipment (convertible from 48VDC to 15VDC)
- Other Switching mode power supply, SMPS

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STR5A450D Series

1. Absolute Maximum Ratings

The polarity value for current specifies a sink as "+," and a source as "-," referencing the IC.
Unless otherwise specified, $T_A = 25\text{ }^{\circ}\text{C}$, all D/ST pins (5 pin to 8pin) are shorted.

Parameter	Symbol	Test Conditions	Pins	Rating	Units	Remarks
Drain Peak Current	I_{DPEAK}	Single pulse	8 – 1	3.6	A	5A451D
				5.2		5A453D
Avalanche Energy ⁽¹⁾	E_{AS}	$I_{LPEAK} = 2.13\text{ A}$	8 – 1	53	mJ	5A451D
		$I_{LPEAK} = 2.46\text{ A}$		72		5A453D
S/OCP Pin Voltage	$V_{S/OCP}$		1 – 3	– 2 to 5	V	
FB Pin Voltage	V_{FB}		2 – 3	– 0.3 to 7	V	
VCC Pin Voltage	V_{CC}		4 – 3	– 0.3 to 32	V	
D/ST Pin Voltage	$V_{D/ST}$		4 – 5	– 0.3 to V_{DSS}	V	
MOSFET Power Dissipation	P_{D1}	⁽²⁾	8 – 1	1.68	W	5A451D
				1.76		5A453D
Control Part Power Dissipation	P_{D2}		4 – 3	1.3	W	
Operating Ambient Temperature	T_{OP}		–	– 40 to 125	$^{\circ}\text{C}$	
Storage Temperature	T_{stg}		–	– 40 to 125	$^{\circ}\text{C}$	
Junction Temperature	T_j		–	150	$^{\circ}\text{C}$	

⁽¹⁾ Single pulse, $V_{DD} = 99\text{ V}$, $L = 20\text{ mH}$

⁽²⁾ When embedding this hybrid IC onto the printed circuit board (copper area in a 15 mm×15 mm)

2. Electrical Characteristics

The polarity value for current specifies a sink as "+," and a source as "-," referencing the IC.
Unless otherwise specified, $T_A = 25\text{ }^{\circ}\text{C}$, all D/ST pins (5 pin to 8pin) are shorted.

Parameter	Symbol	Test Conditions	Pins	Min.	Typ.	Max.	Units	Remarks
Power Supply Startup Operation								
Operation Start Voltage	$V_{CC(ON)}$		4 – 3	13.6	15.0	16.6	V	
Operation Stop Voltage	$V_{CC(OFF)}$		4 – 3	7.3	8.0	8.7	V	
Circuit Current in Operation	$I_{CC(ON)}$	$V_{CC} = 12\text{ V}$	4 – 3	–	–	3.0	mA	
Startup Circuit Operation Voltage	$V_{ST(ON)}$	$V_{CC} = 13.5\text{ V}$	8 – 3	21	29	37	V	
Startup Current	$I_{CC(ST)}$	$V_{CC} = 13.5\text{ V}$	4 – 3	– 3.0	– 1.7	– 0.9	mA	
PWM Operation								
Average PWM Switching Frequency	$f_{OSC(AVG)}$	$V_{FB} = V_{FB(REF)} - 20\text{ mV}$	8 – 3	53	60	67	kHz	
Switching Frequency Modulation Deviation	Δf		8 – 3	–	7.1	–	kHz	
Feedback Reference Voltage	$V_{FB(REF)}$		2 – 3	2.44	2.50	2.56	V	

STR5A450D Series

Parameter	Symbol	Test Conditions	Pins	Min.	Typ.	Max.	Units	Remarks
Feedback Current ⁽¹⁾	$I_{FB(OP)}$	$V_{FB} = 2.3 \text{ V}$	2 – 3	– 2.4	– 0.8	–	μA	
S/OCP Pin Standby Threshold voltage	$V_{OCP(STB)}$		1 – 3	–	0.11	–	V	
Maximum Duty Cycle	D_{MAX}		8 – 3	56	62	69	%	
Protection								
Leading Edge Blanking Time ⁽¹⁾	t_{BW}		–	–	280	–	ns	
OCP Compensation Coefficient ⁽¹⁾	DPC		–	–	15.8	–	mV/ μs	
OCP Compensation Limit Duty ⁽¹⁾	D_{DPC}		–	–	36	–	%	
OCP Threshold Voltage at Zero Duty Cycle	$V_{OCP(L)}$		1 – 3	0.640	0.735	0.830	V	
OCP Threshold Voltage	$V_{OCP(H)}$		1 – 3	0.74	0.83	0.92	V	
OCP Threshold Voltage During LEB (t_{BW})	$V_{OCP(LEB)}$		1 – 3	–	1.61	–	V	
OVP Threshold Voltage	$V_{CC(OVP)}$		4 – 3	27.5	29.3	31.3	V	
OLP Delay Time at Startup	t_{OLP}	$V_{FB} = 0.41 \text{ V}$	8 – 3	53	70	88	ms	
Circuit Current in Overload Protection	I_{OLP}	$V_{CC} = 9 \text{ V}$	4 – 3	–	300	–		
Delay Time of FB Pin Short Protection at Startup	$t_{FB SH}$	$V_{FB} = 0.2 \text{ V}$	8 – 3	13.0	17.5	22.0		
Standby Blanking Time at Startup	$t_{STB(INH)}$	$V_{FB} = 2.6 \text{ V}$	8 – 3	2.0	3.0	4.0	ms	
Thermal Shutdown Operating Temperature ⁽¹⁾	$T_{j(TSD)}$		–	135	–	–	$^{\circ}\text{C}$	
Thermal Shutdown Hysteresis ⁽¹⁾	$T_{j(TSDHYS)}$		–	–	80	–	$^{\circ}\text{C}$	
Power MOSFET								
Drain-to-Source Breakdown Voltage	V_{DSS}	$I_{DS} = 50 \mu\text{A}$	8 – 1	650	–	–	V	
Drain Leakage Current	I_{DSS}	$V_{DS} = V_{DSS}$	8 – 1	–	–	50	μA	
On-resistance	$R_{DS(ON)}$	$I_{DS} = 0.4 \text{ A}$	8 – 1	–	–	4.0	Ω	5A451D
				–	–	1.9		5A453D
Switching Time	t_f		8 – 1	–	–	250	ns	
Thermal Characteristics								
Thermal Resistance Junction to Case ⁽²⁾	θ_{j-C}			–	–	18	$^{\circ}\text{C/W}$	5A451D 5A453D

⁽¹⁾ Guaranteed by design.

⁽²⁾ Case temperature (T_C) measured at the center of the case top surface

3. Performance Curves

3.1 Derating Curves

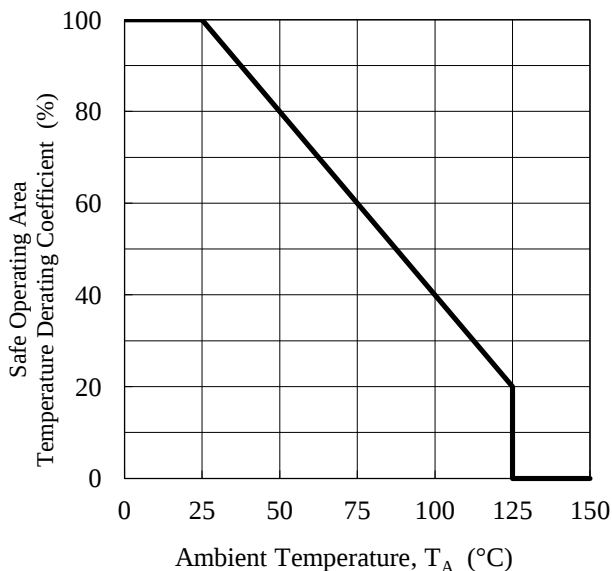


Figure 3-1. SOA Temperature Derating Coefficient Curve

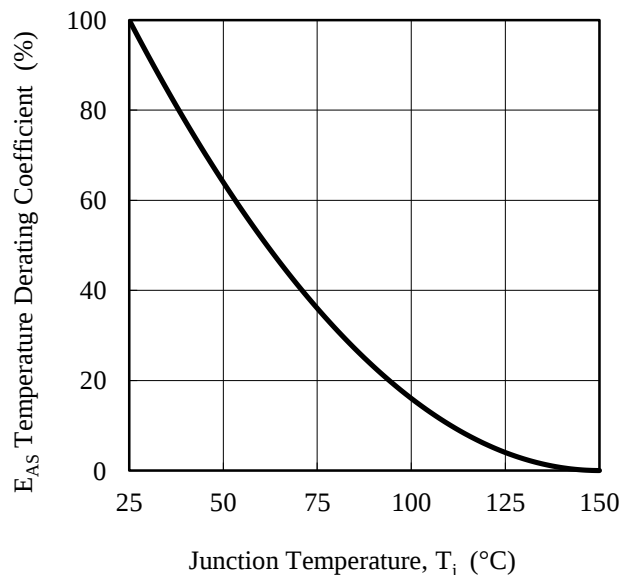
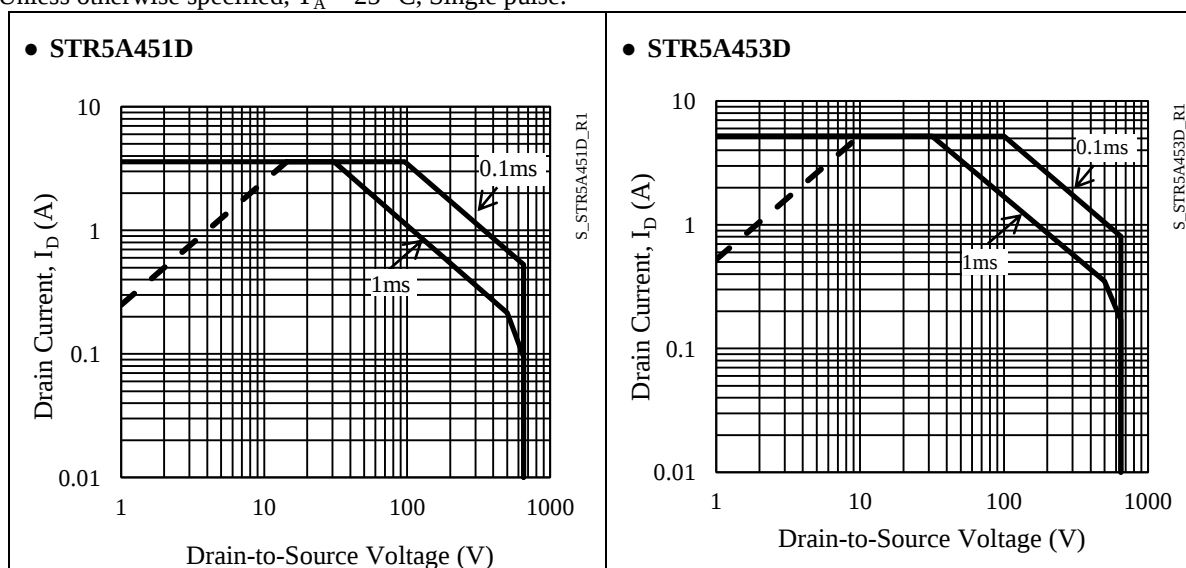


Figure 3-2. Avalanche Energy Derating Coefficient Curve

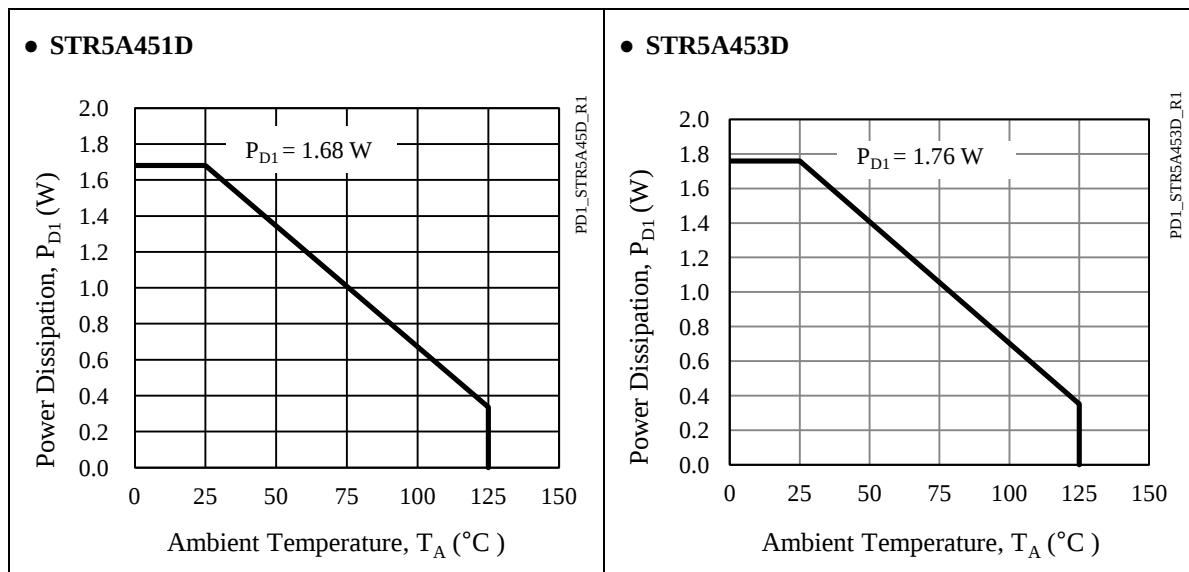
3.2 MOSFET Safe Operating Area Curves

When the IC is used, the safe operating area curve should be multiplied by the temperature derating coefficient derived from Figure 3-1. The broken line in the safe operating area curve is the drain current curve limited by on-resistance.

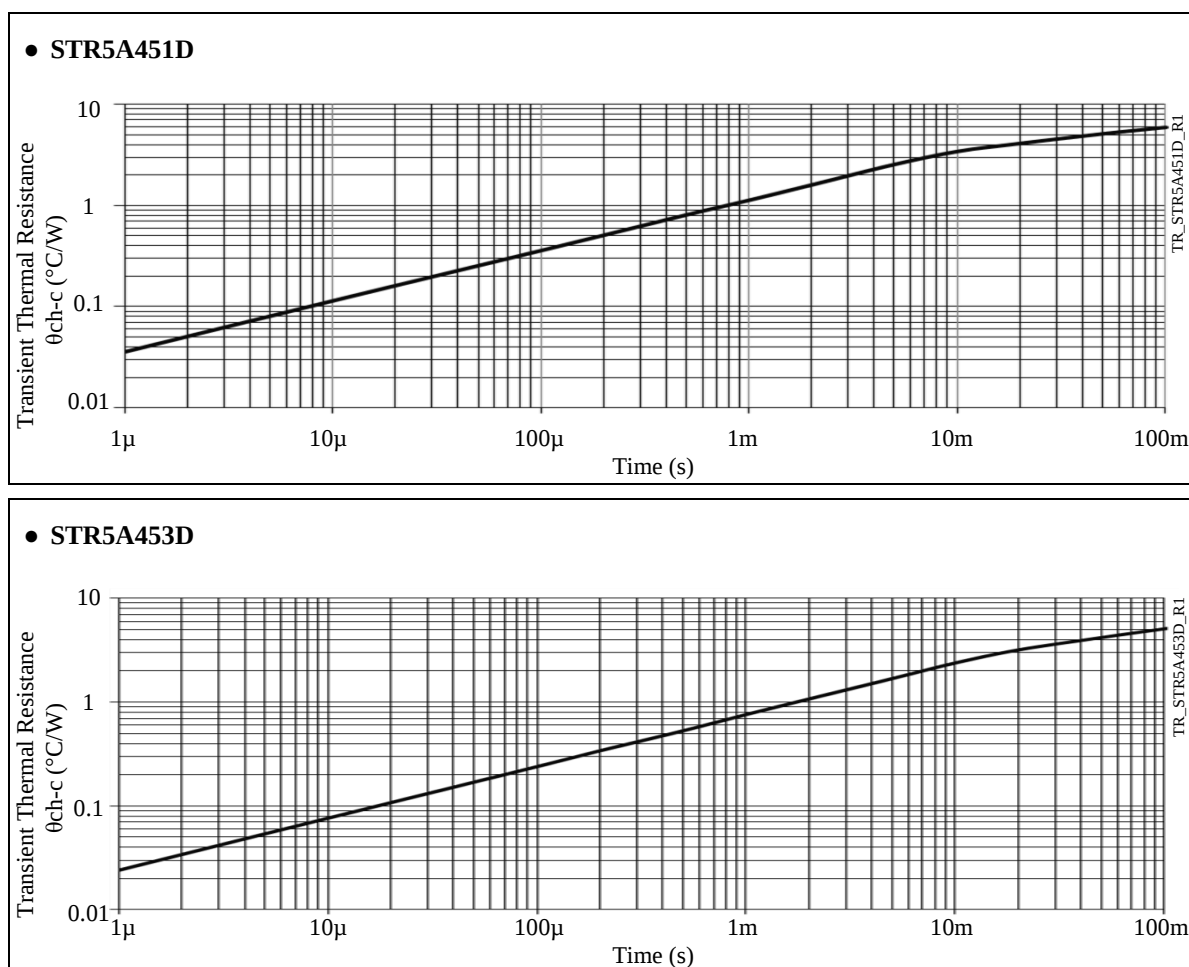
Unless otherwise specified, $T_A = 25^\circ\text{C}$, Single pulse.



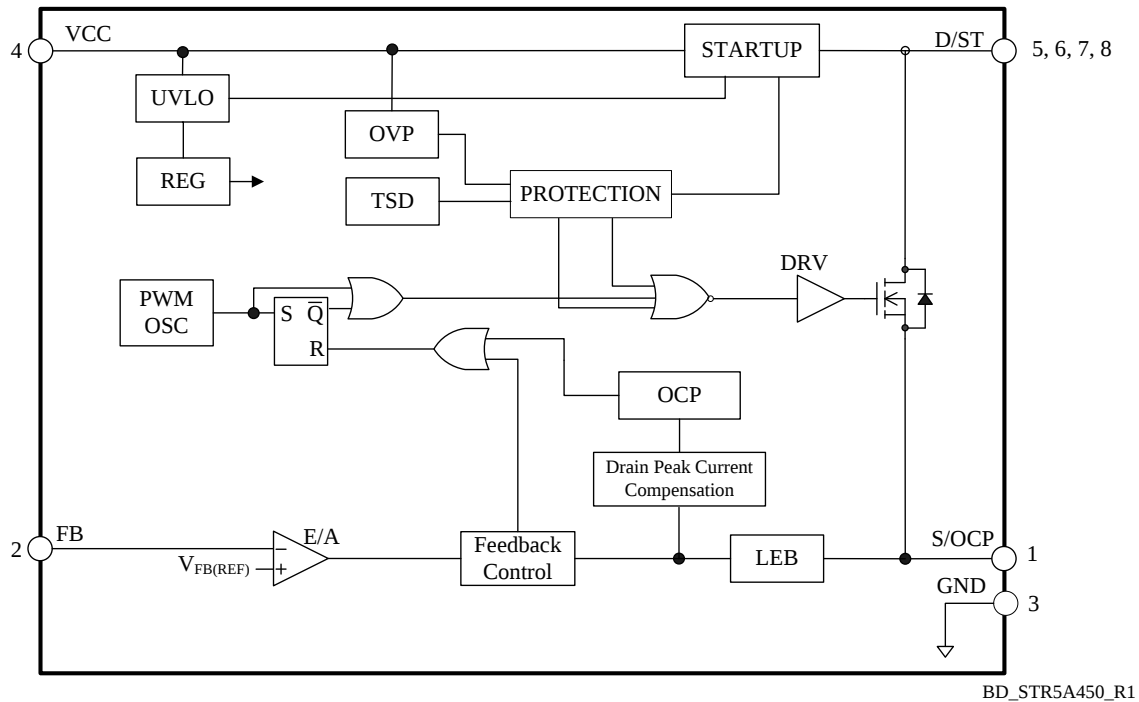
3.3 Ambient Temperature versus Power Dissipation Curves



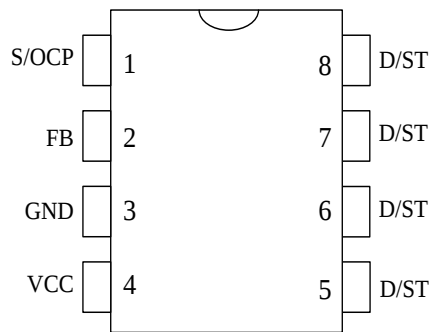
3.4 Transient Thermal Resistance Curves



4. Block Diagram



5. Pin Configuration Definitions



Pin	Name	Descriptions
1	S/OCP	Power MOSFET source and Overcurrent Protection (OCP) signal input
2	FB	Constant voltage control signal input and overload protection signal input
3	GND	Ground
4	VCC	Power supply voltage input for control part and Overvoltage Protection (OVP) signal input
5	D/ST	MOSFET drain and startup current input
6		
7		
8		

6. Typical Applications

Figure 6-1 and Figure 6-2 are the example circuits.

To enhance the heat dissipation, the wide pattern layout of the D/ST pin (5 through 8 pin) is recommended.

When the absolute value of the output voltage $|V_{OUT}|$ is 27.5 V or higher, add a zener diode DZ1 connected to D1 in serial as shown in Figure 6-3. Using the maximum duty cycle of 50 % in the steady state operation, the condition of $|V_{OUT}|$ is shown below:

$$|V_{OUT}| : 11V < |V_{OUT}| - V_{DZ1} < 27.5V$$

$$|V_{OUT}| \text{ in response to the input voltage: For Buck topology, } |V_{OUT}| \leq \frac{1}{2} \times \text{Input voltage}$$

$$\text{For Inverting topology, } |V_{OUT}| \leq \text{Input voltage}$$

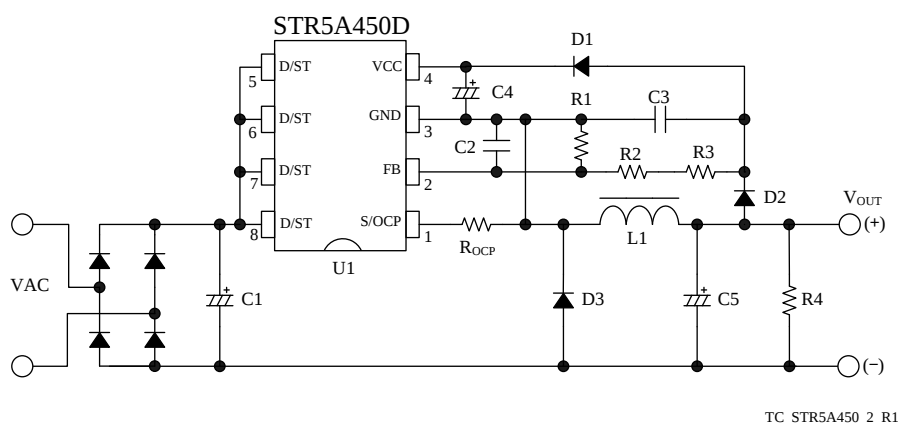


Figure 6-1. Buck Converter

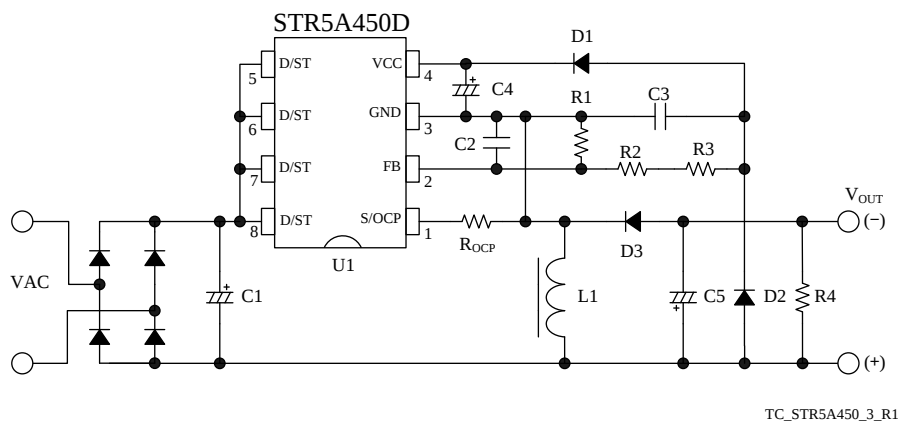


Figure 6-2. Inverting Converter

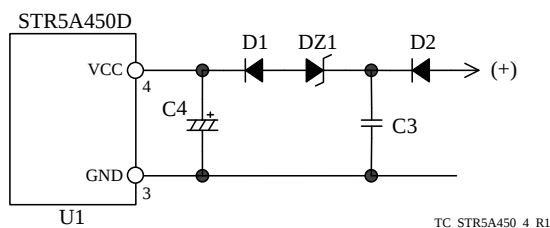
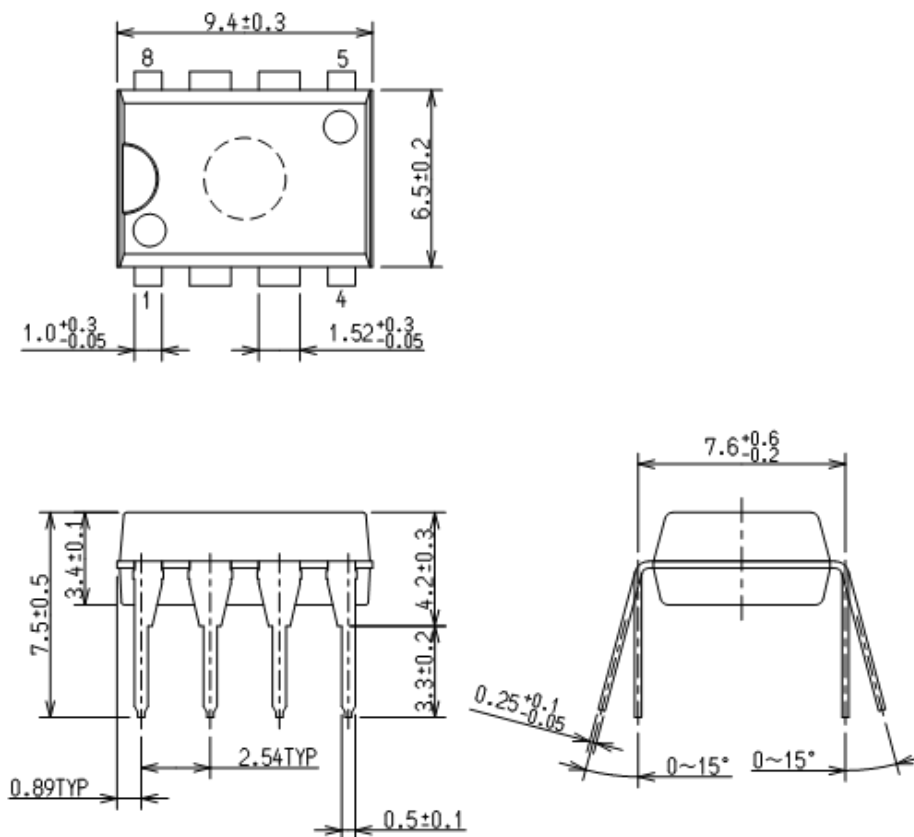


Figure 6-3. Increasing the Absolute value of $|V_{OUT}|$

7. Physical Dimensions

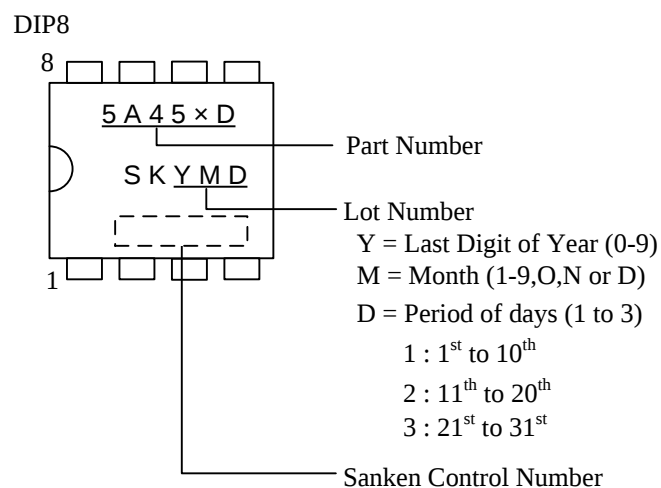
- DIP8



NOTES:

- 1) Units: mm
- 2) Pb-free. Device composition compliant with the RoHS directive

8. Marking Diagram



9. Operational Description

All of the parameter values used in these descriptions are typical values, unless they are specified as minimum or maximum. With regard to current direction, "+" indicates sink current (toward the IC) and "-" indicates source current (from the IC).

The common items of Buck converter and Inverting are described by using Buck converter.

9.1 Startup Operation of IC

Figure 9-1 shows the circuit around VCC pin.

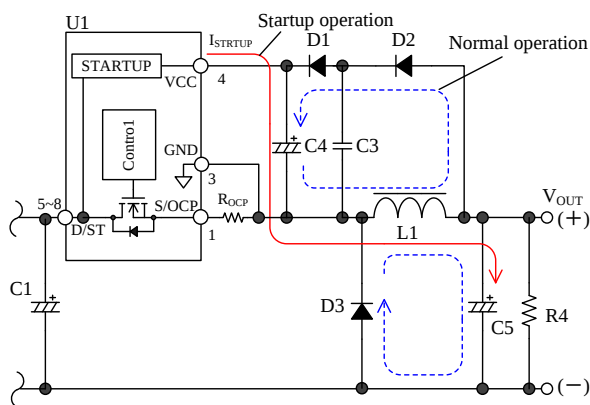


Figure 9-1. VCC Pin Peripheral Circuit in Buck Converter

The IC incorporates the startup circuit. The circuit is connected to D/ST pin. When D/ST pin voltage reaches the Startup Circuit Operation Voltage $V_{ST(ON)} = 29\text{ V}$, the startup circuit starts operation.

During the startup process, the constant current, $I_{CC(ST)} = -1.7\text{ mA}$, charges C4 at VCC pin. When VCC pin voltage increases to $V_{CC(ON)} = 15.0\text{ V}$, the control circuit starts switching operation.

After switching operation begins, the startup circuit turns off automatically so that its current consumption becomes zero.

The approximate startup time t_{START} is calculated as follows:

$$t_{START} = C4 \times \frac{V_{CC(ON)} - V_{CC(INT)}}{|I_{CC(ST)}|} \quad (\text{s}) \quad (1)$$

where,

t_{START} is the startup time of IC (s),

$V_{CC(INT)}$ is the initial voltage on VCC pin (V).

When the internal power MOSFET turns off, the output voltage, V_{OUT} , charges C4 through D1 and D2

(Refer to Figure 9-1).

The voltage between VCC pin and GND pin in the steady state operation is calculated as follows, where V_{FD1} , V_{FD2} and V_{FD3} are the forward voltage of D1, D2 and D3 respectively:

$$V_{CC} = V_{OUT} + V_{FD3} - (V_{FD1} + V_{FD2}) \quad (\text{V}) \quad (2)$$

9.2 Undervoltage Lockout (UVLO)

Figure 9-2 shows the relationship of VCC pin voltage and the circuit current, I_{CC} . When VCC pin voltage increases to $V_{CC(ON)} = 15.0\text{ V}$, the control circuit starts switching operation and the circuit current, I_{CC} , increases. When VCC pin voltage decreases to $V_{CC(OFF)} = 8.0\text{ V}$, the control circuit stops its operation by the Undervoltage Lockout (UVLO) circuit, and reverts to the state before startup.

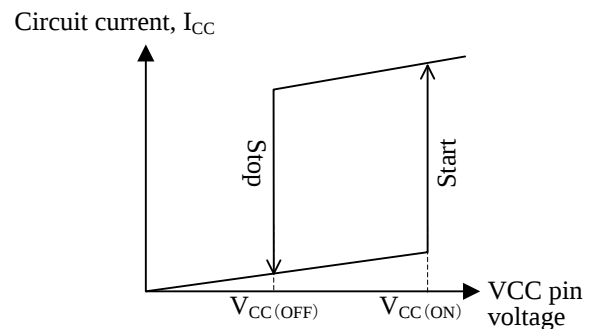


Figure 9-2. Relationship between VCC Pin Voltage and I_{CC}

9.3 Power Supply Startup and Soft Start Function

The Soft Start Function reduces the voltage and the current stress of the internal power MOSFET and the freewheeling diode, D3.

Figure 9-3 shows the startup waveforms. After the IC starts, during the Standby Blanking Time at Startup, $t_{STB(INH)}$, the burst oscillation mode is disabled to operate the soft start.

The IC activates the soft start circuitry during the startup period. The soft start time is fixed to about 10.2 ms. During the soft start period, the overcurrent threshold is increased step-wisely (7 steps). The IC operates switching operation by the frequency responding to FB pin voltage until the output reaches the setting voltage.

Here, the t_{LIM} is defined as the period until FB pin voltage reaches 1.6 V after the IC starts. When the t_{LIM}

reaches the OLP Delay Time at Startup, t_{OLP} , of 70 ms and more, the IC stops switching operation. Thus, it is necessary to adjust the value of output electrolytic capacitor, C5 so that the t_{LIM} is less than t_{OLP} .

If VCC pin voltage reaches $V_{CC(OFF)}$ and a startup failure occurs as shown in Figure 9-4, increase C4 value or decrease C5 value. Since the larger capacitance causes the longer startup time of IC, it is necessary to check and adjust the startup process based on actual operation in the application.

Since the Leading Edge Blanking Function (Refer to Section 9.5) is disabled during the soft start period, the on-time may be less than the Leading Edge Blanking Time ($t_{BW} = 280$ ns).

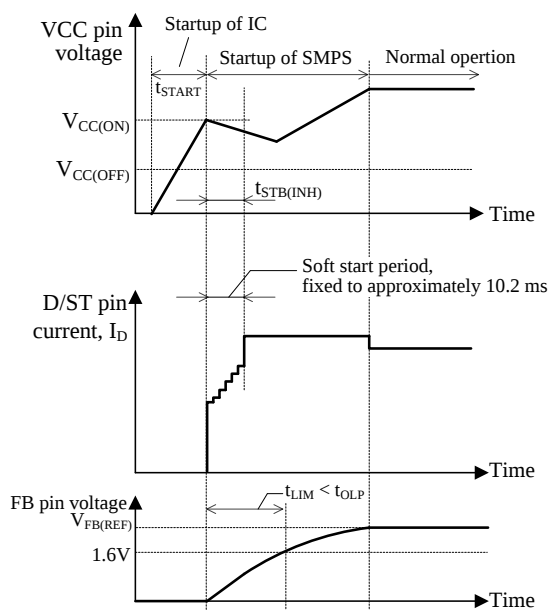


Figure 9-3. Startup Waveforms

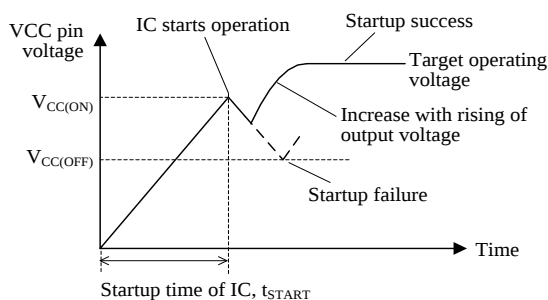


Figure 9-4. VCC Pin Voltage During Startup Period

9.4 Constant Voltage (CV) Control

The constant voltage (CV) control for power supply output adopts the peak-current-mode control method

which enhances the response speed and the stable operation.

The IC controls the peak value of the voltage of a current detection resistor (V_{ROCP}) to be close to target voltage (V_{SC}), comparing V_{ROCP} with V_{SC} by internal FB comparator. Feedback Control circuit receives the target voltage, V_{SC} , reversed FB pin voltage by an error amplifier (Refer to Figure 9-5 and Figure 9-6).

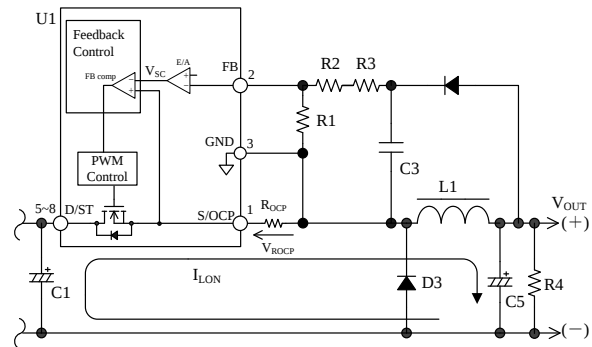


Figure 9-5. FB Pin Peripheral Circuit in Buck Converter

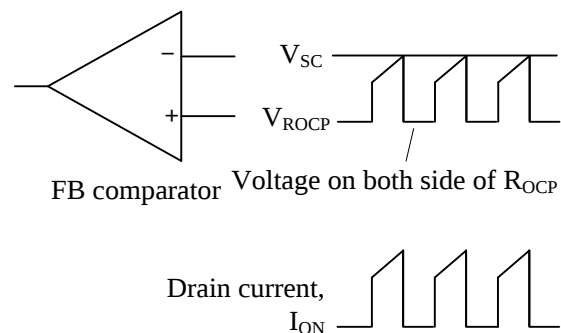


Figure 9-6. Drain Current I_D and FB Comparator in Steady State Operation

• Decreasing load

When the output load decreases, the FB pin voltage increases in response to the increase of the output voltage. Since V_{SC} which is the output voltage of internal error amplifier becomes low, the peak value of V_{ROCP} is controlled to become low, and the peak of the drain current decreases. This control prevents the output voltage from increasing.

• Increasing load

When the output load increases, the control circuit operates the reverse of the former operations. Since V_{SC} becomes high, the peak drain current increases. This control prevents the output voltage from decreasing.

9.4.1 Buck Converter Operation

Figure 9-7 shows the output current path in the Buck converter. Figure 9-8 shows the operational waveforms.

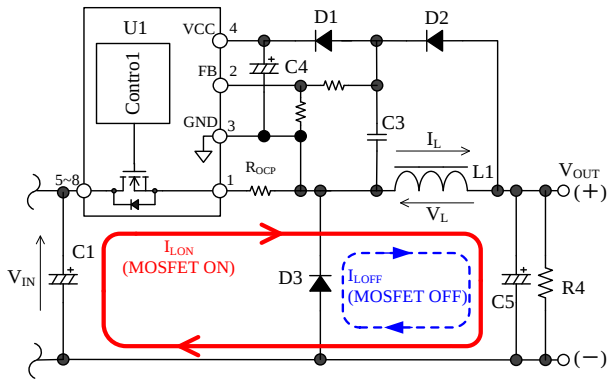


Figure 9-7. Output Current Path in Buck Converter

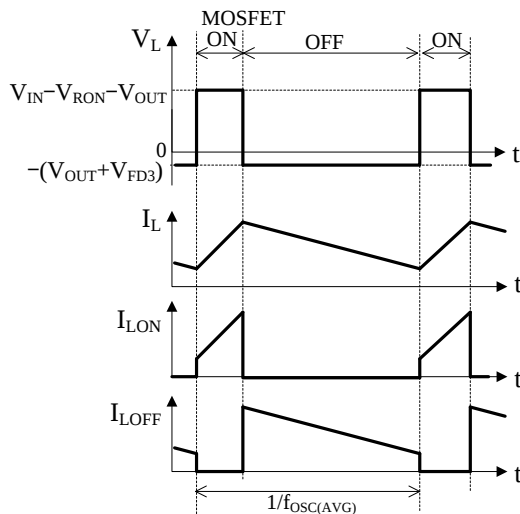


Figure 9-8. Operational Waveforms in Buck Converter

In the Buck converter, the PWM control is described in the following.

1) PWM On-time Period

When the internal power MOSFET turns on, the I_{LON} current flows as shown in Figure 9-7, and the inductor, L1, stores some energy.

Since the I_{LON} flows through the current detection resistor, R_{OCP} , the voltage of R_{OCP} is detected as the current detection voltage, V_{ROCP} .

FB pin voltage is the voltage divided C3 voltage by voltage dividing resistors, and the target voltage, V_{SC} , is given by FB pin voltage.

When V_{ROCP} reaches V_{SC} , the power MOSFET turns off.

2) PWM Off-time Period

When the internal power MOSFET turns off, the back electromotive force occurs in the inductor, L1, the freewheeling diode, D3, is forward biased and turns on. Thus, the I_{LOFF} current flows as shown in Figure 9-7.

As shown in Figure 9-8, after the average switching period, $1/f_{OSC(AVG)}$, the power MOSFET turns on again, and the event moves to the previous 1).

The output current is equal to the average inductor current of L1.

9.4.2 Inverting Converter Operation

Figure 9-9 shows the output current path in the Inverting converter. Figure 9-10 shows the operational waveforms.

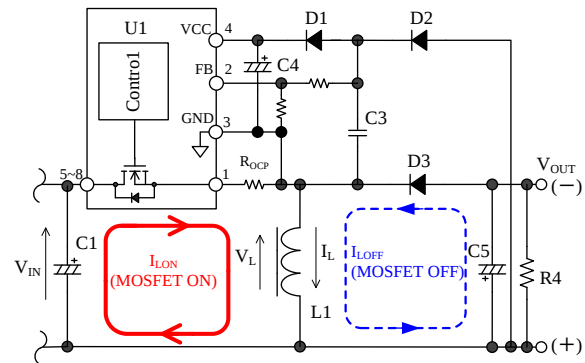


Figure 9-9. Output Current Path in Inverting Converter

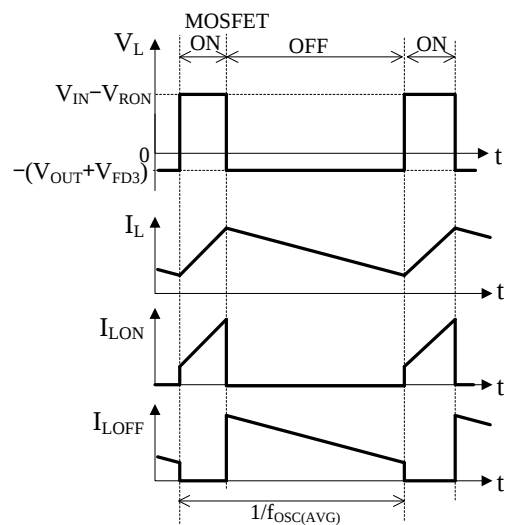


Figure 9-10. Operational Waveforms in Inverting Converter

In the Inverting converter, the PWM control is described in the following.

1) PWM On-time Period

When the internal power MOSFET turns on, the I_{LON} current flows as shown in Figure 9-9, and the inductor, L1, stores some energy.

Since the I_{LON} flows through the current detection resistor, R_{OCP} , the voltage of R_{OCP} is detected as the current detection voltage, V_{ROCP} .

FB pin voltage is the voltage divided C3 voltage by voltage dividing resistors, and the target voltage, V_{SC} , is given by FB pin voltage.

When V_{ROCP} reaches V_{SC} , the power MOSFET turns off.

2) PWM Off-time Period

When the internal power MOSFET turns off, the back electromotive force occurs in the inductor, L1, the freewheeling diode, D3, is forward biased and turns on. Thus, the I_{LOFF} current flows as shown in Figure 9-9

As shown in Figure 9-10, after the average switching period, $1/f_{\text{OSC(AVG)}}$, the power MOSFET turns on again, and the event moves to the previous 1).

The output current is equal to the average current of I_{LOFF} of L1.

9.5 Leading Edge Blanking Function

The constant voltage control for power supply output adopts the peak-current-mode control method. The peak drain current is detected by the current detection resistor, R_{OCP} . Just in turning on the internal power MOSFET, the steep surge current would occur.

If the Overcurrent Protection (OCP) responds to the voltage caused by that surge current, the power MOSFET may be turned off.

To prevent that response, the OCP threshold voltage increases during Leading Edge Blanking ($t_{\text{BW}} = 280 \text{ ns}$) just after the power MOSFET turns on, and this prevents the OCP detection from responding to the surge voltage in turning-on (Refer to Section 9.8.1).

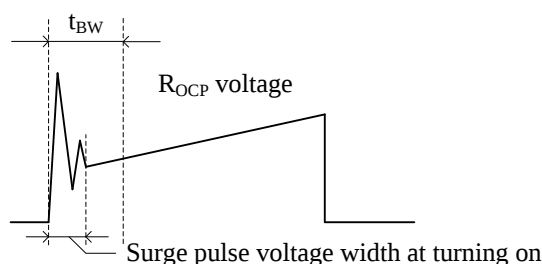


Figure 9-11. Leading Edge Blanking

9.6 Random Switching Function

The switching frequency is randomly modulated by superposing the modulating frequency on $f_{\text{OSC(AVG)}}$. This function reduces the conduction noise compared with other products without this function, and simplifies noise filtering of the input lines of power supply.

9.7 Operation Mode

As shown in Figure 9-12, when the output power is decreasing, together with the decrease of the drain current I_{D} of the internal power MOSFET, the operation mode is automatically changed to the fixed switching frequency mode (60 kHz), to the Green mode controlled the switching frequency (23 kHz to 60 kHz), and to the burst oscillation mode controlled by an internal oscillator. In the Green mode, the number of switching is reduced. In the burst oscillation mode, the switching operation is stopped during a constant period. Thus, the switching loss is reduced, and the power efficiency is improved (Refer to Figure 9-13).

When the output load becomes lower, FB pin voltage increases and S/OCP pin voltage decreases. The S/OCP pin voltage reaches to the S/OCP pin standby threshold voltage, $V_{\text{OCP(STB)}} = 0.11 \text{ V}$, the burst oscillation mode is activated.

As shown in Figure 9-13, the burst oscillation mode consists of the switching period and the non-switching period. The oscillation frequency during the switching period is the Minimum Frequency of about 23 kHz.

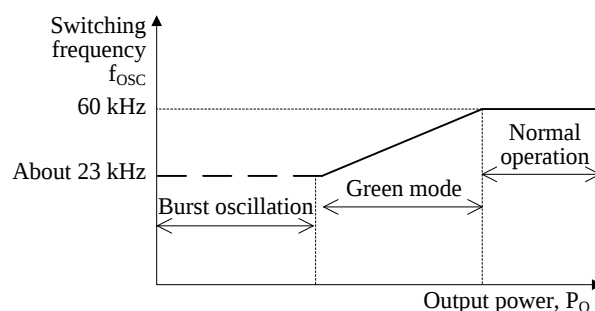


Figure 9-12. Switching Frequency in Response to P_{O}

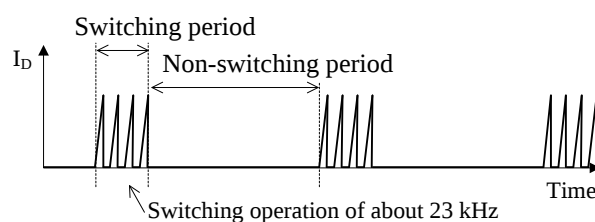


Figure 9-13. Switching Waveform at Burst Oscillation Mode

9.8 Overcurrent Protection (OCP)

9.8.1 OCP Operation

Overcurrent Protection (OCP) detects each drain peak current level of a power MOSFET on pulse-by-pulse basis, and limits the output power when the voltage on the current detection resistor, R_{OCP} , reaches to OCP threshold voltage.

During Leading Edge Blanking Time shown in Figure 9-11, the OCP threshold voltage becomes $V_{OCP(LEB)} = 1.61$ V which is higher than the normal OCP threshold voltage. Changing to this threshold voltage prevents the OCP detection from responding to the surge voltage in turning-on the power MOSFET. This function operates as protection at the condition including output shorted.

When the power MOSFET turns on, the surge voltage width of the S/OCP pin should be less than t_{BW} . To prevent surge voltage, pay extra attention to R_{OCP} trace layout (Refer to Section 10.4).

9.8.2 OCP Input Compensation Function

ICs with PWM control usually have some propagation delay time. The steeper the slope of the actual drain current at a high AC input voltage is, the larger the detection voltage of actual drain peak current is, compared to V_{OCP} . Thus, the peak current has some variation depending on AC input voltage in OCP state. To reduce the variation of peak current in OCP state, the Input Compensation Function is built-in.

This function compensates the OCP threshold voltage so that it depends on AC input voltage, as shown in Figure 9-14.

When AC input voltage is low, the OCP threshold voltage is controlled to become high. Thus this control reduces the difference of peak drain current between at low AC input voltage and at high.

When the on-time is 6 μ s or more, the OCP threshold voltage is $V_{OCP(H)}$ of 0.83 V. When the on-time is less than 6 μ s, that is V_{OCP} shown in Equation (3).

$$V_{OCP} = V_{OCP(L)} + DPC \times 10^3 \times ONTime \quad (3)$$

Where,

$V_{OCP(L)}$: OCP Threshold Voltage at Zero Duty Cycle (V)

DPC: OCP Compensation Coefficient (mV/ μ s)

ONTime: On-time of power MOSFET (μ s)

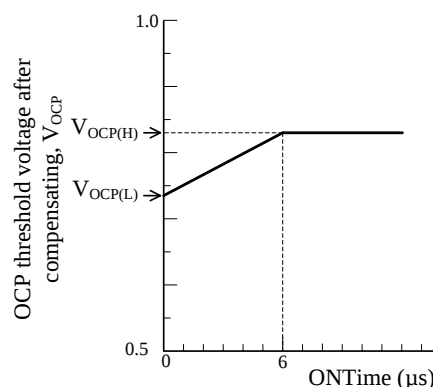


Figure 9-14. Relationship between ONTime and OCP Threshold Voltage after Compensating

9.9 Overload Protection (OLP)

When the voltage on the current detection resistor, R_{OCP} , reaches the OCP threshold voltage, the internal power MOSFET turns off. Figure 9-15 shows the characteristic of output voltage and current.

The output voltage decreases in the overload state, and FB pin voltage also decreases. When the period keeping FB pin voltage less than 1.6 V continues for OLP Delay Time at Startup, $t_{OLP} = 70$ ms, the Overload Protection (OLP) is activated, and the IC stops switching operation. Thus, VCC pin voltage decreases to $V_{CC(OFF)}$, and the control circuit stops operation. After that, the startup circuit is activated, VCC pin voltage increases to $V_{CC(ON)}$ by the startup current, and the control circuit operates again. Thus, the intermittent operation by UVLO is repeated in the OLP state (Refer to Figure 9-16).

This intermittent operation reduces the stress of parts including the power MOSFET and the freewheeling diode. In addition, this operation reduces power consumption because the switching period in this intermittent operation is much shorter than the oscillation stop period.

When the abnormal condition is removed, the IC returns to normal operation automatically.

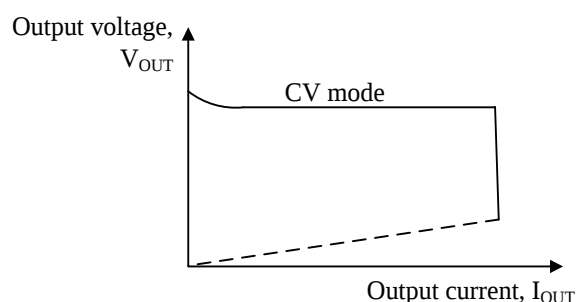


Figure 9-15. Overload Characteristics

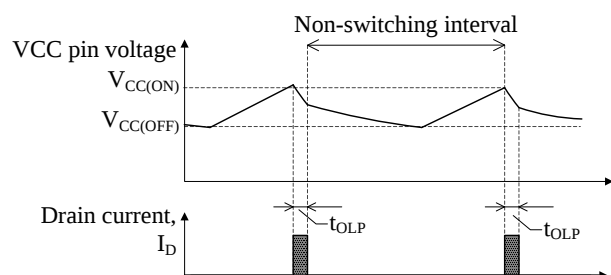


Figure 9-16. OLP Operational Waveform

9.10 Overvoltage Protection (OVP)

When the voltage between VCC pin and GND pin increases to $V_{CC(OVP)} = 29.3$ V or more, the Overvoltage Protection (OVP) is activated and the IC stops switching operation. The intermittent operation by UVLO is repeated in the OVP state. Refer to Section 9.9 about the intermittent operation by UVLO.

When the abnormal condition is removed, the IC returns to normal operation automatically.

The approximate value of output voltage $V_{OUT(OVP)}$ in the OVP condition is calculated by using Equation (4).

$$V_{OUT(OVP)} = V_{CC(OVP)} + V_{FD1} + V_{FD2} - V_{FD3} \quad (4)$$

where,

$V_{OUT(OVP)}$ is voltage of between $V_{OUT}(+)$ and $V_{OUT}(-)$,

V_{FD1} is the forward voltage of D1 in Figure 9-1,

V_{FD2} is the forward voltage of D2, and

V_{FD3} is the forward voltage of D3.

9.11 Thermal Shutdown (TSD)

Figure 9-17 shows the Thermal Shutdown (TSD) operational waveforms.

When the junction temperature of the IC control circuit increases to $T_{j(TSD)} = 135$ °C (min.) or more, the TSD is activated, and the IC stops switching operation. The TSD has a temperature hysteresis. While the junction temperature of the control circuit is more than $T_{j(TSD)} - T_{j(TSD)HYS}$, the Bias Assist Function is enabled when VCC pin voltage decreases to about 9.4 V. While this function is activated, the startup current is supplied to VCC pin in order to keep $V_{CC(OFF)}$ or more, and the IC holds stopping.

While the junction temperature is $T_{j(TSD)} - T_{j(TSD)HYS}$ or less, the Bias Assist Function is disabled, and VCC pin voltage decreases to $V_{CC(OFF)}$ or less. Thus, the control circuit stops operation. After that, the startup circuit is activated, VCC pin voltage increases to $V_{CC(ON)}$ by the

startup current, and the control circuit operates again. The intermittent operation by TSD and UVLO is repeated in the TSD state.

After the fault condition is removed, the IC returns to normal operation automatically.

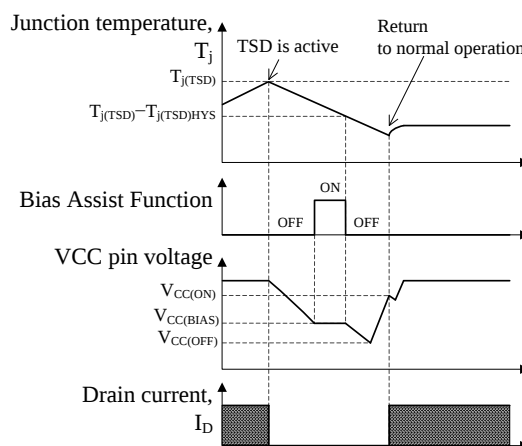


Figure 9-17. TSD Operational Waveforms

10. Design Notes

10.1 External Components

Take care to use properly rated, including derating as necessary, and proper type of components.

Figure 10-1 shows the peripheral circuit of IC in Buck converter.

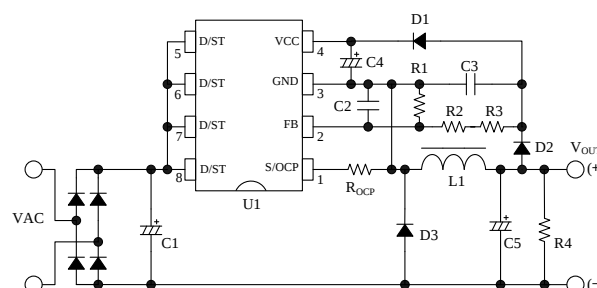


Figure 10-1. Peripheral Circuit of IC in Buck Converter

10.1.1 Input and Output Electrolytic Capacitor

Apply proper derating to ripple current, voltage, and temperature rise.

The value of output electrolytic capacitor, C5, should be fulfilled the following conditions:

- The specification of output ripple
- Enough shorter output voltage rising time in startup than the OLP Delay Time at Startup, $t_{OLP} = 70$ ms.
- Low impedance types, designed for switch mode power supplies, is recommended.

The ESR of C5 should be set in the range of Equation (5).

$$Z_{CO} < \frac{\Delta V_{OR}}{I_{LRP}} \quad (5)$$

where,

Z_{CO} is the ESR of electrolytic capacitor at the operation frequency (Since the ESR in general catalogs is mostly measured at 100 kHz, check the frequency characteristic.),

ΔV_{OR} is the output ripple voltage specification, and I_{LRP} is the ripple current of inductor (Refer to Section 10.3).

10.1.2 Inductor

Apply proper design margin to core temperature rise by core loss and copper loss.

The inductor should be designed so that the inductor current does not saturate. Refer to Section 10.3 about the inductance. The value should be the minimum considered a negative tolerance of inductance and a decline of DC superposition characteristics.

The on-time must be longer than the Leading Edge Blanking Time to control the output voltage constantly.

In the universal input voltage design, the on-time is easy to become short in the condition of maximum AC input voltage and light load. Be careful not to choose too small value for the inductance (The recommended value is 100 μ H or more).

10.1.3 VCC Pin Peripheral Circuit

The reference value of C4 in Figure 10-1 is generally 10 to 47 μ F. Refer to Section 9.1 about the startup time.

10.1.4 FB Pin Peripheral Circuit

As shown in Figure 10-1, FB pin is input the voltage divided the voltage between $V_{OUT}(+)$ and GND pin by resistors.

C3 is the smoothing capacitor. The value of C3

depends on the value of output electrical capacitor, C5. Usually the value of C3 is 0.022 μ F to 0.22 μ F. When C3 value is set larger, the line regulation becomes better, however, the dynamic response of the output voltage becomes worse. Be careful of that value.

The voltage dividing resistor of R1, R2 and R3 is determined by the reference voltage, $V_{FB(REF)} = 2.50$ V, the output voltage, V_{OUT} , and so on. The following Equation (6) shows the relationship of them.

The target value of R1 is about 10 k Ω to 22 k Ω . R2 and R3 should be adjusted in actual operation condition.

The V_F of D2 and D3 affects the output voltage. Thus, the diodes of low V_F should be selected.

$$|V_{OUT}| \cong V_{FB(REF)} \times \frac{R1 + R2 + R3}{R1} + V_{FD2} - V_{FD3}$$

$$\Rightarrow R2 + R3 = \left(\frac{|V_{OUT}| - V_{FD2} + V_{FD3}}{V_{FB(REF)}} - 1 \right) \times R1 \quad (6)$$

where,

V_{FD2} is the forward voltage of D2, and

V_{FD3} is the forward voltage of D3.

10.1.5 Freewheeling Diode

D3 in Figure 10-1 is the freewheeling diode.

When the internal power MOSFET turns on, the recovery current flows through D3. The current affects power loss and noise much. The V_F affects the output voltage. Thus, the diode of fast recovery and low V_F should be selected.

10.1.6 Bleeder Resistance

For light load application, the bleeder resistor, R4, in

Figure 10-1 should be connected to both ends of output capacitor, C5, to prevent the increase of output voltage.

The value of R4 should be satisfied with Equation (7), and should be adjusted in actual operation condition.

$$R4 \leq \frac{|V_{OUT}|}{3mA} \quad (7)$$

10.2 D/ST Pin

When the voltage or the current of the D/ST pins shown in

Figure 10-1 exceeds the Absolute Maximum Ratings, the internal power MOSFET connected to the D/ST pin would be permanently damaged.

10.3 Inductance Calculation

Since this calculation is just on paper, it is necessary to take account of margins and to check operations on actual operation in the application.

The PWM control has the three operation modes shown below. Since each operation mode has that characteristic, it is necessary to take account of choosing the operation mode.

The table on the right shows the comparison of three operation modes in the same input and output condition.

Table 10-1. Operation Mode Comparison

	P _{OW}	L	I _{LR}	P _{RD(ON)}	P _{SW}
CCM	Large	Large	Small	Small	Large
CRM	Middle	Middle	Middle	Middle	Small
DCM	Small	Small	Large	Large	Small

where,

CCM is continuous current mode,

CRM is critical current mode,

DCM is discontinuous current mode,

P_{OW} is capable output power,

L is inductance value of L2,

I_{LR} is ripple inductor current,

P_{RD(ON)} is conduction loss on the power MOSFET,

P_{SW} is switching loss.

10.3.1 Parameter Definition

The following parameters refer to the circuit of Figure 6-1 and Figure 6-2.

V_{DCIN_MIN} is minimum DC input voltage at C2,

V_{DCIN_MAX} is maximum DC input voltage at C2,

V_{OUT} is output voltage,

I_{OUT} is output current,

V_{RON} is on voltage of internal power MOSFET,

Drain current × R_{DS(ON)},

V_{FD1} is D1 forward voltage,

V_{FD2} is D2 forward voltage,

V_{FD3} is D3 forward voltage,

V_{DZ1} is DZ1 zener voltage.

When |V_{OUT}| is 27.5 V or more, add a zener diode or a regulator. Take care of that power loss.

R_{OCP} : Current detection resistor between S/OCP pin and GND pin

When the following have no values, see the values of Section 2. Electrical Characteristics.

D_{ON_MAX} is maximum duty cycle in steady operation, 0.5,

K_{RP_MIN} is 0.4,

V_{ST_MAX} is maximum value of V_{ST(ON)},

V_{DC(MAX)} is maximum DC input voltage, recommended value is 400 V,

V_{CC_MIN} is minimum value of VCC Voltage, 10 V,

V_{CC(OVP)_MIN} is minimum value of V_{CC(OVP)},

I_{DLIM} is less than the value of I_{DPEAK} × the derating supposed as 90 %,

f_{TYP} is typical value of f_{OSC(AVG)},

f_{MIN} is minimum switching frequency, 23 kHz,

V_{OCP(L)_MIN} is minimum value of V_{OCP(L)},

V_{OCP(L)_TYP} is typical value of V_{OCP(L)},

V_{OCP(H)_MIN} is minimum value of V_{OCP(H)},

V_{OCP(H)_TYP} is typical value of V_{OCP(H)},

V_{OCP(H)_MAX} is maximum value of V_{OCP(H)},

V_{OCP(STB)} is typical value of V_{OCP(STB)},

DPC is typical value of DPC.

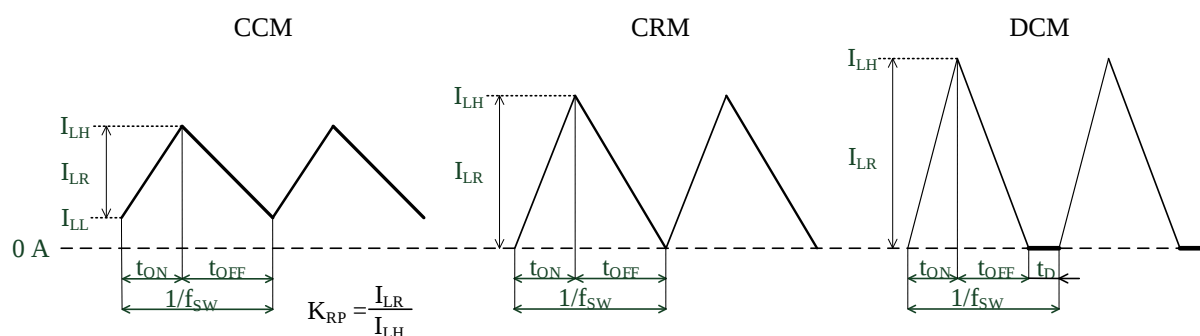


Figure 10-2. Operation Mode of PWM Control

where,

f_{SW} is switching frequency, t_{ON} is on-time, t_{OFF} is off-time, t_D is discontinuous current time,

I_{LH} is upper inductor current, I_{LL} is lower inductor current, I_{LR} is ripple inductor current,

K_{RP} is ripple inductor current ratio, I_{LR}/I_{LH}.

10.3.2 Buck Converter

(B-1) Input and Output Condition

The definition refers to Section 10.3.1.

V_{DCIN_MIN}	Lower value is a higher value or more of either V_{ST_MAX} or $2 \times V_{OUT} + V_{FD3} + V_{RON}$. Upper value is $V_{DC(MAX)}$ or less.
V_{DCIN_MAX}	$V_{DCIN_MIN} \leq V_{DCIN_MAX} < V_{DC(MAX)}$
V_{OUT}	$V_{CC_MIN} + V_{DZ1} - V_{FD3} + (V_{FD1} + V_{FD2}) < V_{OUT} < 0.5 \times (V_{DCIN_MIN} - V_{RON} - V_{FD3})$
I_{OUT}	$I_{OUT} < 0.8 \times I_{DLIM}$. In addition, I_{OUT} also depends on the OCP setting.
V_{DZ1}	Lower value is a higher value or more of either 0 or $V_{OUT} + V_{FD3} - (V_{FD1} + V_{FD2} + V_{CC(OVP)_MIN})$. Upper value is $V_{OUT} + V_{FD3} - (V_{FD1} + V_{FD2} + V_{CC_MIN})$
R_{OCP}	Lower value is $R_{OCP(L)} = \frac{V_{OCP(H)_MAX}}{I_{DLIM}}$, or more.

(B-2) Calculation

There are two calculation ways: L_{CALC} Calculation, and Parameter Calculation assigned L_{USER} .

(B-2-1) L_{CALC} Calculation

The inductance, L_{CALC} , is given by choosing the operation mode at V_{DCIN_MIN} . The parameters of both V_{DCIN_MIN} and V_{DCIN_MAX} are given by L_{CALC} .

(B-2-1-1) Parameters for V_{DCIN_MIN}

(B-2-1-1-1) Duty Cycle in Continuous Operation, D_{CCM1}

$$D_{CCM1} = \frac{V_{OUT} + V_{FD3}}{V_{DCIN_MIN} - V_{RON} + V_{FD3}}$$

The condition of $D_{CCM1} : < 0.5$

(B-2-1-1-2) Choosing the Operation Mode, and K_{RP1} or D_{DCM1}

• Choosing CCM

K_{RP1} is set in the following range.

$$0.4 \leq K_{RP1} < 2 \times \frac{I_{DLIM} - I_{OUT}}{I_{DLIM}} < 1$$

The condition of $I_{OUT} : < 0.8 \times I_{DLIM}$

• Choosing CRM

The condition of $I_{OUT} : \leq 0.5 \times I_{DLIM}$

• Choosing DCM

The duty cycle for DCM, D_{CCM1} , is set in the range of

$$\frac{2 \times I_{OUT} \times D_{CCM1}}{I_{DLIM}} \leq D_{DCM1} < D_{CCM1}$$

The condition of $I_{OUT} : < 0.5 \times I_{DLIM}$

(B-2-1-1-3) Inductor Current

D_{ON1} is denoted the duty cycle. I_{LH1} , I_{LL1} , and I_{LR1} are the upper inductor current, the lower inductor current, and the ripple inductor current, respectively.

• Choosing CCM

$$D_{ON1} = D_{CCM1}$$

$$I_{LH1} = \frac{2 \times I_{OUT}}{2 - K_{RP1}}$$

$$I_{LR1} = K_{RP1} \times I_{LH1}$$

$$I_{LL1} = I_{LH1} - I_{LR1}$$

• Choosing CRM

$$D_{ON1} = D_{CCM1}$$

$$I_{LH1} = 2 \times I_{OUT}$$

$$I_{LR1} = I_{LH1}, I_{LL1} = 0$$

- Choosing DCM

$$D_{ON1} = D_{DCM1}$$

$$I_{LH1} = 2 \times I_{OUT} \times \frac{D_{CCM1}}{D_{DCM1}}$$

$$I_{LR1} = I_{LH1}, I_{LL1} = 0$$

(B-2-1-1-4) Upper Temporary Value of R_{OCP} , $R_{OCP(H)_TMP1}$

$$R_{OCP(H)_TMP1} = \frac{V_{OCP(H)_MAX}}{I_{LH1}}$$

The temporary range of the current detection resistor, R_{OCP} , is given below.

$$R_{OCP(L)} \leq R_{OCP} < R_{OCP(H)_TMP1}$$

If R_{OCP} setting has no range, try the following procedure 1.

- Procedure 1 :
For CCM, reduce K_{RP1} or I_{OUT} .
For CRM, change to CCM.
For DCM, increase D_{DCM1} , or change to CRM or CCM.
After these changes, try to calculate again from Section (B-1) Input and Output Condition.

R_{OCP} setting is set in the previous range.

The switching frequency, f_{SW1} , and the peak inductor current at OCP depend on R_{OCP} . When R_{OCP} is set low, f_{SW1} becomes low, and the peak current becomes large.

(B-2-1-1-5) Switching Frequency, f_{SW1}

The f_{SW1} is given by the following with the I_{LH1} of the choosing operation mode and R_{OCP} .

The following K is a coefficient.

$$K = \left(\frac{f_{TYP} - f_{MIM}}{0.85 \times V_{OCP(L)_TYP} - V_{OCP(STB)}} \right)$$

f_{SW1} is given below by using K.

$$f_{SW1} = K \times (R_{OCP} \times I_{LH1} - V_{OCP(STB)}) + f_{MIM}$$

where,

For $f_{SW1} \leq f_{MIN}$, set to f_{MIN} .

For $f_{SW1} \geq f_{TYP}$, set to f_{TYP} .

(B-2-1-1-6) On-time, t_{ON1}

By D_{ON1} and f_{SW1} of the choosing operation mode,

$$t_{ON1} = \frac{D_{ON1}}{f_{SW1}}$$

If t_{ON1} is less than 500 ns, try the procedure 1 in Section (B-2-1-1-4) to increase it.

(B-2-1-1-7) OCP Threshold Voltage, V_{OCP1}

V_{OCP1} is given below by t_{ON1} .

- For $t_{ON1} \geq 6\mu s$, $V_{OCP1} = V_{OCP(H)_MIN}$
- For $t_{ON1} < 6\mu s$,

$$V_{OCP1} = V_{OCP(L)_MIN} + DPC \times 10^{-3} \times t_{ON1}$$

where, DPC (mV/ μs), t_{ON1} (μs)

(B-2-1-1-8) Current Detection Resistor, R_{OCP}

Upper value at V_{DCIN_MIN} of the R_{OCP} range is given below.

$$R_{OCP(H)1} = \frac{V_{OCP1}}{I_{LH1}}$$

The range of R_{OCP} is given below.

$$R_{OCP(L)} \leq R_{OCP} < R_{OCP(H)1}$$

If R_{OCP} setting has no range, try the procedure 1 in Section (B-2-1-1-4).

If R_{OCP} setting is out of the previous range, try to set it again, and then try to calculate again from Section (B-2-1-1-5).

(B-2-1-1-9) Inductance, L_{CALC}

By I_{LH1} , I_{LL1} , and f_{SW1} of the choosing operation mode,

$$L_{CALC} = \frac{2 \times I_{OUT} \times (V_{OUT} + V_{FD3}) \times (1 - D_{CCM1})}{(I_{LH1}^2 - I_{LL1}^2) \times f_{SW1}}$$

The value should be the minimum considered a negative tolerance of inductance and a decline of DC superposition characteristics.

If L_{CALC} is less than 100 μH , try the procedure 1 of Section (B-2-1-1-4) to increase it.

(B-2-1-1-10) Drain RMS Current and Inductor RMS

Current : I_{DRMS1} , I_{LRMS1}

$$I_{DRMS1} = \sqrt{\left(\frac{1}{3} \times (I_{LH1} - I_{LL1})^2 + I_{LH1} \times I_{LL1}\right) \times D_{ON1}}$$

The conduction loss of $R_{DS(ON)}$ of power MOSFET is estimated to be $I_{DRMS1}^2 \times R_{DS(ON)}$.

$$I_{LRMS1} = \sqrt{\left(\frac{1}{3} \times (I_{LH1} - I_{LL1})^2 + I_{LH1} \times I_{LL1}\right) \times \frac{D_{ON1}}{D_{CCM1}}}$$

This value is equivalent to the rating for inductor.

(B-2-1-2) Parameters for V_{DCIN_MAX}
(B-2-1-2-1) Duty Cycle in Continuous Operation,
 D_{CCM2}

$$D_{CCM2} = \frac{V_{OUT} + V_{FD3}}{V_{DCIN_MAX} - V_{RON} + V_{FD3}}$$

The condition of D_{CCM2} : < 0.5

(B-2-1-2-2) Operation Mode Check

- 1) At first, calculate the following coefficients
 R_{OCP} setting in Section (B-2-1-1-8) and L_{CALC}
calculated in Section (B-2-1-1-9) are used.

$$K = \left(\frac{f_{TYP} - f_{MIM}}{0.85 \times V_{OCP(L_TYP)} - V_{OCP(STB)}} \right)$$

$$M2 = \frac{2 \times I_{OUT} \times (V_{OUT} + V_{FD3}) \times (1 - D_{CCM2})}{L_{CALC}}$$

$$A = 4 \times I_{OUT} \times K \times R_{OCP}$$

$$B = 4 \times I_{OUT} \times \left\{ f_{MIM} - K \times (I_{OUT} \times R_{OCP} + V_{OCP(STB)}) \right\}$$

$$C = -4 \times I_{OUT}^2 \times (f_{MIM} - K \times V_{OCP(STB)}) - M2$$

- 2) Calculate Upper inductor current, I_{LH2}

$$I_{LH2} = \frac{1}{2 \times A} \times \left(-B + \sqrt{B^2 - 4 \times A \times C} \right)$$

- 3) Calculate Switching frequency, f_{SW2}

$$f_{SW2} = K \times (R_{OCP} \times I_{LH2} - V_{OCP(STB)}) + f_{MIM}$$

where,

For $f_{SW2} < f_{MIN}$, set to f_{MIN} .

For $f_{TYP} < f_{SW2}$, set to f_{TYP} .

When f_{SW2} is f_{MIN} or f_{TYP} , calculate I_{LH2} again by the following.

$$I_{LH2} = \frac{M2}{4 \times I_{OUT} \times f_{SW2}} + I_{OUT}$$

For $f_{MIN} \leq f_{SW2} \leq f_{TYP}$, I_{LH2} is the value of the previous 2).

If I_{LH2} is I_{DLIM} or more, try the procedure 1 in Section (B-2-1-1-4) to decrease it.

- 4) Calculate Lower inductor current, I_{LL2}

$$I_{LL2} = 2 \times I_{OUT} - I_{LH2}$$

- 5) The operation mode is given by the following.

- For $I_{LL2} > 0$, CCM
- For $I_{LL2} = 0$, CRM
- For $I_{LL2} < 0$, DCM

(B-2-1-2-3) D_{ON2} , f_{SW2} , I_{LH2} , I_{LL2} of the Operation Mode Result

These parameters are different in the operation mode results of Section (B-2-1-2-2)-5).

- Resulting in CCM

$$D_{ON2} = D_{CCM2}$$

f_{SW2} is the value of Section (B-2-1-2-2) - 3).

I_{LH2} is the value of Section (B-2-1-2-2) - 3).

I_{LL2} is the value of Section (B-2-1-2-2) - 4).

$$I_{LR2} = I_{LH2} - I_{LL2}$$

$$K_{RP2} = \frac{I_{LR2}}{I_{LH2}}$$

- Resulting in CRM

$$D_{ON2} = D_{CCM2}$$

f_{SW2} is the value of Section (B-2-1-2-2) - 3).

$$I_{LH2} = 2 \times I_{OUT}$$

$$I_{LR2} = I_{LH2}, I_{LL2} = 0$$

• Resulting in DCM

1) Draw the graph of the following equations.

By using this, find the values of f_{SW2} and I_{LH2} of DCM.

$$I_{LH2_f} = \left(\frac{f_{SW2} - f_{MIN}}{K} + V_{OCP(STB)} \right) \times \frac{1}{R_{OCP}}$$

$$I_{LH2_DCM} = \sqrt{\frac{M2}{f_{SW2}}}$$

$$I_{LH2_CRM} = 2 \times I_{OUT}$$

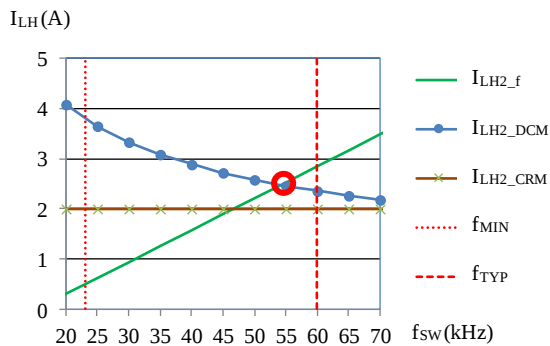


Figure 10-3. I_{LH2} and f_{SW2} of DCM Graph in which the intersection of I_{LH2_f} and I_{LH2_DCM} is in the Range of f_{MIN} to f_{TYP} .

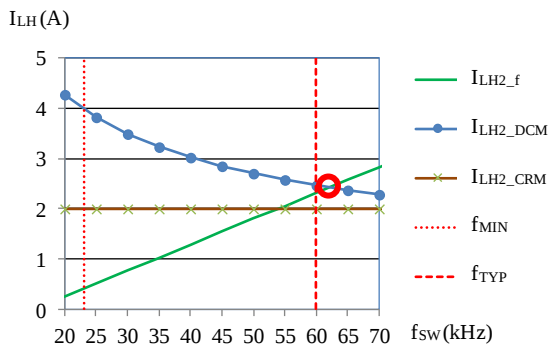


Figure 10-4. I_{LH2} and f_{SW2} of DCM Graph in which the intersection of I_{LH2_f} and I_{LH2_DCM} is out of the Range of f_{MIN} to f_{TYP} .

In DCM, I_{LH} value at the intersection of I_{LH2_f} and I_{LH2_DCM} is bigger than that of I_{LH2_CRM} .

2) Set Switching frequency, f_{SW2}

When f_{SW} at the intersection of I_{LH2_f} and I_{LH2_DCM} is in the range of f_{MIN} to f_{TYP} as shown in Figure 10-3, f_{SW2} is set to that value. When f_{SW} is out of the range as shown in Figure 10-4, f_{SW2} is set to the limited value which is f_{MIN} or f_{TYP} of the over range side.

3) Calculate Duty Cycle D_{ON2}

$$D_{ON2} = D_{DCM2} = 2 \times I_{OUT} \times D_{CCM2} \times \sqrt{\frac{f_{SW2}}{M2}}$$

The condition of $D_{DCM2} : < D_{CCM2}$

4) Calculate I_{LH2} , I_{LL2} , and I_{LR2}

I_{LH2} is the value at the intersection of f_{SW2} which is given in the previous 2) and I_{LH2_DCM} . Otherwise, I_{LH2} is given below.

$$I_{LH2} = 2 \times I_{OUT} \times \frac{D_{CCM2}}{D_{DCM2}}$$

$$I_{LR2} = I_{LH2}, I_{LL2} = 0$$

(B-2-1-2-4) I_{LH2}

If I_{LH2} is I_{DLIM} or more, try the procedure 1 in Section (B-2-1-1-4) to decrease it.

(B-2-1-2-5) On-time, t_{ON2}

$$t_{ON2} = \frac{D_{ON2}}{f_{SW2}}$$

If t_{ON2} is less than 500 ns, try the procedure 1 in Section (B-2-1-1-4) to increase it.

(B-2-1-2-6) OCP Threshold Voltage, V_{OCP2}

V_{OCP2} is given below by t_{ON2} .

- For $t_{ON2} \geq 6\mu s$, $V_{OCP2} = V_{OCP(H)_MIN}$
- For $t_{ON2} < 6\mu s$,

$$V_{OCP2} = V_{OCP(L)_MIN} + DPC \times 10^{-3} \times t_{ON2}$$

where, DPC (mV/ μs)、 t_{ON1} (μs)

(B-2-1-2-7) Current Detection Resistor, R_{OCP}

Upper value at $V_{\text{DCIN_MAX}}$ of the R_{OCP} range is given below.

$$R_{\text{OCP(H)2}} = \frac{V_{\text{OCP2}}}{I_{\text{LH2}}}$$

Denoting $R_{\text{OCP(H)}}$ as a smaller value of either $R_{\text{OCP(H)2}}$ for $V_{\text{DCIN_MAX}}$ or $R_{\text{OCP(H)1}}$ for $V_{\text{DCIN_MIN}}$ in Section (B-2-1-1-8), the range of R_{OCP} is given below.

$$R_{\text{OCP(L)}} \leq R_{\text{OCP}} < R_{\text{OCP(H)}}$$

If R_{OCP} setting has no range, try the procedure 1 in Section (B-2-1-1-4).

If R_{OCP} setting is out of the previous range, try to set it again, and then try to calculate again from Section (B-2-1-1-5).

(B-2-1-2-8) I_{DRMS2} , I_{LRMS2}

These are given by substituting I_{LH2} , I_{LL2} , D_{ON2} , and D_{CCM2} for I_{LH1} , I_{LL1} , D_{ON1} , and D_{CCM1} in the equation of Section (B-2-1-1-10), respectively.

(B-2-1-2-9) Inductor Current Specification

The peak current in OCP operation, I_{OCP} , is given below.

$$I_{\text{OCP}} = \frac{V_{\text{OCP(H)_MAX}}}{R_{\text{OCP}}}$$

The saturation current of the inductor should be enough larger than I_{OCP} .

The rating current refers to the equation of RMS in Section (B-2-1-1-10).

(B-2-2) Parameter Calculation Assigned L_{USER}

Parameter calculation assigned L_{USER} at $V_{\text{DCIN_MIN}}$ and $V_{\text{DCIN_MAX}}$ is similar to the way of Section (B-2-1-2) Parameters for $V_{\text{DCIN_MAX}}$.

Parameters assigned L_{USER} are given by substituting the input voltage and L_{USER} for $V_{\text{DCIN_MAX}}$ and L_{CALC} .

If the conditions of calculation aren't satisfied, increase L_{USER} setting, or decrease I_{OUT} setting, and then try to calculate again.

10.3.3 Inverting Convertor

(I-1) Input and Output Condition

The definition refers to Section 10.3.1. $|V_{OUT}|$ is the absolute value of V_{OUT} .

V_{DCIN_MIN}	Lower value is a higher value or more of either V_{ST_MAX} or $V_{OUT} + V_{FD3} + V_{RON}$. Upper value is $V_{DC(MAX)}$ or less.
V_{DCIN_MAX}	$V_{DCIN_MIN} \leq V_{DCIN_MAX} < V_{DC(MAX)}$
$ V_{OUT} $	$V_{CC_MIN} + V_{DZ1} - V_{FD3} + (V_{FD1} + V_{FD2}) < V_{OUT} < V_{DCIN_MIN} - V_{RON} - V_{FD3}$
I_{OUT}	$I_{OUT} < 0.8 \times I_{DLIM_MIN} \times (1 - D_{CCM1})$. In addition, I_{OUT} also depends on the OCP setting, where, $D_{CCM1} = \frac{V_{OUT} + V_{FD3}}{V_{DCIN_MIN} - V_{RON} + V_{OUT} + V_{FD3}}$
V_{DZ1}	Lower value is a higher value or more of either 0 or $V_{OUT} + V_{FD3} - (V_{FD1} + V_{FD2} + V_{CC(OVP)_MIN})$. Upper value is $V_{OUT} + V_{FD3} - (V_{FD1} + V_{FD2} + V_{CC_MIN})$.
R_{OCP}	Lower value is $R_{OCP(L)} = \frac{V_{OCP(H)_MAX}}{I_{DLIM}}$, or more.

(I-2) Calculation

There are two calculation ways: L_{CALC} Calculation, and Parameter Calculation assigned L_{USER} .

(I-2-1) L_{CALC} Calculation

The inductance, L_{CALC} , is given by choosing the operation mode at V_{DCIN_MIN} . The parameters of both V_{DCIN_MIN} and V_{DCIN_MAX} are given by L_{CALC} .

(I-2-1-1) Parameters for V_{DCIN_MIN}

(I-2-1-1-1) Duty Cycle in Continuous Operation, D_{CCM1} , and Average Inductor Current, I_{LAVG1}

$$D_{CCM1} = \frac{V_{OUT} + V_{FD3}}{V_{DCIN_MIN} - V_{RON} + V_{OUT} + V_{FD3}}$$

The condition of D_{CCM1} : < 0.5

$$I_{LAVG1} = \frac{I_{OUT}}{1 - D_{CCM1}}$$

(I-2-1-1-2) Choosing the Operation Mode, and K_{RP1} or D_{DCM1}

- Choosing CCM
 K_{RP1} is set in the following range.

$$0.4 \leq K_{RP1} < 2 \times \left(1 - \frac{I_{LAVG1}}{I_{DLIM}}\right) < 1$$

The condition of I_{OUT} :

$$< 0.8 \times I_{DLIM} \times (1 - D_{CCM1})$$

- Choosing CRM
The condition of I_{OUT} :

$$\leq 0.5 \times I_{DLIM} \times (1 - D_{CCM1})$$

- Choosing DCM
Duty Cycle, D_{DCM1} , is set in the following range.

$$\frac{2 \times I_{LAVG1} \times D_{CCM1}}{I_{DLIM}} \leq D_{DCM1} < D_{CCM1}$$

The condition of I_{OUT} :

$$< 0.5 \times I_{DLIM} \times (1 - D_{CCM1})$$

(I-2-1-1-3) Inductor Current

D_{ON1} is denoted the duty cycle. I_{LH1} , I_{LL1} , and I_{LR1} are the upper inductor current, the lower inductor current, and the ripple inductor current, respectively.

• Choosing CCM

$$D_{ON1} = D_{CCM1}$$

$$I_{LH1} = \frac{2 \times I_{LAVG1}}{2 - K_{RP1}}$$

$$I_{LR1} = K_{RP1} \times I_{LH1}$$

$$I_{LL1} = I_{LH1} - I_{LR1}$$

• Choosing CRM

$$D_{ON1} = D_{CCM1}$$

$$I_{LH1} = 2 \times I_{LAVG1}$$

$$I_{LR1} = I_{LH1}, I_{LL1} = 0$$

• Choosing DCM

$$D_{ON1} = D_{DCM1}$$

$$I_{LH1} = 2 \times I_{LAVG1} \times \frac{D_{CCM1}}{D_{DCM1}}$$

$$I_{LR1} = I_{LH1}, I_{LL1} = 0$$

(I-2-1-1-4) Upper Temporary Value of R_{OCP} , $R_{OCP(H_TMP1)}$

$$R_{OCP(H_TMP1)} = \frac{V_{OCP(H_MAX)}}{I_{LH1}}$$

The temporary range of the current detection resistor, R_{OCP} , is given below.

$$R_{OCP(L)} \leq R_{OCP} < R_{OCP(H_TMP1)}$$

If R_{OCP} setting has no range, try the following procedure 1.

• Procedure 1 :

For CCM, reduce K_{RP1} or I_{OUT} .

For CRM, change to CCM.

For DCM, increase D_{DCM1} , or change to CRM or CCM.

After these changes, try to calculate again from Section (I-1) Input and Output Condition.

R_{OCP} setting is set in the previous range.

The switching frequency, f_{SW1} , and the peak inductor current at OCP depend on R_{OCP} . When R_{OCP} is set low, f_{SW1} becomes low, and the peak current becomes large.

(I-2-1-1-5) Switching Frequency, f_{SW1}

The f_{SW1} is given by the following with the I_{LH1} of the choosing operation mode and R_{OCP} .

The following K is a coefficient.

$$K = \left(\frac{f_{TYP} - f_{MIM}}{0.85 \times V_{OCP(L_TYP)} - V_{OCP(STB)}} \right)$$

f_{SW1} is given below by using K.

$$f_{SW1} = K \times (R_{OCP} \times I_{LH1} - V_{OCP(STB)}) + f_{MIM}$$

where,

For $f_{SW1} \leq f_{MIN}$, set to f_{MIN} .

For $f_{SW1} \geq f_{TYP}$, set to f_{TYP} .

(I-2-1-1-6) On-time, t_{ON1}

By D_{ON1} and f_{SW1} of the choosing operation mode,

$$t_{ON1} = \frac{D_{ON1}}{f_{SW1}}$$

If t_{ON1} is less than 500 ns, try the procedure 1 in Section (I-2-1-1-4) to increase it.

(I-2-1-1-7) OCP Threshold Voltage, V_{OCP1}

V_{OCP1} is given below by t_{ON1} .

• For $t_{ON1} \geq 6\mu s$, $V_{OCP1} = V_{OCP(H_MIN)}$

• For $t_{ON1} < 6\mu s$,

$$V_{OCP1} = V_{OCP(L_MIN)} + DPC \times 10^{-3} \times t_{ON1}$$

where, DPC (mV/ μs), t_{ON1} (μs)

(I-2-1-1-8) Current Detection Resistor, R_{OCP}

Upper value at V_{DCIN_MIN} of the R_{OCP} range is given below.

$$R_{OCP(H)1} = \frac{V_{OCP1}}{I_{LH1}}$$

The range of R_{OCP} is given below.

$$R_{OCP(L)} \leq R_{OCP} < R_{OCP(H)1}$$

If R_{OCP} setting has no range, try the procedure 1 in Section (I-2-1-1-4).

If R_{OCP} setting is out of the previous range, try to set it again, and then try to calculate again from Section (I-2-1-1-5).

(I-2-1-1-9) Inductance, L_{CALC}

By I_{LH1} , I_{LL1} , and f_{SW1} of the choosing operation mode,

$$L_{CALC} = \frac{2 \times I_{OUT} \times (V_{OUT} + V_{FD3})}{(I_{LH1}^2 - I_{LL1}^2) \times f_{SW1}}$$

The value should be the minimum considered a negative tolerance of inductance and a decline of DC superposition characteristics.

If L_{CALC} is less than 100 μ H, try the procedure 1 of Section (I-2-1-1-4) to increase it.

(I-2-1-1-10) Drain RMS Current and Inductor RMS Current : I_{DRMS1} , I_{LRMS1}

$$I_{DRMS1} = \sqrt{\left(\frac{1}{3} \times (I_{LH1} - I_{LL1})^2 + I_{LH1} \times I_{LL1}\right) \times D_{ON1}}$$

The conduction loss of $R_{DS(ON)}$ of power MOSFET is estimated to be $I_{DRMS1}^2 \times R_{DS(ON)}$.

$$I_{LRMS1} = \sqrt{\left(\frac{1}{3} \times (I_{LH1} - I_{LL1})^2 + I_{LH1} \times I_{LL1}\right) \times \frac{D_{ON1}}{D_{CCM1}}}$$

This value is equivalent to the rating for inductor.

(I-2-1-2) Parameters for V_{DCIN_MAX}

(I-2-1-2-1) Duty Cycle in Continuous Operation, D_{CCM2} , and Average Inductor Current, I_{LAVG2}

$$D_{CCM2} = \frac{V_{OUT} + V_{FD3}}{V_{DCIN_MAX} - V_{RON} + V_{OUT} + V_{FD3}}$$

The condition of $D_{CCM2} : < 0.5$

$$I_{LAVG2} = \frac{I_{OUT}}{1 - D_{CCM2}}$$

(I-2-1-2-2) Operation Mode Check

1) At first, calculate the following coefficients

R_{OCP} setting in Section (I-2-1-1-8) and L_{CALC} calculated in Section (I-2-1-1-9) are used.

$$K = \left(\frac{f_{TYP} - f_{MIM}}{0.85 \times V_{OCP(L)TYP} - V_{OCP(STB)}} \right)$$

$$M2 = \frac{2 \times I_{LAVG2} \times (V_{OUT} + V_{FD3}) \times (1 - D_{CCM2})}{L_{CALC}}$$

$$A = 4 \times I_{AVG2} \times K \times R_{OCP}$$

$$B = 4 \times I_{AVG2} \times \left\{ f_{MIM} - K \times (I_{AVG2} \times R_{OCP} + V_{OCP(STB)}) \right\}$$

$$C = -4 \times I_{AVG2}^2 \times (f_{MIM} - K \times V_{OCP(STB)}) - M2$$

2) Calculate Upper inductor current, I_{LH2}

$$I_{LH2} = \frac{1}{2 \times A} \times (-B + \sqrt{B^2 - 4 \times A \times C})$$

3) Calculate Switching frequency, f_{SW2}

$$f_{SW2} = K \times (R_{OCP} \times I_{LH2} - V_{OCP(STB)}) + f_{MIM}$$

where,

For $f_{SW2} < f_{MIN}$, set to f_{MIN} .

For $f_{TYP} < f_{SW2}$, set to f_{TYP} .

When f_{SW2} is f_{MIN} or f_{TYP} , calculate I_{LH2} again by the following.

$$I_{LH2} = \frac{M2}{4 \times I_{LAVG2} \times f_{SW2}} + I_{LAVG2}$$

For $f_{MIN} \leq f_{SW2} \leq f_{TYP}$, I_{LH2} is the value of the previous 2).

If I_{LH2} is I_{DLIM} or more, try the procedure 1 in Section (I-2-1-1-4) to decrease it.

4) Calculate Lower inductor current, I_{LL2}

$$I_{LL2} = 2 \times I_{LAVG2} - I_{LH2}$$

5) The operation mode is given by the following.

- For $I_{LL2} > 0$, CCM
- For $I_{LL2} = 0$, CRM
- For $I_{LL2} < 0$, DCM

(I-2-1-2-3) D_{ON2} , f_{SW2} , I_{LH2} , I_{LL2} of the Operation Mode Result

These parameters are different in the operation mode results of Section (I-2-1-2-2)-5).

- Resulting in CCM

$$D_{ON2} = D_{CCM2}$$

f_{SW2} is the value of Section (I-2-1-2-2)-3).

I_{LH2} is the value of Section (I-2-1-2-2)-3)

I_{LL2} is the value of Section (I-2-1-2-2)-4)

$$I_{LR2} = I_{LH2} - I_{LL2}$$

$$K_{RP2} = \frac{I_{LR2}}{I_{LH2}}$$

- Resulting in CRM

$$D_{ON2} = D_{CCM2}$$

f_{SW2} is the value of Section (I-2-1-2-2)-3).

$$I_{LH2} = 2 \times I_{LAVG2}$$

$$I_{LR2} = I_{LH2}, I_{LL2} = 0$$

- Resulting in DCM

1) Draw the graph of the following equations.

By using this, find the values of f_{SW2} and I_{LH2} of DCM.

$$I_{LH2_f} = \left(\frac{f_{SW2} - f_{MIN}}{K} + V_{OCP(STB)} \right) \times \frac{1}{R_{OCP}}$$

$$I_{LH2_DCM} = \sqrt{\frac{M2}{f_{SW2}}}$$

$$I_{LH2_CRM} = 2 \times I_{LAVG2}$$

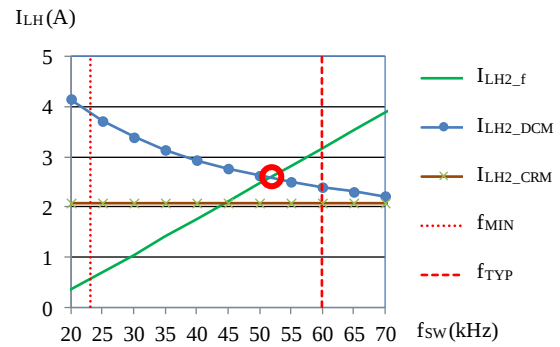


Figure 10-5 I_{LH2} and f_{SW2} of DCM Graph in which the intersection of I_{LH_f} and I_{LH_DCM} is in the range of f_{MIN} to f_{TYP} .

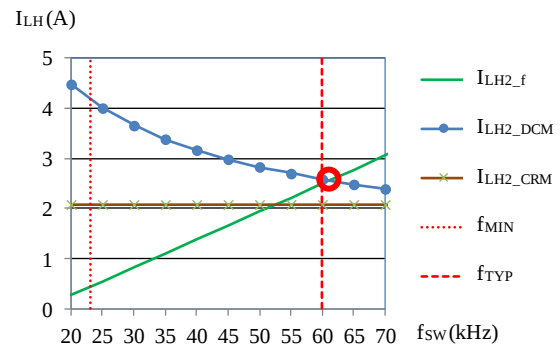


Figure 10-6. I_{LH2} and f_{SW2} of DCM Graph in which the Intersection of I_{LH_f} and I_{LH_DCM} is out of the Range of f_{MIN} to f_{TYP} .

In DCM, I_{LH} value at the intersection of I_{LH2_f} and I_{LH2_DCM} is bigger than that of I_{LH2_CRM} .

2) Set Switching frequency, f_{SW2}

When f_{SW} at the intersection of I_{LH2_f} and I_{LH2_DCM} is in the range of f_{MIN} to f_{TYP} as shown in Figure 10-5, f_{SW2} is set to that value. When f_{SW} is out of the range as shown in Figure 10-6, f_{SW2} is set to the limited value which is f_{MIN} or f_{TYP} of the over range side.

3) Calculate Duty Cycle, D_{ON2}

$$D_{ON2} = D_{DCM2} = 2 \times I_{LAVG2} \times D_{CCM2} \times \sqrt{\frac{f_{SW2}}{M2}}$$

The condition of $D_{DCM2} : < D_{CCM2}$

4) Calculate I_{LH2} , I_{LL2} , and I_{LR2}

I_{LH2} is the value at the intersection of f_{SW2} which is given in the previous 2) and I_{LH2_DCM} . Otherwise, I_{LH2} is given below.

$$I_{LH2} = 2 \times I_{LAVG2} \times \frac{D_{CCM2}}{D_{DCM2}}$$

$$I_{LR2} = I_{LH2}, I_{LL2} = 0$$

(I-2-1-2-4) I_{LH2}

If I_{LH2} is I_{DLIM} or more, try the procedure 1 in Section (I-2-1-1-4) to decrease it.

(I-2-1-2-5) On-time, t_{ON2}

$$t_{ON2} = \frac{D_{ON2}}{f_{SW2}}$$

If t_{ON2} is less than 500 ns, try the procedure 1 in Section (I-2-1-1-4) to increase it.

(I-2-1-2-6) OCP threshold voltage, V_{OCP2}

V_{OCP2} is given below by t_{ON2} .

- For $t_{ON2} \geq 6\mu s$, $V_{OCP2} = V_{OCP(H)_MIN}$
- For $t_{ON2} < 6\mu s$,

$$V_{OCP2} = V_{OCP(L)_MIN} + DPC \times 10^{-3} \times t_{ON2}$$

where, DPC (mV/ μs), t_{ON1} (μs)

(I-2-1-2-7) Current Detection Resistor, R_{OCP}

Upper value at V_{DCIN_MAX} of the R_{OCP} range is given below.

$$R_{OCP(H)2} = \frac{V_{OCP2}}{I_{LH2}}$$

Denoting $R_{OCP(H)}$ as a smaller value of either $R_{OCP(H)2}$ for V_{DCIN_MAX} or $R_{OCP(H)1}$ for V_{DCIN_MIN} in Section (I-2-1-1-8), the range of R_{OCP} is given below.

$$R_{OCP(L)} \leq R_{OCP} < R_{OCP(H)}$$

If R_{OCP} setting has no range, try the procedure 1 in Section (I-2-1-1-4).

If R_{OCP} setting is out of the previous range, try to set it again, and then try to calculate again from Section (I-2-1-1-5).

(I-2-1-2-8) I_{DRMS2} , I_{LRMS2}

These are given by substituting I_{LH2} , I_{LL2} , D_{ON2} , and D_{CCM2} for I_{LH1} , I_{LL1} , D_{ON1} , and D_{CCM1} in the equation of Section (I-2-1-1-10), respectively.

(I-2-1-2-9) Inductor Current Specification

The peak current in OCP operation, I_{OCP} , is given below.

$$I_{OCP} = \frac{V_{OCP(H)_MAX}}{R_{OCP}}$$

The saturation current of the inductor should be enough larger than I_{OCP} .

The rating current refers to the equation of RMS in Section (I-2-1-1-10).

(I-2-2) Parameter Calculation Assigned L_{USER}

Parameter calculation assigned L_{USER} at V_{DCIN_MIN} and V_{DCIN_MAX} is similar to the way of Section (I-2-1-2) Parameters for V_{DCIN_MAX} .

Parameters assigned L_{USER} are given by substituting the input voltage and L_{USER} for V_{DCIN_MAX} and L_{CALC} .

If the conditions of calculation aren't satisfied, increase L_{USER} setting, or decrease I_{OUT} setting, and then try to calculate again.

10.4 PCB Trace Layout

Since the PCB circuit trace design and the component layout significantly affects operation, EMI noise, and power dissipation, the high frequency PCB trace should be low impedance with small loop and wide trace.

In addition, the ground traces affect radiated EMI noise, and wide, short traces should be taken into account.

Figure 10-7 and Figure 10-8 show the circuit design example.

1) Main Circuit Trace Layout

This is the main trace containing switching currents, and thus it should be as wide trace and small loop as possible.

2) Freewheeling Loop Layout

This is the trace for the current of freewheeling diode, D3, and thus it should be as wide trace and small loop as possible.

3) Control Ground Trace Layout

Since the operation of IC may be affected from the large current of the main trace that flows in control ground trace, the control ground trace should be separated from main trace and connected at single point grounding.

4) VCC Trace Layout

This is the trace for supplying power to the IC, and thus it should be as small loop as possible. If C4 and the IC are distant from each other, placing a capacitor such as film capacitor C_f (about 0.1 μ F to 1.0 μ F) close to the VCC pin and the GND pin is recommended.

5) FB Trace Layout

The divided voltage by R2+R3 and R1 of output voltage is input to the FB pin.

To increase the detection accuracy, R3 and R1 should be connected to the bottom of C3 and the GND pin, respectively. The trace between R1, R2 and the FB pin should be as short as possible.

6) Thermal Considerations

Since the internal power MOSFET has a positive thermal coefficient of R_{DS(ON)}, consider it in thermal design.

Since the copper area under the IC and the GND pin trace act as a heatsink, its traces should be as wide as possible.

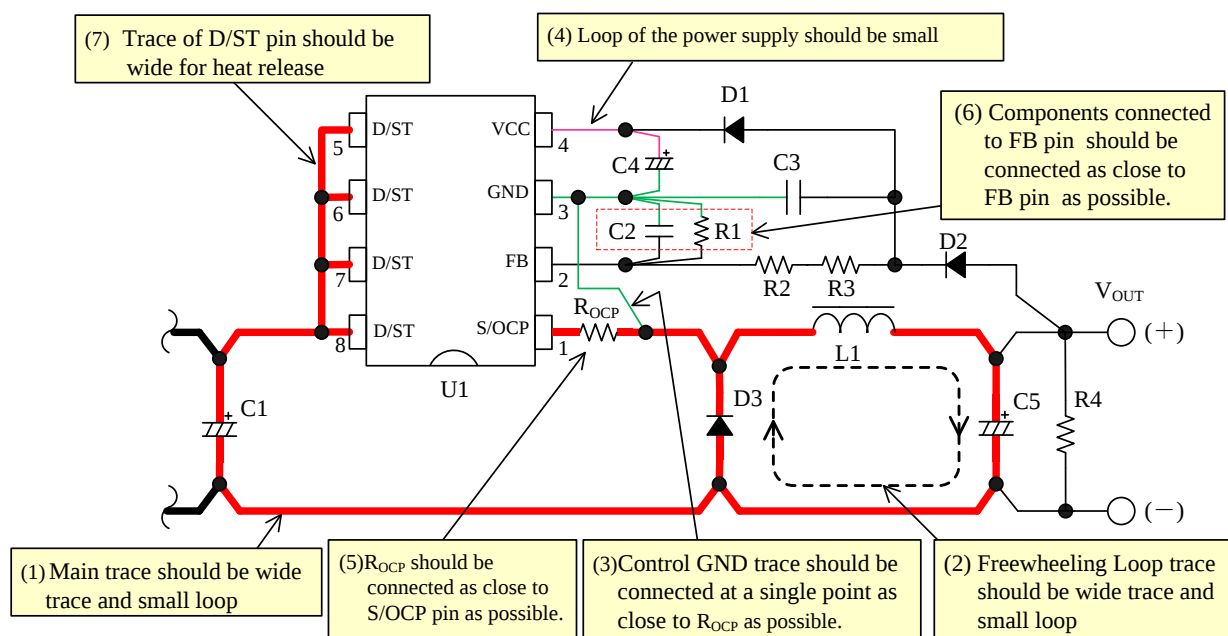


Figure 10-7 Peripheral circuit example around the IC for Buck converter

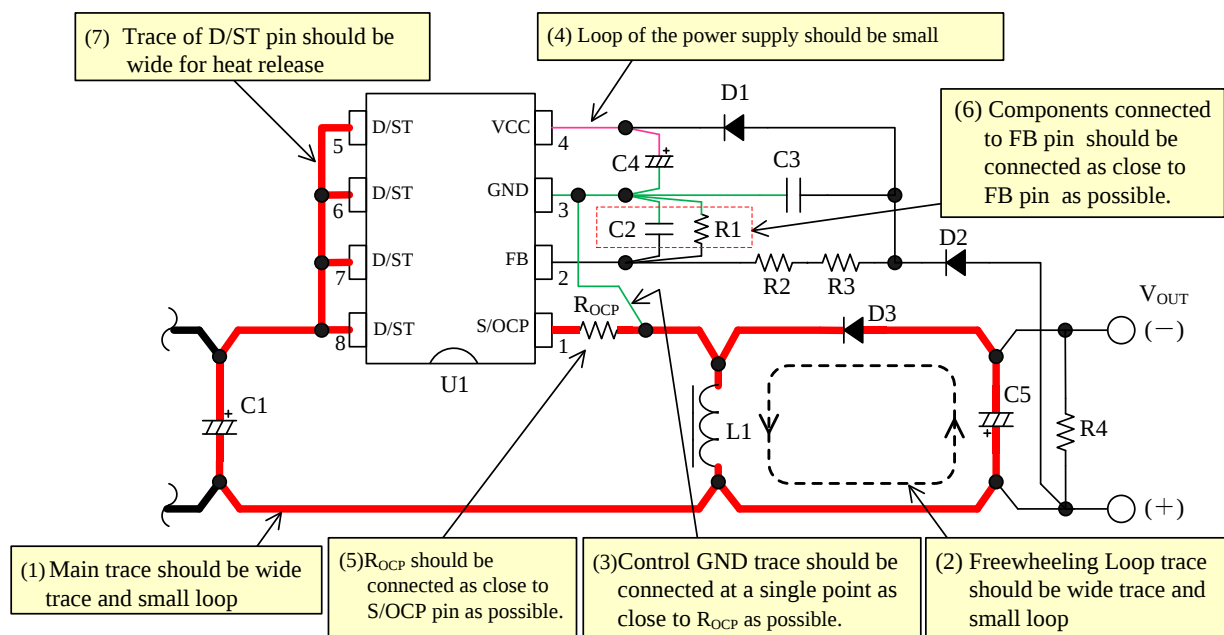


Figure 10-8 Peripheral circuit example around the IC for Inverting converter

11. Reference Design of Power Supply

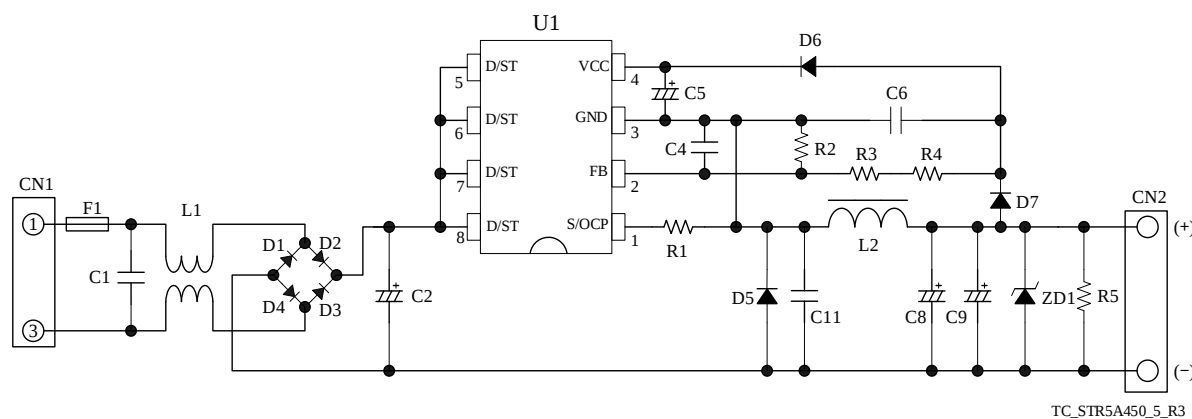
11.1 Buck Converter

As an example, the following show the power supply specification, the circuit schematic, the bill of materials, and the transformer specification.

- Power supply specification

IC	STR5A453D
Input voltage	AC 85 V to AC 265 V
Maximum output power	15 W (max.)
Output voltage	15 V
Output current	1 A

- Circuit schematic



- Bill of materials

Symbol	Part type	Ratings ⁽¹⁾	Recommended Sanken Parts
F1	Fuse	250 V, 2 A	
C1	Film capacitor	275 V, 0.1 μ F	
C2	Electrolytic capacitor	400 V, 56 μ F	
C4	⁽²⁾ Ceramic capacitor	50 V, 470 pF	
C5	Electrolytic capacitor	50 V, 10 μ F	
C6	Ceramic capacitor	50 V, 2.2 μ F	
C8, C9	Electrolytic capacitor	25 V, 470 μ F	
C11	Ceramic capacitor	2 kV, 22 pF	
D1, D2, D3, D4	Diode	600 V, 1 A	
D5	Fast recovery diode	600 V, 3 A	RL4A
D6	Fast recovery diode	90 V, 1 A	SJPB-D9
D7	Fast recovery diode	600 V, 0.5 A	AG01A
ZD1	Zener diode	$V_Z = 18.8$ V (min.)	SJPZ-E20
L1	⁽²⁾ CM inductor	10 mH	
L2	Inductor	180 μ H	
R1	Resistor	0.33 Ω , 1 W	
R2	⁽²⁾ Resistor	10 k Ω , 1/8 W	
R3	⁽²⁾ Resistor	47 k Ω , 1/8 W	
R4	⁽²⁾ Resistor	4.7 k Ω , 1/8 W	
R5	⁽²⁾ Resistor	6.8 k Ω , 1/4 W	
U1	AC/DC convertor IC	650 V/1.9 Ω	STR5A453D

⁽¹⁾ Unless otherwise specified, the voltage rating of capacitor is 50 V or less and the power rating of resistor is 1/8 W or less.

⁽²⁾ It is necessary to be adjusted based on actual operation in the application.

STR5A450D Series

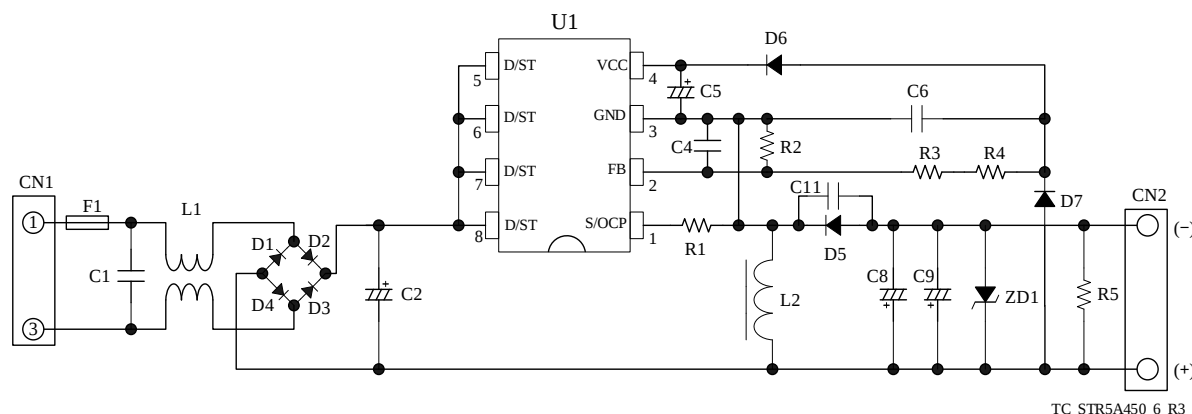
11.2 Inverting Converter

As an example, the following show the power supply specification, the circuit schematic, the bill of materials, and the transformer specification.

- Power supply specification

IC	STR5A453D
Input voltage	AC 85 V to AC 265 V
Maximum output power	15 W (max.)
Output voltage	- 15 V
Output current	1 A

- Circuit schematic



- Bill of materials

Symbol	Part type	Ratings ⁽¹⁾	Recommended Sanken Parts
F1	Fuse	250 V, 2 A	
C1	Film capacitor	275 V, 0.1 μ F	
C2	Electrolytic capacitor	400 V, 56 μ F	
C4 ⁽²⁾	Ceramic capacitor	50 V, 470 pF	
C5	Electrolytic capacitor	50 V, 10 μ F	
C6	Ceramic capacitor	50 V, 2.2 μ F	
C8, C9	Electrolytic capacitor	25 V, 470 μ F	
C11	Ceramic capacitor	2 kV, 22 pF	
D1, D2, D3, D4	Diode	600 V, 1 A	
D5	Fast recovery diode	600 V, 3 A	RL4A
D6	Fast recovery diode	90 V, 1 A	SJPB-D9
D7	Fast recovery diode	600 V, 0.5 A	AG01A
ZD1	Zener diode	$V_Z = 18.8$ V (min.)	SJPZ-E20
L1 ⁽²⁾	CM inductor	10 mH	
L2	Inductor	180 μ H	
R1	Resistor	0.33 Ω , 1 W	
R2 ⁽²⁾	Resistor	10 k Ω , 1/8 W	
R3 ⁽²⁾	Resistor	47 k Ω , 1/8 W	
R4 ⁽²⁾	Resistor	4.7 k Ω , 1/8 W	
R5 ⁽²⁾	Resistor	6.8 k Ω , 1/4 W	
U1	AC/DC convertor IC	650 V/1.9 Ω	STR5A453D

⁽¹⁾ Unless otherwise specified, the voltage rating of capacitor is 50 V or less and the power rating of resistor is 1/8 W or less.

⁽²⁾ It is necessary to be adjusted based on actual operation in the application.

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