# Critical Current Mode Buck LED Driver IC
# LC5910S

**Data Sheet**

## Description

The LC5910S is the buck single-output LED driver IC that achieves the LED drive with few components, high efficiency, and high accuracy. The IC has various protections and configures various LED circuits. The PWM dimming and the three-level dimming (the reference voltage selection function for LED current limiting) are available.

## Features

### Converter Parts

- Critical Current Mode (CRM) Control
  (Low switching loss, low noise, reduction in the number of components)
- Enable Function
- Bottom Detection Voltage 100 mV (typ.)

### LED Control Parts

- PWM Dimming Function
- Reference Voltage Selection Function for LED Current Limiting (three levels, 75% to 100%)
- Current Reference Accuracy: ±1%

### Protections

- LED Output Short Circuit Protection: Pulse-by-pulse
- Current Detection Short Circuit Protection: Auto-restart
- Input Voltage Drop Protection: Auto-restart
- Overvoltage Protection (OVP): Auto-restart, fault output
- Thermal Shutdown (TSD) with Hysteresis: Auto-restart
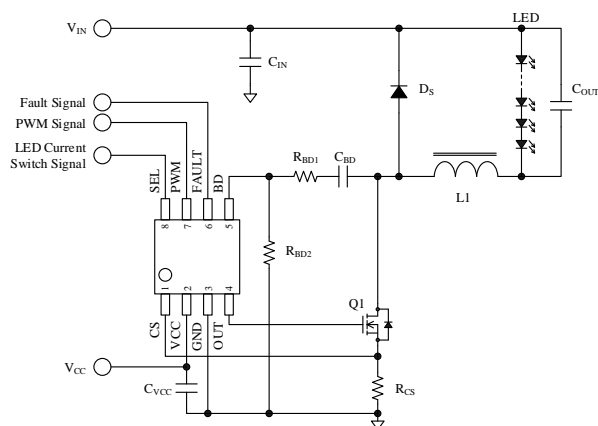
## Package

SOP8

Not to scale

## Specification

- Recommended Supply Voltage: 12 V (min.) to 17 V (max.)
- Circuit Current at Standby: 100 µA (typ.)

## Application

- LED Back Light
- LED Lighting Equipment
- LED Bulbs

## Typical Application

# Contents

## 1. Absolute Maximum Ratings

Current polarities are defined as follows: current going into the IC (sinking) is positive current (+); and current coming out of the IC (sourcing) is negative current (−).

Unless specifically noted, $T_A = 25$ °C.

| Parameter | Symbol | Pins | Rating | Unit |
|---|---|---|---|---|
| CS Pin Voltage | $V_{CS}$ | 1−3 | −0.3 to 18.0 | V |
| VCC Pin Voltage | $V_{CC}$ | 2−3 | −0.3 to 18.0 | V |
| OUT Pin Voltage | $V_{OUT}$ | 4−3 | −0.3 to 18.0 | V |
| BD Pin Voltage | $V_{BD}$ | 5−3 | −1.0 to 18.0 | V |
| FAULT Pin Voltage | $V_{FAULT}$ | 6−3 | −0.3 to 18.0 | V |
| PWM Pin Voltage | $V_{PWM}$ | 7−3 | −0.3 to 18.0 | V |
| SEL Pin Voltage | $V_{SEL}$ | 8−3 | −0.3 to 18.0 | V |
| OUT Pin Sink/Source Current | $I_{OUT}$ | 4−3 | −1.5 to 1.5 | A |
| BD Pin Sink/Source Current | $I_{BD}$ | 5−3 | −4.0 to 4.0 | mA |
| Allowable Dissipation[1][2] | $P_D$ | — | 1.2 | W |
| Thermal Resistance between Junction and Lead (pin 3) | $\theta_{j\text{-}Pin}$ | — | 65 | °C/W |
| Thermal Resistance between Junction and Ambient [2] | $\theta_{j\text{-}A}$ | — | 95 | °C/W |
| Junction Temperature[3] | $T_j$ | — | 150 | °C |
| Operating Ambient Temperature[1] | $T_{op}$ | — | −40 to 125 | °C |
| Storage Temperature | $T_{stg}$ | — | −40 to 150 | °C |

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[1] Limited by junction temperature.

[2] The IC is mounted on the glass-epoxy board ($40 \times 40$ mm) with copper area ($25 \times 25$ mm).

[3] The temperature of thermal shutdown operation is 150 °C (typ.).

## 2. Recommended Operating Range

The recommended operating range shows the operating conditions that are required for maintaining the normal circuit function shown in the electrical characteristics. The IC should be used within the recommended operating range.

Unless specifically noted, $T_A = 25$ °C.

| Parameter | Symbol | Min. | Typ. | Max. | Unit |
|---|---|---|---|---|---|
| Input Voltage Range | $V_{CC}$ | 12 | — | 17 | V |
| Operating Ambient Temperature Range | $T_{OP}$ | −40 | — | 85 | °C |

## 3. Electrical Characteristics

Current polarities are defined as follows: current going into the IC (sinking) is positive current (+); and current coming out of the IC (sourcing) is negative current (−).

Unless specifically noted, $T_A$ = 25 °C, $V_{CC}$ = 12 V.

| Parameter | Symbol | Conditions | Pins | Min. | Typ. | Max. | Unit |
|---|---|---|---|---|---|---|---|
| Operation Start Voltage | $V_{CC(ON)}$ | | 2−3 | 10.0 | 11.0 | 12.0 | V |
| Operation Stop Voltage | $V_{CC(OFF)}$ | | 2−3 | 9.0 | 10.0 | 11.0 | V |
| Operation Start Stop Hysteresis | $V_{CC(HYS)}$ | | 2−3 | 0.5 | 1.0 | 3.0 | V |
| Circuit Current in Operation | $I_{CC(ON)}$ | | 2−3 | — | 1.1 | 1.8 | mA |
| Circuit Current in Non-operation | $I_{CC(OFF)}$ | $V_{PWM}$ = 0 V | 2−3 | — | 100 | 170 | μA |
| PWM Pin On Threshold Voltage | $V_{PWM(ON)}$ | | 7−3 | 1.6 | 2.0 | 2.4 | V |
| PWM Pin Off Threshold Voltage | $V_{PWM(OFF)}$ | | 7−3 | 0.8 | 1.1 | 1.4 | V |
| PWM Pin Sink Current | $I_{PWM}$ | $V_{PWM}$ = 3.3 V | 7−3 | 0.50 | 1.25 | 3.00 | μA |
| Standby Mode Switching Time | $t_{ST\_BY}$ | $V_{PWM}$ = 3.3 V → 0 V | 7−3 | 20 | 36 | 57 | ms |
| PWM Disable VSEL Pin Voltage | $V_{SEL\_DIS}$ | $V_{PWM}$ = 3.3 V | 8−3 | 0 | — | 0.4 | V |
| CS Pin Reference Voltage 1 | $V_{CS1}$ | | 1−3 | 742.5 | 750 | 757.5 | mV |
| CS Pin Reference Voltage 2 | $V_{CS2}$ | | 1−3 | 990 | 1000 | 1010 | mV |
| CS Pin Reference Voltage 3 | $V_{CS3}$ | | 1−3 | 1089 | 1100 | 1111 | mV |
| CS Pin Overvoltage Protection Threshold Voltage 1 | $V_{CSOVP1}$ | $V_{PWM}$ = 3.3 V | 1−3 | 2.4 | 2.7 | 3.1 | V |
| CS Pin Overvoltage Protection Threshold Voltage 2 | $V_{CSOVP2}$ | $V_{PWM}$ = 0 V | 1−3 | 0.40 | 0.72 | 1.00 | V |
| CS Pin Blanking Time | $t_{LEB}$ | | 1−3 | | 320 | | ns |
| Overvoltage Protection Restart Time | $t_{RESTART}$ | | 1−3 | 5.0 | 11.0 | 19.0 | ms |
| Maximum On-time | $t_{ONMAX}$ | $V_{CS}$ = 0 V | 4−3 | 15.0 | 20.0 | 29.0 | μs |
| BD Pin Detection Voltage | $V_{BD(L)}$ | | 5−3 | 70 | 100 | 170 | mV |
| BD Pin Detection Hysteresis Voltage | $V_{BD(HYS)}$ | | 5−3 | — | 100 | — | mV |
| BD Pin Time Out Time 1 | $t_{BD(TOUT1)}$ | $V_{CS}$ = 1.5 V | 5−3 | 15.0 | 20.0 | 29.0 | μs |
| BD Pin Time Out Time 2 | $t_{BD(TOUT2)}$ | $V_{CS}$ = 0 V | 5−3 | 300 | 570 | 900 | μs |
| BD Pin Detection Mask Time | $t_{BDMSK}$ | | 5−3 | 0.3 | 0.62 | 1.10 | μs |
| OUT Pin On-resistance (High)* | $R_{OUT(HIGH)}$ | $I_{OUT}$ = 30 mA | 4−3 | — | 30 | — | Ω |
| OUT Pin On-resistance (Low)* | $R_{OUT(LOW)}$ | $I_{OUT}$ = −30 mA | 4−3 | — | 15 | — | Ω |
| FAULT Pin Output Resistance | $R_{FAULT}$ | | 6−3 | 300 | 610 | 1000 | Ω |
| Thermal Shutdown Operation Temperature* | $T_{SD}$ | | — | — | 150 | — | °C |
| Thermal Shutdown Temperature Hysteresis* | $T_{SD(HYS)}$ | | — | — | 33 | — | °C |

* Ensured by design, not product tested.

## 4. Block Diagram
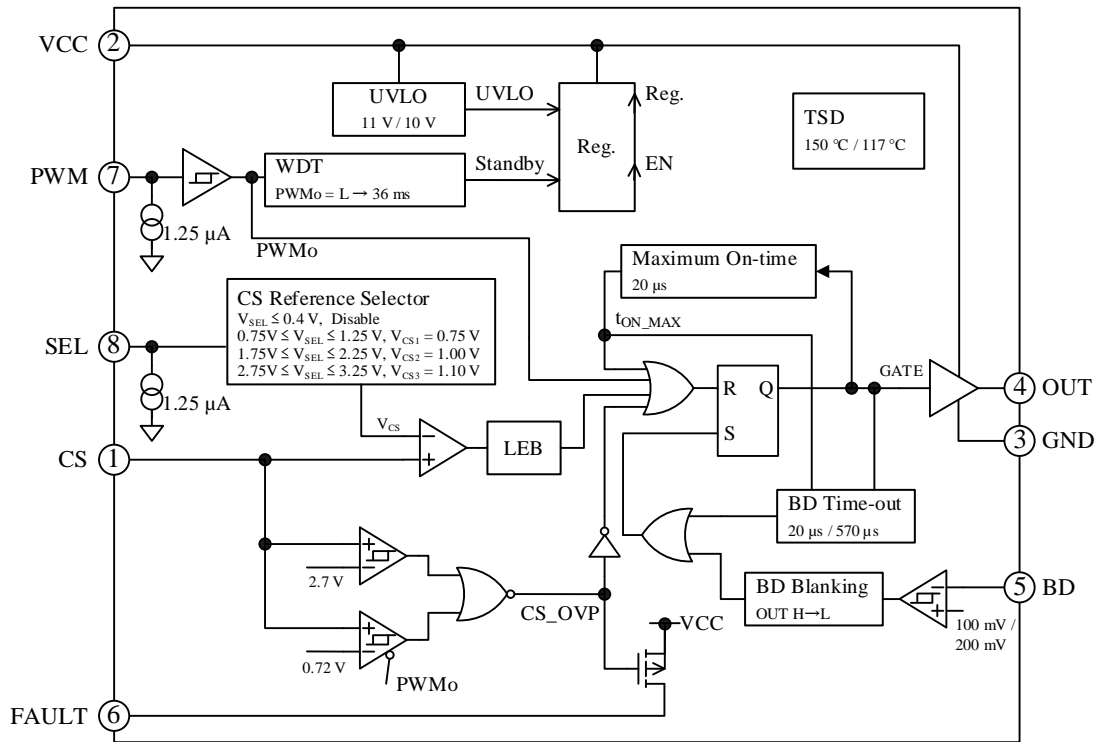


Figure 4-1.   LC5910S Block Diagram

## 5. Pin Configuration Definitions
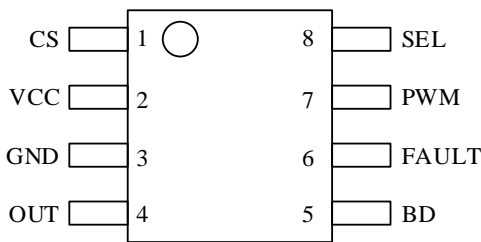


| Pin | Name | Descriptions |
|---|---|---|
| 1 | CS | Current Detection Signal Input. |
| 2 | VCC | Power supply voltage input (within the recommended operating range, 12 V to 17 V). A capacitor is connected between the VCC and GND pins in order to supply stable power supply voltage to the IC. |
| 3 | GND | Ground |
| 4 | OUT | Signal output for the gate drive of the power MOSFET. |
| 5 | BD | The resistor for adjusting the off-time is connected. |
| 6 | FAULT | Fault signal output. This pin outputs the signal (the signal can be used for the setting to stop the pre converters such as PFC.) |
| 7 | PWM | PWM dimming signal input. This pin inputs the PWM signal for dimming the LED string. |
| 8 | SEL | Reference voltage select signal input. This pin inputs the DC voltage signal to select the internal reference voltage that controls the LED current. |

# 6. Typical Applications
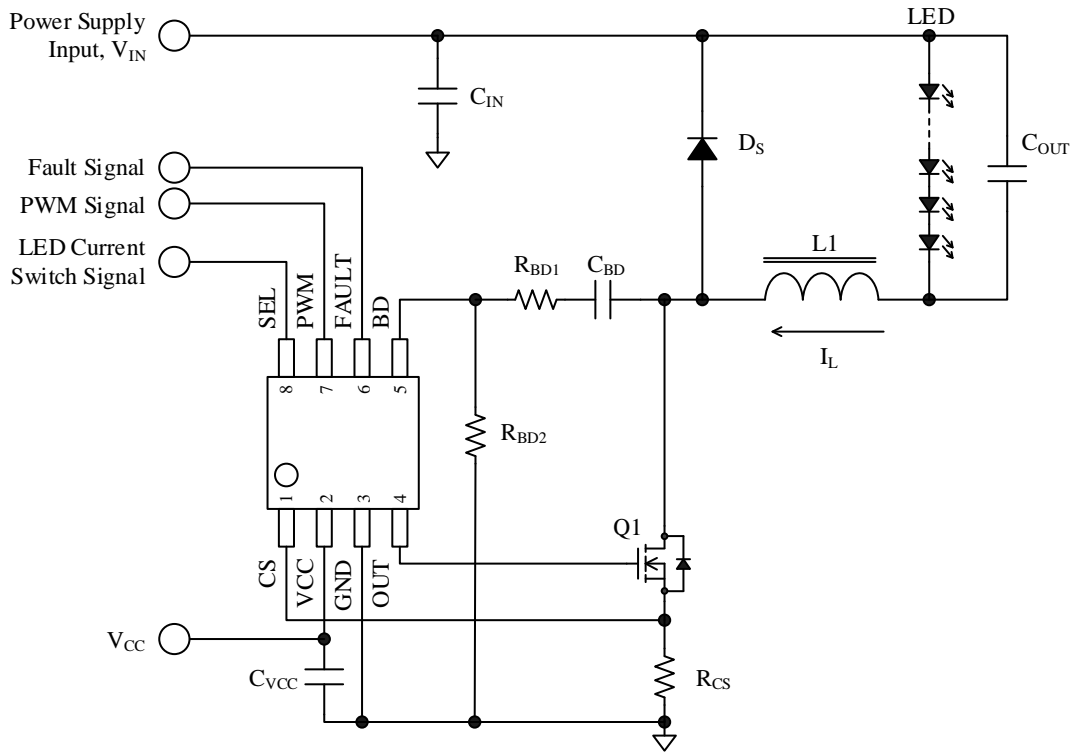


Figure 6-1.   LC5910S Typical Application

## 7. Physical Dimension

● **SOP8 Package**
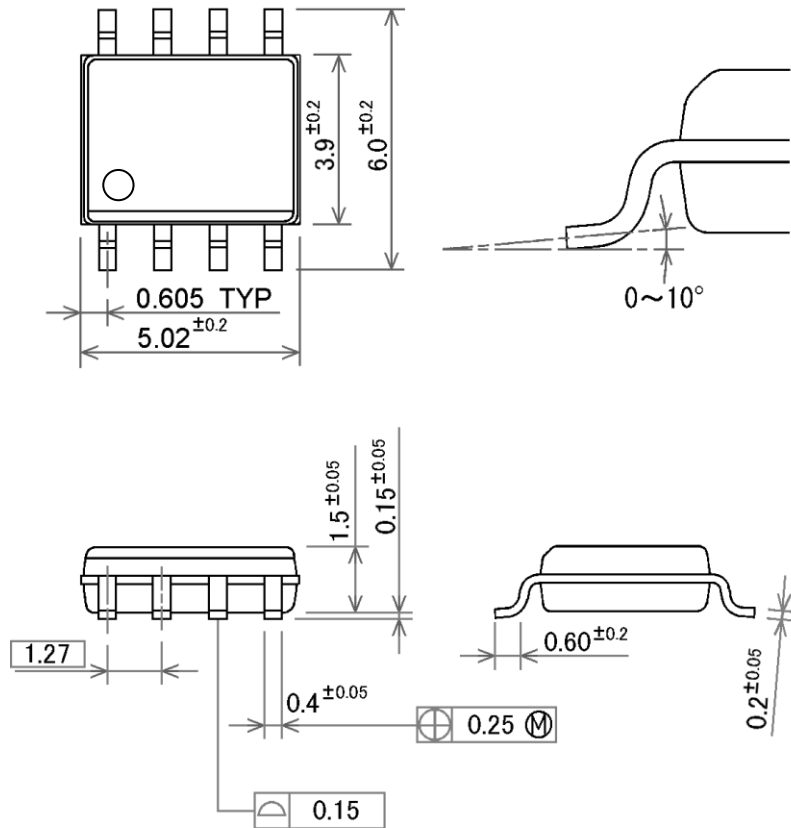


**NOTES:**

- Dimensions in millimeters
- Bare lead frame: Pb-free (RoHS compliant)

● **SOP8 Land Pattern Example**
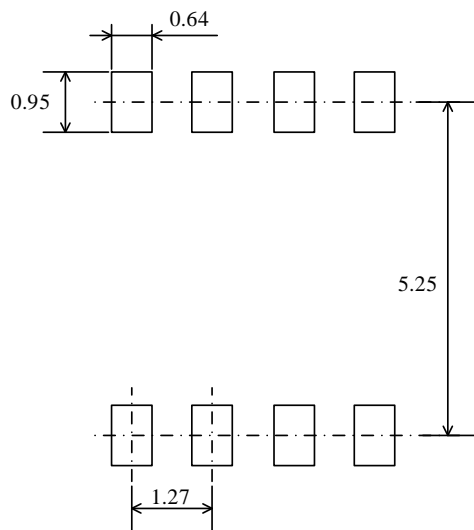


Dimensions in millimeters

## 8. Marking Diagram

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8 □ □ □ □
  ┌──────────┐
  │ LC5910   │──── Part Number
  │          │
  │ S K Y M D│──── Lot Number:
  │ ○ ┌┄┄┄┄┐ │        Y is the last digit of the year of manufacture (0 to 9)
  │   └┄┄┄┄┘ │        M is the month of the year (1 to 9, O, N or D)
  └──────────┘        D is a period of days,
1 □ □ □ □                 1: the first 10 days of the month (1st to 10th)
                          2: the second 10 days of the month (11th to 20th)
                          3: the last 10-11 days of the month (21st to 31st)

                  ──── Control Number
```
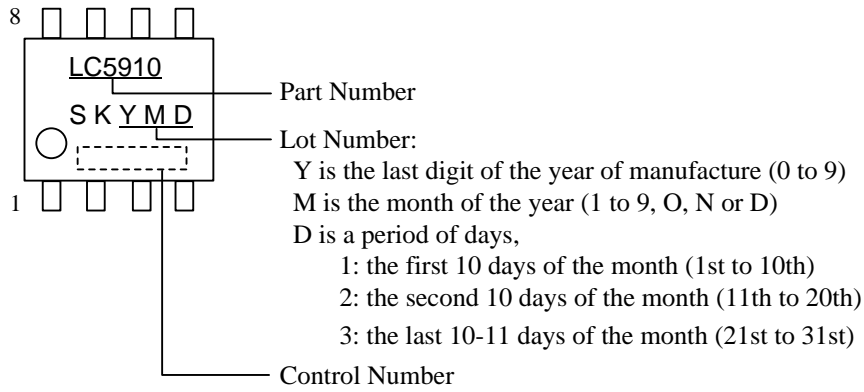
## 9. Operational Description

All the characteristic values given in this section are typical values, unless they are specified as minimum or maximum. Current polarities are defined as follows: current going into the IC (sinking) is positive current (+); and current coming out of the IC (sourcing) is negative current (−).

## 9.1 Operation in Critical Current Mode (CRM)

Figure 9-1 shows the LED drive circuit example using the LC5910.



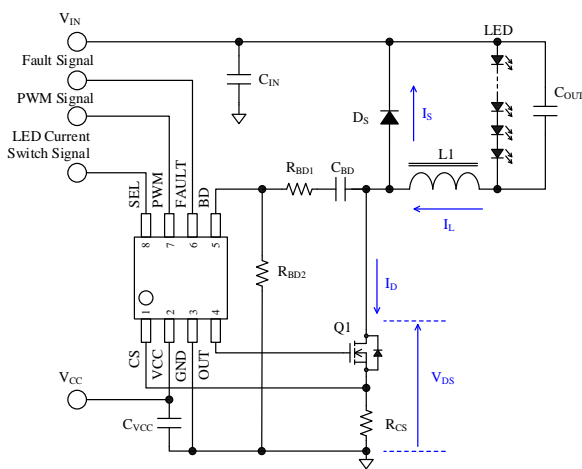Figure 9-1. LED Drive Circuit Example using the LC5910S

The IC uses the Critical Current Mode (CRM) control. To drive the LED string, the IC controls the on-time and off-time of the external power MOSFET as follows:

● On-time period:
When the CS pin detects the peak of the external inductor current, $I_L$, the on-time period is terminated..
● Off-time period:
When the BD pin detects decrease of the voltage, $V_{DS}$, between drain and source of the external power MOSFET, the off-time period is terminated.

As a result, the waveform of the inductor current, $I_L$, becomes triangular as shown in Figure 9-2. The LED current, $I_{LED}$, is half of the peak value of the inductor current, $I_L$.

The IC controls the peak value of the inductor current, $I_L$, and stabilizes the LED current, $I_{LED}$.

See Figure 4-1 and Figure 6-1 for circuit symbols.

The inductor current, $I_L$, is converted into a voltage by the current detection resistor, $R_{CS}$, and input to the CS pin. When the voltage becomes equal to the internal reference voltage, $V_{CS}$, the OUT pin output is turned off.

The off-time period is set by the $V_{DS}$ waveform that is

input to the BD pin (see Section 9.5). When the BD pin voltage decreases to the BD pin detection voltage, $V_{BD(L)}$, the off-time period is terminated and the turn-on of the next cycle is started.

As described above, the IC always turns on at the $V_{DS}$ of the power MOSFET decreasing in the CRM control. Therefore, the CRM control reduces the switching loss and noise more than the PWM continuous current mode (CCM) which switches hard. The CRM control requires no phase compensation and fewer components, resulting in the cost reduction in system.

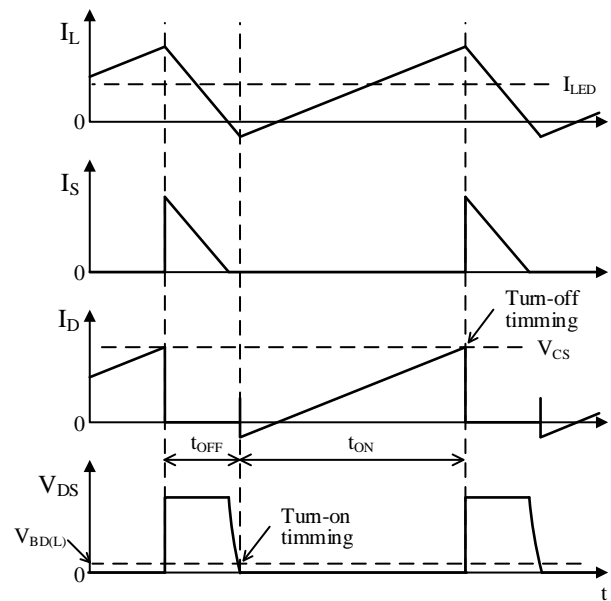The oscillation frequency of the CRM control depends on the input voltage.



Figure 9-2. CRM Control of the LC5910S

## 9.2 Enable

The IC has the enable function. When the SEL pin voltage decreases 0.4 V or lower, the OUT pin signal is fixed low. A pull-down resistor is connected internally between the SEL and the GND pins.

## 9.3 Reference Voltage Select Function for LED Current Limit

The LED current, $I_{LED}$, is controlled using the peak value of the inductor current, $I_L$. $I_L$ is converted into a voltage by the current detection resistor, $R_{CS}$, and input to the CS pin. The IC controls the voltage to be equal to the reference voltage of the internal comparator, $V_{CS}$. The reference voltage of the comparator can be set to three levels according to the DC voltage applied to the SEL pin (see Table 9-1). The function enables altering the LED current with the resistance of the current detection resistor, $R_{CS}$, fixed.

If the different frequency switching noises of the other converter on PCB superimposes on the SEL pin, the RC filter shown in Figure 9-3 is required. The RC filter must be connected <u>close to the SEL pin</u>. Due to the delay caused by the combination of $R_{SEL}$ and $C_{SEL}$, it takes time for the SEL pin voltage to settle at the determined $V_{SEL}$ after the DC voltage is applied to the SEL pin. Be sure to confirm the actual operation and adjust the constants.

Table 9-1.  The Relation between SEL Pin Voltage and Internal Reference Voltage

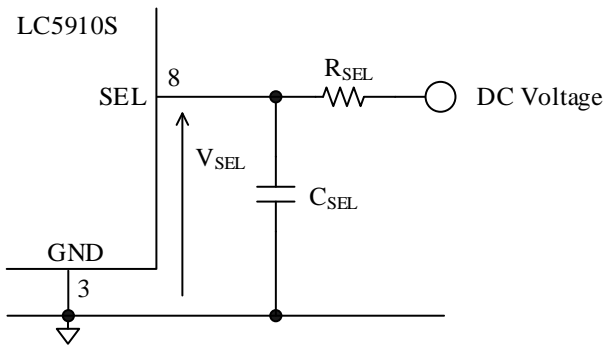| SEL Pin Voltage, $V_{SEL}$ | Internal Reference Voltage, $V_{CS}$ (typ.) |
|---|---|
| $V_{SEL} \leq 0.40$ V | (Enable state) |
| $0.75V \leq V_{SEL} \leq 1.25$ V | $V_{CS1} = 750$ mV |
| $1.75V \leq V_{SEL} \leq 2.25$ V | $V_{CS2} = 1000$ mV |
| $2.75V \leq V_{SEL} \leq 3.25$ V | $V_{CS3} = 1100$ mV |



Figure 9-3.  RC filter of SEL Pin

## 9.4  LED Current Setting

As shown in Figure 9-2, the LED current, $I_{LED}$, is controlled so that the peak of the inductor current, $I_L$, at the power MOSFET turn-on is equal to the reference voltage, $V_{CS}$, set by the SEL pin. When the power MOSFET turns off, the energy stored in the inductor is regenerated through the freewheeling diode, $D_S$, and the power MOSFET turns on at the timing of the end of energy regeneration. By repeating this, the waveform of the $I_L$ becomes triangular with the current determined by the $R_{CS}$ and the $V_{CS}$ at the top, and the $I_{LED}$ is controlled to be half of the peak value of $I_L$. The $I_{LED}$ is calculated by the Equation (1).

$$I_{LED} = 0.5 \times \frac{V_{CS}}{R_{CS}} \qquad (1)$$

where:

$V_{CS}$ is the reference voltage set by the SEL pin (see Section 9.2), and

$R_{CS}$ is the resistance of the current detection resistor.

## 9.5  Bottom Detection Function (Off-time Period Termination Detection)

For the off-time period setting, the voltage between drain and source, $V_{DS}$, is used. The $V_{DS}$ is input to the BD pin from the drain pin through a coupling capacitor and a voltage dividing resistor.

As shown in Figure 9-3, when the power MOSFET turns off, the energy stored in the inductor is regenerated through the freewheeling diode, $D_S$. When the current flowing in the $D_S$ becomes zero, the $V_{DS}$ decreases due to the free oscillation by the inductor, L, and the voltage resonance of parasitic capacitance between drain and source, Cds. When the BD pin voltage decreases to the BD pin detection voltage, $V_{BD(L)} = 100$ mV, or lower, the function terminates the off-time period and turn on the power MOSFET.

The BD pin detection mask time, $t_{BDMASK} = 0.62$ μs (typ.), prevents misdetection due to surge and ringing waveform immediately after the power MOSFET turns off.

If the BD pin voltage maintains above $V_{BD(L)}$ during $\geq t_{BD(TOUT1)}$ of 20 μs or more after the power MOSFET turns off, the power MOSFET is forcibly turned on.

The standard constant for the BD pin is as follows:

When $V_{IN} = 160$ V and $V_{LED} = 130$ V, $C_{BD} = 15$ to $100$ pF, $R_{BD1} = 63$ kΩ, and $R_{BD2} = 2.2$ kΩ.

If $R_{BD1}$ decreases with fixing $R_{BD2}$, the turn-on delay increases.. $C_{BDF}$, which is for noise countermeasure, should be connected as needed. However, adding the $C_{BDF}$ increases the turn-on delay.

Since the bottom detection voltage of $V_{DS}$ of the BD pin is $V_{BD(L)} = 100$ mV, it is strictly detected a little earlier than the bottom point. (Depending on the constant of the BD pin detection circuit, the turn-on is delayed and the bottom point of $V_{DS}$ may be adjusted to approximately 0 V).
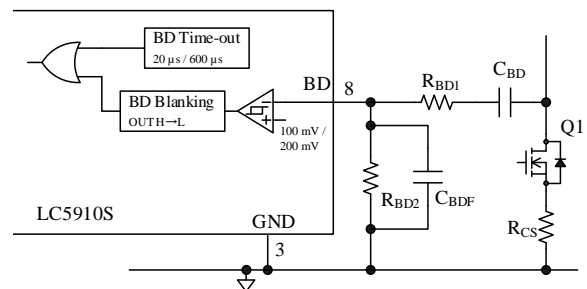


Figure 9-4.  BD Pin Connection

## 9.6  Maximum On-time

In case the current detection resistor, $R_{CS}$, is shorted or the supply voltage, $V_{IN}$, decreases, the OUT pin

output signal of the is kept in the logic high state; and the power MOSFET may be destroyed. To prevent this event, the OUT pin output signal is limited by the maximum on-time.

When the on-time period exceeds the maximum on-time, $t_{ONMAX} = 20$ μs (typ.), the OUT pin output signal becomes logic low, and outputs the logic high signal again in $t_{BD(TOUT2)} = 570$ μs.

## 9.7    PWM Dimming

The PWM pin is the input pin of the PWM dimming signal. The PWM dimming signal that satisfies the following conditions is input to the PWM pin:

On threshold voltage, $V_{PWM(ON)} = 2$ V, and

Off threshold voltage, $V_{PWM(OFF)} = 1.1$ V.

The voltage of 2.7 V to 3.3 V is recommended for the peak voltage of the PWM signal. The pull-down resistor is connected between the PWM and the GND pins.

When the period during which the PWM pin voltage is lower than $V_{PWM(OFF)}$ is 36 ms or more, the LC5910S enters standby mode. In standby mode, the current consumption of the IC is reduced. When the PWM pin voltage exceeds the $V_{PWM(ON)}$, the IC recovers from the standby mode.

In order to decrease the dv/dt of the PWM dimming signal, the RC filter circuit should be connected to the PWM pin as shown in Figure 9-5. However, care should be taken when signals with high frequency are input.
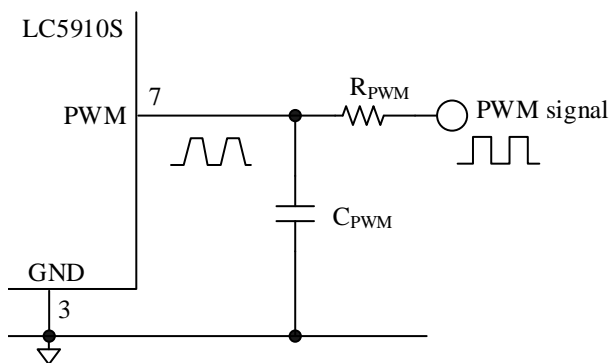


Figure 9-5.    RC filter of PWM Pin

## 9.8    External Power MOSFET Gate Drive

Figure 9-6 shows the peripheral circuit of the OUT pin. The OUT pin is for driving the external power MOSFET gate. The peak output voltage of the OUT pin depends on the VCC pin voltage. When the input voltage of the VCC pin is 17 V, the output voltage of the OUT pin is also around 17 V. Therefore, it is required to choose the external power MOSFET having the gate breakdown voltage of ±20 V or ±30 V, and choose the power MOSFET such that the threshold voltage between

gate and source meets $V_{GS(TH)} < V_{OUT}$ in all operating temperature range.

In a general EMI noise countermeasure, the dv/dt of the gate voltage of the power MOSFET is decreased to slow the switching speed. Note that, however, the switching loss increases. The circuit resistance of the drive output incorporated in the LC5910S is as follows:

30 Ω (typ.) for source, and 15 Ω (typ.) for sink.

The resistance above can not be changed. Therefore, the switching speed is adjusted by external components as shown in Figure 9-6 and Figure 9-7.

The components in Figure 9-6 of the gate drive circuit of the power MOSFET should be chosen as follows:

$R_{G1}$ is around 100 Ω, $R_{G2}$ is around 10 Ω, and $D_G$ is a Schottky diode having the same breakdown voltage as the gate breakdown voltage of the external power MOSFET.

Figure 9-7 shows a method of discharging with the transistor, $Q_G$ at the power MOSFET turn-off. At turn-on, the gate of the power MOSFET is charged via $R_{G1}$, $D_G$, and $R_{G2}$ from the OUT pin. At turn-off, the bias voltage of $Q_G$ is the forward voltage, $V_F$, of $D_G$. Decreasing $R_{G2}$ increases the switching speed at turn-off. In order to prevent malfunction of the IC due to the rapid dv/dt of the drain voltage of the power MOSFET, $R_{GS}$ is added between gate and ground of the power MOSFET as needed. $R_{GS}$ is around 10 kΩ to 100 kΩ.
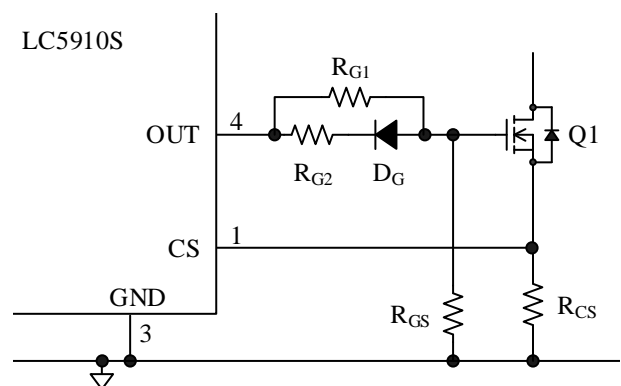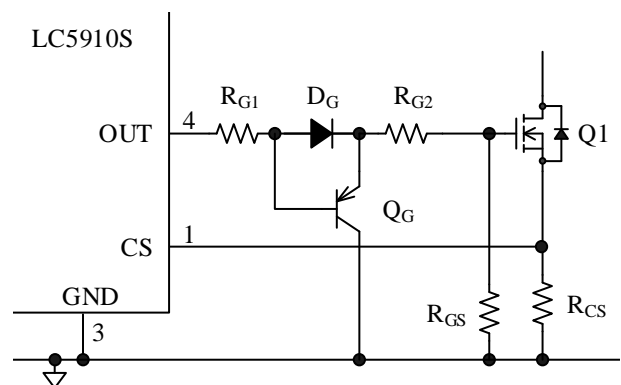


Figure 9-6.    OUT Pin Peripheral Circuit (1)



Figure 9-7.    OUT Pin Peripheral Circuit (2)

## 9.9 Overvoltage Protection (OVP)

When the inductance is saturated or shorted, the voltage between both ends of the output current resistor, $R_{CS}$, increases, resulting in the increase in the CS pin voltage. When the CS pin voltage meets either of the following conditions, the overvoltage protection (OVP) is activated.

● The CS pin voltage is the overvoltage protection threshold voltage, $V_{CSOVP1} = 2.7$ V, or higher

● PWM pin voltage is in the logic low state, and the CS pin voltage is the overvoltage protection threshold voltage, $V_{CSOVP2} = 0.72$ V, or higher

When the OVP operates, the OUT pin voltage becomes logic low level, and the fault signal is output from the FAULT pin.

When the CS pin voltage decreases to be $V_{CSOVP1}$, or $V_{CSOVP2}$, or lower, and the overvoltage protection restart time, $t_{RESTART} = 11.0$ ms, is exceeded, the fault signal output is stopped and the LC5910S restarts (see Section 9.10 for the detail of the fault signal).

Though the leading edge blanking (LEB) circuit is incorporated in the CS pin, the RC filter should be added as needed as shown in Figure 9-8 when large noises are superimposed at the voltage signal between both ends of the $R_{CS}$.

The standard constant for RC filter is as follows:

The $R_{CSF}$ is around 1 kΩ, and the $C_{CSF}$ is around 220 pF.

If the RC time constant is large, the response delay becomes large, and the operation may be unstable. Therefore, be sure to confirm the actual operation and adjust the constant.
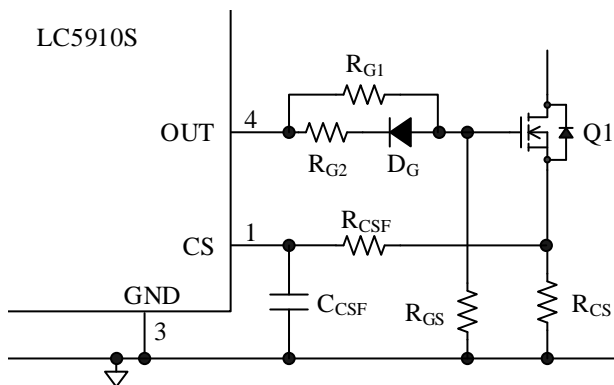


Figure 9-8.   RC Filter of CS Pin

## 9.10 Fault Signal

Figure 9-9 shows the peripheral circuit of the FAULT pin. FAULT pin is connected to the drain of the P-channel MOSFET in the IC. When the overvoltage state is detected (see Section 9.9), the internal P-channel MOSFET turns on, and the FAULT pin voltage increases to the voltage of the VCC pin.

In normal operation, the FAULT pin is in the high impedance state.

The fault signal can be used for the protection operation to suppress the power supply to the LED driver by sending signals via optocoupler to the primary-side off-line converter IC or the PFC IC.
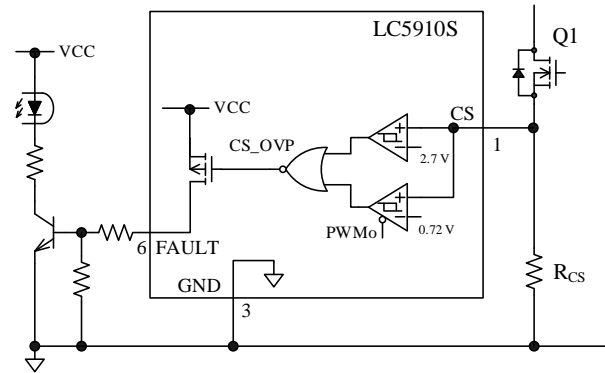


Figure 9-9.   FAULT Pin Peripheral Circuit

## 9.11 Thermal Shutdown (TSD)

When the junction temperature of the IC reaches the thermal shutdown operation temperature, $T_{SD} = 150$ °C, or higher, the thermal shutdown (TSD) is activated and stops the oscillation. The TSD has the temperature hysteresis, $T_{SD(HYS)} = 30$ °C. When the temperature of the IC decreases to be $T_{SD} - T_{SD(HYS)}$, or lower, the TSD automatically restarts the normal operation.

The TSD protects the IC when the loss of the IC increases due to the instantaneous short-circuit of the OUT pin. This does not guarantee the operation including the reliability in the short-circuit state for long period or the state where the heat generation continues.

## 10. Circuit Constant Setting

### 10.1 Inductor Setting

The on-time period depends on the input voltage, $V_{IN}$, and inductance, and is determined by the point where the IC detects the peak value of inductor current, $I_{L(PEAK)}$.
In the control of the IC, the off-time period is determined by the point where the BD pin detects the $V_{DS}$ drop after the regenerative current flowing through the freewheeling diode, $D_S$, becomes zero. Therefore, the off time, $t_{OFF}$, is the value that the delay time, $t_{ONDLY}$, of the voltage resonant part is added to the off time, $t_{OFF\_S}$ (see Figure 10-1). $t_{OFF\_S}$ is determined by cycle length and on-time.

The design procedure of inductor is shown below.



Figure 10-1.  LC5910S Operational Waveform

(1) Duty D

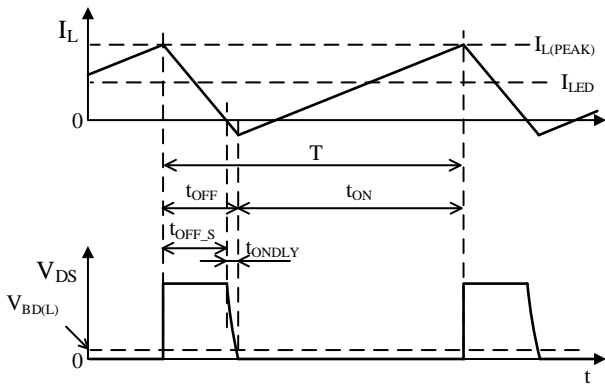Duty D is calculated by the following equation.

$$D = \frac{V_{LED}}{V_{IN}} \tag{2}$$

(2) On-time, $t_{ON}$

When the switching period is T, the on time, $t_{ON}$, is as follows:

$$t_{ON} = T \times D \tag{3}$$

(3) Off-time, $t_{OFF\_S}$

The off time, $t_{OFF\_S}$, until the regenerative current flowing through the freewheeling diode becomes zero is calculated by the following equation.

$$t_{OFF\_S} = T - t_{ON} \tag{4}$$

(4) Inductor

The peak current of the inductor, $I_{L(PEAK)}$, is twice the LED average current, $I_{LED}$. The value of the inductor, L, such that the peak current is $I_{L(PEAK)}$ is calculated by the following equation.

$$L = \frac{V_{LED} \times t_{OFF\_S}}{I_{L(PEAK)}} \tag{5}$$

where:
$t_{OFF\_S}$ is calculated by Equation (19), and
$V_{LED}$ is the voltage across the LED string.

(5) Current Detection Resistor, $R_{CS}$

The $R_{CS}$ value is calculated by the following equation.

$$R_{CS} = \frac{V_{CS}}{I_{L(PEAK)}} \tag{6}$$

(6) Delay Time, $t_{ONDLY}$

The delay time, $t_{ONDLY}$, is calculated by the following equation.

$$t_{ONDLY} = \pi \times \sqrt{L \times Cds} \tag{7}$$

(7) Off-time, $t_{OFF}$

The off time, $t_{OFF}$, is the value that $t_{ONDLY}$, is added to $t_{OFF\_S}$ calculated by (19).

$$t_{OFF} = t_{OFF\_S} + t_{ONDLY} \tag{8}$$

(8) Corrected Frequency, $f_{SW}$'

The frequency, $f_{SW}$', considering the delay time, $t_{ONDLY}$, is calculated by the following equation.

$$f_{SW}' = \frac{1}{(t_{ON} + t_{OFF})} \tag{9}$$

$f_{SW}$' is later than $f_{SW}$ that is set as a target operating frequency by the delay time, $t_{ONDLY}$. In order to adjust $f_{SW}$' to the set value, the value of the inductor, L, should be decreased and the on-time should be short. Even though the on-time is adjusted, the peak inductor current, $I_{L(PEAK)}$, is always twice the $I_{LED}$ if $V_{IN}$, $V_{CS}$, and $R_{CS}$ are fixed.
As shown in Equation (7), however, when L is reduced, $t_{ONDLY}$ also becomes short. Therefore, the waveform should be confirmed on actual operation and the constant of the BD pin should be adjusted so that a sufficient delay time can be secured (the power MOSFET turns on at the bottom of $V_{DS}$).

Based on the calculated L value, it is necessary to select an inductor that does not magnetically saturate at the maximum current. The heat generation by the DCR of the winding should be below the manufacturer guaranteed value.

● **Calculation Example**

The value of the inductor is calculated by the Equation (2) to (9) using the set value in Table 10-1.

Table 10-1.   Set Value of Inductance Calculation

| Parameter | Set Value |
|---|---|
| Input Voltage, $V_{IN}$ | 160 V |
| LED String Voltage, $V_{LED}$ | 130 V |
| LED Average Current, $I_{LED}$ | 350 mA |
| LED Current Detection Threshold Voltage, $V_{CS}$ | 1000 mV |
| Target Operating Frequency, $f_{SW}$ | 100 kHz |
| Capacitance between Gate and Drain, Cds | 81 pF (Cds = Coss – Crss, for Coss and Crss, refer to the data sheet of the power MOSFET) |

(1) Duty, D

$$D = \frac{130 \text{ V}}{160 \text{ V}} = 0.8125$$

(2) On-time, $t_{ON}$

By the equation, $f_{SW}$ = 100 kHz, the switching frequency, T, is 10 μs.

$$t_{ON} = 10 \text{ μs} \times 0.8125 = 8.125 \text{ μs}$$

(3) Off-time, $t_{OFF\_S}$

$$t_{OFF\_S} = 10 \text{ μs} - 8.125 \text{ μs} = 1.875 \text{ μs}$$

(4) Inductor

By the equation, LED average current, $I_{LED}$ = 350 mA, the inductor peak current, $I_{L(PEAK)}$ is 700 mA.

$$L = \frac{130 \text{ V} \times 1.875 \text{ μs}}{700 \text{ mA}} = 348.2 \text{ μH}$$

From the calculated value, 330 μH should be chosen for the inductor value.

(5) Current Detection Resistor, $R_{CS}$

$$R_{CS} = \frac{1000 \text{ mV}}{0.7 \text{ A}} = 1.428 \text{ Ω}$$

(6) Delay time, $t_{ONDLY}$

$$t_{ONDLY} = \pi \times \sqrt{330 \text{ μH} \times 81 \text{ pF}} = 0.514 \text{ μs}$$

(7) Off-time, $t_{OFF}$

$$t_{OFF} = 1.875 \text{ μs} + 0.514 \text{ μs} = 2.389 \text{ μs}$$

(8) Corrected Frequency, $f_{SW}'$

$$f_{SW}' = \frac{1}{(8.125 \text{ μs} + 2.389 \text{ μs})} = 95.11 \text{ kHz}$$

$f_{SW}'$ is later than the target operating frequency, 100 kHz, by $t_{ONDLY}$. In order to adjust $f_{SW}'$ to the set value, the value of the inductor, L, should be decreased and the on-time should be short.

In the calculation example above, $V_{CS2}$ = 1.0 V is assumed to be 100%.

Table 10-2. shows the design values when the SEL pin voltage is switched using the inductor of the L value (330 μH) set in the calculation example and the current detection resistor, $R_{CS}$ (the input voltage, $V_{IN}$, is constant). In the application that the SEL pin voltage is changed, it is required to choose the inductor that does not saturate at the maximum current even in $V_{CS3}$.

Table 10-2.   Calculation Result of Internal Reference Voltage and Design Value when SEL Pin Voltage is Switched

| Parameter | $V_{CS1}$ = 750 mV | $V_{CS2}$ = 1000 mV | $V_{CS3}$ = 1100 mV |
|---|---|---|---|
| $I_{L(PEAK)}$ | 525 mA | 700 mA | 770 mA |
| $I_{LED}$ | 262 mA | 350 mA | 385 mA |
| $t_{ON}$ | 6.07 μs | 8.13 μs | 8.90 μs |
| $t_{OFF\_S}$ | 1.40 μs | 1.87 μs | 2.05 μs |
| $t_{ONDLY}$ | 0.514 μs | 0.514 μs | 0.514 μs |
| T | 7.98 μs | 10.51 μs | 11.46 μs |
| $f_{SW}'$ | 125.25 kHz | 95.11 kHz | 87.23 kHz |

## 10.2 Input Smoothing Electrolytic Capacitor, $C_{IN}$, Setting

Since the IC provides the CRM control where the inductor current fluctuates from zero to the peak, ripple current becomes larger than in case of CCM control.

The ripple current of the input capacitor, $C_{IN}$, is calculated assuming the worst condition (all the power is supplied to the LED driver circuit from $C_{IN}$ for a period of time). In delay time, the negative current flows through $C_{IN}$ as shown in Figure 10-2.
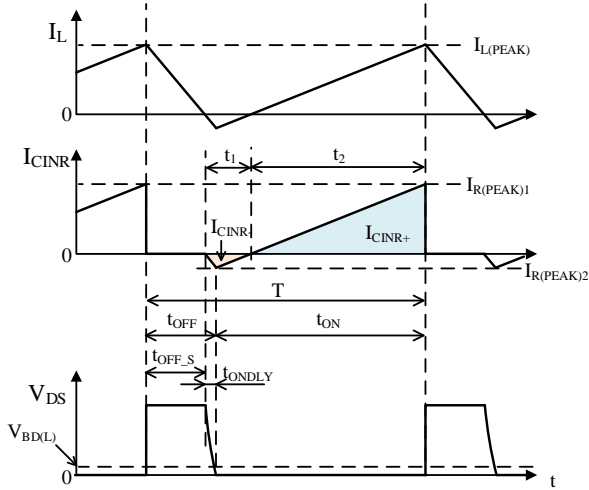


Figure 10-2.　$C_{IN}$ Ripple Current (worst condition)

The current flowing in $C_{IN}$ during the period, $t_1$, in Figure 10-2 has a triangular waveform whose peak value is $I_{R(PEAK)2}$. The effective value of this current, $I_{CINR-}$, is calculated by Equation (10).

$$I_{CINR-} = I_{R(PEAK)2} \times \sqrt{\frac{t_1}{3T}} \qquad (10)$$

$I_{CIN(RIPPLE)}$ discharging from $C_{IN}$ during the period, $t_2$, in Figure 10-2 has a triangular waveform whose peak value is $I_{R(PEAK)1}$. The effective value of this current, $I_{CINR+}$, is calculated by Equation (11).

$$I_{CINR+} = I_{R(PEAK)1} \times \sqrt{\frac{t_2}{3T}} \qquad (11)$$

From Equation (10) and (11), the total ripple current of $C_{IN}$, $I_{CINR}$, is calculated by the following equation.

$$I_{CINR} = \sqrt{I_{CINR-}^2 + I_{CINR+}^2} \qquad (12)$$

The calculated value is the maximum ripple current

considering the worst condition. A capacitor that the ripple current calculated by Equation (12) can flow should be chosen. Care should be taken in using an electrolytic capacitor. The ripple current eventually should be confirmed on actual operation.

It is required to select input capacitors having sufficient margins to the maximum applied voltage according to recommended use conditions of capacitor manufacturers.

● **Calculation Example**

The total ripple current, $I_{CINR}$, of $C_{IN}$, is calculated by Equation (10), (11), and (12).

If $t_1 = 0.7$ μs, $I_{R(PEAK)2} = 0.26$ A, and the cycle, $T = 10$ μs (the frequency $f_{SW} = 100$ kHz), $I_{CINR-}$, is calculated as follows:

$$I_{CINR-} = 0.26 \text{ A} \times \sqrt{\frac{0.7 \text{ μs}}{3 \times 10 \text{ μs}}} = 0.039 \text{ Arms}$$

When $t_2 = 6.4$ μs, $I_{R(PEAK)1} = I_{L(PEAK)} = 0.7$ A, and the cycle, $T = 10$ μs (frequency, $f_{SW} = 100$ kHz), $I_{CINR+}$ is calculated as follows:

$$I_{CINR+} = 0.7 \text{ A} \times \sqrt{\frac{6.4 \text{ μs}}{3 \times 10 \text{ μs}}} = 0.323 \text{ Arms}$$

From the above, the total ripple current, $I_{CINR}$, is as follows:

$$I_{CINR} = \sqrt{0.039^2 + 0.323^2} = 0.325 \text{ Arms}$$

From the above, a capacitor that can permit the ripple current of 0.325 Arms or higher must be selected for $C_{IN}$.

## 10.3 Output Smoothing Capacitor, $C_{OUT}$, Setting

Since the IC provides the CRM control where the inductor current fluctuates from zero to the peak, it is required to connect the output smoothing capacitor, $C_{OUT}$, to the both ends of the LED string, and reduce the ripple voltage of the LED string.

The ripple current, $I_{COUTR}$, flowing in $C_{OUT}$, is calculated by Equation (13).

$$I_{COUTR} = \frac{I_{L(PEAK)}}{2\sqrt{3}} \qquad (13)$$

When the equivalent series resistor of the smoothing capacitor, $C_{OUT}$, is ESR, the ripple voltage, $V_{LED(RIPPLE)}$,

of $C_{OUT}$, is expressed by Equation (14).

$$V_{LED(RIPPLE)} = I_{L(PEAK)} \times ESR \qquad (14)$$

A capacitor that the ripple current calculated by Equation (13) can flow is required for $C_{OUT}$. The voltage across $C_{OUT}$ is the sum of $V_F$ in the LED string. It is required to select the breakdown voltage of $C_{OUT}$ having margins to the maximum applied voltage considering the ripple voltage in Equation (14) according to recommended use conditions of capacitor manufacturers.
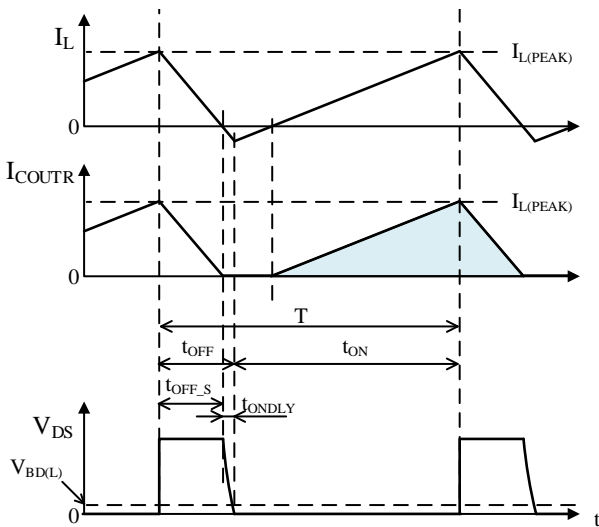


Figure 10-3.   $C_{OUT}$ Ripple Current

● **Calculation Example**

If $I_{L(PEAK)} = 0.7$ A, the ripple current, $I_{COUTR}$, flowing in $C_{OUT}$ is calculated by Equation (13) as follows:

$$I_{COUTR} = \frac{0.7\,A}{2\sqrt{3}} = 0.202\ Arms$$

From the above, a capacitor that can permit the ripple current of 0.202 Arms or higher should be selected for $C_{OUT}$.

When ESR = 100 m$\Omega$ and $I_{L(PEAK)} = 0.7$ A, the ripple voltage, $V_{LED(RIPPLE)}$, of $C_{OUT}$ is calculated by Equation (14) as follows:

$$V_{LED(RIPPLE)} = 0.7\,A \times 100\ m\Omega\ =\ 70\ mVp\!-\!p$$

It is required to select the withstand voltage of $C_{OUT}$ having margins to the maximum applied voltage considering the ripple voltage of 70 mVp-p according to recommended use conditions of capacitor manufacturers.

## 10.4  Current Detection Resistor, $R_{CS}$, Setting

For the current detection resistor, $R_{CS}$, noninductive resistors such as metal plate resistors, metal film resistors, and carbon film resistors should be used. If inductive resistors such as winding wire type are used, malfunction may occur due to the surge voltage by parasitic inductance component.

Axial lead and radial lead resistor should be mounted with the lead as short as possible.

● **$R_{CS}$ Loss Calculation**

The switching current flows in $R_{CS}$ in the on-time period of the power MOSFET. The current flowing in $R_{CS}$, $I_{RCS}$, is calculated by the following equation.

$$I_{RCS} = I_{LED} \times D \qquad (15)$$

where,
$I_{LED}$ is LED current, and
D is duty

The average loss of $R_{CS}$, $P_{RCS}$, in Equation (15), is calculated by the following equation.

$$P_{RCS} = (I_{RCS})^2 \times R_{CS} \qquad (16)$$

When $V_{CS}$ is switched by the SEL pin input voltage, the power dissipation should be calculated with the maximum value, $V_{CS3} = 1.1$ V.

In an abnormal operation state such as a short between the drain and source pins of the external MOSFET , the detection resistor, $R_{CS}$, may be damaged. In order to avoid damage, the following measures should be taken.

- Increase the $R_{CS}$ power rating.
- Insert the protective fuse that melts before $R_{CS}$ is damaged into the power supply of the LED driver circuit.
- Using the FAULT pin of the LC5910S, stop the pre-converter that generates the supply power of the LED driver circuit.

● **Calculation Example**

Table 10-3.   Set Value of Current Detection Resistance Calculation

| Parameter | Set Value |
|---|---|
| Detection Resistor, $R_{CS}$ | 1.428 Ω |
| Reference Voltage, $V_{CS}$ | 1.0 V ($V_{SEL}$ = 0.75 V to 1.25 V) |
| LED Current, $I_{LED}$ | 0.35 A ($I_{L(PEAK)}$ = 0.7 A) |
| LED String Voltage, $V_{LED}$ | 130 V |
| Input Voltage, $V_{IN}$ | 160 V |
| Duty, D | 0.8125 |

Using the set value in Table 10-3., the loss of resistance is calculated by Equation (15) and Equation (16).

$$I_{RCS} = 0.35\ A \times 0.8125 = 0.284\ A$$

$$P_{RCS} = (0.284\ A)^2 \times 1.428\ \Omega = 0.115\ W$$

## 11.   Design Notes

### 11.1   External Components

Components fit for the use condition should be used.

### 11.1.1   Inductor

It is required to set design margin properly for temperature rise due to copper loss and iron loss, and for magnetic saturation.

### 11.1.2   Input and Output Smoothing Electrolytic Capacitor

It is required to set a design margin properly for the ripple current, voltage, and lifetime. The electrolytic capacitor used must have high allowable ripple current for switching power supplies and low impedance.

### 11.1.3   Current Detection Resistor

Because high-frequency switching current flows through the current detection resistor, a resistor with low internal inductance must be chosen. In addition, the resistor is required to be selected considering the allowable loss.

### 11.1.4   Freewheeling Diode

The freewheeling diode, $D_S$, that regenerates energy during the off-time period of the external power MOSFET (see Figure 6-1) is selected from fast recovery diodes with short recovery time, $t_{rr}$, or from Schottky diodes.

The peak of the forward current, $I_F$, of the freewheeling diode is twice the $I_{LED}$, and flows in the $t_{OFF}$ period of the power MOSFET. $I_F$ flows repeatedly at the same switching frequency as the power MOSFET. Therefore, a diode should be selected considering the allowable loss.

Do not use a general rectification diode used for commercial power supply rectification because its $t_{rr}$ is long and a large short-circuit current flows during the recovery period. This short-circuit current may cause not only the heat generation of the diode but also malfunction of the main circuit, resulting in damage.

### 11.1.5   External Power MOSFET

● **Breakdown Voltage between Drain and Source**

The input voltage, $V_{IN} - V_F$ (the forward voltage of the freewheeling diode) is applied between the drain and source of the power MOSFET when it is off. Considering surges at turn-off, the power MOSFET whose drain-source breakdown voltage is more than twice $V_{IN}$ should be selected.

● **Capacitance between Drain and Source (Cds)**

The capacitance between drain and source (Cds) affects the delay time, $t_{ONDLY}$. $t_{ONDLY}$ becomes longer as the capacitance becomes larger (see Section 10.1).

Although Cds is not described in the data sheet of the power MOSFET, it can be calculated from the output capacitance, Coss, and the feedback capacitance, Crss, as follows:

$$Coss = Cds - Cgd \qquad (17)$$

$$Crss = Cgd \qquad (18)$$

where, Cgd is the capacitance between gate and drain,

From Equation (17) and (18), Cds is calculated by the following equation.

$$Cds = Coss - Crss \qquad (19)$$

● **Breakdown Voltage between Gate and Source**

The gate drive voltage of the LC5910S varies in proportion to the VCC pin voltage. Therefore, in the specification that VCC voltage rises to the upper limit of 17 V of the recommended operating range, a power MOSFET with gate-source breakdown voltage of 20 V to 30 V should be selected.

When a stabilized voltage of 12 V is input to the VCC pin, the crest value in the output pulse of the OUT pin is about 12 V.

● **Others**

In general, the larger the package and the lower the on-resistance of a power MOSFET, the larger the capacitance (e.g. Ciss) between junctions. Therefore, the larger drive current is required. Considering the drive capability of the LC5910S, a power MOSFET with package size smaller than TO 220 is recommend.

## 11.2 PCB Trace Layout

The switching power supply circuit includes high frequency and high voltage current paths that affect the IC operation, noise interference, and power dissipation. Therefore, PCB trace layouts and component placements play an important role in circuit designing. High frequency and high voltage current loops must be as small as possible with wide trace, in order to maintain a low-impedance state (see Figure 11-1).

In addition, ground traces should be as wide and short as possible so that radiated EMI levels can be reduced.

When the input/output conditions exceed the Safety Extra Low Voltage (SELV), component layout and pattern distance considering safety standards are required.
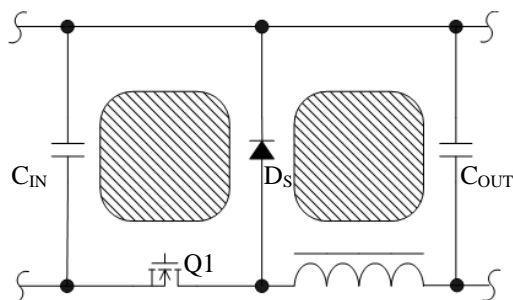


Figure 11-1. High Frequency Loop (shaded area)

(1) Main Circuit Trace Layout

The high frequency loop as shown in Figure 11-1 and the loop including the VCC pin and the GND pin are the main trace flowing switching currents.

This traces must be as wide layout and small loop as possible.

(2) Around the GND Pin

In order to prevent the switching current of the main circuit from influencing the control circuit, the control ground must be separated form the main trace and be connected near the GND pin.

(3) $R_{CS}$ Trace Layout

$R_{CS}$ should be placed as close as possible to the CS pin. In order to reduce noise at current detection, the detection trace must be separated, and be connected to near $R_{CS}$ from the CS pin.

(4) Peripheral Components of the IC

The components connected to each pin must be placed as close as possible to the IC, and must be connected as short as possible. The ground of components for detection of the IC must be connected near the GND pin. Extra attention should be paid so that the IC ground does not become a common impedance with the main trace. Do not place the IC or small signal pattern just under the inductor, L. The IC may malfunction due to the leak magnetic flux.

(5) Output Smoothing Capacitor, $C_{OUT}$

The output smoothing capacitor, $C_{OUT}$ is placed close to the LED string with a minimum length of traces.

(6) Thermal Considerations

Because the power MOSFET has a positive thermal coefficient of $R_{DS(ON)}$, care should be taken for thermal design. Particularly in the case of surface mount components, the drain pin pattern functions as a heat sink. Therefore, the pattern must be designed as wide as possible.

## 12. PCB Pattern Layout
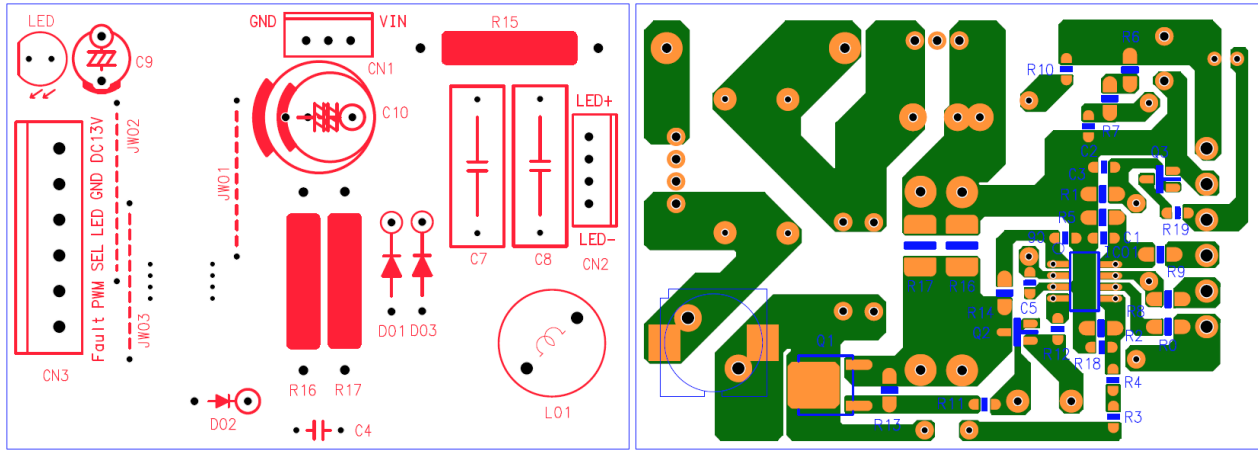


Front Side   Back Side

Figure 12-1.   Pattern Layout Example
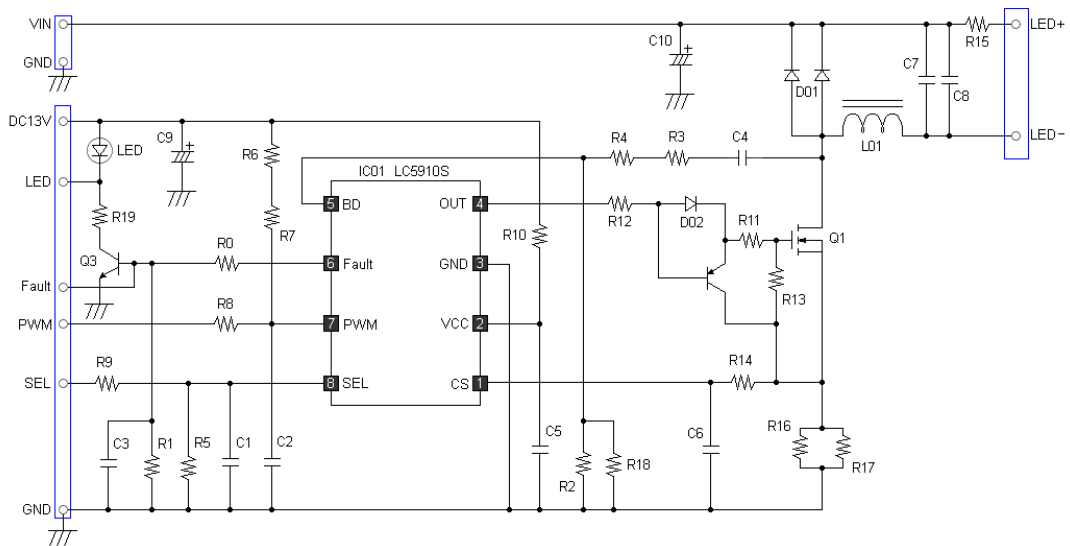


*Since this is the evaluation board, components for adjustment are included.

Figure 12-2.   Pattern Layout Circuit Diagram

## 13. Reference Design of Power Supply

As an example, the followings show the power supply specification and the bill of materials. For the circuit diagram of the bill of materials, see Figure 12-2.

● **Power Supply Specification**

| | |
|---|---|
| Input Voltage | DC250 V |
| VCC Pin Voltage | 13 V |
| Output Voltage | DC200 V |
| LED Current | 0.478 A ($V_{SEL}$ = 1.0V) |

● **Bill of Material**

| Symbol | Part Type | Rating | Notes |
|---|---|---|---|
| L01* | Inductor | 0.47 mH | |
| C1 | Ceramic | 1 nF | |
| C2 | Ceramic | 100 pF | |
| C3 | Ceramic | Open | |
| C4 | Ceramic | 15 pF, 1 kV | |
| C5 | Ceramic | 0.47 μF | |
| C6* | Ceramic | 100 pF, 50 V | |
| C7 | Ceramic | Open | |
| C8 | Ceramic | 0.47 μF, 400 V | |
| C9 | Electrolytic | 22 μF, 25 V | |
| C10 | Electrolytic | 10 μF, 250 V | |
| D01 | Fast Recovery Diode | 600 V, 2 A | |
| D02 | Diode | 60 V, 0.5 A | |
| Q1 | N-channel Power MOSFET | 250 V, 7.5A, 0.4Ω | |
| Q2 | PNP Transistor | −60 V, −0.6 A | |
| Q3 | NPN Transistor | 40 V, 0.6 A | |
| R0 | General | 1.8 kΩ | |
| R1 | General | Open | |
| R2 | General | 2.2 kΩ | |
| R3 | General | 33 kΩ | |
| R4 | General | 30 kΩ | |
| R5 | General | Open | |
| R6 | General | 470 kΩ | |
| R7 | General | 470 kΩ | |
| R8 | General | 1 kΩ | |
| R9 | General | 510 kΩ | |
| R10 | General | 10 Ω | |
| R11* | General | 7.5 Ω | |
| R12* | General | 47 Ω | |
| R13* | General | 10 kΩ | |
| R14* | General | 100 Ω | |
| R15 | General | 1 Ω, 2 W | |
| R16 | General | 2.3 Ω, 2 W | |
| R17 | General | Open | |
| R18 | General | Open | |
| R19 | General | 4.7 kΩ | |
| LED | — | — | LED for Fault detection |

* Adjustment is required on actual operation.

## 14. Design Flow Chart

The flow chart below is specialized for selection of constants. Measures against noise and heat dissipation on actual operation are not included. Therefore, another adjustment is required.

```
                  START

        V_LED = V_F × n
        V_IN
        I_LED
        Condition Setting

        Target Frequency Setting  ←┐
                                    │
        Calculation of Duty, D      │
                                    │
        t_ON、t_OFF_S Calculation    │
                                    │
              ◇ t_ON ≤ 20μs ◇ ──No──┘
                    │ Yes

        Inductance
        Calculation

        Power MOSFET
        Selection

        Delay Time, t_ONDLY
        Calculation

        t_OFF Calculation
        Corrected Frequency
        Calculation
```

```
        V_SEL Setting

        R_CS Setting

        C_IN Setting

        C_OUT Setting

        Peripheral Components
        Selection such as
        Free Wheeling
        Diode

        Actual Operation
        Confirmation

        R_BD, C_BD Adjustment  ←┐
                                 │
        ◇ Check the bottom-on ◇ ─No─┘
        ◇ of the BD pin wave ◇
        ◇ -form ◇
              │ Yes
            END
```

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