# Wide Input Voltage Range, High Efficiency Fault Tolerant LED Driver

## Features and Benefits

- AEC-Q100 Qualified
- Wide input voltage range of 5 to 40 V for start/stop, cold crank and load dump requirements
- Fully integrated LED current sinks and boost converter with 60 V DMOS
- Sync function to synchronize boost converter switching frequency up to 2.3 MHz, allowing operation above the AM band
- Excellent input voltage transient response
- Single resistor primary OVP minimizes $V_{OUT}$ leakage
- Internal secondary OVP for redundant protection
- LED current of 80 mA per channel
- Drives up to 12 series LEDs in 4 parallel strings
- 0.7% to 0.8% LED to LED matching accuracy
- PWM and analog dimming inputs
- 5000:1 PWM dimming at 200 Hz
- Provides driver for external PMOS input disconnect switch
- Extensive protection against:
  ▫ Shorted boost switch or inductor
  ▫ Shorted FSET or ISET resistor
  ▫ Shorted output
  ▫ Open or shorted LED pin
  ▫ Open boost Schottky
  ▫ Overtemperature (OTP)

## Package: 20-pin TSSOP with exposed thermal pad (suffix LP)
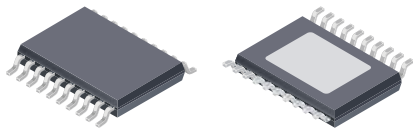
*Not to scale*

## Description

The A8514 is a multi-output white LED driver for small-size LCD backlighting. It integrates a current-mode boost converter with internal power switch and four current sinks. The boost converter can drive up to 48 LEDs, 12 LEDs per string, at 80 mA. The LED sinks can be paralleled together to achieve even higher LED currents, up to 320 mA. The A8514 can operate with a single power supply, from 5 to 40 V, which allows the part to withstand load dump conditions encountered in automotive systems.

The A8514 can drive an external P-FET to disconnect the input supply from the system in the event of a fault. The A8514 provides protection against output short and overvoltage, open or shorted diode, open or shorted LED pin, shorted boost switch or inductor, shorted FSET or ISET resistor, and IC overtemperature. A dual level cycle-by-cycle current limit function provides soft start and protects the internal current switch against high current overloads.

The A8514 has a synchronization pin that allows PWM switching frequencies to be synchronized in the range of 580 kHz to 2.3 MHz. The high switching frequency allows the A8514 to operate above the AM radio band.

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## Applications:

LCD backlighting or LED lighting for:
▫ Automotive infotainment
▫ Automotive cluster
▫ Automotive center stack
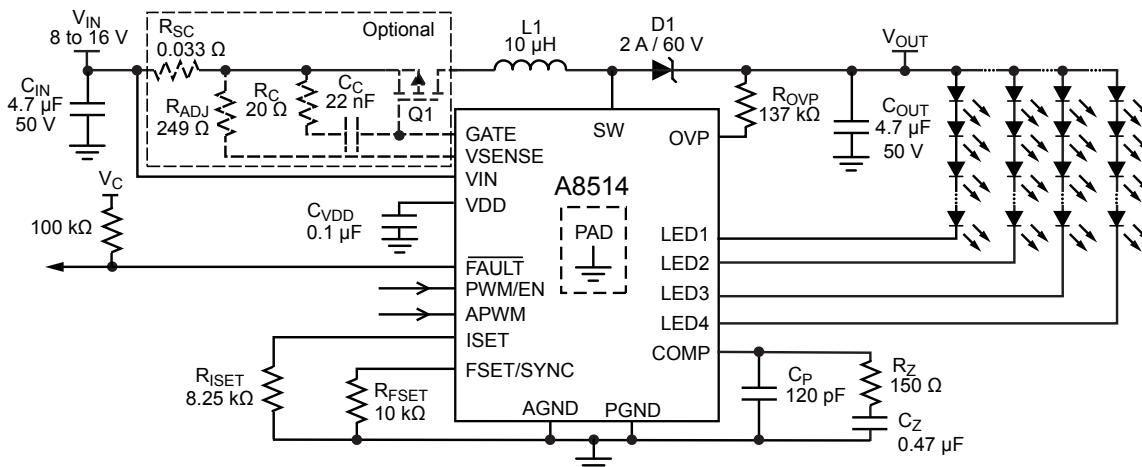
## Typical Application Circuit



Figure 1. Application with VIN to ground short protection, using optional P-MOSFET for input disconnect protection

## Description (continued)

The A8514 is provided in a 20-pin TSSOP package (suffix LP) with an exposed pad for enhanced thermal dissipation. It is lead (Pb) free, with 100% matte tin lead frame plating.

### Selection Guide

| Part Number | Packing* |
|---|---|
| A8514KLPTR-T | 4000 pieces per 13-in. reel |

*Contact Allegro™ for additional packing options

### Absolute Maximum Ratings*

| Characteristic | Symbol | Notes | Rating | Unit |
|---|---|---|---|---|
| LEDx Pins | | | –0.3 to 55 | V |
| OVP Pin | | | –0.3 to 60 | V |
| VIN, VSENSE, GATE Pins | | VSENSE and GATE pins should not exceed $V_{IN}$ by more than 0.4 V | –0.3 to 40 | V |
| SW Pin | | Continuous | –0.6 to 62 | V |
| | | t < 50 ns | –1.0 | V |
| $\overline{FAULT}$ Pin | | | -0.3 to 40 | V |
| ISET, FSET, APWM, COMP Pins | | | –0.3 to 5.5 | V |
| All Other Pins | | | –0.3 to 7 | V |
| Operating Ambient Temperature | $T_A$ | Range K | –40 to 125 | ºC |
| Maximum Junction Temperature | $T_J$(max) | | 150 | ºC |
| Storage Temperature | $T_{stg}$ | | –55 to 150 | ºC |

*Stresses beyond those listed in this table may cause permanent damage to the device. The Absolute Maximum ratings are stress ratings only, and functional operation of the device at these or any other conditions beyond those indicated in the Electrical Characteristics table is not implied. Exposure to Absolute Maximum-rated conditions for extended periods may affect device reliability.

## Table of Contents

Allegro MicroSystems, LLC
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**Pin-out Diagram**

```
       GATE   1           20   SW
     VSENSE   2           19   OVP
        VIN   3           18   PGND
      FAULT   4           17   PGND
       COMP   5           16   PGND
       APWM   6           15   VDD
     PWM/EN   7           14   LED1
  FSET/SYNC   8           13   LED2
       ISET   9           12   LED3
       AGND  10           11   LED4
```

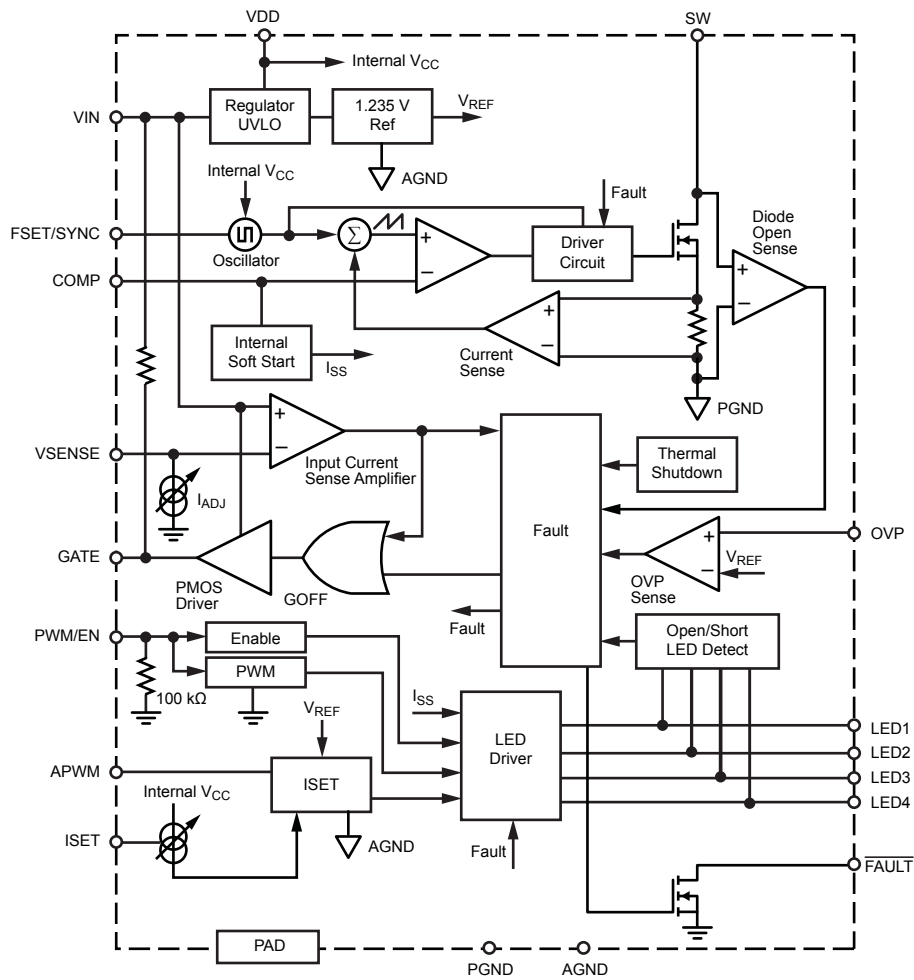## Terminal List Table

| Number | Name | Function |
|---|---|---|
| 1 | GATE | Output gate driver pin for external P-channel FET control. |
| 2 | VSENSE | Connect this pin to the negative sense side of the current sense resistor $R_{SC}$. The threshold voltage is measured as $V_{IN} - V_{SENSE}$. There is also a fixed current sink to allow for trip threshold adjustment. |
| 3 | VIN | Input power to the A8514 as well as the positive input used for current sense resistor. |
| 4 | $\overline{FAULT}$ | Indicates a fault condition. Connect a 100 kΩ resistor between this pin and the required logic level voltage. The pin is an open drain type configuration that will be pulled low when a fault occurs. |
| 5 | COMP | Output of the error amplifier and compensation node. Connect a series $R_Z$-$C_Z$ network from this pin to ground for control loop compensation. |
| 6 | APWM | Analog trimming option for dimming. Applying a digital PWM signal to this pin adjusts the internal $I_{SET}$ current. |
| 7 | PWM/EN | PWM dimming pin, used to control the LED intensity by using pulse width modulation. Also used to enable the A8514. |
| 8 | FSET/SYNC | Frequency/synchronization pin. A resistor $R_{FSET}$ from this pin to ground sets the switching frequency. This pin can also be used to synchronize two or more A8514s in the system. The maximum synchronization frequency is 2.3 MHz. |
| 9 | ISET | Connect the $R_{ISET}$ resistor between this pin and ground to set the 100% LED current. |
| 10 | AGND | LED signal ground. |
| 11,12,13,14 | LEDx | Connect the cathodes of the LED strings to these pins. |
| 15 | VDD | Output of internal LDO; connect a 0.1 µF decoupling capacitor between this pin and ground. |
| 16,17.18 | PGND | Power ground for internal DMOS device. |
| 19 | OVP | Overvoltage Condition (OVP) sense; connect the $R_{OVP}$ resistor from $V_{OUT}$ to this pin to adjust the overvoltage protection. |
| 20 | SW | The drain of the internal DMOS switch of the boost converter. |
| – | PAD | Exposed pad of the package providing enhanced thermal dissipation. This pad must be connected to the ground plane(s) of the PCB with at least 8 vias, directly in the pad. |

## Thermal Characteristics may require derating at maximum conditions, see application information

| Characteristic | Symbol | Test Conditions* | Value | Unit |
|---|---|---|---|---|
| Package Thermal Resistance | $R_{\theta JA}$ | On 2-layer PCB, 3 in.$^2$ | 40.0 | ºC/W |
| | | On 4-layer PCB based on JEDEC standard (estimated) | 29.0 | ºC/W |

*Additional thermal information available on the Allegro website

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## Functional Block Diagram

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**ELECTRICAL CHARACTERISTICS[1,2]** Valid at $V_{IN}$ = 16 V, $T_A$ = 25°C, ● indicates specifications guaranteed by design and characterization over the full operating temperature range with $T_A = T_J$ = –40°C to 125°C; unless otherwise noted

| Characteristics | Symbol | Test Conditions | | Min. | Typ. | Max. | Unit |
|---|---|---|---|---|---|---|---|
| **Input Voltage Specifications** | | | | | | | |
| Operating Input Voltage Range[3] | $V_{IN}$ | | ● | 5 | – | 40 | V |
| UVLO Start Threshold | $V_{UVLOrise}$ | $V_{IN}$ rising | ● | – | – | 4.35 | V |
| UVLO Stop Threshold | $V_{UVLOfall}$ | $V_{IN}$ falling | ● | – | – | 3.90 | V |
| UVLO Hysteresis[2] | $V_{UVLOHYS}$ | | | 300 | 450 | 600 | mV |
| **Input Currents** | | | | | | | |
| Input Quiescent Current | $I_Q$ | PWM/EN = $V_{IH}$; SW = 2 MHz, no load | ● | – | 5.5 | 10 | mA |
| Input Sleep Supply Current | $I_{QSLEEP}$ | $V_{IN}$ = 16 V, $V_{PWMEN} = V_{FSETSYNC}$ = 0 V | ● | – | 2 | 10.0 | µA |
| **Input Logic Levels (PWM/EN and APWM)** | | | | | | | |
| Input Logic Level-Low | $V_{IL}$ | $V_{IN}$ throughout operating input voltage range | ● | – | – | 400 | mV |
| Input Logic Level-High | $V_{IH}$ | $V_{IN}$ throughout operating input voltage range | ● | 1.5 | – | – | V |
| PWM/EN Pin Open Drain Pull-down Resistor | $R_{PWMEN}$ | PWM/EN = 5 V | | 60 | 100 | 140 | kΩ |
| APWM Pull-down Resistor | $R_{APWM}$ | PWM/EN = $V_{IH}$ | | 60 | 100 | 140 | kΩ |
| **APWM** | | | | | | | |
| APWM Frequency[2] | $f_{APWM}$ | $V_{IH}$ = 2 V, $V_{IL}$ = 0 V | ● | 20 | – | 1000 | kHz |
| **Error Amplifier** | | | | | | | |
| Open Loop Voltage Gain | $A_{VOL}$ | | | 44 | 48 | 52 | dB |
| Transconductance | $g_m$ | $\Delta I_{COMP}$ = ±10 µA | | 750 | 990 | 1220 | µA/V |
| Source Current | $I_{EA(SRC)}$ | $V_{COMP}$ = 1.5 V | | – | –350 | – | µA |
| Sink Current | $I_{EA(SINK)}$ | $V_{COMP}$ = 1.5 V | | – | 350 | – | µA |
| COMP Pin Pull-down Resistance | $R_{COMP}$ | $\overline{FAULT}$ = 0 | | – | 2000 | – | Ω |
| **Overvoltage Protection** | | | | | | | |
| Overvoltage Threshold | $V_{OVP(th)}$ | OVP connected to $V_{OUT}$ | ● | 7.7 | 8.1 | 8.5 | V |
| OVP Sense Current | $I_{OVPH}$ | | ● | 188 | 199 | 210 | µA |
| OVP Leakage Current | $I_{OVPLKG}$ | $R_{OVP}$ = 40.2 kΩ, $V_{IN}$ = 16 V, PWM/EN = $V_{IL}$ | ● | – | 0.1 | 1 | µA |
| Secondary Overvoltage Protection | $V_{OVP(sec)}$ | | ● | 53 | 55 | 58 | V |
| **Boost Switch** | | | | | | | |
| Switch On-Resistance | $R_{SW}$ | $I_{SW}$ = 0.750 A, $V_{IN}$ = 16 V | ● | 75 | 300 | 600 | mΩ |
| Switch Leakage Current | $I_{SWLKG}$ | $V_{SW}$ = 16 V, PWM/EN = $V_{IL}$ | ● | – | 0.1 | 1 | µA |
| Switch Current Limit | $I_{SW(LIM)}$ | | ● | 3.0 | 3.5 | 4.2 | A |
| Secondary Switch Current Limit[2] | $I_{SW(LIM2)}$ | Higher than $I_{SW(LIM)}$(max) for all conditions, device latches when detected | | – | 7.00 | – | A |
| Soft Start Boost Current Limit | $I_{SWSS(LIM)}$ | Initial soft start current for boost switch | | – | 700 | – | mA |
| Minimum Switch On-Time | $t_{SWONTIME}$ | | ● | 60 | 85 | 111 | ns |
| Minimum Switch Off-Time | $t_{SWOFFTIME}$ | | ● | 30 | 47 | 68 | ns |

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**ELECTRICAL CHARACTERISTICS[1,2]** (continued) Valid at $V_{IN}$ = 16 V, $T_A$ = 25°C, ● indicates specifications guaranteed by design and characterization over the full operating temperature range with $T_A$ = $T_J$ = –40°C to 125°C; unless otherwise noted

| Characteristics | Symbol | Test Conditions | | Min. | Typ. | Max. | Unit |
|---|---|---|---|---|---|---|---|
| **Oscillator Frequency** | | | | | | | |
| Oscillator Frequency | $f_{SW}$ | $R_{FSET}$ = 10 kΩ | ● | 1.8 | 2 | 2.2 | MHz |
| | | $R_{FSET}$ = 20 kΩ | ● | 0.9 | 1 | 1.1 | MHz |
| | | $R_{FSET}$ = 35.6 kΩ | | 520 | 580 | 640 | kHz |
| FSET/SYNC Pin Voltage | $V_{FSET}$ | $R_{FSET}$ = 10 kΩ | | – | 1.00 | – | V |
| FSET Frequency Range | $f_{FSET}$ | | | 580 | – | 2500 | kHz |
| **Synchronization** | | | | | | | |
| Synchronized PWM Frequency | $f_{SWSYNC}$ | | ● | 580 | – | 2300 | kHz |
| Synchronization Input Minimum Off-Time | $t_{PWSYNCOFF}$ | | ● | 150 | – | – | ns |
| Synchronization Input Minimum On-Time | $t_{PWSYNCON}$ | | ● | 150 | – | – | ns |
| SYNC Input Logic Voltage | $V_{SYNC(H)}$ | FSET/SYNC pin, high level | ● | – | – | 0.4 | V |
| | $V_{SYNC(L)}$ | FSET/SYNC pin, low level | ● | 2.0 | – | – | V |
| **LED Current Sinks** | | | | | | | |
| LEDx Accuracy | $Err_{LED}$ | $I_{SET}$ = 120 µA | ● | – | – | 3 | % |
| LEDx Matching | $\Delta LEDx$ | $I_{SET}$ = 120 µA | ● | – | – | 3 | % |
| LEDx Regulation Voltage | $V_{LED}$ | $V_{LED1}$=$V_{LED2}$=$V_{LED3}$=$V_{LED4}$, $I_{SET}$ = 120 µA | ● | 600 | 700 | 800 | mV |
| $I_{SET}$ to $I_{LEDx}$ Current Gain | $A_{ISET}$ | $I_{SET}$ = 120 µA | ● | 633 | 653 | 672 | A/A |
| ISET Pin Voltage | $V_{ISET}$ | | | 0.988 | 1.003 | 1.018 | V |
| Allowable ISET Current | $I_{SET}$ | | ● | 20 | – | 120 | µA |
| $V_{LED}$ Short Detect | $V_{LEDSC}$ | While LED sinks are in regulation, sensed from LEDx pin to ground | ● | 4.6 | 5.1 | 5.6 | V |
| Soft Start LEDx Current | $I_{LEDSS}$ | Current through each enabled LEDx pin during soft start | | – | 2.0 | – | mA |
| Maximum PWM Dimming Until Off-Time[2] | $t_{PWML}$ | Measured while PWM/EN = low, during dimming control and internal references are powered-on (exceeding $t_{PWML}$ results in shutdown) | | – | 32,750 | – | $f_{SW}$ cycles |
| Minimum PWM On-Time | $t_{PWMH}$ | First cycle when powering-up device | ● | – | 0.75 | 2 | µs |
| PWM High to LED-On Delay | $t_{dPWM(on)}$ | Time between PWM enable and LED current reaching 90% of maximum | ● | – | 0.5 | 1 | µs |
| PWM Low to LED-Off Delay | $t_{dPWM(off)}$ | Time between PWM enable going low and LED current reaching 10% of maximum | ● | – | 360 | 500 | ns |

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**ELECTRICAL CHARACTERISTICS[1,2]** (continued) Valid at $V_{IN}$ = 16 V, $T_A$ = 25°C, ● indicates specifications guaranteed by design and characterization over the full operating temperature range with $T_A$ = $T_J$ = –40°C to 125°C; unless otherwise noted

| Characteristics | Symbol | Test Conditions | | Min. | Typ. | Max. | Unit |
|---|---|---|---|---|---|---|---|
| **GATE Pin** | | | | | | | |
| GATE Pin Sink Current | $I_{GSINK}$ | $V_{GS}$ = $V_{IN}$ | | – | −104 | – | µA |
| Gate Fault Shutdown Greater than 2X Current[2] | $t_{GFAULT2}$ | | | – | – | 3 | µs |
| Gate Fault Shutdown Greater than 1–2X Current | $t_{GFAULT1}$ | | | – | 10,000 | – | $f_{SW}$ cycles |
| Gate Voltage | $V_{GS}$ | Gate to source voltage measured when gate is on | | – | –6.7 | – | V |
| **VSENSE Pin** | | | | | | | |
| VSENSE Pin Sink Current | $I_{ADJ}$ | | ● | 18.8 | 20.3 | 21.8 | µA |
| VSENSE Trip Point | $V_{SENSEtrip1}$ | Measured between VIN and VSENSE, $R_{ADJ}$ = 0 Ω | ● | 94 | 104 | 114 | mV |
| VSENSE 2X Trip[2] | $V_{SENSEtrip2}$ | 2X $V_{SENSEtrip}$, instantaneous shutdown, $R_{ADJ}$ = 0 Ω | | – | 180 | – | mV |
| **FAULT Pin** | | | | | | | |
| FAULT Pull-Down Voltage | $V_{FAULT}$ | $I_{FAULT}$ = 1 mA | ● | – | – | 0.5 | V |
| FAULT Pin Leakage Current | $I_{FAULTLKG}$ | $V_{FAULT}$ = 5 V | | – | – | 1 | µA |
| **Thermal Protection (TSD)** | | | | | | | |
| Thermal Shutdown Threshold[2] | $T_{SD}$ | Temperature rising | | – | 165 | – | °C |
| Thermal Shutdown Hysteresis[2] | $T_{SDHYS}$ | | | – | 20 | – | °C |

[1]For input and output current specifications, negative current is defined as coming out of the node or pin (sourcing); positive current is defined as going into the node or pin (sinking).
[2]Ensured by design and characterization, not production tested.
[3]Minimum $V_{IN}$ = 5 V is only required at startup. After startup is completed, the IC is able to function down to $V_{IN}$ = 4 V.
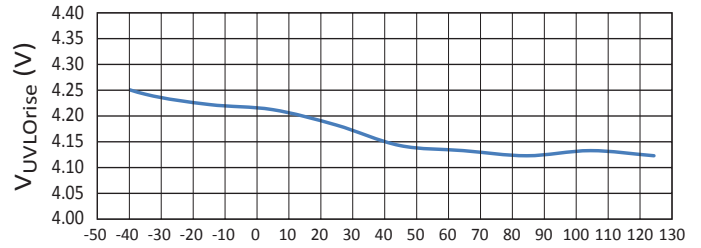
## Characteristic Performance

$T_A = T_J$

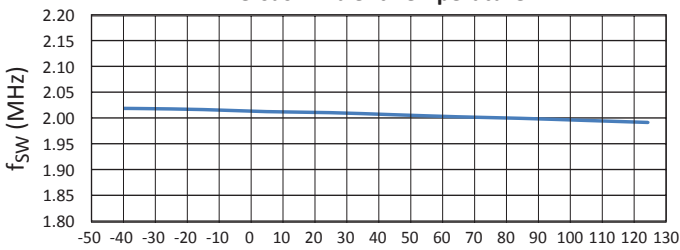### VIN Input Sleep Mode Current versus Ambient Temperature
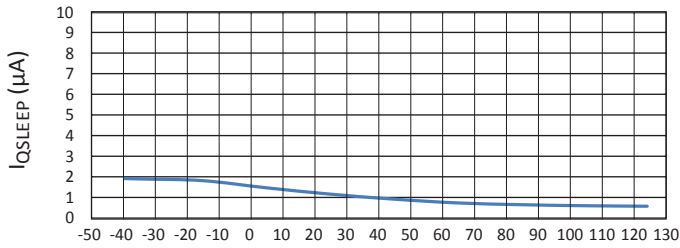
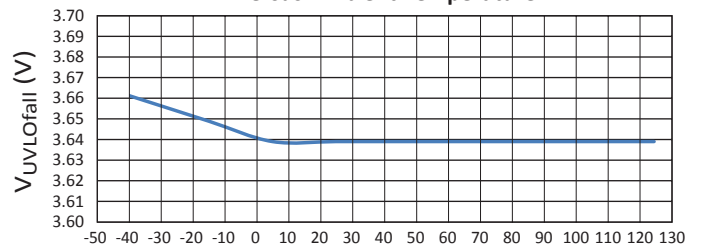### VIN UVLO Start Threshold Voltage versus Ambient Temperature
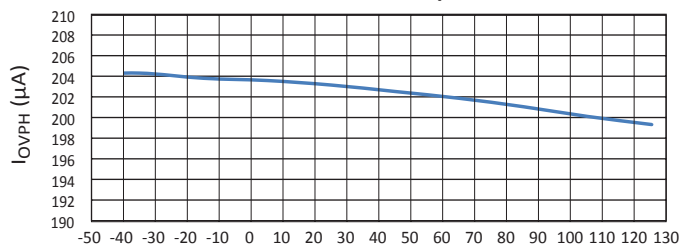
### Switching Frequency versus Ambient Temperature

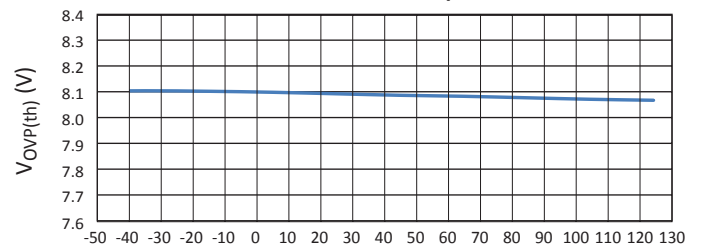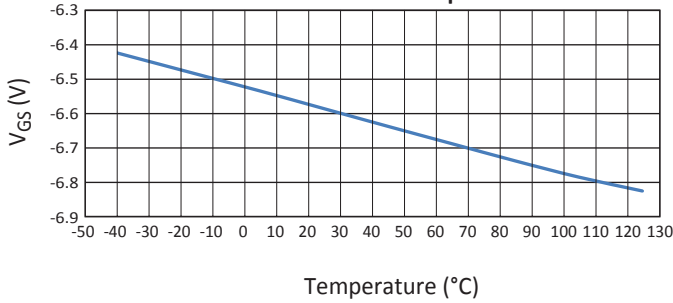### VIN UVLO Stop Threshold Voltage versus Ambient Temperature

### OVP Pin Sense Current versus Ambient Temperature

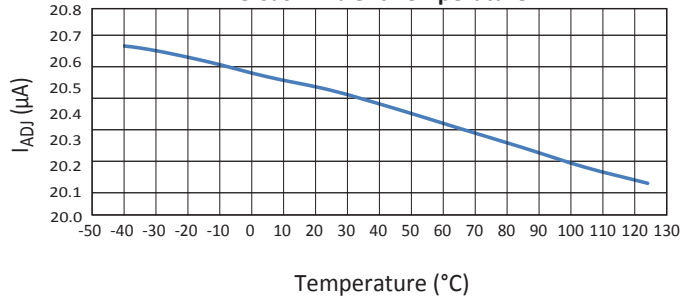### OVP Pin Overvoltage Threshold versus Ambient Temperature

**Input Disconnect Switch Gate to Source Voltage versus Ambient Temperature**
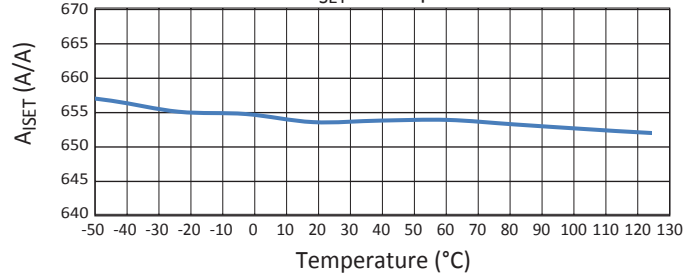
**VSENSE Pin Sink Current versus Ambient Temperature**

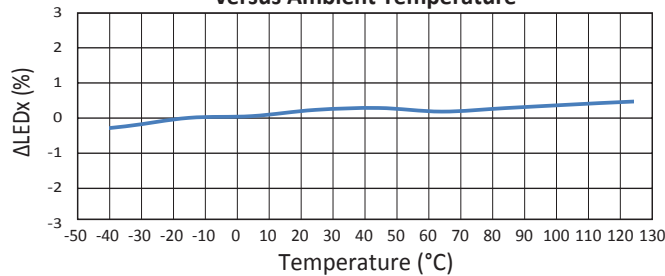**LED Current versus Ambient Temperature**
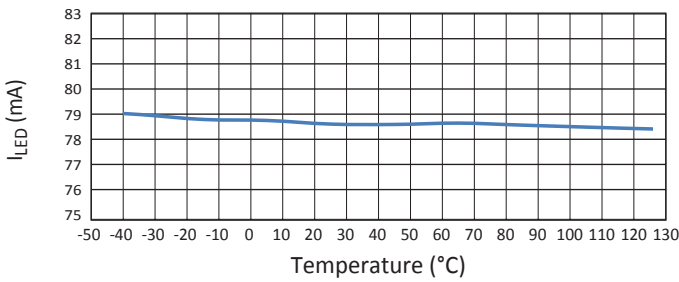
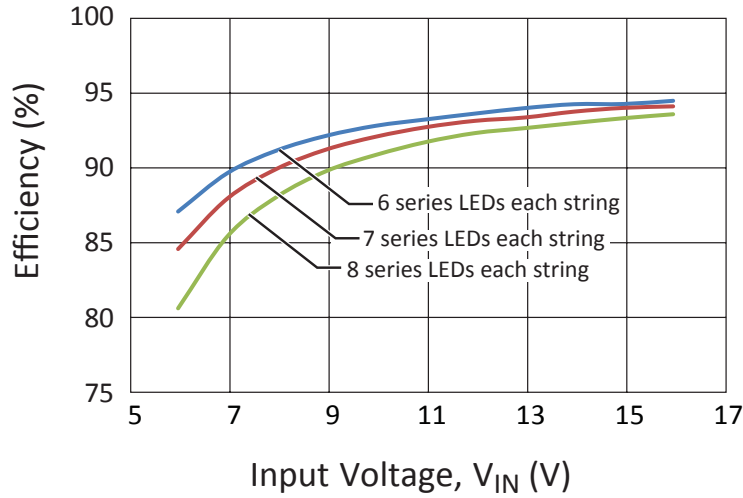**I$_{SET}$ to LED Current Gain versus Ambient Temperature**
I$_{SET}$ = 120 µA

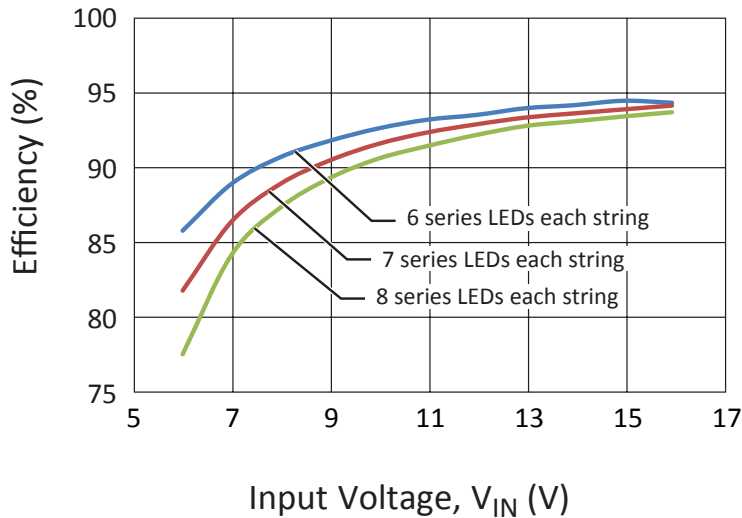**LED to LED Matching Accuracy versus Ambient Temperature**

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**Efficiency for Various 4-String Configurations**

$I_{LED}$ = 70 mA, LED $V_f$ ≈ 3.2 V



Efficiency (%) vs Input Voltage, $V_{IN}$ (V)

- 6 series LEDs each string
- 7 series LEDs each string
- 8 series LEDs each string

**Efficiency for Various 4-String Configurations**

$I_{LED}$ = 80 mA, LED $V_f$ ≈ 3.2 V



Efficiency (%) vs Input Voltage, $V_{IN}$ (V)

- 6 series LEDs each string
- 7 series LEDs each string
- 8 series LEDs each string

## Functional Description

The A8514 incorporates a current-mode boost controller with internal DMOS switch, and four LED current sinks. It can be used to drive four LED strings of up to 12 white LEDs in series, with current up to 80 mA per string. For optimal efficiency, the output of the boost stage is adaptively adjusted to the minimum voltage required to power all of the LED strings. This is expressed by the following equation:

$$V_{OUT} = \max ( V_{LED1},..., V_{LED4} ) + V_{REG} \qquad (1)$$

where

$V_{LEDx}$ is the voltage drop across LED strings 1 through 4, and

$V_{REG}$ is the regulation voltage of the LED current sinks (typically 0.7 V at the maximum LED current).

### Enabling the IC

The IC turns on when a logic high signal is applied on the PWM/EN pin with a minimum duration of $t_{PWMH}$ for the first clock cycle, and the input voltage present on the VIN pin is greater than the 4.35 V necessary to clear the UVLO ($V_{UVLOrise}$) threshold. The power-up sequence is shown in figure 2. Before the LEDs are enabled, the A8514 driver goes through a system check to determine if there are any possible fault conditions that might prevent the system from functioning correctly. Also, if the FSET/SYNC pin is pulled low, the IC will not power-up. More information on the FSET/SYNC pin can be found in the Sync section of this datasheet.
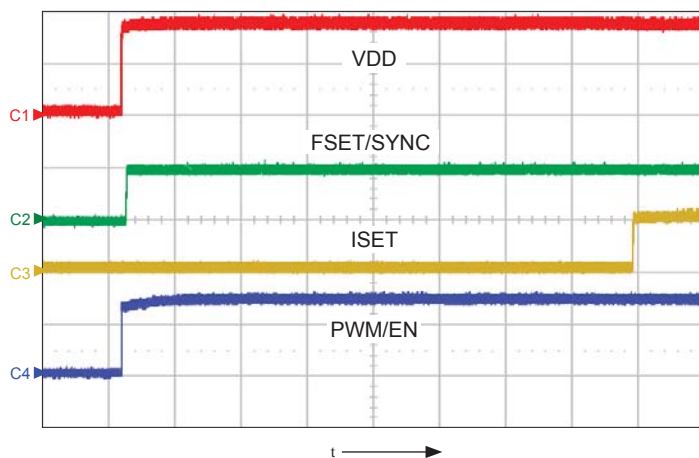
### Powering up: LED pin short-to-ground check

The VIN pin has a UVLO function that prevents the A8514 from powering-up until the UVLO threshold is reached. After the VIN pin goes above UVLO, and a high signal is present on the PWM/EN pin, the IC proceeds to power-up. As shown in figure 3, at this point the A8514 enables the disconnect switch and checks if any LEDx pins are shorted to ground and/or are not used.

The LED detect phase starts when the GATE voltage of the disconnect switch is equal to $V_{IN} - 4.5$ V. After the voltage threshold on the LEDx pins exceeds 120 mV, a delay of between 3000 and 4000 clock cycles is used to determine the status of the pins. Thus, the LED detection duration varies with the switching frequency, as shown in the following table:

| Switching Frequency (MHz) | Detection Time (ms) |
|---|---|
| 2 | 1.5 to 2 |
| 1 | 3 to 4 |
| 0.800 | 3.75 to 5 |
| 0.600 | 5 to 6.7 |

The LED pin detection voltage thresholds are as follows:

| LED Pin Voltage | LED Pin Status | Action |
|---|---|---|
| <70 mV | Short-to-ground | Power-up is halted |
| 150 mV | Not used | LED removed from operation |
| 325 mV | LED pin in use | None |



Figure 2. Power-up diagram; shows VDD (ch1, 2 V/div.), FSET/SYNC (ch2, 1 V/div.), ISET (ch3, 1 V/div.), and PWM/EN (ch4, 2 V/div.) pins, time = 200 µs/div.
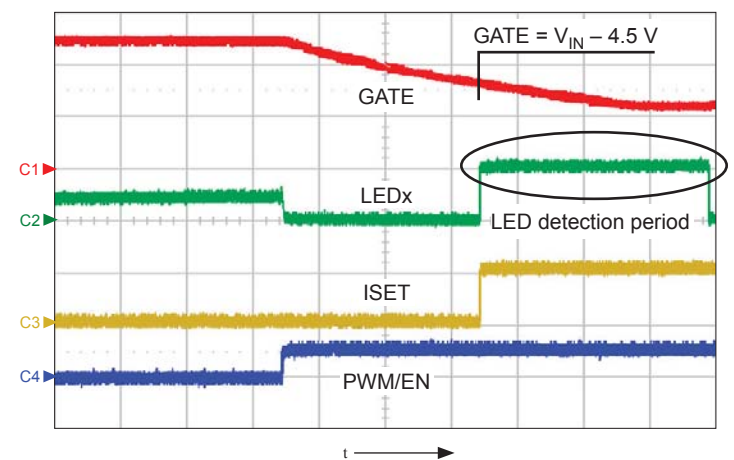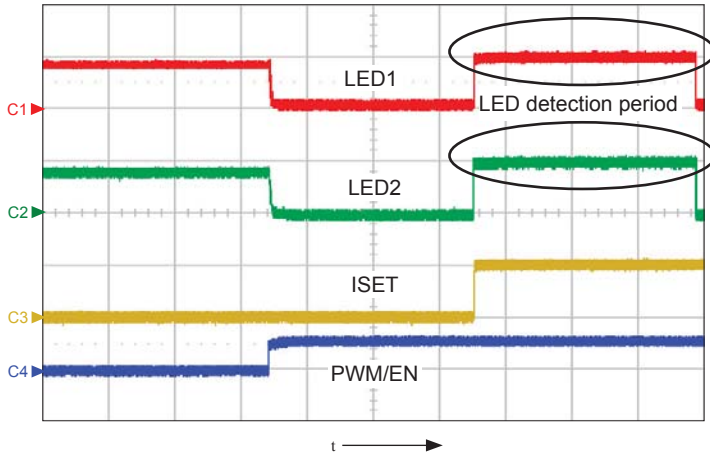


Figure 3. Power-up diagram; shows the relationship of an LEDx pin with respect to the gate voltage of the disconnect switch (if used) during the LED detect phase, as well as the duration of the LED detect phase for a switching frequency of 2 MHz; shows GATE (ch1, 5 V/div.), LED (ch2, 500 mV/div.), ISET (ch3, 1 V/div.), and PWM/EN (ch4, 5 V/div.) pins, time = 500 µs/div.

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4A. An LED detect occurring when both LED pins are selected to be used; shows LED1 (ch1, 500 mV/div.), LED2 (ch2, 500 mV/div.), ISET (ch3, 1 V/div.), and PWM/EN (ch4, 5 V/div.) pins, time = 500 µs/div.
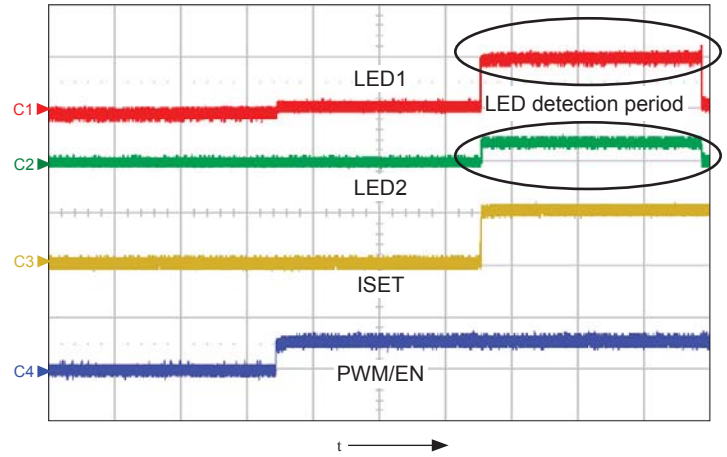


4B. Example with LED2 pin not being used; the detect voltage is about 150 mV; shows LED1 (ch1, 500 mV/div.), LED2 (ch2, 500 mV/div.), ISET (ch3, 1 V/div.), and PWM/EN (ch4, 5 V/div.) pins, time = 500 µs/div.
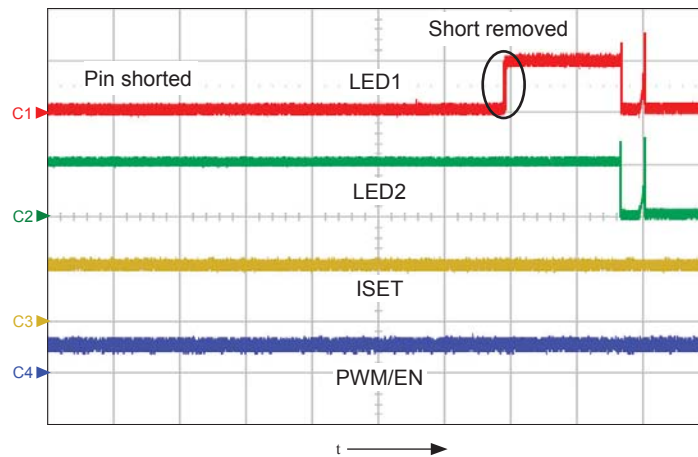


4C. Example with one LED shorted to ground. The IC will not proceed with power-up until the shorted LED pin is released, at which point the LED is checked to see if it is being used; shows LED1 (ch1, 500 mV/div.), LED2 (ch2, 500 mV/div.), ISET (ch3, 1 V/div.), and PWM/EN (ch4, 5 V/div.) pins, time = 1 ms/div.

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All unused pins should be connected with a 2.37 kΩ resistor to ground, as shown in figure 5. The unused pin, with the pull-down resistor, will be taken out of regulation at this point and will not contribute to the boost regulation loop.

If a LEDx pin is shorted to ground the A8514 will not proceed with soft start until the short is removed from the LEDx pin. This prevents the A8514 from powering-up and putting an uncontrolled amount of current through the LEDs.

## Soft start function

During soft start the LEDx pins are set to sink ($I_{LEDSS}$) and the boost switch current is reduced to the $I_{SWSS(LIM)}$ level to limit the inrush current generated by charging the output capacitors. When the converter senses that there is enough voltage on the LEDx pins the converter proceeds to increase the LED current to the preset regulation current and the boost switch current limit is switched to the $I_{SW(LIM)}$ level to allow the A8514 to deliver the necessary output power to the LEDs. This is shown in figure 6.

## Frequency selection

The switching frequency on the boost regulator is set by the resistor connected to the FSET/SYNC pin. The switching frequency can be can be anywhere from 580 kHz to 2.3 MHz. Figure 7 shows the typical switching frequencies for various resistor values, with the relationship between $R_{FSET}$ and typical switching frequency given as:

$$f_{SW} = k / (R_{FSET} + R_{INT}), \text{ or} \qquad (2)$$
$$R_{FSET} = k / f_{SW} - R_{INT}$$

where $R_{FSET}$ is in in kilohms, $f_{SW}$ is in megahertz, k = 20.9 and $R_{INT}$ (internal resistance of FSET pin) = 0.6 kΩ.
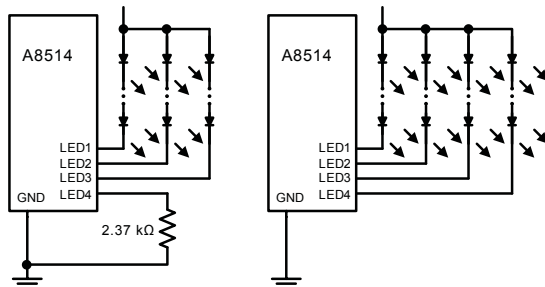
Figure 5. Channel select setup: (left) using only LED1, LED2, and LED3, and (right) using all four channels.

In case during operation a fault occurs that will increase the switching frequency, the FSET/SYNC pin is clamped to a maximum switching frequency of no more than 3.5 MHz. If the FSET/SYNC pin is shorted to GND the part will shut down. For more details see the Fault Mode table later in this datasheet.
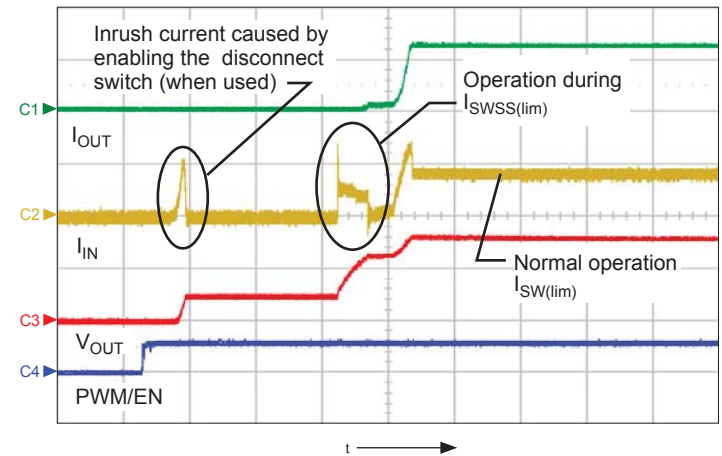
Figure 6. Startup diagram showing the input current, output voltage, and output current; shows $I_{OUT}$ (ch1, 200 mA/div.), $I_{IN}$ (ch2, 1 A/div.), $V_{OUT}$ (ch3, 20 V/div.), and PWM/EN (ch4, 5 V/div.), time = 1 ms/div.
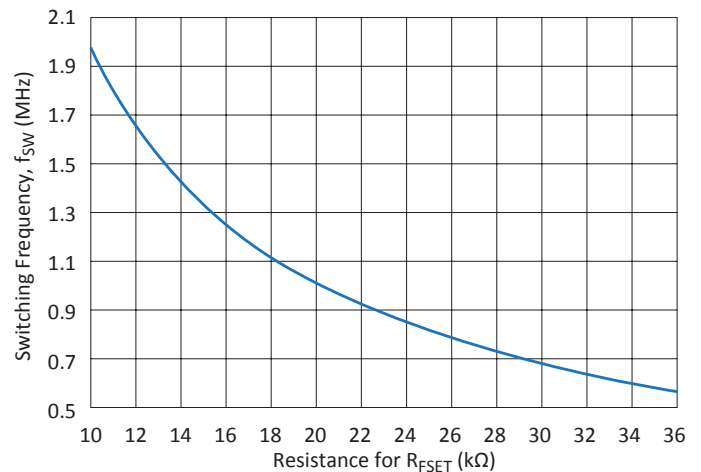
Figure 7. Typical Switching Frequency versus value of $R_{FSET}$ resistor

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**Sync**

The A8514 can also be synchronized using an external clock on the FSET/SYNC pin. Figure 8 shows the correspondence of a sync signal and the FSET/SYNC pin, and figure 9 shows the result when a sync signal is detected: the LED current does not show any variation while the frequency changeover occurs. At power-up if the FSET/SYNC pin is held low, the IC will not power-up. Only when the FSET/SYNC pin is tri-stated to allow the pin to rise, to about 1 V, or when a synchronization clock is detected, will the A8514 try to power-up.

The basic requirement of the sync signal is 150 ns minimum on-time and 150 ns minimum off time, as indicated by the specifications for $t_{PWSYNCON}$ and $t_{PWSYNCOFF}$. Figure 10 shows the timing for a synchronization clock into the A8514 at 2.2 MHz. Thus any pulse with a duty cycle of 33% to 66% at 2.2 MHz can be used to synchronize the IC.

The SYNC pulse duty cycle ranges for selected switching frequencies are:

| SYNC Pulse Frequency (MHz) | Duty Cycle Range (%) |
|---|---|
| 2.2 | 33 to 66 |
| 2 | 30 to 70 |
| 1 | 15 to 85 |
| 0.800 | 12 to 88 |
| 0.600 | 9 to 91 |

If during operation a sync clock is lost, the IC will revert to the preset switching frequency that is set by the resistor $R_{FSET}$. During this period the IC will stop switching for a maximum period of about 7 µs to allow the sync detection circuitry to switch over to the externally preset switching frequency.

If the clock is held low for more than 7 µs, the A8514 will shut down. In this shutdown mode the IC will stop switching, the input disconnect switch is open, and the LEDs will stop sinking current. To shutdown the IC into low power mode, the user must disable the IC using the PWM pin, by keeping the pin low for a period of 32,750 clock cycles. If the FSET/SYNC pin is released at any time after 7 µs, the A8514 will proceed to soft start.
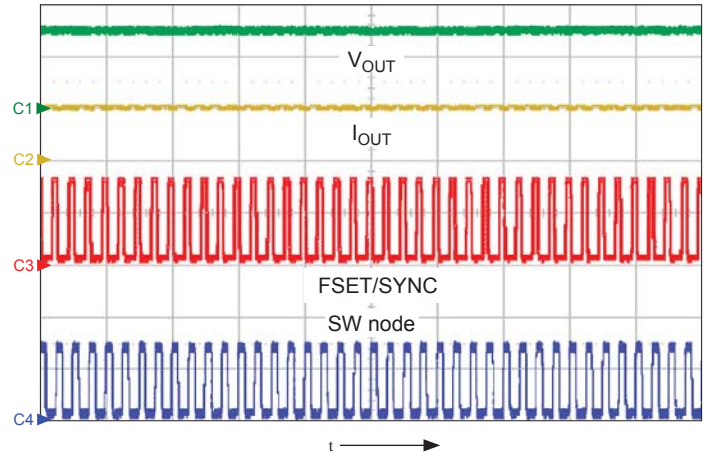


Figure 8. Diagram showing a synchronized FSET/SYNC pin and switch node; shows $V_{OUT}$ (ch1, 20 V/div.), $I_{OUT}$ (ch2, 200 mA/div.), FSET/SYNC (ch3, 2 V/div.), and SW node (ch4, 20 V/div.), time = 2 µs/div.
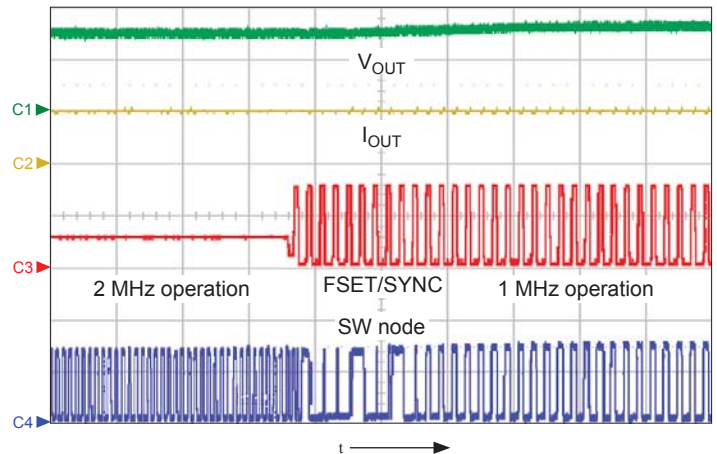


Figure 9. Transition of the SW waveform when the SYNC pulse is detected. The A8514 switching at 2 MHz, applied SYNC pulse at 1 MHz; shows $V_{OUT}$ (ch1, 20 V/div.), $I_{OUT}$ (ch2, 200 mA/div.), FSET/SYNC (ch3, 2 V/div.), and SW node (ch4, 20 V/div.), time = 5 µs/div.
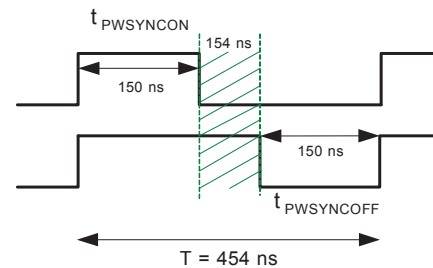


Figure 10. SYNC pulse on and off time requirements.

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## LED current setting and LED dimming

The maximum LED current can be up to 80 mA per channel, and is set through the ISET pin. To set the $I_{LED}$ current, connect a resistor, $R_{ISET}$, between this pin and ground, according to the following formula:

$$R_{ISET} = (1.003 \times 653) / I_{LED} \qquad (3)$$

where $I_{LED}$ is in A and $R_{ISET}$ is in $\Omega$. This sets the maximum current through the LEDs, referred to as the *100% current*. Standard $R_{ISET}$ values, at gain equals 653, are as follows:

| Standard Closest $R_{ISET}$ Resistor Value (kΩ) | LED current per LED, $I_{LED}$ (mA) |
|---|---|
| 8.25 | 80 |
| 10.2 | 65 |
| 16.5 | 40 |
| 22.1 | 30 |

## PWM dimming

The LED current can be reduced from the 100% current level by PWM dimming using the PWM/EN pin. When the PWM/EN pin is pulled high, the A8514 turns on and all enabled LEDs sink 100% current. When PWM/EN is pulled low, the boost converter and LED sinks are turned off. The compensation (COMP) pin is floated, and critical internal circuits are kept active. The typical PWM dimming frequencies fall between 200 Hz and 1 kHz. Figures 11A to 11D provide examples of PWM switching behavior.
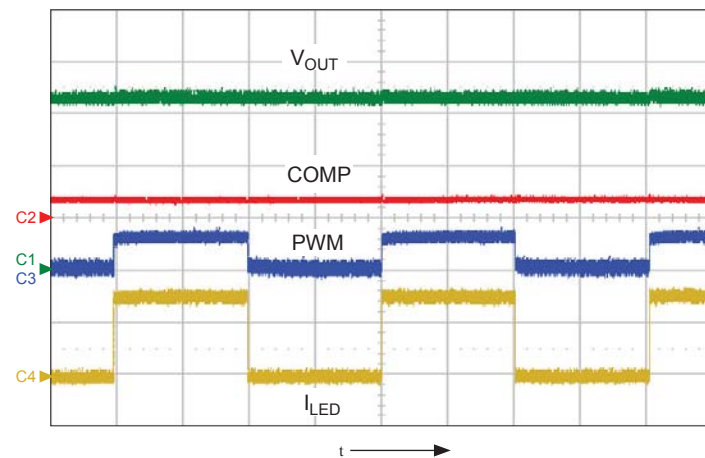


Figure 11B. Typical PWM diagram showing $V_{OUT}$, $I_{LED}$, and COMP pin as well as the PWM signal. PWM dimming frequency is 500 Hz at 1% duty cycle ; shows $V_{OUT}$ (ch1, 10 V/div.), COMP (ch2, 2 V/div.), PWM (ch3, 5 V/div.), and $I_{LED}$ (ch4, 50 mA/div.), time = 500 µs/div.



Figure 11C. Delay from rising edge of PWM signal to LED current; shows PWM (ch1, 2 V/div.), and $I_{LED}$ (ch2, 50 mA/div.), time = 200 ns/div.



Figure 11A. Typical PWM diagram showing $V_{OUT}$, $I_{LED}$, and COMP pin as well as the PWM signal. PWM dimming frequency is 500 Hz at 50% duty cycle; shows $V_{OUT}$ (ch1, 10 V/div.), COMP (ch2, 2 V/div.), PWM (ch3, 5 V/div.), and $I_{LED}$ (ch4, 50 mA/div.), time = 500 µs/div.
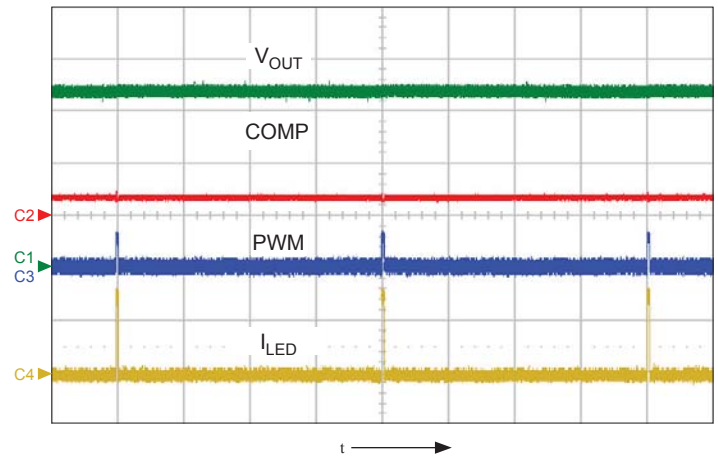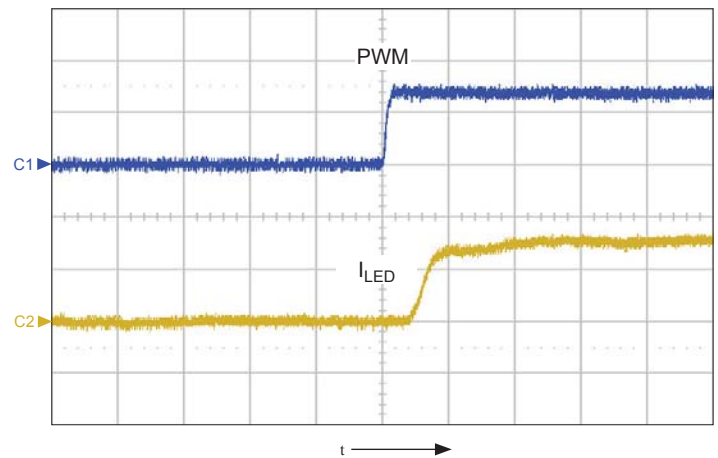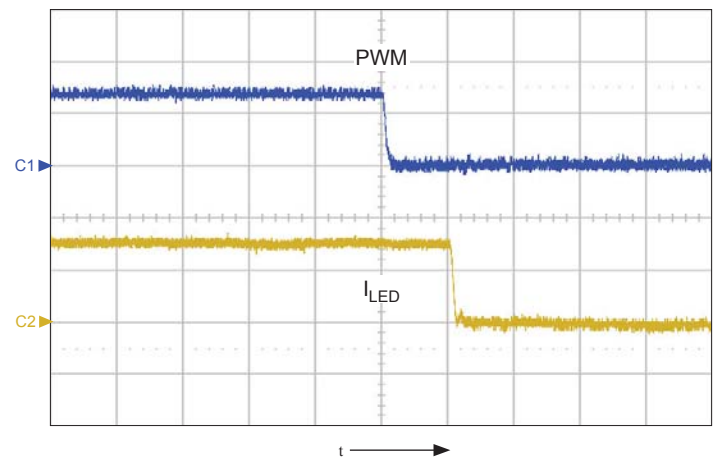


Figure 11D. Delay from falling edge of PWM signal to LED current turn off; shows PWM (ch1, 2 V/div.), and $I_{LED}$ (ch2, 50 mA/div.), time = 200 ns/div.

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Another important feature of the A8514 is the PWM signal to LED current delay. This delay is typically less than 500 ns, which allows greater accuracy at low PWM dimming duty cycles, as shown in figure 12.

### APWM pin
The APWM pin is used in conjunction with the ISET pin (see figure 13). This is a digital signal pin that internally adjusts the ISET current. When this pin is not used it should be tied to ground.

The typical input signal frequency is between 20 kHz and 1 MHz.

The duty cycle of this signal is inversely proportional to the percentage of current that is delivered to the LEDs (figure 14).

To use this pin for a trim function, the user should set the maximum output current to a value higher than the required current by at least 5%. The LED $I_{SET}$ current is then trimmed down to the appropriate value. Another consideration that also is important is the limitation of the user APWM signal duty cycle. In some cases it might be preferable to set the maximum $I_{SET}$ current to be 25% to 50% higher, thus allowing the APWM signal to have duty cycles that are between 25% and 50%.
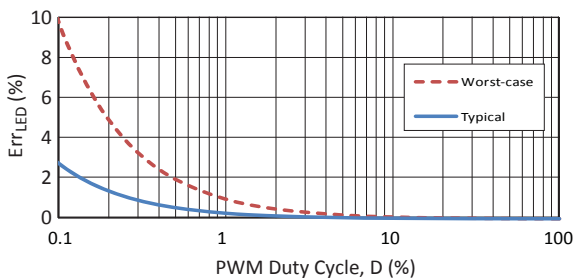


Figure 12. Percentage Error of the LED current versus PWM duty cycle (at 200 Hz PWM frequency).
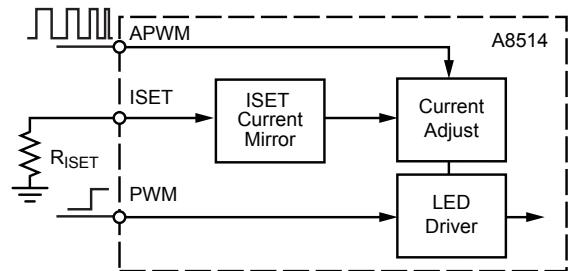


Figure 13. Simplified block diagram of the APWM and ISET circuit.
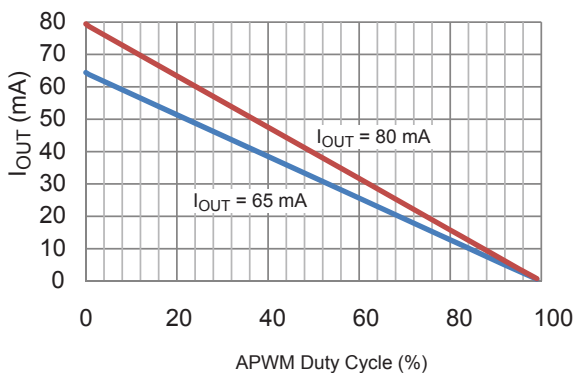


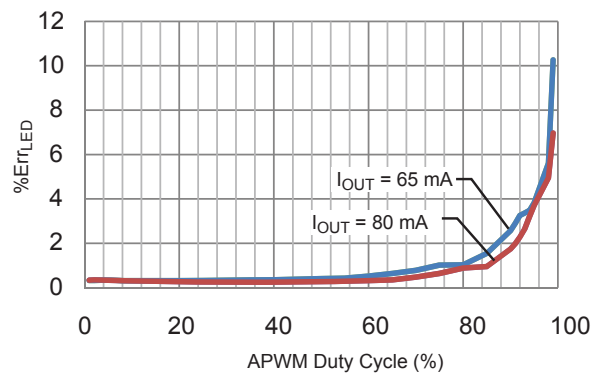Figure 14. Output current versus duty cycle; 200 kHz APWM signal.



Figure 15. Percentage Error of the LED current versus PWM duty cycle; 200 kHz APWM signal.

As an example, a system that delivers a full LED current of 80 mA per LED would deliver 60 mA of current per LED when an APWM signal is applied with a duty cycle of 25% (figures 16 and 17).

Although the order in which APWM and the PWM signal are enabled does not matter, when enabling the A8514 into low current output while PWM and APWM dimming, the APWM signal should be enable before or at the same time as the PWM signal. This sequence will prevent the light output intensity from changing during power up of the IC.

Figure 18 shows the sequencing of the APWM and PWM signal during power-up to prevent inadvertent light intensity changes. The full intensity light output with no APWM or PWM dimming is 80 mA per channel.
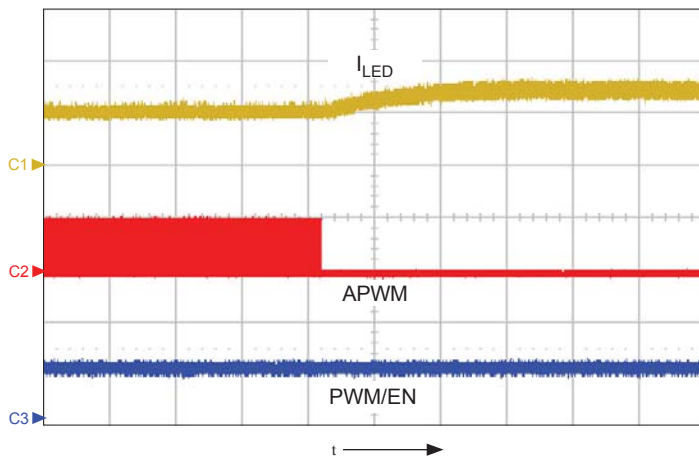
Figure 16. Diagram showing the transition of LED current from 60 mA to 80 mA, when a 25% duty cycle signal is removed from the APWM pin. PWM = 1; shows $I_{LED}$ (ch1, 50 mA/div.), APWM (ch2, 10 V/div.), and PWM/EN (ch3, 5 V/div.), time = 500 µs/div.
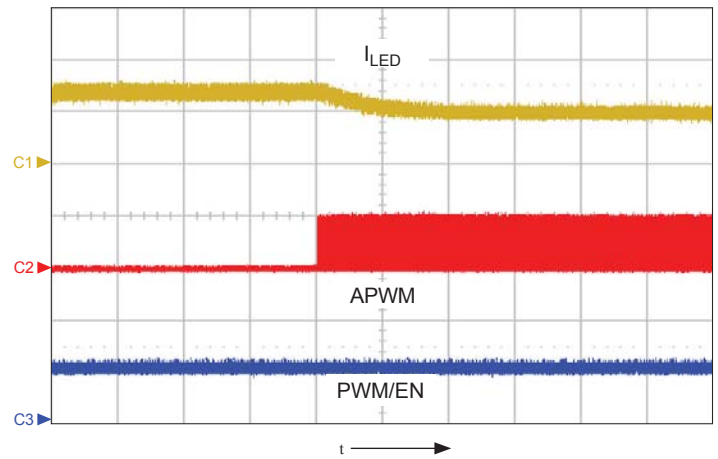
Figure 17. Diagram showing the transition of LED current from 80 mA to 60 mA, when a 25% duty cycle signal is applied to the APWM pin; PWM = 1; shows $I_{LED}$ (ch1, 50 mA/div.), APWM (ch2, 10 V/div.), and PWM/EN (ch3, 5 V/div.), time = 500 µs/div.
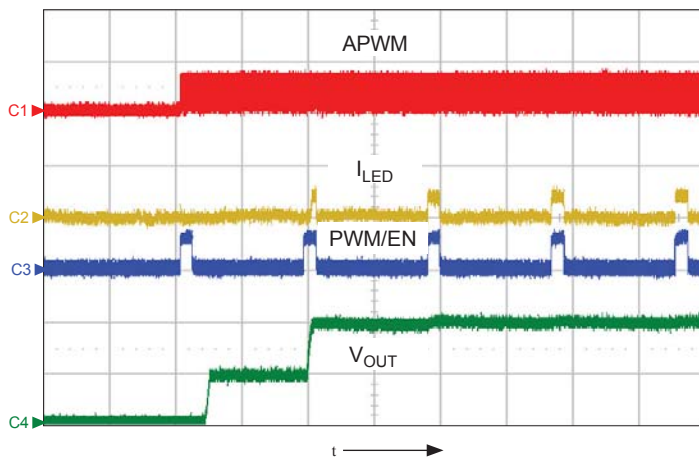
Figure 18. Diagram showing power-up sequencing LED current of 5 mA per channel with a 10% duty cycle PWM signal and a 95% duty cycle APWM signal; shows APWM (ch1, 5 V/div.), $I_{LED}$ (ch2, 50 mA/div.), PWM/EN (ch3, 5 V/div.), and $V_{OUT}$ (ch4, 10 V/div.), time = 500 µs/div.
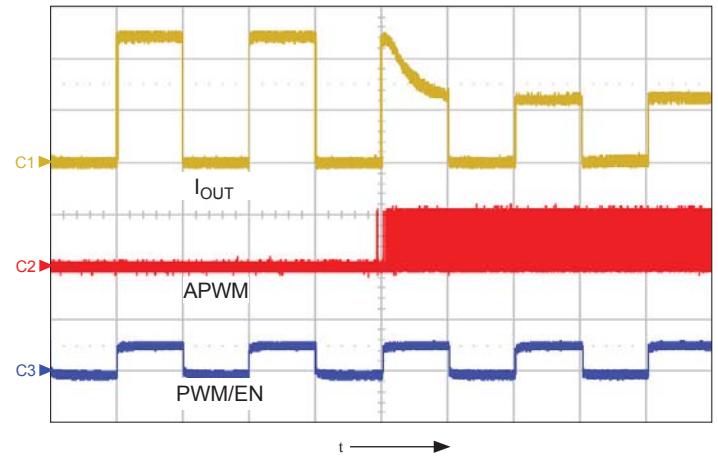
Figure 19. Transition of output current level when a 50% duty cycle signal is applied to the APWM pin, in conjunction with a 50% duty cycle PWM dimming being applied to the PWM pin; shows $I_{OUT}$ (ch1, 50 mA/div.), APWM (ch2, 10 V/div.), and PWM/EN (ch3, 5 V/div.), time = 500 µs/div.

Although the APWM dimming function has a wide frequency range, if this function is used strictly as an analog dimming function it is recommended to use frequency ranges between 50 and 500 kHz for best accuracy. The frequency range must be considered only if the user is not using this function as a closed loop trim function. Another limitation is that the propagation delay between this APWM signal and $I_{OUT}$ takes several milliseconds to change the actual LED current. This effect is shown in figures 16, 17, and 19.

### Analog dimming

The A8514 can also be dimmed by using an external DAC or another voltage source applied either directly to the ground side of the $R_{ISET}$ resistor or through an external resistor to the ISET pin (see figure 19). The limit of this type of dimming depends on the range of the ISET pin. In the case of the A8514 the limit is 20 to 125 µA.

• For a single resistor (panel A of figure 20), the ISET current is controlled by the following formula:

$$I_{SET} = \frac{V_{ISET} - V_{DAC}}{R_{ISET}} \tag{4}$$

where $V_{ISET}$ is the ISET pin voltage and $V_{DAC}$ is the DAC output voltage.

When the DAC voltage is 0 V the LED current will be at its

maximum. To keep the internal gain amplifier stable, the user should not decrease the current through the $R_{ISET}$ resistor to less than 20 µA

• For a dual-resistor configuration (panel B of figure 20), the $I_{SET}$ current is controlled by the following formula:

$$I_{SET} = \frac{V_{ISET}}{R_{ISET}} - \frac{V_{DAC} - V_{ISET}}{R_1} \tag{5}$$

The advantage of this circuit is that the DAC voltage can be higher or lower, thus adjusting the LED current to a higher or lower value of the preset LED current set by the $R_{ISET}$ resistor:

 ▫ $V_{DAC}$ = 1.003 V; the output is strictly controlled by $R_{ISET}$
 ▫ $V_{DAC}$ > 1.003 V; the LED current is reduced
 ▫ $V_{DAC}$ < 1.003 V; the LED current is increased

### LED short detect

Both LEDx pins are capable of handling the maximum $V_{OUT}$ that the converter can deliver, thus providing protection from the LEDx pin to $V_{OUT}$ in the event of a connector short.

An LEDx pin that has a voltage exceeding $V_{LEDSC}$ will be removed from operation (see figure 21). This is to prevent the IC from dissipating too much power by having a large voltage present on an LEDx pin.



Figure 20. Simplified diagrams of voltage control of $I_{LED}$: typical applications using a DAC to control $I_{LED}$ using a single resistor (upper), and dual resistors (lower).



Figure 21. Example of the disabling of an LED string when the LED pin voltage is increased above 4.6 V; shows $I_{OUT}$ (ch1, 200 mA/div.), LED1 (ch2, 5 V/div.), and PWM/EN (ch3, 5 V/div.), time = 10 µs/div.

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While the IC is being PWM-dimmed, the IC rechecks the disabled LED every time the PWM signal goes high, to prevent false tripping of an LED short event. This also allows some self-correction if an intermittent LED pin short to $V_{OUT}$ is present.
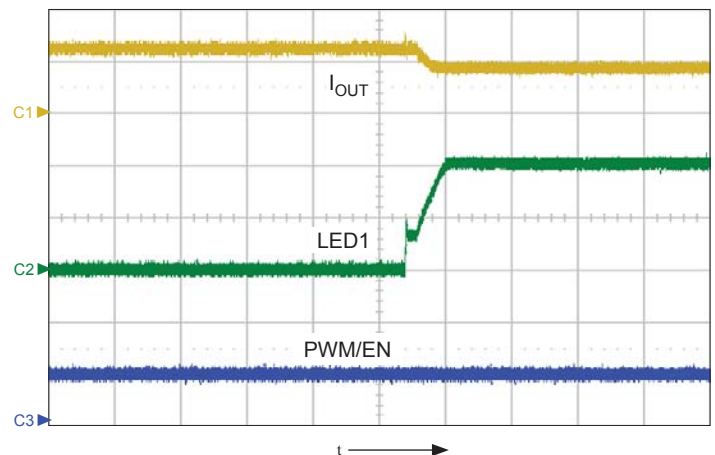
### Overvoltage protection

The A8514 has overvoltage protection (OVP) and open Schottky diode (D1 in figure 1) protection. The OVP protection has a default level of 8.1 V and can be increased up to 53 V by connecting resistor $R_{OVP}$ between the OVP pin and $V_{OUT}$. When the current into the OVP pin exceeds 199 µA (typical), the OVP comparator goes low and the boost stops switching.

The following equation can be used to determine the resistance for setting the OVP level:

$$R_{OVP} = ( V_{OUTovp} - V_{OVP(th)} ) / I_{OVPH} \qquad (6)$$

where:

$V_{OUTovp}$ is the target overvoltage level,

$R_{OVP}$ is the value of the external resistor, in Ω,

$V_{OVP(th)}$ is the pin OVP trip point found in the Electrical Characteristics table, and

$I_{OVPH}$ is the current into the OVP pin.

There are several possibilities for why an OVP condition would be encountered during operation, the two most common being: a disconnected output, and an open LED string. Examples of these are provided in figures 22 and 23.

Figure 22 illustrates when the output of the A8514 is disconnected from load during normal operation. The output voltage instantly increases up to OVP voltage level and then the boost stops switching to prevent damage to the IC. If the output is drained off, eventually the boost might start switching for a short duration until the OVP threshold is hit again.

Figure 23 displays a typical OVP event caused by an open LED string. After the OVP condition is detected, the boost stops
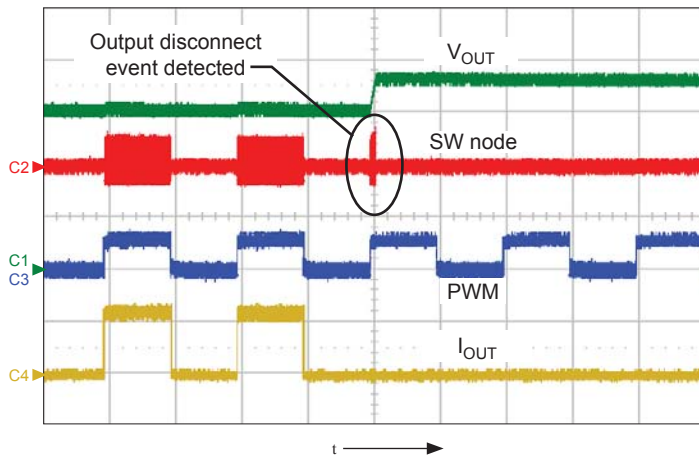


Figure 22. OVP protection in an output disconnect event; shows $V_{OUT}$ (ch1, 10 V/div.), SW node (ch2, 50 V/div.), PWM (ch3, 5 V/div.), and $I_{OUT}$ (ch4, 200 mA/div.), time = 1 ms/div.
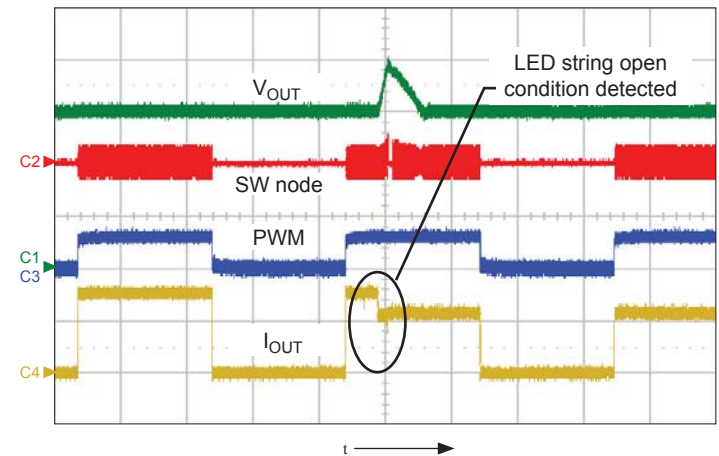


Figure 23. OVP protection in an open LED string event; shows $V_{OUT}$ (ch1, 10 V/div.), SW node (ch2, 50 V/div.), PWM (ch3, 5 V/div.), and $I_{OUT}$ (ch4, 200 mA/div.), time = 500 µs/div.

switching, and the open LED string is removed from operation. Afterwards V$_{OUT}$ is allowed to fall, and eventually the boost will resume switching and the A8514 will resume normal operation.

A8514 also has built-in secondary overvoltage protection to protect the internal switch in the event of an open diode condition. Open Schottky diode detection is implemented by detecting overvoltage on the SW pin of the device. If voltage on the SW pin exceeds the device safe operating voltage rating, the A8514 disables and remains latched. To clear this fault, the IC must be shut down either by using the PWM/EN signal or by going below

the UVLO threshold on the VIN pin. Figure 24 illustrates this. As soon as the switch node voltage (SW) exceeds 60 V, the IC shuts down. Due to small delays in the detection circuit, as well as there being no load present, the switch node voltage will rise above the trip point voltage.

Figure 25 illustrates when the A8514 is being enabled during an open diode condition. The IC goes through all of its initial LED detection and then tries to enable the boost, at which point the open diode is detected.
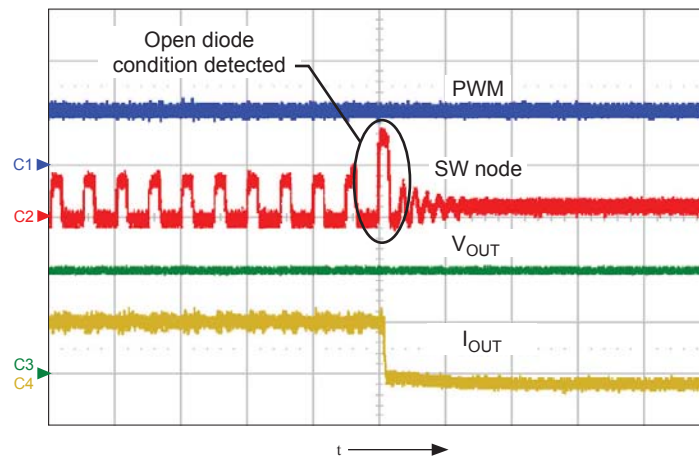
Figure 24. OVP protection in an open Schottky diode event, while the IC is in normal operation; shows PWM (ch1, 5 V/div.), SW node (ch2, 50 V/div.), V$_{OUT}$ (ch3, 20 V/div.), and I$_{OUT}$ (ch4, 200 mA/div.), time = 1 μs/div.
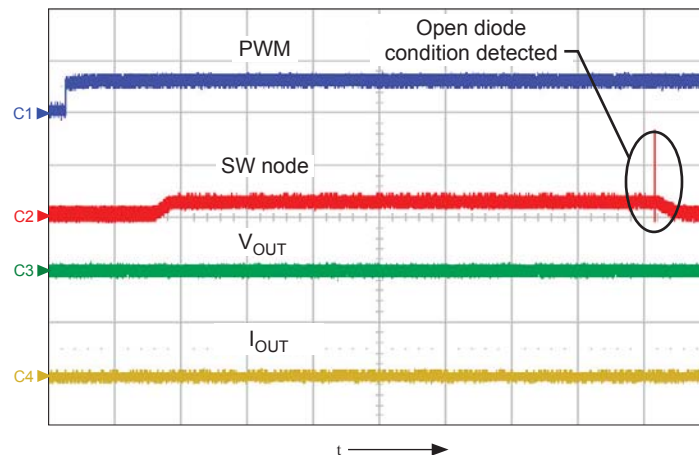
Figure 25. OVP protection when the IC is enabled during an open diode condition; shows PWM (ch1, 5 V/div.), SW node (ch2, 50 V/div.), V$_{OUT}$ (ch3, 10 V/div.), and I$_{OUT}$ (ch4, 200 mA/div.), time = 500 μs/div.

### Boost switch overcurrent protection

The boost switch is protected with cycle-by-cycle current limiting set at a minimum of 3.0 A. There is also a secondary current limit that is sensed on the boost switch. When detected this current limit immediately shuts down the A8514. The level of this current limit is set above the cycle-by-cycle current limit to protect the switch from destructive currents when the boost inductor is shorted. Various boost switch overcurrent conditions are shown in figures 26 through 28.
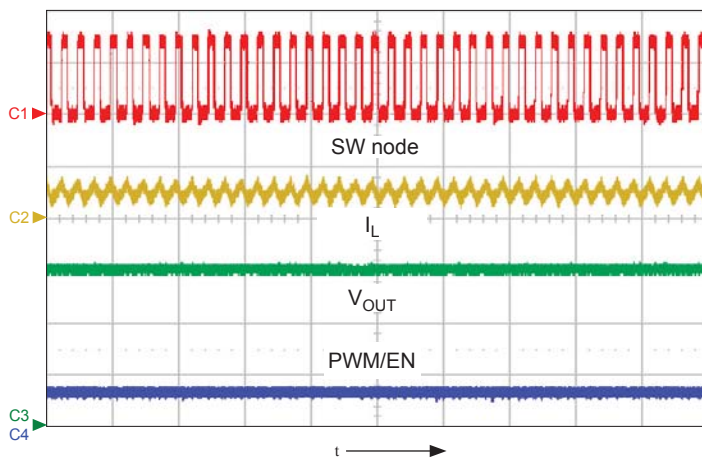


Figure 26. Normal operation of the switch node (SW); inductor current ($I_L$) and output voltage ($V_{OUT}$) for 9 series LEDs in each of four strings configuration; shows SW node (ch1, 20 V/div.), inductor current $I_L$ (ch2, 1 A/div.), $V_{OUT}$ (ch3, 10 V/div.), and PWM/EN (ch4, 5 V/div.), time = 2 µs/div.
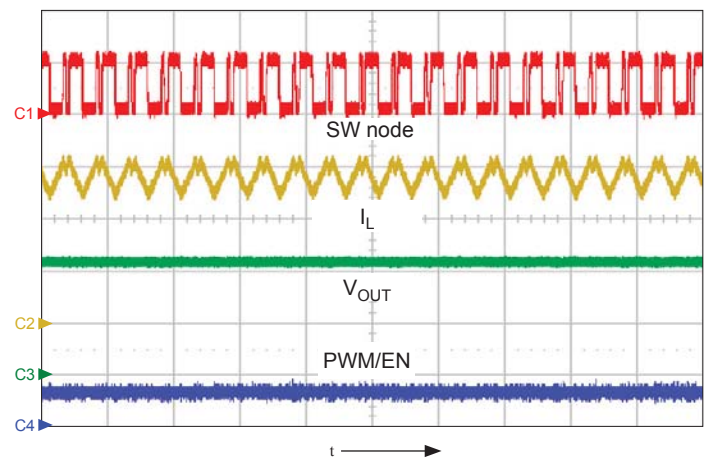


Figure 27. Cycle-by-cycle current limiting; inductor current (yellow trace, $I_L$), note reduction in output voltage as compared to normal operation with the same configuration (figure 26); shows SW node (ch1, 20 V/div.), inductor current $I_L$ (ch2, 1 A/div.), $V_{OUT}$ (ch3, 10 V/div.), and PWM/EN (ch4, 5 V/div.), time = 2 µs/div.
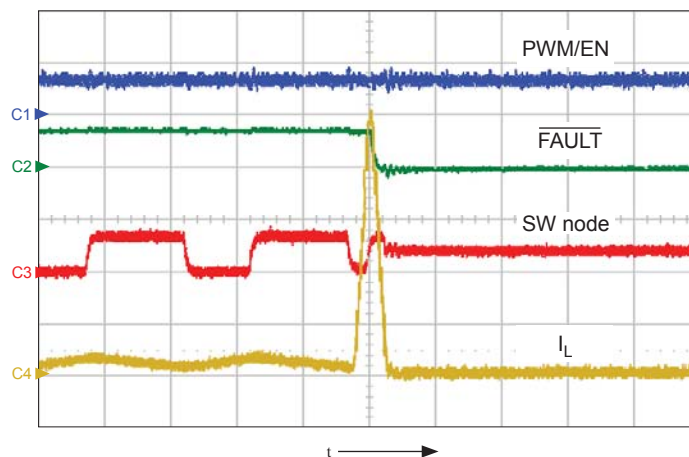


Figure 28. Secondary boost switch current limit; when this limit is hit, the A8514 immediately shuts down; shows PWM (ch1, 5 V/div.), $V_{OUT}$ (ch2, 5 V/div.), SW node (ch3, 50 V/div.), and inductor current $I_L$ (ch4, 2 A/div.), time = 100 ns/div.

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## Input overcurrent protection and disconnect switch

The primary function of the input disconnect switch is to protect the system and the device from catastrophic input currents during a fault condition. The external circuit implementing the disconnect is shown in figure 29. If the input disconnect switch is not used, the VSENSE pin must be tied to VIN and the GATE pin must be left open.

When selecting the external PMOS, check for the following parameters:

• Drain-source breakdown voltage $V_{(BR)DSS}$ > –40 V
• Gate threshold voltage (make sure it is fully conducting at $V_{GS}$ = –4 V, and cut-off at –1 V)
• $R_{DS(on)}$: Make sure the on-resistance is rated at $V_{GS}$ = –4.5 V or similar, not at –10 V; derate it for higher temperature

The input disconnect switch has two modes of operation:

• **1X mode** When the input current is between one and two times the preset current limit value, the disconnect switch enters a constant-current mode for a maximum duration of 10,000 cycles or 5 ms at 2 MHz. During this time, the Fault flag is set immediately and the disconnect switch goes into a linear mode of operation, in which the input current will be limited to a value approximate to the 1X current trip point level (figure 30). If the fault corrects itself before the expiration of the timer, the Fault flag will be removed and normal operation will resume.

The user can also during this time decide whether to shut down the A8514. To immediately shut down the device, pull the FSET/SYNC pin low for more than 7 µs. After the FSET/SYNC pin has been low for a period longer than 7 µs, the IC will stop switching, the input disconnect switch will open, and the LEDx pins will stop sinking current. The A8514 can be powered-down into low power mode. To do so, disable the IC by keeping the PWM/EN pin low for a period of 32,750 clock cycles. To keep the disconnect switch stable while the disconnect switch is in 1X mode, use a 22 nF capacitor for $C_C$ and a 20 Ω resistor for $R_C$.



Figure 30. Showing typical wave forms for a 3-A, 1X current limit under a fault condition; shows $f_{SW}$ = 800 kHz, $\overline{FAULT}$ (ch1, 5 V/div.), $I_{IN}$ (ch2, 2 A/div.), GATE (ch3, 5 V/div.), and PWM/EN (ch4, 5 V/div.), time = 5 ms/div.
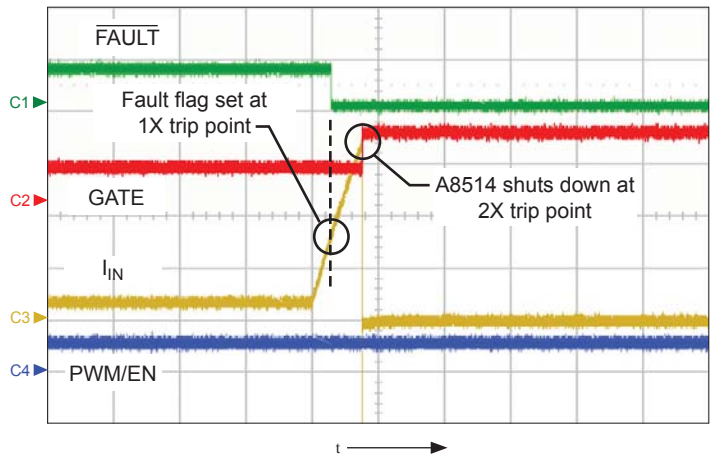


Figure 31. 2X mode, secondary overcurrent fault condition. $I_{IN}$ is the input current through the switch. The Fault flag is set at the 1X current limit, and when the 2X current limit is reached the A8514 disables the gate of the disconnect switch (GATE); shows $\overline{FAULT}$ (ch1, 5 V/div.), GATE (ch2, 10 V/div.), $I_{IN}$ (ch3, 2 A/div.), and PWM/EN (ch4, 5 V/div.), time = 5 µs/div.
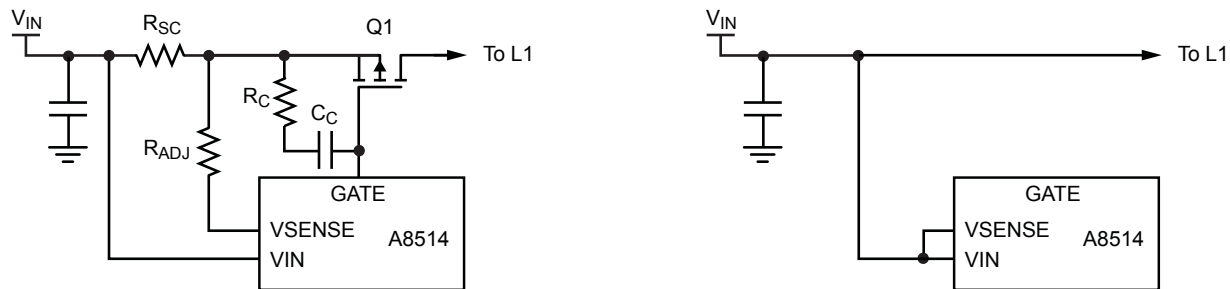


Figure 29. Typical circuit (left) with the input disconnect feature implemented, and (right) without the input disconnect feature.
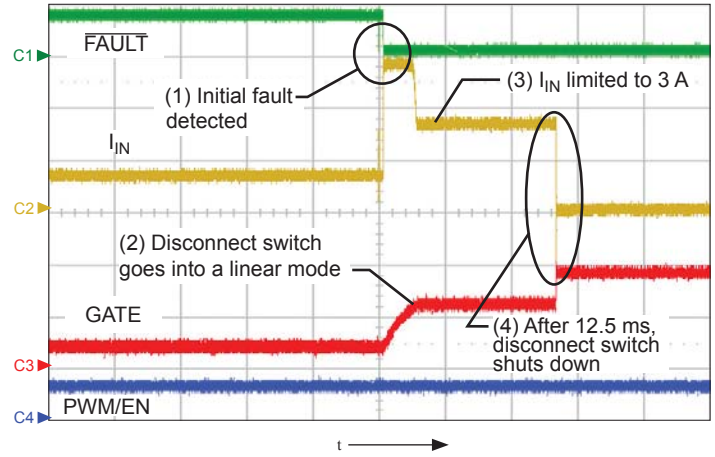
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• **2X current limit** If the input current level goes above 2X of the preset current limit threshold, the A8514 will shut down in less than 3 μs regardless of user input (figure 31). This is a latched condition. The Fault flag is also set to indicate a fault. This feature is meant to prevent catastrophic failure in the system due to inductor short to ground, switch pin short to ground, or output short to ground.

## Setting the current sense resistor

The typical threshold for the current sense circuit is 104 mV, when $R_{ADJ}$ is 0 Ω. This voltage can be trimmed by the $R_{ADJ}$ resistor. The typical 1X trip point should be set at about 3 A, which coincides with the cycle-by-cycle current limit minimum threshold.

For example, given 3 A of input current, and the calculated maximum value of the sense resistor, $R_{SC}$ = 0.033 Ω.

The $R_{SC}$ chosen is 0.03 Ω, a standard.

Also:

$$R_{ADJ} = (V_{SENSETRIP} - V_{ADJ}) / I_{ADJ} \qquad (7)$$

The trip point voltage is calculated as:

$$V_{ADJ} = 3.0 \text{ A} \times 0.03 \text{ Ω} = 0.090 \text{ V}$$

$$R_{ADJ} = (0.104 - 0.09 \text{ V}) / (20.3 \text{ μA}) = 731 \text{ Ω}$$

## Input UVLO

When $V_{IN}$ and $V_{SENSE}$ rise above the $V_{UVLOrise}$ threshold, the A8514 is enabled. A8514 is disabled when $V_{IN}$ falls below the $V_{UVLOfall}$ threshold for more than 50 μs. This small delay is used to avoid shutting down because of momentary glitches in the input power supply. When $V_{IN}$ falls below 4.35 V, the IC will shut down (see figure 32).

## VDD

The VDD pin provides regulated bias supply for internal circuits. Connect the capacitor $C_{VDD}$ with a value of 0.1 μF or greater to this pin. The internal LDO can deliver no more than 2 mA of current with a typical $V_{DD}$ of about 3.5 V, enabling this pin to serve as the pull-up voltage for the $\overline{FAULT}$ pin.

## Shutdown

If the PWM/EN pin is pulled low for more than $t_{PWML}$ (32,750 clock cycles), the device enters shutdown mode and clears all
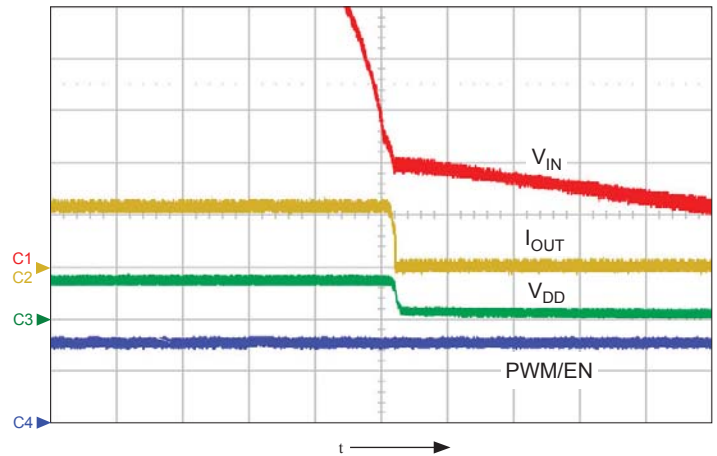


Figure 32. Shutdown showing a falling input voltage ($V_{IN}$); shows $V_{IN}$ (ch1, 2 V/div.), $I_{OUT}$ (ch2, 200 mA/div.), $V_{DD}$ (ch3, 5 V/div.), and PWM/EN (ch4, 2 V/div.), time = 5 ms/div.



Figure 33. Shutdown using the enable function, showing the 16 ms delay between the PWM/EN signal and when the VDD and GATE of the disconnect switch turns off; shows GATE (ch1, 10 V/div.), $I_{OUT}$ (ch2, 200 mA/div.), $V_{DD}$ (ch3, 5 V/div.), and PWM/EN (ch4, 2 V/div.), time = 5 ms/div.

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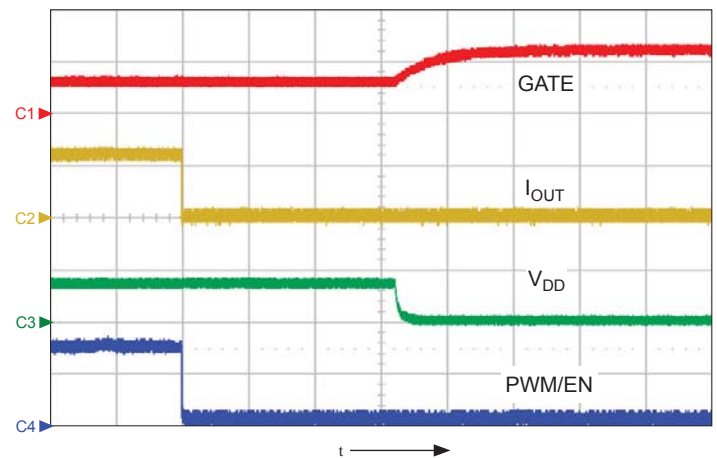115 Northeast Cutoff
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internal fault registers. As an example, at a 2 MHz clock fre-quency, it will take approximately 16.3 ms to shut down the IC into the low power mode (figure 33). When the A8514 is shut down, the IC will disable all current sources and wait until the PWM/EN signal goes high to re-enable the IC. If faster shut down is required, the FSET/SYNC pin can be used.

### Fault protection during operation

The A8514 constantly monitors the state of the system to deter-mine if any fault conditions occur during normal operation. The response to a triggered fault condition is summarized in the Fault Mode table.

The possible fault conditions that the device can detect are: Open LED pin, LED pin shorted to ground, shorted inductor, $V_{OUT}$ short to ground, SW pin shorted to ground, ISET pin shorted to ground, and input disconnect switch source shorted to ground.

Note the following:

• Some of the protection features might not be active during startup, to prevent false triggering of fault conditions.

• Some of these faults will not be protected if the input disconnect switch is not being used. An example of this is $V_{OUT}$ short to ground.

### Fault Mode Table

| Fault Name | Type | Active | Fault Flag Set | Description | Boost | Disconnect switch | Sink driver |
|---|---|---|---|---|---|---|---|
| Primary switch overcurrent protection (cycle-by-cycle current limit) | Auto-restart | Always | No | This fault condition is triggered by the cycle-by-cycle current limit, $I_{SW(LIM)}$. | Off for a single cycle | On | On |
| Secondary switch current limit | Latched | Always | Yes | When the current through the boost switch exceeds secondary current SW limit ($I_{SW(LIM2)}$) the device immediately shuts down the disconnect switch, LED drivers, and boost. The Fault flag is set. To re-enable the device, the PWM/EN pin must be pulled low for 32,750 clock cycles. | Off | Off | Off |
| Input disconnect current limit | Latched | Always | Yes | The device is immediately shut off if the voltage across the input sense resistor is 2X the preset current value. The Fault flag is set. If the input current limit is between 1X and 2X, the Fault flag is set but the IC will continue to operate normally for $t_{GFAULT1}$ or until it is shut down. To re-enable the device the PWM/EN pin must be pulled low for 32,750 clock cycles. | Off | Off | Off |
| Secondary OVP | Latched | Always | Yes | Secondary overvoltage protection is used for open diode detection. When diode D1 opens, the SW pin voltage will increase until $V_{OVP(SEC)}$ is reached. This fault latches the IC. The input disconnect switch is disabled as well as the LED drivers, and the Fault flag is set. To re-enable the part the PWM pin must be pulled low for 32,750 clock cycles. | Off | Off | Off |

*Continued on the next page…*

## Fault Mode Table (continued)

| Fault Name | Type | Active | Fault Flag Set | Description | Boost | Disconnect Switch | Sink driver |
|---|---|---|---|---|---|---|---|
| LED Pin Short Protection | Auto-restart | Startup | No | This fault prevents the device from starting-up if either of the LEDx pins are shorted. The device stops soft-start from starting while either of the LEDx pins are determined to be shorted. After the short is removed, soft-start is allowed to start. | Off | On | Off |
| LED Pin open | Auto-restart | Normal Operation | No | When an LEDx pin is open the device will determine which LED pin is open by increasing the output voltage until OVP is reached. Any LED string not in regulation will be turned off. The device will then go back to normal operation by reducing the output voltage to the appropriate voltage level. | On | On | Off for open pins. On for all others. |
| ISET Short Protection | Auto-restart | Always | No | This fault occurs when the ISET current goes above 150% of the maximum current. The boost will stop switching, the disconnect switch will turn off, and the IC will disable the LED sinks until the fault is removed. When the fault is removed the IC will try to regulate to the preset LED current. | Off | On | Off |
| FSET/SYNC Short Protection | Auto-restart | Always | Yes | Fault occurs when the FSET/SYNC current goes above 150% of maximum current, about 180 µA. The boost will stop switching, the disconnect switch will turn off, and the IC will disable the LED sinks until the fault is removed. When the fault is removed the IC will try to restart with soft-start. | Off | Off | Off |
| Overvoltage Protection | Auto-restart | Always | No | Fault occurs when OVP pin exceeds $V_{OVP(th)}$ threshold. The A8514 will immediately stop switching to try to reduce the output voltage. If the output voltage decreases then the A8514 will restart switching to regulate the output voltage. | Stop during OVP event. | On | On |
| LED Short Protection | Auto-restart | Always | No | Fault occurs when the LED pin voltage exceeds $V_{LEDSC}$. When the LED short protection is detected the LED string that is above the threshold will be removed from operation. | On | On | Off for shorted pins. On for all others. |
| Overtemperature Protection | Auto-restart | Always | No | Fault occurs when the die temperature exceeds the overtemperature threshold, 165°C. | Off | Off | Off |
| VIN UVLO | Auto-restart | Always | No | Fault occurs when $V_{IN}$ drops below $V_{UVLO}$, 3.90 V maximum. This fault resets all latched faults. | Off | Off | Off |

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## Application Information

### Design Example for Boost Configuration

This section provides a method for selecting component values when designing an application using the A8514. The resulting design is diagrammed in figure 34.

Assumptions: For the purposes of this example, the following are given as the application requirements:

- $V_{BAT}$: 10 to 14 V
- Quantity of LED channels, $\#_{CHANNELS}$: 4
- Quantity of series LEDs per channel, $\#_{SERIESLEDS}$: 10
- LED current per channel, $I_{LED}$: 60 mA
- $V_f$ at 60 mA: 3.2 V
- $f_{SW}$: 2 MHz
- $T_A$(max): 65°C
- PWM dimming frequency: 200 Hz, 1% duty cycle

Procedure: The procedure consists of selecting the appropriate configuration and then the individual component values, in an ordered sequence.

**Step 1** Connect LEDs to pins LED1 and LED2.

**Step 2** Determining the LED current setting resistor $R_{ISET}$:

$$R_{ISET} = (V_{ISET} \times A_{ISET}) / I_{LED} \tag{7}$$
$$= (1.003 \text{ (V)} \times 653) / 60 \text{ mA} = 10.92 \text{ k}\Omega$$

Choose a 11.00 kΩ resistor.

**Step 3** Determining the OVP resistor. The OVP resistor is connected between the OVP pin and the output voltage of the converter.

**Step 3a** The first step is determining the maximum voltage based on the LED requirements. The regulation voltage, $V_{LED}$, of the A8514 is 700 mV. A constant term, 2 V, is added to give margin to the design due to noise and output voltage ripple.

$$V_{OUT(OVP)} = \#_{SERIESLEDS} \times V_f + V_{LED} + 2 \text{ (V)} \tag{8}$$

$$= 10 \times 3.2 \text{ V} + 0.7 \text{ V} + 2 \text{ V}$$
$$= 34.7 \text{ V}$$

Then the OVP resistor is:

$$R_{OVP} = (V_{OUT(OVP)} - V_{OVP(th)}) / I_{OVPH} \tag{9}$$
$$= (34.7 \text{ (V)} - 8.1 \text{ (V)}) / 199 \text{ (µA)} = 133.67 \text{ k}\Omega$$

where both $I_{OVPH}$ and $V_{OVP(th)}$ are taken from the Electrical Characteristics table.

Chose a value of resistor that is higher value than the calculated $R_{OVP}$. In this case a value of 137 kΩ was selected. Below is the actual value of the minimum OVP trip level with the selected resistor:

$$V_{OUT(OVP)} = 137 \text{ (k}\Omega) \times 199 \text{ (µA)} + 8.1 \text{ (V)} = 35.36 \text{ V}$$

**Step 3b** At this point a quick check must be done to see if the conversion ratio is acceptable for the selected frequency.

$$D_{maxofboost} = 1 - t_{SWOFFTIME} \times f_{SW} \tag{10}$$
$$= 1 - 68 \text{ (ns)} \times 2.0 \text{ (MHz)} = 86.4\%$$

where the minimum off-time ($t_{SWOFFTIME}$) is found in the Electrical Characteristics table.

The Theoretical Maximum $V_{OUT}$ is then calculated as:

$$V_{OUT}(\text{max}) = \frac{V_{IN}(\text{min})}{1 - D_{maxofboost}} - V_d \tag{11}$$

$$= \frac{10 \text{ (V)}}{1 - 0.864} - 0.4 \text{ (V)} = 73.13 \text{ V}$$

where $V_d$ is the diode forward voltage.

The Theoretical Maximum $V_{OUT}$ value must be greater than the value $V_{OUT(OVP)}$. If this is not the case, the switching frequency of the boost converter must be reduced to meet the maximum duty cycle requirements.

**Step 4** Selecting the inductor. The inductor must be chosen such that it can handle the necessary input current. In most applications, due to stringent EMI requirements, the system must operate in continuous conduction mode throughout the whole input voltage range.

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**Step 4a** Determining the duty cycle, calculated as follows:

$$D(\text{max}) = 1 - \frac{V_{IN}(\text{min})}{V_{OUT(OVP)} + V_d} \tag{12}$$

$$= 1 - \frac{10 \ (V)}{35.36 \ (V) + 0.4 \ (V)} = 72.04\%$$

**Step 4b** Determining the maximum and minimum input current to the system. The minimum input current will dictate the inductor value. The maximum current rating will dictate the current rating of the inductor. First, the maximum input current, given:

$$I_{OUT} = \#_{CHANNELS} \times I_{LED} \tag{13}$$

$$= 4 \times 0.060 \ (A) = 0.240 \ A$$

then:

$$I_{IN}(\text{max}) = \frac{V_{OUT(OVP)} \times I_{OUT}}{V_{IN}(\text{min}) \times \eta} \tag{14}$$

$$= \frac{35.36 \ (V) \times 240 \ (mA)}{10 \ (V) \times 0.90} = 0.94 \ A$$

where η is efficiency.

Next, calculate minimum input current, as follows:

$$I_{IN}(\text{min}) = \frac{V_{OUT(OVP)} \times I_{OUT}}{V_{IN}(\text{max}) \times \eta} \tag{15}$$

$$= \frac{35.36 \ (V) \times 240 \ (mA)}{14 \ (V) \times 0.90} = 0.67 \ A$$

A good approximation of efficiency, η, can be taken from the efficiency curves located in the datasheet. A value of 90% is a good starting approximation.

**Step 4c** Determining the inductor value. To ensure that the inductor operates in continuous conduction mode, the value of the inductor must be set such that the ½ inductor ripple current is not greater than the average minimum input current. A first past assumes $I_{ripple}$ to be 40% of the maximum inductor current:

$$\Delta I_L = I_{IN}(\text{max}) \times I_{ripple} \tag{16}$$

$$= 0.94 \times 0.40 = 0.376 \ A$$

then:

$$L = \frac{V_{IN}(\text{min})}{\Delta I_L \times f_{SW}} \times D(\text{max}) \tag{17}$$

$$= \frac{10 \ (V)}{0.376 \ (A) \times 2 \ (MHz)} \times 0.72 = 9.57 \ \mu H$$

**Step 4d** Double-check to make sure the ½ current ripple is less than $I_{IN}(\text{min})$:

$$I_{IN}(\text{min}) > {}^1/_2 \ \Delta I_L \tag{18}$$

$$0.67 \ A > 0.19 \ A$$

A good inductor value to use would be 10 µH.

**Step 4e** This step is used to verify that there is sufficient slope compensation for the inductor chosen. The slope compensation value is determined by the following formula:

$$\text{Slope Compensation} = \frac{3.6 \times f_{SW}}{2 \times 10^6} = 3.6 \ A / \mu s \tag{19}$$

Next insert the inductor value used in the design:

$$\Delta I_{Lused} = \frac{V_{IN}(\text{min}) \times D(\text{max})}{L_{used} \times f_{SW}} \tag{20}$$

$$= \frac{10 \ (V) \times 0.72}{10 \ (\mu H) \times 2.0 \ (MHz)} = 0.36 \ A$$

Calculate the minimum required slope:

$$\text{Required Slope (min)} = \frac{\Delta I_{Lused} \times 1 \times 10^{-6}}{\dfrac{1}{f_{SW}} \times (1 - D(\text{max}))} \tag{21}$$

$$= \frac{0.36 \ (A) \times 1 \times 10^{-6}}{\dfrac{1}{2.0 \ (MHz)} \times (1 - 0.72)} = 2.57 \ A/\mu s$$

If the minimum required slope is greater than the calculated slope compensation, the inductor value must be increased.

Note: The slope compensation value is in A/µs, and $1 \times 10^{-6}$ is a constant multiplier.

**Step 4f** Determining the inductor current rating. The inductor current rating must be greater than the $I_{IN}(\text{max})$ value plus the ripple current $\Delta I_L$, calculated as follows:

$$L(\text{min}) = I_{IN}(\text{max}) + {}^1/_2 \ \Delta I_{Lused} \tag{22}$$

$$= 0.94 \ (A) + 0.36 \ (A) / 2 = 1.12 \ A$$

**Step 5** Determining the resistor value for a particular switching frequency. Use the $R_{FSET}$ values shown in figure 7. For example, a 10 kΩ resistor will result in a 2 MHz switching frequency.

**Step 6** Choosing the proper switching diode. The switching diode must be chosen for three characteristics when it is used in LED lighting circuitry. The most obvious two are: current rating of the diode and reverse voltage rating.

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The reverse voltage rating should be such that during operation condition, the voltage rating of the device is larger than the maximum output voltage. In this case it is $V_{OUT(OVP)}$.

The peak current through the diode is calculated as:

$$I_{dp} = I_{IN}(max) + {}^1\!/_2\,\Delta I_{Lused} \qquad (23)$$

$$= 0.94\ (A) + 0.36\ (A) / 2 = 1.12\ A$$

The third major component in deciding the switching diode is the reverse current, $I_R$, characteristic of the diode. This characteristic is especially important when PWM dimming is implemented. During PWM off-time the boost converter is not switching. This results in a slow bleeding off of the output voltage, due to leakage currents. $I_R$ can be a large contributor, especially at high temperatures. On the diode that was selected in this design, the current varies between 1 and 100 µA.

**Step 7** Choosing the output capacitors. The output capacitors must be chosen such that they can provide filtering for both the boost converter and for the PWM dimming function. The biggest factors that contribute to the size of the output capacitor are: PWM dimming frequency and PWM duty cycle. Another major contributor is leakage current, $I_{LK}$. This current is the combination of the OVP leakage current as well as the reverse current of the switching diode. In this design the PWM dimming frequency is 200 Hz and the minimum duty cycle is 1%. Typically, the voltage variation on the output, $V_{COUT}$, during PWM dimming must be less than 250 mV, so that no audible hum can be heard. The capacitance can be calculated as follows:

$$C_{OUT} = I_{LK} \times \frac{1 - D(min)}{f_{PWM(dimming)} \times V_{COUT}} \qquad (24)$$

$$= 200\ \mu A \times \frac{1 - 0.01}{200\ Hz \times 0.250\ V} = 3.96\ \mu F$$

A capacitor larger than 3.96 µF should be selected due to degradation of capacitance at high voltages on the capacitor. A ceramic 4.7 µF 50 V capacitor is a good choice to fulfill this requirement. Corresponding capacitors include:

| Vendor | Value | Part number |
|--------|-------|-------------|
| Murata | 4.7 µF 50 V | GRM32ER71H475KA88L |
| Murata | 2.2 µF 50 V | GRM31CR71H225KA88L |

The rms current through the capacitor is given by:

$$I_{COUT}rms = I_{OUT}\sqrt{\frac{D(max) + \dfrac{\Delta I_{Lused}}{I_{IN}(max) \times 12}}{1 - D(max)}} \qquad (25)$$

$$= 0.240\ (A)\sqrt{\frac{0.72 + \dfrac{0.36\ (A)}{0.94\ (A) \times 12}}{1 - 0.72}} = 0.39\ A$$

The output capacitor must have a current rating of at least 390 mA. The capacitor selected in this design was a 4.7 µF 50 V capacitor with a 3 A current rating.

**Step 8** Selecting input capacitor. The input capacitor must be selected such that it provides a good filtering of the input voltage waveform. To reduce the switching frequency noise, a good rule of thumb is to set the input voltage high frequency ripple $\Delta V_{IN}$ to be 1% of the minimum input voltage. The minimum input capacitor requirements are as follows:

$$C_{IN} = \frac{\Delta I_{Lused}}{8 \times f_{SW} \times \Delta V_{IN}} \qquad (26)$$

$$= \frac{0.36\ (A)}{8 \times 2\ (MHz) \times 0.1\ (V)} = 0.23\ \mu F$$

The rms current through the capacitor is given by:

$$C_{IN}rms = \Delta I_{Lused} / \sqrt{12} = 0.104\ A \qquad (27)$$

A good ceramic input capacitor with ratings of 2.2 µF 50 V or 4.7 µF 50 V will suffice for this application. Corresponding capacitors include:

| Vendor | Value | Part number |
|--------|-------|-------------|
| Murata | 4.7 µF 50 V | GRM32ER71H475KA88L |
| Murata | 2.2 µF 50 V | GRM31CR71H225KA88L |

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*Selecting the electrolytic input capacitor according to dimming transient*

During a PWM dimming transient, unless an adequate input capacitor is used, the input voltage drops significantly.

The input capacitor ripple current, $\Delta I$, during the dimming transient is the same as the input maximum DC current, and can be calculated by:

$$\Delta I = I_{INDC}(max) = \frac{V_{OUT} \times I_{OUT}}{V_{IN}(min) \times \eta} \tag{28}$$

where $V_{IN}(min)$ is the minimum input voltage, 10 V.

Consider the case where: $\eta = 0.88$, $V_{IN}(min) = 10$ V, $V_{OUT} = 33.1$ V, $I_{OUT} = 0.24$ A, then:

$$\Delta I = I_{INDC}(max)$$
$$= (33.1 \times 0.24) / (10 \times 0.88) = 0.9 \text{ A}$$

Allowing $V_{IN}$ to drop by $\Delta V_{IN} = 0.5$ V, and considering the feedback loop bandwidth, or cross over frequency, to be $f_C = 30$ kHz, the input drop will last $\Delta T$, calculated by :

$$\Delta T = 1 / f_C = 33 \times 10^{-6} \text{ (second)} \tag{29}$$

The required electrolytic capacitor will be:

$$C_{IN} = \frac{(\Delta I \times \Delta T) \times 10^6}{\Delta V_{IN}} = 59.4 \text{ µF} \tag{30}$$

If this issue is important to the customer, it is recommended to use a 50 V/ 68 µF, low ESR value electrolytic capacitor.

**Step 9** Choosing the input disconnect switch components. Set the input disconnect 1X current limit to 3 A by choosing a sense resistor. The calculated maximum value of the sense resistor is:

$$R_{SC}(max) = V_{SENSEtrip} / 3.0 \text{ (A)} \tag{31}$$
$$= 0.104 \text{ (V)} / 3.0 \text{ (A)} = 0.035 \text{ }\Omega$$

The $R_{SC}$ chosen is 0.033 Ω, a standard.

The trip point voltage must be:

$$V_{ADJ} = 3.0 \text{ (A)} \times 0.033 \text{ (}\Omega\text{)} = 0.099 \text{ (V)}$$
$$R_{ADJ} = (V_{SENSEtrip} - V_{ADJ}) / I_{ADJ} \text{ (typ)} \tag{32}$$
$$R_{ADJ} = (0.104 \text{ (V)} - 0.099 \text{ (V)}) / 20.3 \text{ (µA)} = 246.31 \text{ }\Omega$$

A value of 249 Ω was chosen for this design.

**Step 10** See appendix A for a detailed description of how to calculate $R_Z$, $C_Z$, and $C_P$. Using $L_1 = 10$ µH, $C_{OUT} = (4.7$ µF + 2.2 µF ), and $f_C = 30$ kHz, the calculation results for $R_Z$, $C_Z$, and $C_P$ are: $R_Z = 499$ Ω, $C_Z = 100$ nF, and $C_P = 320$ pF.
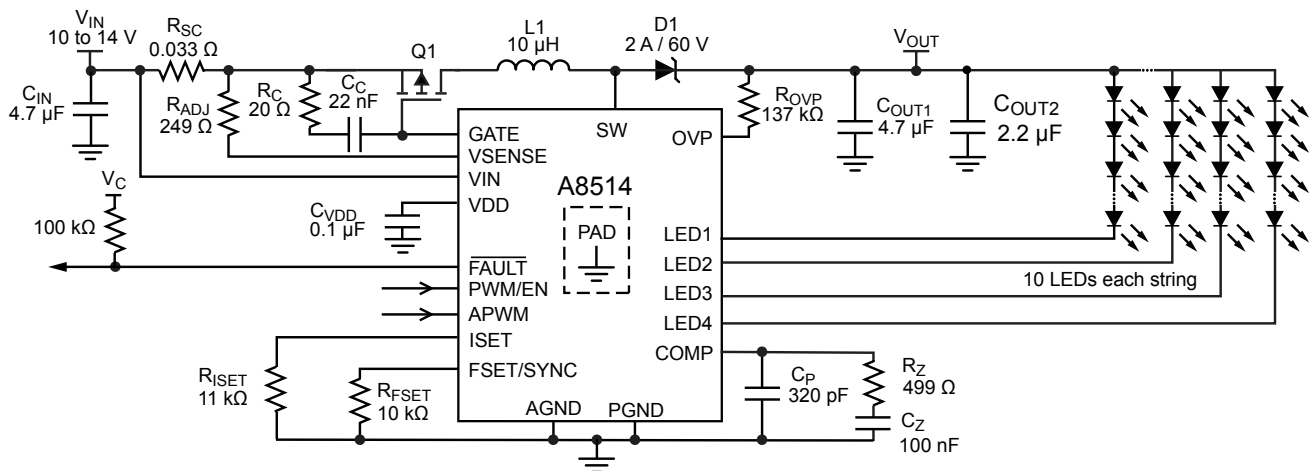


Figure 34. The schematic diagram showing calculated values from the design example above.

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## Design Example for SEPIC Configuration

This section provides a method for selecting component values when designing an application using the A8514 in SEPIC (Single-Ended Primary-Inductor Converter) circuit. SEPIC topology has the advantage that it can generate a positive output voltage either higher or lower than the input voltage. The resulting design is diagrammed in figure 35.

Assumptions: For the purposes of this example, the following are given as the application requirements:

• $V_{BAT}$: 6 to 14 V ( $V_{IN}$(min): 5 V and $V_{IN}$(max): 16 V )

• Quantity of LED channels, $\#_{CHANNELS}$: 4

• Quantity of series LEDs per channel, $\#_{SERIESLEDS}$: 4

• LED current per channel, $I_{LED}$: 60 mA

• LED $V_f$ at 60 mA: ≈ 3.3 V

• $f_{SW}$: 2 MHz

• $T_A$(max): 65°C

• PWM dimming frequency: 200 Hz, 1% duty cycle

Procedure: The procedure consists of selecting the appropriate configuration and then the individual component values, in an ordered sequence.

**Step 1** Connecting LEDs to LEDx pins. If only some of the LED channels are needed, the unused LEDx pins should be pulled to ground using a 1.5 kΩ resistor.

**Step 2** Determining the LED current setting resistor $R_{ISET}$:

$$R_{ISET} = (V_{ISET} \times A_{ISET}) / I_{LED} \qquad (33)$$
$$= (1.003 \text{ (V)} \times 653) / 0.60 \text{ (A)} = 10.92 \text{ kΩ}$$

Choose an 11.00 kΩ 1% resistor.

**Step 3** Determining the OVP resistor. The OVP resistor is connected between the OVP pin and the output voltage of the converter.

**Step 3a** The first step is determining the maximum voltage based on the LED requirements. The regulation voltage, $V_{LED}$, of the

A8514 is 700 mV. A constant term, 2 V, is added to give margin to the design due to noise and output voltage ripple.

$$V_{OUT(OVP)} = \#_{SERIESLEDS} \times V_f + V_{LED} + 2 \text{ (V)} \qquad (34)$$
$$= 4 \times 3.3 \text{ (V)} + 0.7 \text{ (V)} + 2 \text{ (V)} = 15.9 \text{ V}$$

Then the OVP resistor is:

$$R_{OVP} = (V_{OUT(OVP)} - V_{OVP(th)}) / I_{OVPH} \qquad (35)$$
$$= (15.9 \text{ (V)} - 8.1 \text{ (V)}) / 0.199 \text{ (mA)} = 39.196 \text{ kΩ}$$

where both $I_{OVPH}$ and $V_{OVP(th)}$ are taken from the Electrical Characteristics table.

In this case a value of 39.2 kΩ was selected. Below is the actual value of the minimum OVP trip level with the selected resistor:

$$V_{OUT(OVP)} = 39.2 \text{ (kΩ)} \times 0.199 \text{ (mA)} + 8.1 \text{ (V)} = 15.9 \text{ V}$$

**Step 3b** At this point a quick check must be done to determine if the conversion ratio is acceptable for the selected frequency.

$$D_{max} = 1 - t_{SWOFFTIME} \times f_{SW} \qquad (36)$$
$$= 1 - 68 \text{ (ns)} \times 2 \text{ (MHz)} = 86.4\%$$

where the minimum off-time ($t_{SWOFFTIME}$) is found in the Electrical Characteristics table.

The Theoretical Maximum $V_{OUT}$ is then calculated as:

$$V_{OUT}(max) = V_{IN}(min) \times \frac{D_{max}}{1 - D_{max}} - V_d \qquad (37)$$
$$= 5 \text{ (V)} \times \frac{0.86}{1 - 0.86} - 0.4 \text{ (V)} = 30.3 \text{ V}$$

where $V_d$ is the diode forward voltage.

The Theoretical Maximum $V_{OUT}$ value must be greater than the value $V_{OUT(OVP)}$. If this is not the case, it may be necessary to reduce the frequency to allow the boost to convert the voltage ratios.

**Step 4** Selecting the inductor. The inductor must be chosen such that it can handle the necessary input current. In most applica-

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tions, due to stringent EMI requirements, the system must operate in continuous conduction mode throughout the whole input voltage range.

**Step 4a** Determining the duty cycle, calculated as follows:

$$D(\text{max}) = \frac{V_{\text{OUT(OVP)}} + V_{\text{d}}}{V_{\text{IN}}(\text{min}) + V_{\text{OUT(OVP)}} + V_{\text{d}}} \tag{38}$$

$$= \frac{15.9 \text{ (V)} + 0.4 \text{ (V)}}{5 \text{ (V)} + 15.9 \text{ (V)} + 0.4 \text{ (V)}} = 76.5\%$$

**Step 4b** Determining the maximum and minimum input current to the system. The minimum input current will dictate the inductor value. The maximum current rating will dictate the current rating of the inductor. First, the maximum input current, given:

$$I_{\text{OUT}} = \#_{\text{CHANNELS}} \times I_{\text{LED}} \tag{39}$$

$$= 4 \times 0.060 \text{ (A)} = 0.240 \text{ A}$$

then:

$$I_{\text{IN}}(\text{max}) = \frac{V_{\text{OUT(OVP)}} \times I_{\text{OUT}}}{V_{\text{IN}}(\text{min}) \times \eta} \tag{40}$$

$$= \frac{15.9 \text{ (V)} \times 0.24 \text{ (A)}}{5 \text{ (V)} \times 0.90} = 0.848 \text{ A}$$

where η is efficiency.

Next, calculate minimum input current, as follows:

$$I_{\text{IN}}(\text{min}) = \frac{V_{\text{OUT(OVP)}} \times I_{\text{OUT}}}{V_{\text{IN}}(\text{max}) \times \eta} \tag{41}$$

$$= \frac{15.9 \text{ (V)} \times 0.24 \text{ (A)}}{16 \text{ (V)} \times 0.90} = 0.265 \text{ A}$$

**Step 4c** Determining the inductor value. To ensure that the inductor operates in continuous conduction mode, the value of the inductor must be set such that the ½ inductor ripple current is not greater than the average minimum input current. As a first pass assume $I_{\text{ripple}}$ to be 30% of the maximum inductor current:

$$\Delta I_{\text{L}} = I_{\text{IN}}(\text{max}) \times I_{\text{ripple}} \tag{42}$$

$$= 0.848 \times 0.30 = 0.254 \text{ A}$$

then:

$$L = \frac{V_{\text{IN}}(\text{min})}{\Delta I_{\text{L}} \times f_{\text{SW}}} \times D(\text{max}) \tag{43}$$

$$= \frac{5 \text{ (V)}}{0.254 \text{ (A)} \times 2 \text{ (MHz)}} \times 0.765 = 7.53 \text{ µH}$$

**Step 4d** Double-check to make sure the ½ current ripple is less than $I_{\text{IN}}(\text{min})$:

$$I_{\text{IN}}(\text{min}) > \tfrac{1}{2} \Delta I_{\text{L}} \tag{44}$$

$$0.265 \text{ A} > 0.127 \text{ A}$$

A good inductor value to use would be 10 µH.

**Step 4e** Next insert the inductor value used in the design to determine the actual inductor ripple current:

$$\Delta I_{\text{Lused}} = \frac{V_{\text{IN}}(\text{min}) \times D(\text{max})}{L_{\text{used}} \times f_{\text{SW}}} \tag{45}$$

$$= \frac{5 \text{ (V)} \times 0.765}{10 \text{ (µH)} \times 2.0 \text{ (MHz)}} = 0.191 \text{ A}$$

**Step 4f** Determining the inductor current rating. The inductor current rating must be greater than the $I_{\text{IN}}(\text{max})$ value plus half of the ripple current $\Delta I_{\text{L}}$, calculated as follows:

$$L(\text{min}) = I_{\text{IN}}(\text{max}) + \tfrac{1}{2} \Delta I_{\text{Lused}} \tag{46}$$

$$= 0.848 \text{ (A)} + 0.096 \text{ (A)} = 0.944 \text{ A}$$

**Step 5** Determining the resistor value for a particular switching frequency. Use the $R_{\text{FSET}}$ values shown in figure 7. For example, a 10 kΩ resistor will result in a 2 MHz switching frequency.

**Step 6** Choosing the proper switching diode. The switching diode must be chosen for three characteristics when it is used in LED lighting circuitry. The most obvious two are: current rating of the diode and reverse voltage rating.

The reverse breakdown voltage rating for the output diode in a SEPIC circuit should be:

$$V_{BD} > V_{OUT(OVP)}(max) + V_{IN}(max) \quad (47)$$
$$> 15.9 \ (V) + 16 \ (V) = 31.9 \ V$$

because the maximum output voltage in this case is $V_{OUT(OVP)}$.

The peak current through the diode is calculated as:

$$I_{dp} = I_{IN}(max) + {}^1\!/_2 \, \Delta I_{Lused} \quad (48)$$
$$= 0.848 \ (A) + 0.096 \ (A) = 0.944 \ A$$

The third major component in deciding the switching diode is the reverse current, $I_R$ , characteristic of the diode. This characteristic is especially important when PWM dimming is implemented. During PWM off-time the boost converter is not switching. This results in a slow bleeding off of the output voltage, due to leakage currents. $I_R$ can be a large contributor, especially at high temperatures. On the diode that was selected in this design, the current varies between 1 and 100 µA. It is often advantageous to pick a diode with a much higher breakdown voltage, just to reduce the reverse current. Therefore for this example, pick a diode rated for a $V_{BD}$ of 60 V, instead of just 40 V.

**Step 7** Choosing the output capacitors. The output capacitors must be chosen such that they can provide filtering for both the boost converter and for the PWM dimming function. The biggest factors that contribute to the size of the output capacitor are: PWM dimming frequency and PWM duty cycle. Another major contributor is leakage current, $I_{LK}$. This current is the combination of the OVP leakage current as well as the reverse current of the switching diode. In this design the PWM dimming frequency is 200 Hz and the minimum duty cycle is 1%. Typically, the voltage variation on the output, $V_{COUT}$, during PWM dimming must be less than 250 mV, so that no audible hum can be heard. The capacitance can be calculated as follows:

$$C_{OUT} = I_{LK} \times \frac{1 - D(min)}{f_{PWM(dimming)} \times V_{COUT}} \quad (49)$$
$$= 200 \ (\mu A) \times \frac{1 - 0.01}{200 \ (Hz) \times 0.250 \ (V)} = 3.96 \ \mu F$$

A capacitor larger than 3.96 µF should be selected due to degradation of capacitance at high voltages on the capacitor. Select a 4.7 µF capacitor for this application.

The rms current through the capacitor is given by:

$$I_{COUT}rms = I_{OUT} \sqrt{\frac{D(max)}{1 - D(max)}} \quad (50)$$
$$= 0.240 \ (A) \sqrt{\frac{0.765}{1 - 0.765}} = 0.433 \ A$$

The output capacitor must have a ripple current rating of at least 500 mA. The capacitor selected for this design is a 4.7 µF 50 V capacitor with a 1.5 A current rating.

**Step 8** Selecting input capacitor. The input capacitor must be selected such that it provides a good filtering of the input voltage waveform. A estimation rule is to set the input voltage ripple, $\Delta V_{IN}$, to be 1% of the minimum input voltage. The minimum input capacitor requirements are as follows:

$$C_{IN} = \frac{\Delta I_{Lused}}{8 \times f_{SW} \times \Delta V_{IN}} \quad (51)$$
$$= \frac{0.191 \ (A)}{8 \times 2 \ (MHz) \times 0.05 \ (V)} = 0.24 \ \mu F$$

The rms current through the capacitor is given by:

$$C_{IN}rms = \frac{\Delta I_{Lused}}{\sqrt{12}} \quad (52)$$
$$= \frac{0.191 \ (A)}{\sqrt{12}} = 0.055 \ A$$

A good ceramic input capacitor with a rating of 2.2 µF 25 V will suffice for this application.

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**Step 9** Selecting coupling capacitor $C_{SW}$. The minimum capacitance of $C_{SW}$ is related to the maximum voltage ripple allowed across it:

$$C_{SW} = \frac{I_{OUT} \times D_{MAX}}{\Delta V_{SW} \times f_{SW}} \tag{53}$$

$$= \frac{0.24\ (A) \times 0.765}{0.1\ (V) \times 2\ (MHz)} = 0.92\ \mu F$$

The rms current requirement of the coupling capacitor is given by:

$$I_{CSW}rms = I_{IN}(max) \sqrt{\frac{1 - D(max)}{D(max)}} \tag{54}$$

$$= 0.848\ (A) \sqrt{\frac{1 - 0.765}{0.765}} = 0.47\ A$$

The voltage rating of the coupling capacitor must be greater than $V_{IN}(max)$, or 16 V in this case. A ceramic capacitor rated for 2.2 µF 25 V will suffice for this application.
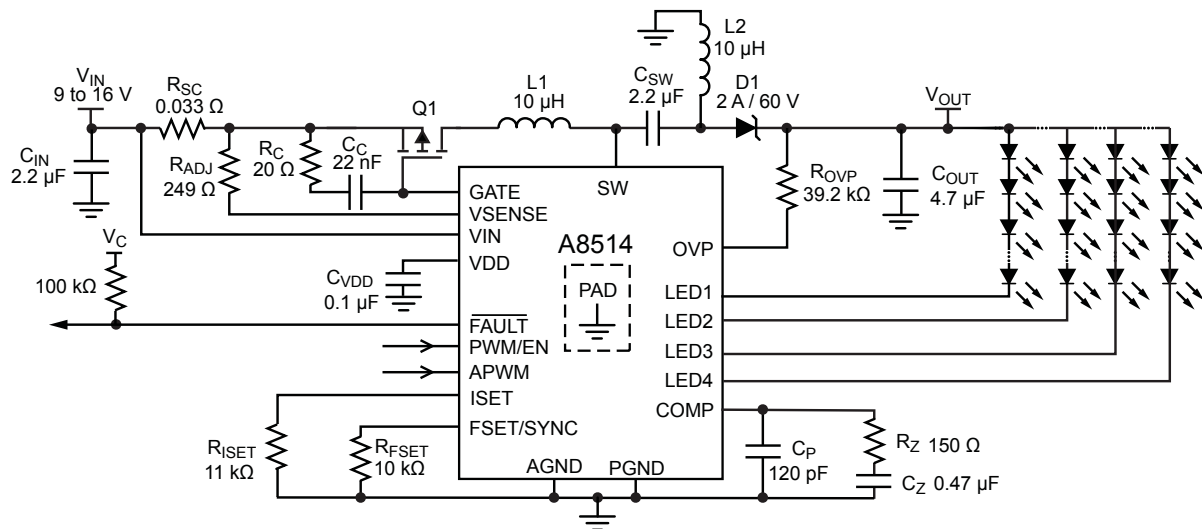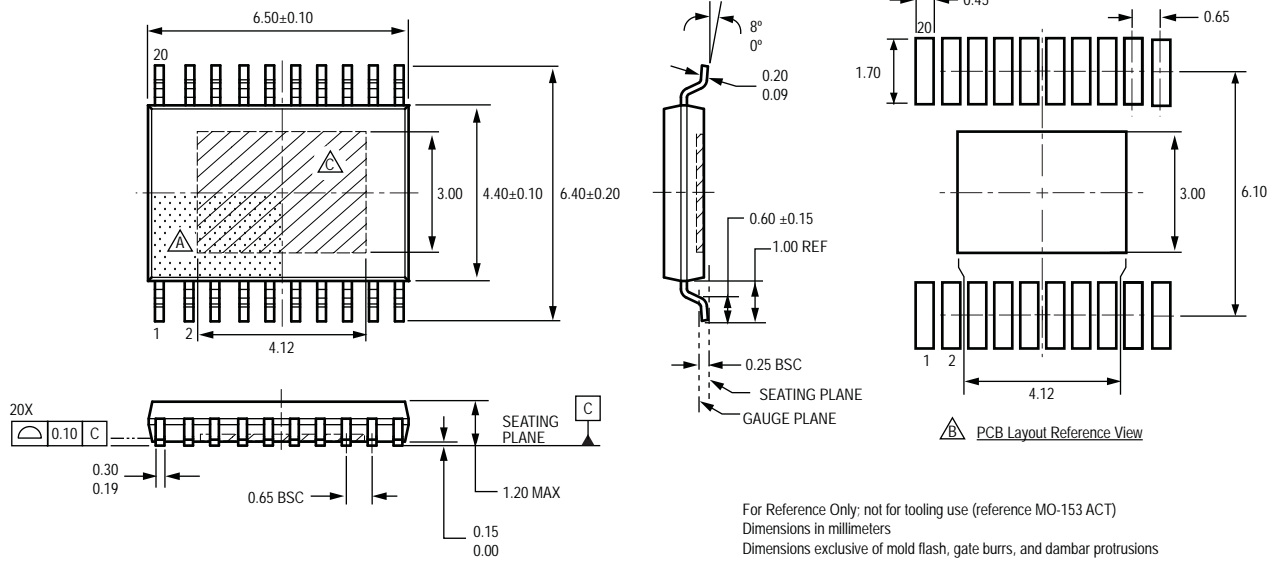


Figure 35. Typical application showing SEPIC configuration, with accurate input current sense, and VSENSE to ground protection.

**Package LP, 20-Pin TSSOP with Exposed Thermal Pad**

For Reference Only; not for tooling use (reference MO-153 ACT)
Dimensions in millimeters
Dimensions exclusive of mold flash, gate burrs, and dambar protrusions
Exact case and lead configuration at supplier discretion within limits shown

⚠Ⓐ Terminal #1 mark area

⚠Ⓑ Reference land pattern layout (reference IPC7351
SOP65P640X110-21M);
All pads a minimum of 0.20 mm from all adjacent pads; adjust as
necessary to meet application process requirements and PCB layout
tolerances; when mounting on a multilayer PCB, thermal vias at the
exposed thermal pad land can improve thermal dissipation (reference
EIA/JEDEC Standard JESD51-5)

⚠Ⓒ Exposed thermal pad (bottom surface); dimensions may vary with device

Ⓑ PCB Layout Reference View

20X

SEATING
PLANE

GAUGE PLANE

**Revision History**

| Revision | Revision Date | Description of Revision |
|----------|---------------|------------------------|
| Rev. 5 | May 20, 2013 | Update application information, add appendix A |
|  |  |  |

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## Appendix A. Feed Back Loop Components Calculation for Peak Current Control Boost Converter Used in LED Drivers Applications

This appendix provides an examination of the factors involved in calculating the transfer function of a peak current controlled boost converter, an output to control transfer function, and recommendations for stabilizing the feedback loop closed system. An example of a complete small signal model of a peak-current-mode boost converter is shown in figure A-2. The A8514 is an example of a boost converter that drives 4 LED strings with 10 LEDs in each string.

### Power Stage Transfer Function

Using a frequency-based model, the transfer function (control to output) of boost power stage peak-current control is given by the following equation:

$$T_P(f) = A_P \times \frac{\left(1 + \frac{2 \times \pi \times f \times j}{\omega_Z}\right) \times \left(1 - \frac{2 \times \pi \times f \times j}{\omega_{RHP}}\right)}{\left(1 + \frac{2 \times \pi \times f \times j}{\omega_P}\right) \times \left(1 + \frac{2 \times \pi \times f \times j}{Q_D \times \omega_S} - \frac{(2 \times \pi \times f \times j)^2}{\omega_S^2}\right)} \quad \text{(A-1)}$$

$A_P$ is the DC gain,

$\omega_Z$ is the angular frequency of the output capacitor ESR zero, $f_Z$,

$\omega_{RHP}$ is the angular frequency of the right-half plane zero, $f_{RHP}$,

$\omega_P$ is the angular frequency of the output load pole, $f_P$,

$Q_D$ is the inductor peak current sampling double pole quality or damping factor, and

$\omega_S$ is the double-pole angular frequency oscillation.

Figure A-1 shows the plot of the power stage logarithmic transfer function as gain, $G_{P(f)}$, versus frequency. with $G_{P(f)}$ given by:

$$G_P(f) = 20 \times \log(|T_P(f)|) \quad \text{(A-2)}$$

The next sections define the components of $T_P(f)$.

*$A_P$, DC gain*

The DC gain is defined as follows:

$$A_P = \frac{1 - D(\text{nom})}{R_I} \times \frac{R_S \times R_{EQ}}{R_S + R_D + R_{EQ}} \quad \text{(A-3)}$$

where

• D is the PWM duty cycle, calculated as:

$$D(\text{nom}) = (V_{OUT} - V_{IN}(\text{nom})) / V_{OUT} \quad \text{(A-4)}$$

where

$$V_{OUT} = N_L \times V_f + V_{REG} + V_D \quad \text{(A-5)}$$

and

$N_L$ is the quantity of LEDs per string,

$V_f$ is the nominal forward voltage drop for each LED diode,

$V_{REG}$ is the current sink regulated voltage for each LED string, and

$V_D$ is the Schottky diode forward voltage drop.

• $R_I$ is the current sense resistor, which is connected in series with the boost power switch,

• $R_S$ is the LED sink pin sense resistor, which is usually located inside the IC and can be calculated from the following equation:

$$R_S = V_{REG} / I_{LED} \quad \text{(A-6)}$$

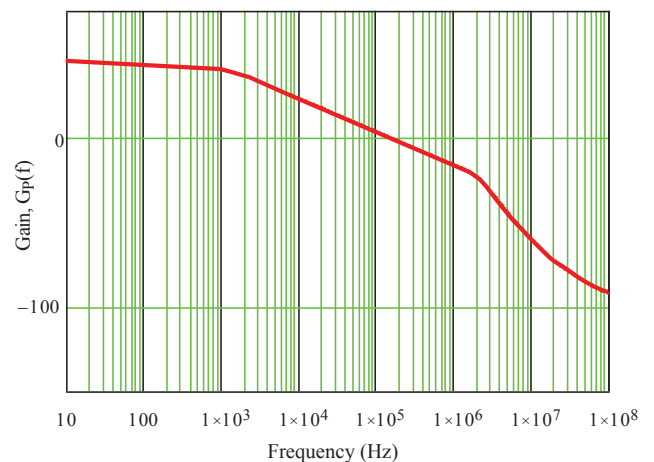where $I_{LED}$ is the current through one LED string,



Figure A-1. Plot of power stage transfer function versus frequency

- $R_{EQ}$ is the output nominal operating resistance, which is given by the following equation:

$$R_{EQ} = V_{OUT} / I_{LEDT} \qquad \text{(A-7)}$$

where $I_{LEDT}$ is the total output current through all LED strings:

$$I_{LEDT} = N_S \times I_{LED} \qquad \text{(A-8)}$$

and $N_S$ is the total quantity of LED strings, and

- $R_D$ is the total dynamic resistance of an LED string, which can be taken from the datasheets of the LEDs being used, or measured in the lab, as follows:

1. Apply a voltage, $V_1$, from one end of an LED string to the other end.

2. Measure the current, $I_1$, through the string.

3. Repeat for another voltage, $V_2$, and measure the current, $I_2$.

4. Calculate the result as:

$$R_D = (V_2 - V_1) / (I_2 - I_1) \qquad \text{(A-9)}$$

$Q_D$, *inductor peak current sampling double pole quality*

$$Q_D = \frac{1}{\pi \times [0.5 - D(\text{nom}) + (1 - D(\text{nom})) \times \text{IFSC}]} \qquad \text{(A-10)}$$

where

IFSC is the implemented factor of inductor slope compensation, and is given by:

$$\text{IFSC} = (\text{ISC} / \text{CSC}) \times \text{FSC} \qquad \text{(A-11)}$$

and

ISC is the IC implemented slope compensation in A/µs, which can be taken from the IC datasheet, and
CSC is the calculated slope compensation also in A/µs, given by:

$$CSC = \frac{\Delta I \times \text{FSC} \times 10^{-6}}{(1/f_{SW}) \times (1 - D(\text{max}))} \qquad \text{(A-12)}$$

and

$$\Delta I = (V_{IN}(\text{min}) \times D(\text{max})) / L_1 \times f_{SW}, \text{ and} \qquad \text{(A-13)}$$

FSC is the Ridley's factor slope compensation, given by:

$$\text{FSC} = 1 - 0.18 / D(\text{max}) \qquad \text{(A-14)}$$

$\omega_Z$, *angular frequency of the output capacitor ESR zero, $f_Z$*

$$\omega_Z = 1 / (\text{ESR} \times C_{OUT}) \qquad \text{(A-15)}$$

$\omega_{RHP}$, *angular frequency of the right-half plane zero, $f_{RHP}$*

$$\omega_{RHP} = R_{EQ} / (1 - D(\text{max}))^2 \times L_1) \qquad \text{(A-16)}$$

where

$$D(\text{max}) = (V_{OUT} - V_{IN}(\text{min})) / V_{OUT} \qquad \text{(A-17)}$$

$\omega_P$, *angular frequency of the output load pole, $f_P$*

$$\omega_P = \frac{R_S + R_D + R_{EQ}}{(R_S + R_D + \text{ESR}) \times R_{EQ} \times C_{OUT}} \qquad \text{(A-18)}$$

$\omega_S$, *angular frequency oscillation of the double pole that occurs at half of the switching frequency, $f_{SW}$*

$$\omega_S = \pi \times f_{SW} \qquad \text{(A-19)}$$

**Output to Control Transfer Function**

When using peak current mode control for a DC-to-DC converter, a type II PI error amplifier compensation circuit is sufficient to stabilize the converter. For controlling the current sink voltage and as a result controlling the output, the A8514 IC uses a high bandwidth transconductance amplifier, shown as A1 in figure A-2.

A transconductance amplifier is actually a voltage-controlled current source. It converts any error voltage at its input pins to a current flowing out of its output pin at $V_C$. The transconductance gain of the error amplifier, $g$, is defined as:

$$g = I_{AMP} / V_{error} \qquad \text{(A-20)}$$

In figure A-2, $R_{AMP}$ represents the output impedance of the transconductance amplifier (A1). $R_{AMP}$ usually has a high value and it is neglected in the calculation of the error amplifier transfer function.

$R_Z$, $C_Z$, and $C_P$ represent the external Type II compensation network. From an AC point of view, the non-inverting pin of A1 is connected to a DC reference voltage, $V_{REG}$, which is a virtual

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A-2

AC ground. Therefore, the transfer function of the compensation circuit is derived as follows:

$$T_{EA}(f) = \frac{V_C(f)}{V_{OUT}(f)} \qquad (A\text{-}21)$$

$$= \frac{-1 \times I_{AMP} \times Z_C(f)}{V_{ERROR} \times \left(\dfrac{R_S + R_D}{R_S}\right)} \qquad (A\text{-}22)$$

applying equation A-20:

$$T_{EA}(f) = -1 \times \left(\frac{R_S \times g}{R_S + R_D}\right) \times Z_C(f) \qquad (A\text{-}23)$$

where

$$Z_C(f) = \frac{\left(R_Z + \dfrac{1}{2 \times \pi \times f \times j \times C_Z}\right) \times \left(\dfrac{1}{2 \times \pi \times f \times j \times C_P}\right)}{\left(R_Z + \dfrac{1}{2 \times \pi \times f \times j \times C_Z}\right) + \left(\dfrac{1}{2 \times \pi \times f \times j \times C_P}\right)} \qquad (A\text{-}24)$$

Figure A-3 shows the logarithmic transfer function for the output to control compensation circuit, with gain, $G_{EA}(f)$. given by:

$$G_{EA}(f) = 20 \times \log(|T_{EA}(f)|) \qquad (A\text{-}25)$$

The transfer function has a single pair of pole and zero in addi-tion to the pole at the origin. The pole at the origin is defined by $C_P$ and $R_{AMP}$. The zero is defined by $R_Z$ and $C_Z$. The zero frequency location is selected to compensate or cancel the power train load pole. It is defined by:

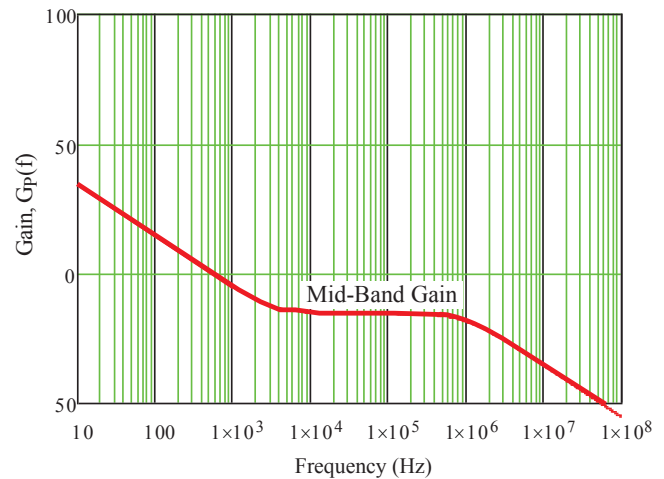$$f_{ZEA} = 1/(2 \times \pi \times R_Z \times C_Z) \qquad (A\text{-}26)$$



Figure A-3. Plot of error amplifier stage transfer function versus frequency
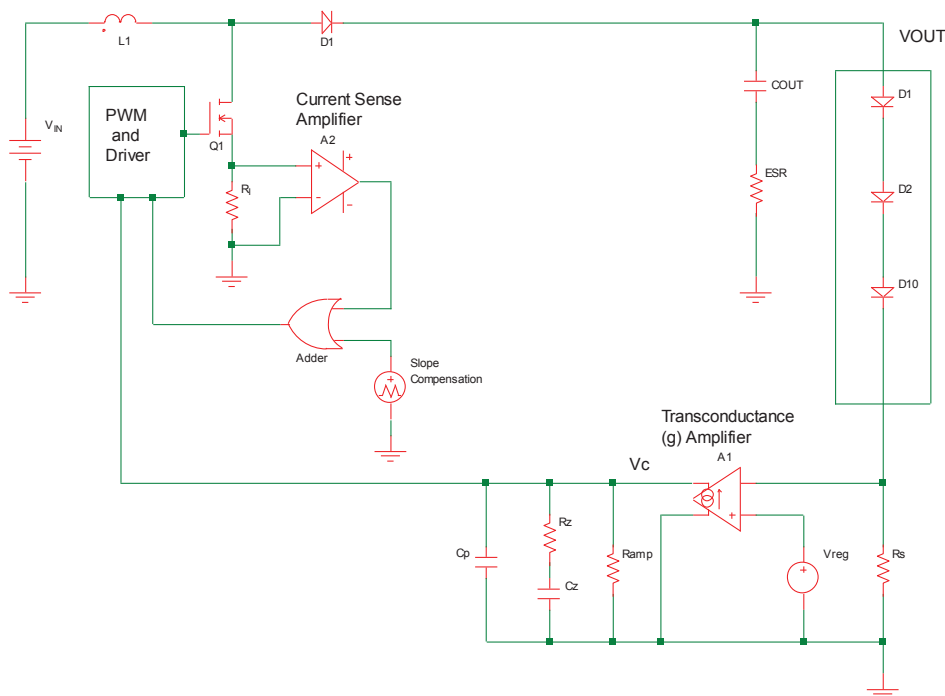


Figure A-2. Small signal model of a peak-current-mode boost converter;
the four strings of the A8514 are represented by one string in this example

The error amplifier pole frequency is selected to compensate for or cancel the power train ESR zero. This is the case if the frequency of the ESR zero is small or below the switching frequency. Otherwise, it is selected to be at half switching frequency. This pole frequency determines the end of mid-band gain of the error amplifier transfer function, so it ensures that the closed loop system cross-over frequency is below half switching frequency, which is important for stability issues. The pole frequency is defined by:

$$f_{PEA} = \frac{1}{2 \times \pi \times R_Z \times \left( \frac{C_Z \times C_P}{C_Z + C_P} \right)} \tag{A-27}$$

## Stabilizing the Closed Loop System

In this section, calculations are provided for selecting optimal $R_Z$, $C_Z$, and $C_P$. The closed loop system will be stable if the total system transfer function rolls off while crossing over at a phase margin of approximately 90° or –20 dB per decade. It is recommended that the phase margin does not fall below 45°. For higher stability, the cross over frequency should be much less than the right half plane zero and smaller than half of the switching frequency.

To achieve that, first fix the mid-band gain of the error amplifier transfer function. Make it equal in value to the power train gain at the cross over frequency, but negative so the total closed loop gain will be 0 dB. Then position the compensation pole and zero. Here are step-by-step procedures on how to calculate the compensation network components:

1. Calculate $R_Z$ such that the negative mid-band gain of the error amplifier will be equal to the power train gain at the required system bandwidth or cross over frequency.

1a. Calculate the cross over frequency to be much less than the RHP zero and lower than the half-switching frequency. A 20 to 30 kHz cross over frequency is appropriate for LED applications, calculated as follows:

$$f_C = 0.015 \times f_{SW} \tag{A-28}$$

1b. Calculate, or preferably measure, the power train gain at $f_C$, which is $G_P(f_C)$, then multiply it by –1.

1c. To compensate for the difference from the error amplifier gain at $f_{ZEA}$ and the actual mid-band gain, subtract an additional 3 dB:

$$-G_P(f_C) - 3 \text{ dB} \tag{A-29}$$

1d. Convert the calculated gain to a linear gain:

$$10^{\left( \frac{-G_P(f_C) - 3}{20} \right)} \tag{A-29}$$

1e. Calculate $R_Z$:

$$R_Z = \frac{10^{\left( \frac{-G_P(f_C) - 3}{20} \right)}}{g \times \left( \frac{R_S}{R_S + R_D} \right)} \tag{A-30}$$

2. Select a value for $C_Z$.

2a. Calculate the frequency for the error-amplifier compensation zero, $f_{ZEA}$. This zero should cancel the dominant low frequency pole of power train. Therefore, $f_{ZEA}$ should be close to $f_P$. Usually it is selected to be $^1/_5$ to $^1/_{10}$ of $f_C$:

$$f_{ZEA} = f_C / 10 \tag{A-31}$$

2b. Cz can be calculated by applying equation A-26:

$$C_Z = 1 / (2 \times \pi \times R_Z \times f_{ZEA}) \tag{A-32}$$

3. Select a value for $C_P$.

3a. Select a frequency for the error-amplifier compensation pole, $f_{PEA}$. This pole determines the error-amplifier end of the mid-band region. It is selected to cancel the power train ESR zero. However, if ceramic capacitors are used at the output, the ESR zero will be at very high frequency. In this case, the $f_{PEA}$ is selected to be at half of the switching frequency to ensure that $f_C$ is at lower than half the switching frequency and as a result a higher phase margin can be achieved. $f_{PEA}$ is given by:

$$f_{PEA} = 0.5 \times f_{SW} \tag{A-33}$$

3b. $C_P$ can be calculated by applying equation A-27:

$$C_P = \frac{C_Z}{2 \times \pi \times R_Z \times C_Z \times f_{PEA} - 1} \tag{A-34}$$

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A-4

The closed-loop system transfer function is given by:

$$T_S(f) = T_P(f) \times T_{EA}(f) \tag{A-35}$$

The closed-loop system logarithmic transfer function gain is given by:

$$G_S(f) = 20 \times \log(|T_S(f)|) \tag{A-36}$$

Figure A-4 shows the closed loop logarithmic transfer function as

gain versus frequency. As shown in figure A-4, if the above methods are implemented the transfer function rolls off while crossing over with around a –20 dB per decade, which results in around a 90° phase margin.

Finally, it is recommended to measure the gain and phase margin of the whole system closed loop. If necessary, the compensation components values could be tweaked to obtain the required cross over frequency and phase margin.
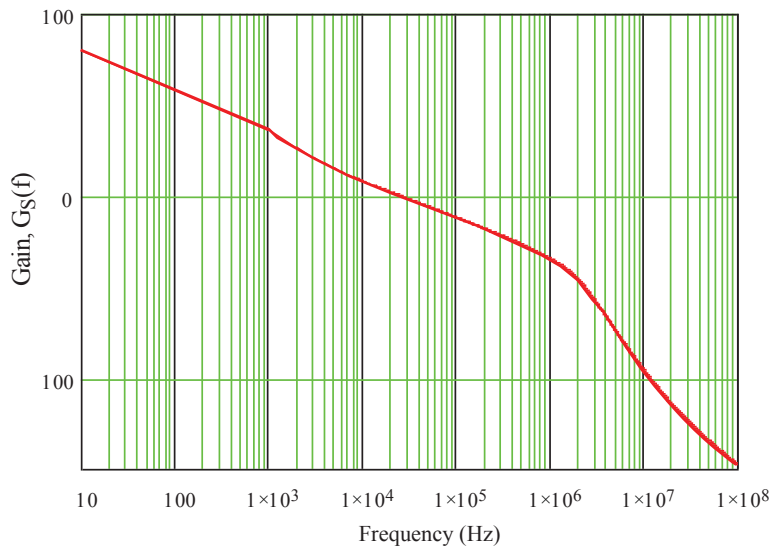


Figure A-4. Plot of the whole system closed loop transfer function gain versus frequency, with a cross over frequency, $f_C$, of 30 kHz

**Measuring the Feedback Loop Gain and Phase Margin**
It is always necessary to measure the feedback loop gain and phase margin of a power converter to make sure the converter runs stably and responds quickly to line or load transients. In addition, to calculate the feedback-loop component values, it is necessary first to calculate or preferably to measure only the power-stage transfer function at the required cross over frequency. Below, one method for measuring the power-stage and the closed-loop whole system transfer functions is presented.

*Power Stage Transfer Function Measurement*
The power stage or control to output transfer function can be measured using any gain/phase analyzer. Figure A-5 shows a block diagram for the whole closed-loop system. To measure the power-stage transfer function, implement the following steps:

1. First, temporarily, use a large value capacitor for $C_Z$, say 4.7 µF, and a small value resistor for $R_Z$, say 100 Ω, to roll-off the control loop at very low frequency.

2. On the PCB cut the trace between VOUT and the LED strings.

3. Connect a 10 Ω resistor from VOUT to the LED strings.

4. Connect the sweeping signal, $V_S$, leads from the spectrum analyzer line (red) to VOUT and the neutral (black) to the LED string, across the 10 Ω resistor.

5. Hook the voltage probe V2 (red) to VOUT (B1) and the ground lead to PCB GND.

6. Hook the voltage probe V1 (blue) to $V_C$, so the gain would be $G_P(f) = B1 / A2$.

7. Run the sweep.

8. When the sweep is completed, to read the power stage gain $G_P(f_C)$ at the selected frequency, $f_C$, place the analyzer screen cursor at that frequency.
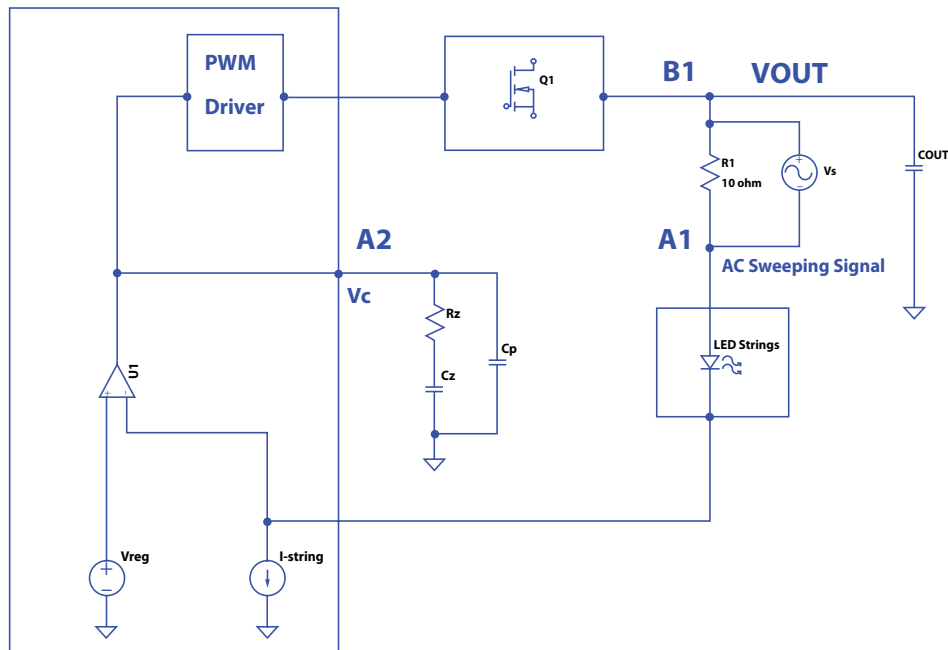


Figure A-5. Simplified block diagram for the closed-loop whole system to show how to measure the gain of the power stage or closed-loop system gain and phase margin

*Whole Closed-Loop System Transfer Function Gain and Phase Margin Measurement*

The closed-loop whole system transfer function gain and phase margin can be measured using the following steps:

1. Change $R_Z$, $C_Z$, and $C_P$ to be the same as the calculated values.

2. Follow same steps 2 through 5, shown above.

3. Hook the voltage probe V1 (blue) to A1, so the gain would be $G_S(f) = B1/A1$.

4. Run the sweep.

5. When the sweep is completed, to read the phase margin at the cross over frequency, $f_C$, place the analyzer screen cursor at $f_C$.

6. To read the gain margin, place the analyzer screen cursor where the phase margin is zero.

The whole system closed loop is considered stable if the phase margin is larger than 45°. It is also recommended to have the gain margin as large as possible. Larger than around –7 dB is sufficient.

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