THERMAL DERATING TECHNIQUES FOR LED DRIVER ICS—RUN YOUR LEDS COOLER FOR BETTER LIFE

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INTRODUCTION

LEDs recently popularized for automotive illumination are replacing the vast variety of traditional incandescent lights and high-intensity-discharge (HID) lights. LEDs have found use in most automotive applications, such as headlights, tail-lights, indicators, and infotainment backlighting.

High-power LED driver technology has revolutionized lighting-system design. LEDs are six to seven times more efficient than incandescent lights and twice as efficient as fluorescent lights. Along with higher efficiencies, LEDs offer easier control for changes of styling, color, and brightness.

At elevated temperatures, however, LEDs—like other semi-conductor devices—suffer from poor performance, reduced life span, reduced light output, and change in color of light emitted. Therefore, it is necessary that thermal management and the consideration of the effects of elevated temperatures are addressed properly. The typical lifetime of LEDs versus temperature is plotted in Figure 1.

THERMAL DERATING

LEDs are more efficient than conventional light sources, such as incandescent or fluorescent lights. However, LEDs still convert a considerable amount of electrical energy into heat. This heat causes a rise in junction temperature, which hampers the performance and lifespan of the LEDs.

Thermal derating is a technique in which the LED driver device or IC is operated at reduced power to avoid damage due to excessive heat dissipation in the LEDs or the IC itself. If temperature increases more than safe limit, output current or current via LEDs is reduced to avoid damage due to heat.

Most LED driver ICs have a built-in, fixed, thermal-derating and thermal-shutdown (TSD) function. This feature monitors the IC junction temperature: If it rises beyond the expected level, output current is reduced; if temperature rises beyond the TSD level, the IC shuts down. This TSD and thermal derating function helps to protect the IC only. Practicality typically requires the IC to be located away from the LEDs, which requires additional protection or thermal derating to protect the LEDs.

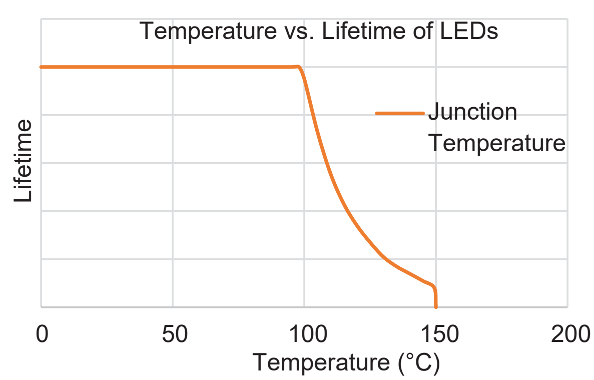

Figure 1: Typical Temperature vs. Lifetime Curve of LED

DIMMING TECHNIQUES

To accomplish LED dimming, the average current provided by the LED driver to the LEDs is reduced to meet the requirements. This reduction in average current also results in lower average power dissipation through the LEDs.

LED current dimming can be achieved in two ways:

- Analog dimming
- Pulse-width-modulated (PWM) dimming

Regardless of the technique used, the goal is to reduce the average output current to operate the LEDs within safe temperature limits.

Analog Dimming

Analog dimming reduces the peak LED current, which limits power dissipation. Analog dimming can be achieved by varying either the feedback (CS pin) or the reference (ADIM pin) of the LED current regulator.

The advantages of analog dimming include implementation ease, noise reduction due to DC operation, and cost reduction.

The disadvantage of analog dimming is the potential for the change in DC current to change the color of the LEDs.

PWM Dimming

PWM dimming regulates the average current through the LEDs by chopping the current at the required frequency and duty cycle, per:

Equation 1:

$$I_{LED(Average)} = I_{LED(Peak)} \times Duty\ cycle.$$

The typical frequency range for PWM dimming of LEDs is between 100 Hz and 2 kHz. The lower limit of 100 Hz is defined by the capability of the human eye: If the frequency of flicker or dimming is faster than 100 Hz, the human eye cannot perceive the light flicker. The upper limit of 2 kHz is approximated for utility: Higher frequencies offer little additional benefit because accuracy is hindered at lower duty cycles by slew rates and on-off timings of LEDs, field-effect transistors (FETs), etc.; and electromagnetic interference (EMI) issues become considerable at higher frequencies.

The advantages of PWM dimming include consistency in light color—because peak current remains constant, the color of the light emitted by the LEDs does not change—and higher PWM dimming efficiency at light load.

The disadvantages of PWM dimming is noise from passive components, such as multilayer ceramic capacitors (MLCCs). Because these components are susceptible to the piezoelectric effect, when the frequency of PWM dimming is in the audible range, audible switching noise is created, which results in EMI issues that require additional circuitry and extra care in the design and implementation thereof.

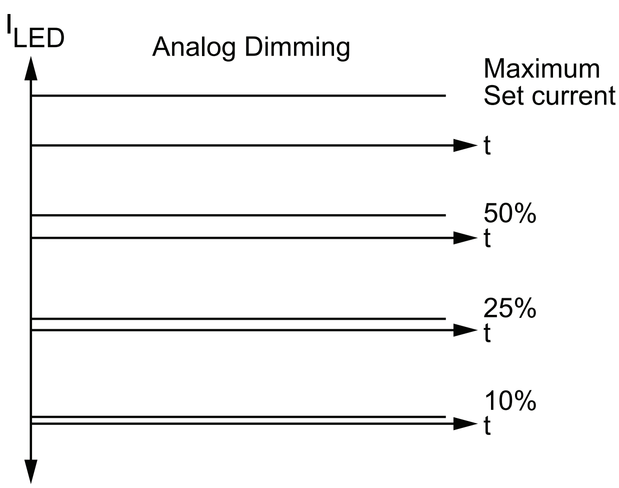

Figure 2: Analog Dimming

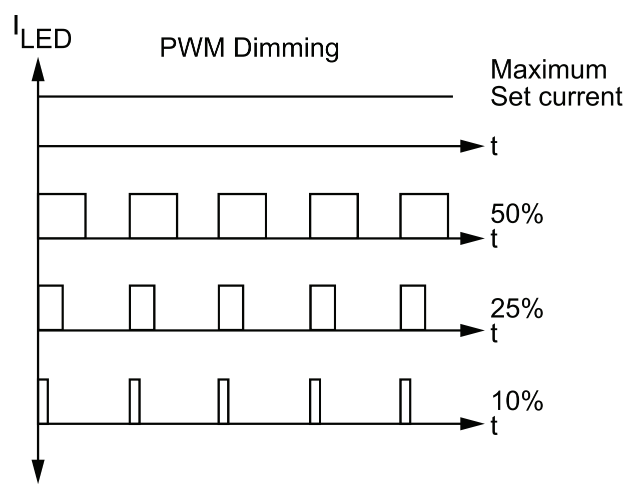

Figure 3: PWM Dimming

THERMAL DERATING FOR ICS WITH DEDICATED CURRENT-SET PIN

Many ICs have a dedicated pin to set output current. Voltage on or current through this pin sets the value of output current.

To set the derating threshold, a thermistor can be used in parallel or in series, depending on the application, with a current-setting resistor, as shown in Figure 4. To enable the derating threshold to be set based on LED temperature, a negative-temperature-coefficient/positive-temperature-coefficient (NTC/PTC) thermistor can be placed near the LEDs.

As soon as temperature increases to greater than the set threshold, the combination of the current-set resistor and the NTC/PTC derate the output current in proportion to the temperature rise.

For example, the Allegro A6274 LED driver IC [1] has ISET pins used to set the output current via six channels. The LED current is controlled by six matching linear current regulators between the VIN pin and each of the LEDx outputs. The nominal output current at each LEDx pin is determined by:

Equation 2:

$$I_{LEDx} = \frac{298}{R_{ISET}}\ ; \text{and}$$

Equation 3:

$$I_{LEDx} = g_{ILED} \times I_{SETx},$$

where g_{ILED} is gain (248 A/A), I_{LEDX} is in mA, and R_{ISET} is in kΩ.

Usually, NTCs are preferred to PTCs. In the circuit shown in Figure 5, as temperature increases, NTC resistance decreases; and, as soon as the threshold is crossed, NTC resistance drops such that current in the IREF pin is dominated more by V_{CC} and output current is reduced.

Using V_{BIAS} = 5 V, V_{REF} = 1.2 V (the voltage reference at the ISET pin), and:

Equation 4:

$$I_{NTC} = \frac{3.8}{R_{NTC}}\ ; \text{and}$$

Equation 5:

$$I_{SET1} = \frac{1.2}{R_{ISET1}} - I_{NTC},$$

Set current = 60 mA, and R_{ISET1} = 5 kΩ.

A derating curve for this circuit, with NTCS0805E3684JXT, is shown in Figure 6. Variation in resistance of NTC and corresponding change in output current is shown in Table 1. The main drawback with such an arrangement is that the derating does not have a sharp knee point; derating starts as soon as R_{NTC} changes. More-accurate control requires additional transistor or operational-amplifier (op-amp) circuitry.

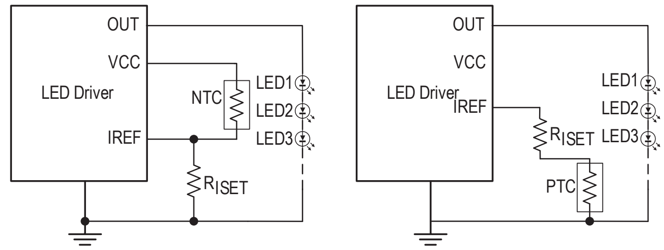

Figure 4: Combinations for Thermistor and R_{ISET} for Derating

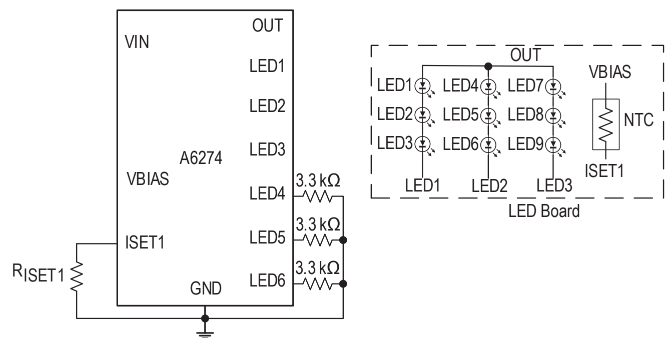

Figure 5: A6274 with NTC

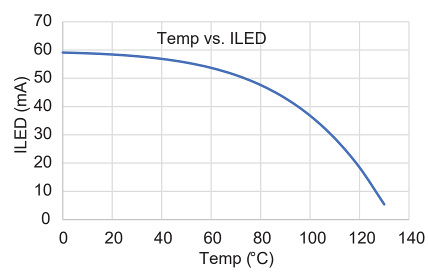

Figure 6: Temperature vs. I_{LED}

Table 1: R_{NTC} vs. Output Current Variation with Temperature

Temp (°C)	R_{NTC} (Ω)	I_{NTC} (µA)	I_{SET1} (µA)	I_{LEDx} (mA)
0	2271498.3	1.673	238.327	59.105
10	1373851.2	2.766	237.234	58.834
20	854123.99	4.449	235.551	58.417
30	544694.97	6.976	233.024	57.790
40	355643.75	10.685	229.315	56.870
50	237332.9	16.011	223.989	55.549
60	161621.74	23.512	216.488	53.689
70	112155.08	33.882	206.118	51.117
80	79204.16	47.977	192.023	47.622
90	56854.96	66.837	173.163	42.944
100	41438.65	91.702	148.298	36.778
110	30635.51	124.039	115.961	28.758
120	22952.42	165.560	74.440	18.461
130	17412.04	218.240	21.760	5.397

[1] https://www.allegromicro.com/en/products/regulate/led-drivers/led-drivers-for-lighting/a6274-a6284

THERMAL DERATING FOR ICS WITH DEDICATED ANALOG DIMMING PIN

An IC with a dedicated analog dimming pin adjusts the sense voltage or output current in proportion to the voltage on the analog dimming pin. This analog dimming pin can be used for thermal derating proportional to the LED temperature.

Consider the circuit shown in Figure 7. Voltage on the analog dimming (ADIM) pin is set by the voltage divider from VCC to ground. The resistor from ADIM to ground can be replaced by an NTC placed near the LED board. As temperature increases to greater than the set threshold, NTC resistance reduces such that ADIM voltage also reduces. As voltage on the ADIM pin decreases, output current decreases in proportion to the LED temperature rise.

For example, the Allegro A80804 LED driver IC [2] has two ADIM pins. ADIM2 is better suited for thermal-derating applications.

A resistor divider from VBIAS to GND can be used to set the desired ADIM voltages. The current-sense reference is 500 mV in the A80804 and 200 mV in the A80804-1.

To use analog dimming with ADIM2, set V_{ADIM2} between 10% and 50% of V_{BIAS}. Derating does not occur when V_{ADIM2} exceeds $V_{BIAS}/2$. To set the ADIM2 voltage, the NTC can be used on an LED board, and feedback can be taken from the NTC (see Figure 9).

Select the value of R_1 such that V_{SENSE} = 0.5 V at the knee point. After the knee point, derating starts according to:

Equation 6:

$$V_{SENSE} = 1.125 \times \frac{V_{ADIM2}}{V_{BIAS}} - 0.0625\,.$$

Here, the derating starting temperature is 100°C, R_{NTC} at 100°C is 6.236 kΩ, and V_{ADIM2} is 2.5 V. For this V_{ADIM2}, R_1 is 6.236 kΩ.

Results for the A80804 with the NTCS0805E3104XT are shown in Table 2 and Figure 10.

Table 2: R_{NTC} vs. V_{ADIM} and V_{SENSE}

Temp	R_{NTC} (Ω)	R (Ω)	V_{ADIM2}/V_{BIAS}	V_{SENSE}
20	125811	6200	0.953	0.500
25	100000	6200	0.942	0.500
50	34897	6200	0.849	0.500
70	16601	6200	0.728	0.500
85	9988	6200	0.617	0.500
98	6300	6200	0.504	0.500
100	6236	6200	0.501	0.500
125	3055	6200	0.330	0.330
150	1610	6200	0.206	0.206

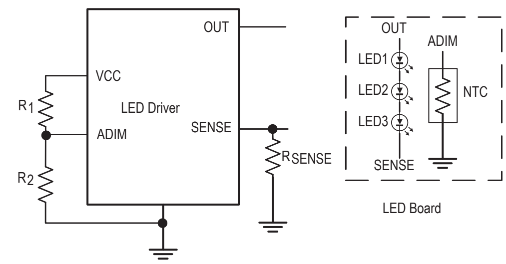

Figure 7: NTC Connection for LED Driver with Separate ADIM Pin

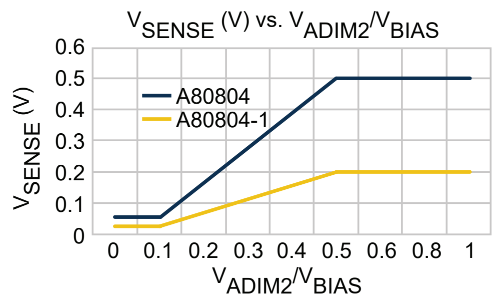

Figure 8: A80804 SENSE Voltage vs. ADIM and BIAS Ratio

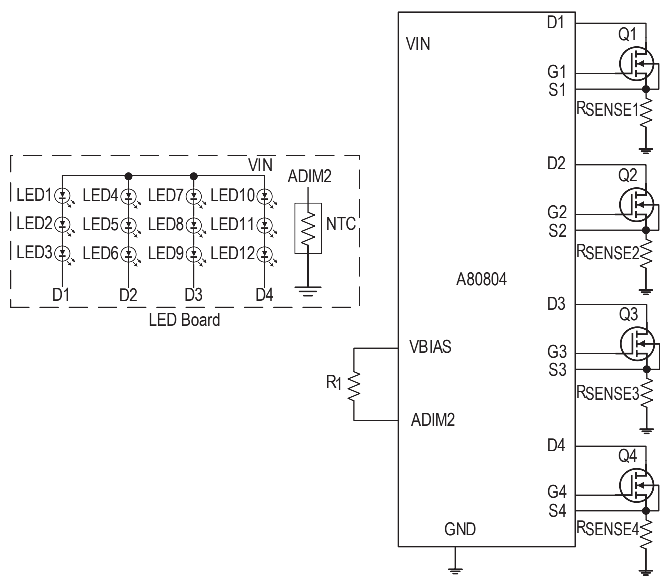

Figure 9: A80804 Thermal Derating Using Analog Dimming

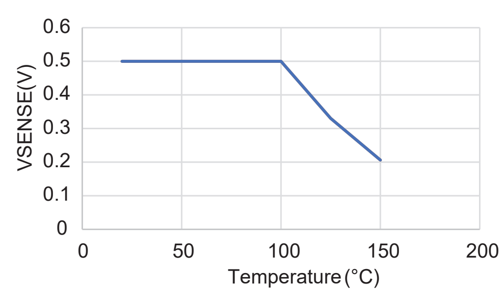

Figure 10: V_{SENSE} vs. Temperature

[2] https://www.allegromicro.com/en/products/regulate/led-drivers/led-drivers-for-lighting/a80804

THERMAL DERATING FOR ICS WITHOUT DEDICATED ANALOG DIMMING PIN

For simplicity, many ICs have only a feedback pin to set or control the output current. Those ICs do not have additional features like dimming. For such ICs, additional circuitry can be added to achieve analog dimming, and this circuitry can also be used for thermal derating. Analog dimming can be achieved in different ways.

Derating Using Transistor in Emitter-Follower Configuration and NTC

A transistor can be used in an emitter-follower mode, with an NTC between the collector and the base terminal. Consider the circuit shown in Figure 11.

Whenever temperature is less than the desired value, R_{NTC} is very high. A transistor used in an emitter-follower configuration has very low voltage on the base pin, which results in the SENSE pin voltage being dominated almost solely by the R_{SENSE} feedback. Hence, if temperature is less than the set value, the IC works with 100% output current set by R_{SENSE}.

As soon as the temperature increases to greater than the set value, R_{NTC} begins to reduce. As R_{NTC} begins to reduce, the base voltage of the transistor begins to increase. As long as the base voltage is less than the emitter voltage, the transistor remains in the off state. When R_{NTC} reduces to a level such that the base voltage increases to greater than the emitter voltage + 0.6 V, the transistor begins to conduct, which results in lower output current proportional to temperature rise.

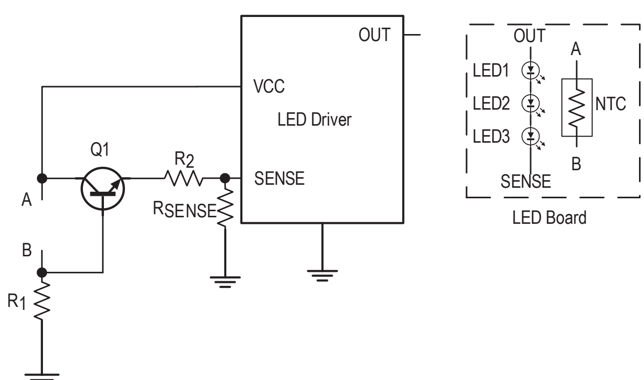

Figure 11: LED Driver with Transistor in Emitter-Follower Configuration and

NTC for Thermal Derating

Example Using [Allegro A6217 Buck Regulator](https://www.allegromicro.com/en/products/regulate/led-drivers/led-drivers-for-lighting/a6217) [3]

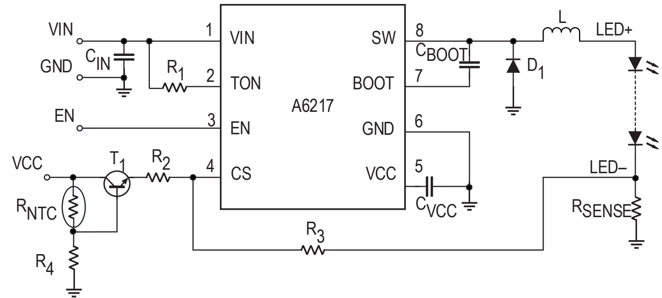

Figure 12: A6217 with Thermal Derating By Control of the Current Sense (CS) Voltage

- Part number of NTC: (NTCS0805E3104XT)
- R_{NTC} = 9.98 kΩ (85°C)
- R_{NTC} = 3.05 kΩ (125°C)
- R_{NTC} = 1.61 kΩ (150°C)
- V_{CC} = 5.3 V
- Design Expectations
  - □ I_{LED} = Full set value up to 85°C
  - □ I_{LED} = 1/2 of set I_{LED} value at 125°C
  - □ I_{LED} = 0 at 150°C
  - □ Above 85°C, I_{LED} decreases linearly
- Definitions
  - □ V_{CE} = Collector-to-source voltage of the transistor
  - □ V_{BE} = Base-to-emitter voltage of the transistor
  - □ V_{CS} = Current-sense voltage of the A6217
  - □ V_B = Base voltage of the transistor
  - □ V_E = Emitter voltage of the transistor
  - □ V_{SENSE} = Voltage across the sense resistor
- Calculations
  At 85°C (i.e., the temperature above which derating begins), using $V_{R4} = V_{CS} + V_{BE} = 0.2 + 0.6 = 0.8$ and:

  Equation 7:

$$V_{R4} = \frac{(V_{CC} \times R_4)}{(R_{NTC@85°C} + R_4)},$$

  R_4 = 1.77 kΩ.

[3] https://www.allegromicro.com/en/products/regulate/led-drivers/led-drivers-for-lighting/a6217

At 150°C (the maximum temperature at which output current is zero):

Equation 8:

$$V_B = \frac{(V_{CC} \times R_4)}{(R_{NTC@150°C} + R_4)} = 2.775V,$$

where $V_E = V_B - V_{BE} = 2.775 - 0.6 = 2.175$ V.

Assuming $R_3 = 1$ kΩ and using:

Equation 9:

$$V_{CS} = \frac{R_3}{(R_3 + R_2)} \times V_E; \text{ and}$$

Equation 10:

$$\frac{R_3}{R_2} = \frac{V_{CS}}{(V_E - V_{CS})} \times V_E,$$

$R_2 = 9.9$ kΩ.

Components can then be selected using:

Equation 11:

$$V_{SENSE} = V_{CS} - \frac{(V_E - V_{CS}) \times R_3}{R_2}.$$

The resulting selected components are $R_3 = 1$ kΩ, $R_2 = 9.9$ kΩ, $R_4 = 1.77$ kΩ, $V_{CS} = 0.2$ V, $V_{BE} = 0.6$ V, and $R_{SENSE} = 0.2$ Ω, selected for 1 A I_{LED}.

When temperature is less than 85°C, V_E remains at 0.2 V. This is because $V_B - V_{BE} < V_{CS}$, so LED current passes through R_{SENSE} only.

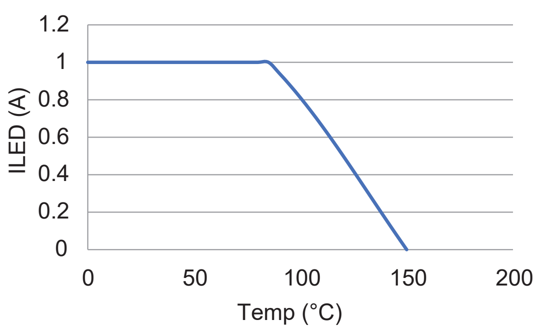

Figure 13: A6217 Thermal Derating, I_{OUT} vs. Temperature

Derating Using Op-Amp and NTC for Better Accuracy

For better accuracy, an alternative to NTC and transistor-based circuit solutions is to use an op-amp to sense the change in temperature.

The op-amp can be used as a differential amplifier. Voltage of the inverting terminal can be set by the resistor divider. Noninverting terminal voltage is variable and set by the NTC.

When temperature is below the set threshold, RNTC is very high; hence, the inverting terminal voltage is very low, and the output of the op-amp is low. The voltage of the CS pin voltage is set by feedback from R_{SENSE} only.

As the temperature rises, R_{NTC} decreases, and noninverting terminal voltage increases. As soon as R_{NTC} goes below the designed value, the output of the op-amp increases such that it supplies the CS pin voltage along with the R_{SENSE} feedback. Output current reduces to protect the LEDs from overheating.

Usually, ICs have internal low-voltage dropouts (LDOs)—namely, V_{CC}, V_{REG}, V_{BIAS}, among others—which have accuracy close to 5%. If better accuracy is needed, the accurate external LDO can be used to set the voltage of the inverting and noninverting pin voltages of the comparator.

Example Using Allegro A6217 Buck Regulator [3]

Consider the Allegro A6217 buck regulator. The A6217 has a CS pin, which senses the voltage across R_{SENSE} and regulates the current via LEDs. Duty cycle is adjusted to maintain the SENSE voltage equal to 200 mV.

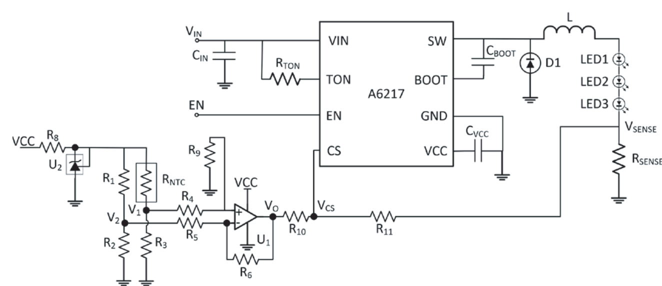

Figure 14: A6217 Buck LED Driver and Op-Amp with LDO for Derating Proportional to Temperature

Known components:

- A6217: Buck-type LED driver
- U1: LM2904 (op-amp)
- U2: TL431 (adjustable LDO)
- Set output voltage for U2 = 2.5 V
- NTC (Thermistor): NTCS0805E3104FXT
- V_{IN} = 12 V, I_{OUT} = 0.8 A
- R_{SENSE} = 0.22 Ω, R2 = 330 Ω

Derating circuit components are calculated using R_{10} = 10 kΩ, R_4 = R_5 = 100 kΩ, R_{11} = 330 Ω, as follows:

1. Select the value of R_3 equal to the value R_{NTC} at the point where derating is expected to start.
   Here, R_{NTC} = 11.78 kΩ at 80°C, so R_3 = 12 kΩ.
   Select R_1 = R_2 = R_3.
2. Calculate V_O of the op-amp circuit as:

   Equation 12:

   $$V_{SENSE} = \frac{V_{CS} \times (R_2 + R_3)}{R_3} - \frac{V_O \times R_2}{R_3}.$$

   For example, because current is expected to derate by half when temperature is 125°C, V_{SENSE} is 100 mV, and V_{CS} = 200 mV (equivalent to the voltage level that the IC tries to maintain on the CS pin), resulting in a calculated value of V_O = 3.23 V.
3. Calculate the value of feedback resistor R_6 at the point where the end-point derating should take place, using R_9 = R_6, and:

   Equation 13:

   $$V_O = \frac{R_6}{R_5} \times (V_1 - V_2),$$

   where V_2 is set by the resistor divider formed by R_1 and R_2, as R_1 = R_2, V_2 = 1.25 V.

   Here, at 125°C, R_{NTC} = 3.055 kΩ because R_3 = 12 kΩ and V_1 = 1.9927 V.

   From Equation 13, R_6 can be calculated as R_6 = 440 kΩ.

The final component values are:

- Starting point for derating = 80°C, R_{NTC} at 80°C = 11.78 kΩ
- End point for derating = 125°C, R_{NTC} at 125°C = 3.055 kΩ
- R_3 = 12 kΩ, feedback resistor, R_6 = R_9 = 440 kΩ

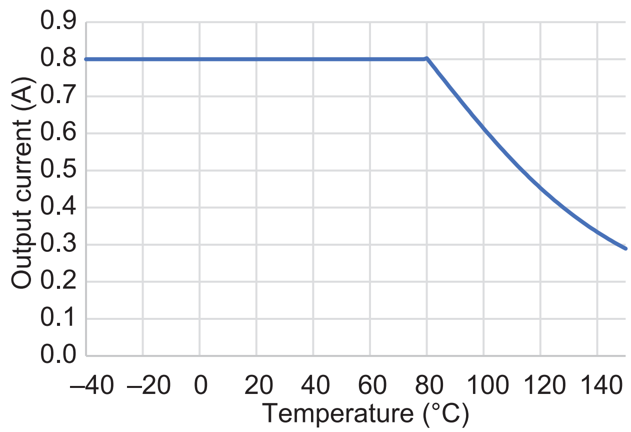

Figure 15: A6217 Temperature vs. Output Current

THERMAL DERATING FOR ICS WITH INTERNAL PWM DIMMING OPTION

Many different LED driver ICs operate with an external PWM dimming signal; and many have the capability to generate an internal PWM dimming signal that can be used for PWM dimming of the LEDs. For such ICs, the internal PWM dimming option is used to set the frequency of the PWM signal by controlling the resistance from the frequency-setting pin to ground. The duty cycle of the PWM signal is usually set by adjusting the voltage on the duty-setting pin of the IC or the resistance from the duty-setting pin to ground.

Additional circuitry can be added to adjust the duty cycle as required for thermal derating. NTC feedback can be used to set the resistor value of the V_{DR} pin. The NTC can be placed at the system where temperature monitoring and derating are required.

Consider the example of the Allegro A80804 four-channel linear LED driver, shown in Figure 16. The A80804 has a VDR pin. The voltage on the VDR pin sets the internal PWM dimming duty cycle.

The PWM duty cycle depends on the ratio of the voltage at the VDR and VBIAS pins. For better accuracy, use a voltage divider from VBIAS to VDR. The internal duty cycle range is 2% to 90%. Refer to Figure 17.

Equation 14:

$$Duty = 146 \times \frac{V_{VDR}}{V_{VBIAS}}$$

Depending on the LED temperature, feedback to the VDR pin can be derived in many ways. A simple and cost-effective solution can be an NTC, as shown in Figure 16.

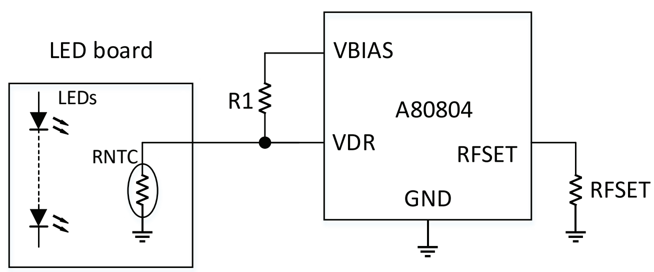

Figure 16: A80804, 100% Duty Cycle During Typical Operation and Thermal Derating Using PWM Dimming

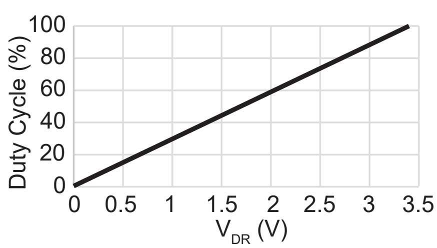

Figure 17: A80804 VDR Pin Voltage vs. Duty Cycle

When temperature is less than the rated value of the NTC:

- The resistance of the NTC is very high.
- V_{DR} has voltage close to V_{BIAS}.
- The IC operates with 100% duty cycle (no PWM dimming).

As soon as temperature increase beyond the set value:

- R_{NTC} begins to decrease proportionally to the temperature rise.
- V_{DR} begins to decrease.
- The decrease in V_{DR} reduces the duty cycle proportionally to the temperature rise.
- The reduced duty cycle causes a reduction in the average current flowing via the LEDs, keeping the peak current constant.

Hence, when temperature exceeds the rated value of the NTC, the average output power reduces, which results in a reduction in temperature.

The total range for the duty cycle reduction is 100% to 2% for the Allegro A80804. V_{DR} can be varied from 0 to 3.6 V for 0 to 100% duty. For voltage, with greater than 3.6 V on V_{DR}, duty remains at 100%.

Consider the circuit shown in Figure 16. Set R_1 such that, when temperature reaches the derating threshold, V_{DR} = 3.6 V. Consider this example using:

- Expected start of derating = 80°C
- NTC (Thermistor) = NTCS0805E3104FXT
- NTC resistance at 80°C = 11.78 kΩ
- V_{BIAS} for A80804 = 5 V
- Set I_{OUT} = 1 A

Using:

Equation 15:

$$V_{DR} = \left(\frac{R_{NTC}}{R_1 + R_{NTC}}\right) \times V_{BIAS}$$

R_1 = 4.6 kΩ. Duty/output current vs. temperature are shown in Figure 18.

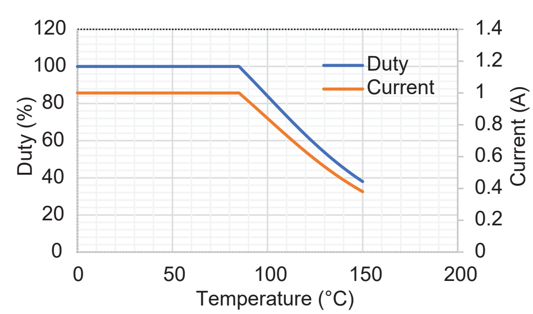

Figure 18: A80804 Thermal Derating Using Internal PWM Dimming Feature

HOW TO SELECT THE NTC

Thermal Resistance (θ)

LED manufacturers provide information about the LED thermal resistance. Thermal resistance dictates rise in the junction temperature above ambient temperature per watt of power dissipation (in units of thermal resistance °C/W).

The junction-to-ambient thermal resistance (θ_{JA}) is specified by most LED manufacturers, given by:

Equation 16:

$$\theta_{JA} = \left(\frac{T_J - T_A}{P}\right)$$

where:

- θ_{JA}: Junction-to-ambient thermal resistance, °C/W—depends on various factors, such as PCB design, LED construction, air flow, etc.
- T_J: Junction temperature of the chip.
- T_A: Ambient temperature.
- P: Power dissipated by the device.

Knowing these four parameters and the maximum desired LED temperature, the Allegro NTC Thermal Derating spreadsheet [4] can be used to select the NTC.

CONCLUSION

Thermal-derating techniques designed to safeguard LEDs are dependent on the temperature of the LEDs. Use of analog and PWM dimming features in LED drivers that can reduce LED temperature and extend LED life has been detailed in this application note, including:

1. Introduction to how the life of an LED is dependent on temperature.
2. Overview of analog and PWM dimming techniques, including advantages and disadvantages of both.
3. Thermal derating for ICs that have a separate current setting pin, and analog dimming using a dedicated current-setting pin.
4. Thermal derating for ICs that have a separate analog dimming pin.
5. Thermal derating for ICs that do not have a separate analog-dimming pin:
   A. Using a transistor in an emitter-follower configuration.
   B. Using a separate op-amp circuit.
6. Thermal derating using PWM dimming techniques for ICs that include the PWM dimming option.

The Allegro NTC Thermal Derating spreadsheet [4] can be used to select an application-specific NTC.

[4] https://www.allegromicro.com/-/media/files/application-notes/NTC-Thermal-Derating

Revision History

Number	Date	Description	Responsibility
–	May 16, 2025	Initial release	S. Gadgil