

# **LED Temperature Protection by Vf Monitoring**

*Florent Muret, Olivier Mellin*

## **ABSTRACT**

LEDs are often driven in current. As temperature increases, LEDs are gradually driven with less current to save them from premature aging and protect them from thermal damage. This regulation often requires external sensors while the forward voltage of LEDs ( $V_f$ ) varies with temperature monotonically. Moreover, similarly to PN junctions in processors,  $V_f$  is a better image of the LED temperature as there is no thermal inertia or thermal resistance that comes into play. Modern LED drivers like the [TPS929120-Q1](#) monitor LED  $V_f$  to diagnose faults like open/short. This application report shows that it is possible to use this forward voltage to monitor the temperature with accuracy and perform thermal foldback without an external sensor or a conditioning circuit. This application report also provides an application example of how to use this solution with a next generation LED driver, the [TPS929120-Q1](#), and explains how it is possible.

## **Contents**

1	Introduction .....	2
2	Challenges in Today's Design .....	2
3	Using LED Forward Voltage as a Sensor .....	3
4	$V_f$ vs Temperature .....	5
5	Global Process .....	8
6	LED Aging Effect on the Forward Voltage.....	8
7	Using $V_f$ as a Temperature Sensor with TPS929120-Q1 .....	9
8	How to Program MCU to Perform Thermal Foldback Using $V_f$ .....	12
9	Conclusion .....	16

## **List of Figures**

1	Basic Process in Automotive Lighting for LED Temperature Protection .....	2
2	Derating Curve Current in LED vs Temperature .....	3
3	Monitoring the Full LED String .....	3
4	Monitoring One LED.....	3
5	Relative Forward Voltage vs Junction Temperature .....	5
6	Forward Current vs Forward Voltage (Red) <sup>2</sup> .....	5
7	Relative Forward Voltage vs Junction Temperature at Different Currents .....	6
8	Coefficient a Slope .....	6
9	Coefficient b Slope .....	6
10	Coefficient c Slope.....	6
11	Relative Forward Voltage vs Temperature .....	7
12	Relative Forward Voltage vs Temperature with Different Duty Cycle - 200 mA Peak Current.....	8
13	$V_f$ vs Temperature-aged LED .....	9
14	Aged LED $\Delta V_f$ Error Compared to a Reference .....	9
15	TPS929120-Q1 One Channel, Amplifier, and Resistor Saving While Using LED $V_f$ .....	10
16	Temperature Calculated with $V_f$ Compared to an Accurate Sensor Reference .....	11
17	Simulation NTC Slope with 5 V Regulated Voltage and Resistor Divider Bridge.....	12
18	Slope 1 k $\Omega$ Resistor.....	12

19	Slope 10 kΩ Resistor .....	12
20	Basic Process: Proof of Concept with a Microcontroller .....	13
21	MSP430 Code Routine Steps for Thermal Derating.....	13
22	Error Evolution Compared to the TMP107 Over Time .....	15
23	Error Evolution Compared to the TMP107 Over Time .....	15

**List of Tables**

1	Precision Table Depending on the ADC on a Range of 25°C–100°C for a Typical Red LED .....	4
2	Result for 75 mA Drive with a 10 LED String on TPS929120.....	11
3	Components Used for Simulation .....	11

**Trademarks**

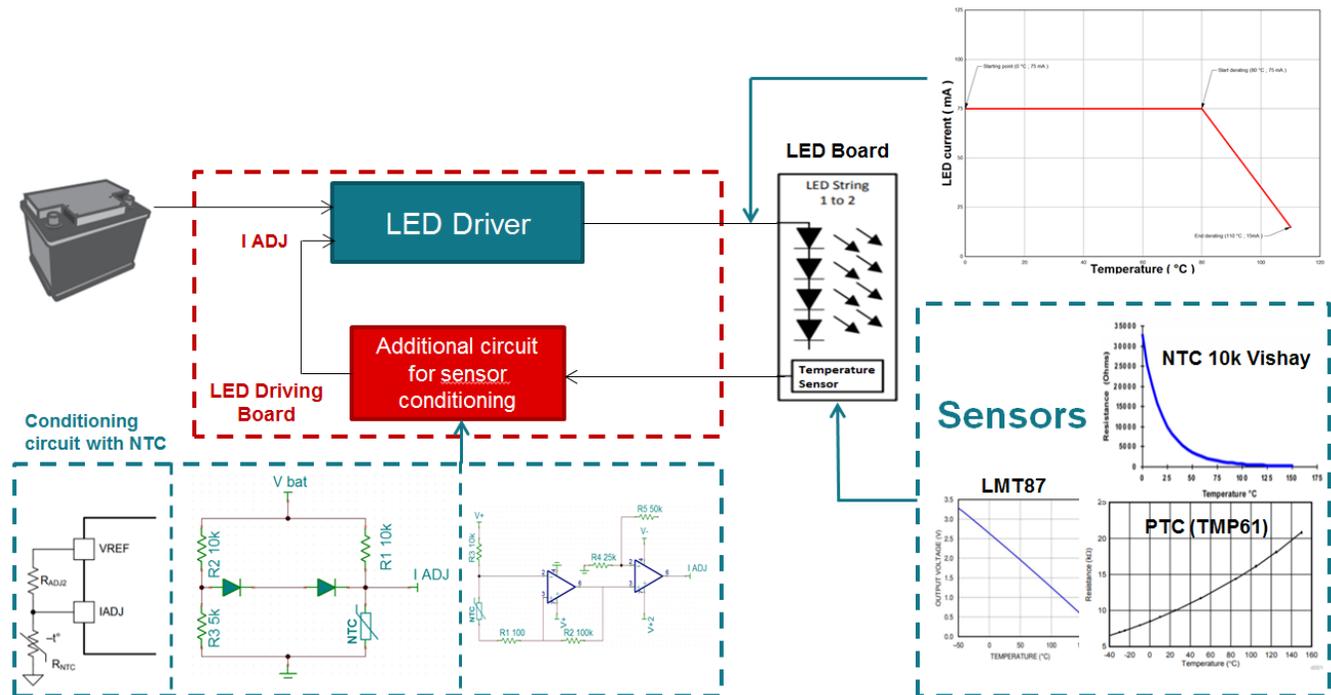
All trademarks are the property of their respective owners.

**1 Introduction**

As the LED forward voltage decreases monotonically while temperature increases, instead of using an external sensor, this application report proposes a way of using this forward voltage in order to sense the temperature and protect those LEDs from being damaged at high temperatures. The main advantage of this method is that it permits removing the temperature sensor on the LED board as well as its conditioning circuit, which can be significant in terms of cost and size. Moreover, the forward voltage gives an exact image of the temperature inside the LED unlike an NTC, which senses the board temperature.

**2 Challenges in Today's Design**

When LEDs are driven at high temperatures, they suffer from irreversible damage in terms of efficiency and lumen flux, therefore, need to be replaced. To avoid this, in most applications, the LED board includes one or several temperature sensors, depending on the size of the PCB. When the sensor detects that the temperature reaches a pre-defined limit, the current gradually decreases in order to cool down the LED. Most of the time, the temperature is monitored by NTC or PTC, mainly because of its cheap cost, and the current derating is completed either by passives (resistors, diodes) or potentially even an op amp.



**Figure 1. Basic Process in Automotive Lighting for LED Temperature Protection**

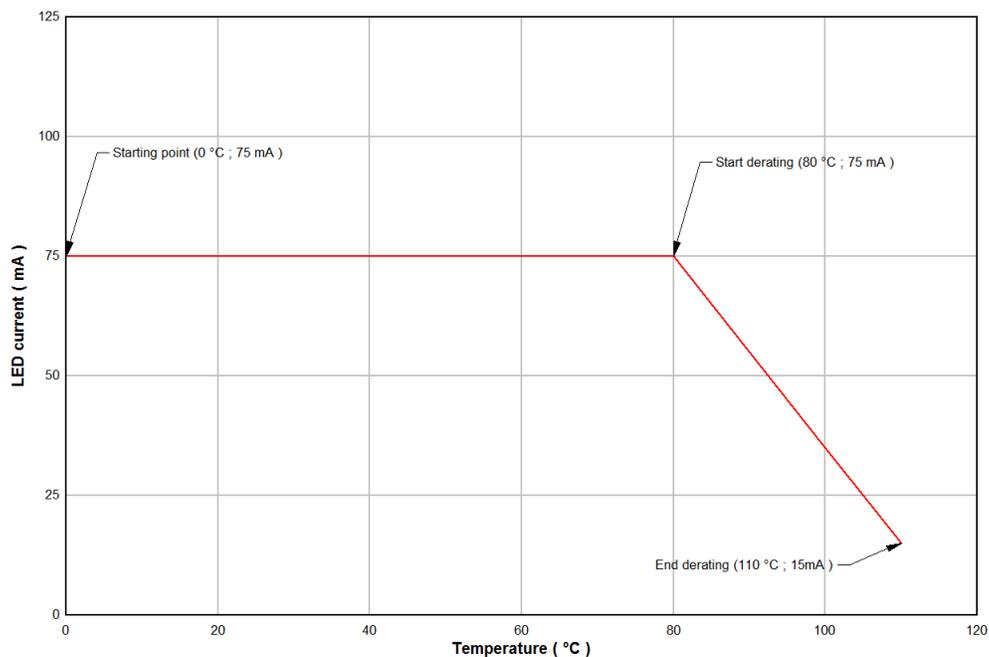
The thermal foldback (reduction of the LED current from a certain temperature) can be designed with discrete components biasing the Iset PIN voltage of a LED driver (the Iset pin regulates the output current), but it requires at least an operational amplifier and some resistors in order to linearize the slope. Moreover, sometimes the manufacturer requires a second operational amplifier to increase the derating slope. The thermal foldback can be performed using an ADC combined with the PWM dimming to decrease the LED current.

### 2.1 The Main Characteristics of the Thermal Foldback Curve

The typical foldback curve is characterized by three points which are each described by a current and a temperature per Figure 2:

- **Starting point:** The nominal current flowing into the LED before the trigger of the thermal foldback. At this temperature, the LED protection starts.
- **Start derating:** The current value before it starts to decrease. At this temperature, the thermal foldback starts.
- **End derating:** This is the final current value. At this temperature, the current reduction is stopped.

Figure 2 provides a quick overview about the regulation slope which sums up those parameters.



**Figure 2. Derating Curve Current in LED vs Temperature**

Today's temperature sensing is mostly done using NTC or PTC. They both have their own accuracy which are typically  $\pm 2.5^{\circ}\text{C}$  for PTC and between  $\pm 0.5\%$  and  $\pm 5\%$  for NTC. In addition, they measure the ambient or PCB temperature rather than the internal LED temperature, which the Vf does naturally.

In any case, there is a need for a temperature sensor and all the extra components needed to fulfill the circuit requirements: resistor, diode, and amplifier. Moreover, it adds extra engineering time. The design challenge is to reduce the cost and the size of the board as much as possible. This application report provides a guide about how to use the LED Vf as a temperature sensor and its drawback.

### 3 Using LED Forward Voltage as a Sensor

The LED forward voltage can be used in analog using a threshold with an amplifier and resistor. Due to the non-linearity of the slope, it may be easier for the processing to use an ADC to sample the Vf value. There are two ways to connect the ADC:

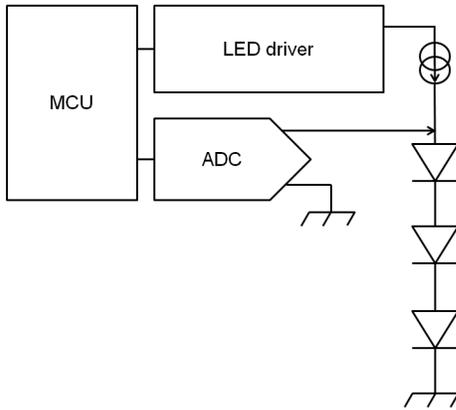


Figure 3. Monitoring the Full LED String

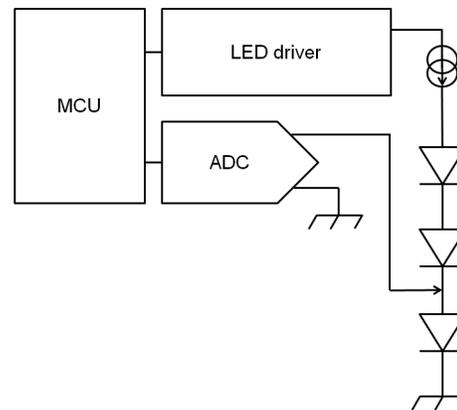


Figure 4. Monitoring One LED

- Monitoring the full LED string:** It allows an image of the temperature in the LED string by creating an average of all the LEDs forward voltage. The additional benefits are that the ADC input range is optimized (for high Vref ADC) and faults diagnostic can be completed similar to the [TPS929120-Q1](#) (single LED short, short to the ground, short to bat, and so forth). Nevertheless, if one LED gets hotter than the others on the string, it cannot be detected.
- Monitoring one LED per string:** It permits to have a perfect image of the temperature on one LED, but if there is one part of the string that is damaged, it cannot be detected, but the averaging and the LED string diagnostic are lost.

The critical parameters of the ADC are then the input range and the effective resolution. While monitoring a string of LED, the ADC range has to be as close as possible to the maximum voltage of the LED strings (at the lowest temperature).

Depending on the LED drive, the Vf can change with temperature from a few mV to hundreds of mV on the range of 25°C–100°C for a red LED. This voltage variation is even bigger for green and blue LEDs, which makes the measurement more accurate.

To illustrate this, [Table 1](#) shows a typical red LED. The Vf variation with temperature from 25°C–100°C is 80 mV for a 25 mA drive and 140 mV for a 200 mA drive. [Table 1](#) shows the precision in °C for one LSB depending on the ADC resolution.

Table 1. Precision Table Depending on the ADC on a Range of 25°C–100°C for a Typical Red LED

ADC FEATURES		PRECISION IN °C PER LSB	
ADC range (V)	Bits	Min variation = 80 mV	Max variation = 140 mV
2.5 V (1 LED)	8	9.1	5.2
	10	4.5	2.6
	12	2.2	1.3
10 V (4 LEDs in series)	8	9.1	7.0
	10	4.5	3.4
	12	2.2	1.7

The precision in °C can be calculated with [Equation 1](#):

$$Precision_{ADC} = \frac{temperature_{range}}{\frac{2^N}{V_{range}} \times Nb_{LED} \times V_{ref\,variation}}$$

where

- Temperature range is the considered range of temperature
- N is number of bit of the ADC
- Nb LED is the number of LED in the strings
- Vref variation is the difference of Vref from the start of the range to the end

(1)

Later, this application report uses a 12-bit ADC with a 2.5-V Vref and an 8-bit ADC with a 20.5 V Vref to compare the results.

#### 4 Vf vs Temperature

Beyond temperature, LED forward voltage mainly depends on three parameters:

- **Aging:** If aging affects the Vf, the delta Vf vs. temperature slope remains the same. See [Section 6](#) for more details.
- **Input current:** The higher the current flowing into the LED is, the higher the forward voltage across the junction is.
- **PWM:** When using PWM current instead of linear current, the Vf variation is higher and the linearity is affected.

Also, the color of the LED has a great influence on Vf value as well as the Vf vs. temperature slope. The typical red LED has a nominal Vf at 25°C around 2 V whereas the Vf of the blue and green LED is around 3 V. The variation is even greater for blue and green as can be seen in [Figure 5](#).

Here is a typical curve of Vf vs. temperature at a nominal current (recommended operating current for a certain LED). The forward voltage is often referred to as relative to its 25°C value per [Equation 2](#):

$$\Delta V_f = V_f - V_{f_{25^\circ\text{C}}} \tag{2}$$

[Dominant S8RTB](#) provides some typical I/V and Vf/Temperature curves for RGB LEDs.

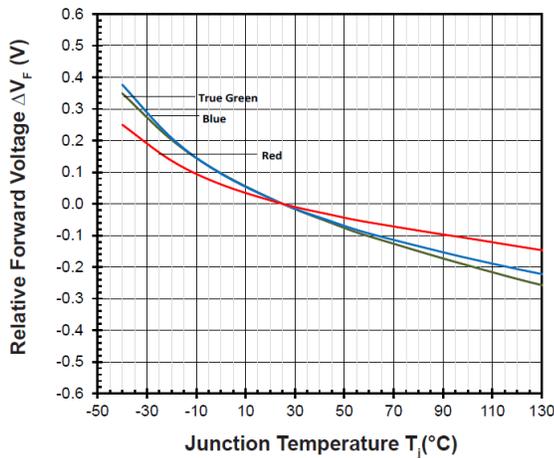


Figure 5. Relative Forward Voltage vs Junction Temperature

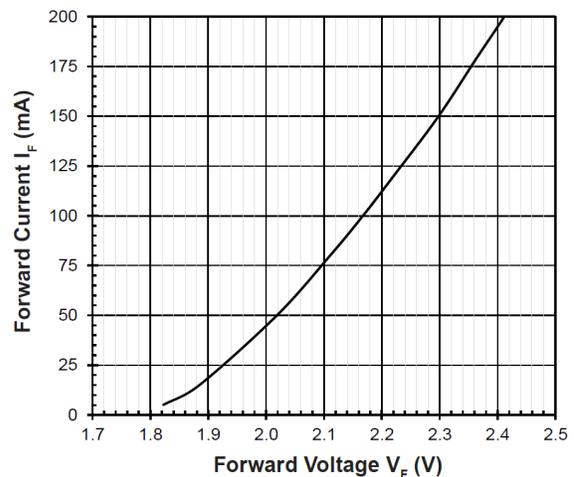


Figure 6. Forward Current vs Forward Voltage (Red)<sup>2</sup>

Notice that on the range of 30°C–130°C, the shape of the curve is pretty linear, which is interesting as the derating often occurs in that region.

#### Constant current:

As previously mentioned, the behavior of the forward voltage over temperature depends on the current flowing into the junction. The data was collected from the LED [LR G5AP](#).

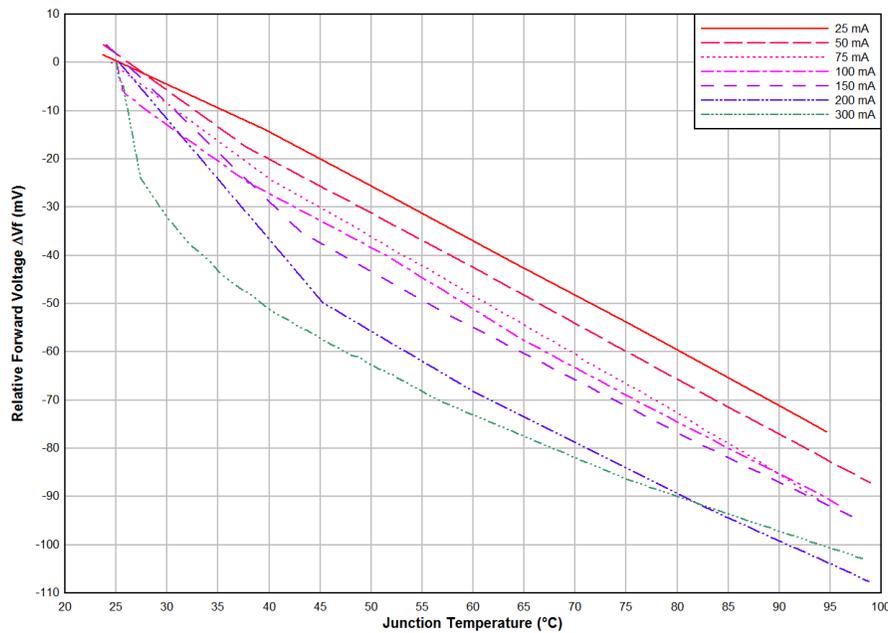


Figure 7. Relative Forward Voltage vs Junction Temperature at Different Currents

As seen in Figure 7, when the current is low, the curve has good linearity whereas when the driven current is higher, the slope gets curvy, which is mostly due to the fact that the LED is getting more intrinsic heat from the current flowing through its PN junction.

A second order equation can be used to define the variation of Vf vs temperature:

$$\Delta V_f = ax^2 + bx + c$$

where

- $\Delta V_f$  is the relative forward voltage (mV)
- $x$  is the temperature ( $^{\circ}\text{C}$ )

(3)

Those three coefficients are calculated based on the trendline of the previous calibration slope. Specifically for the LED LR G5AP, the a, b, and c coefficients vary with current per Figure 8–Figure 10.

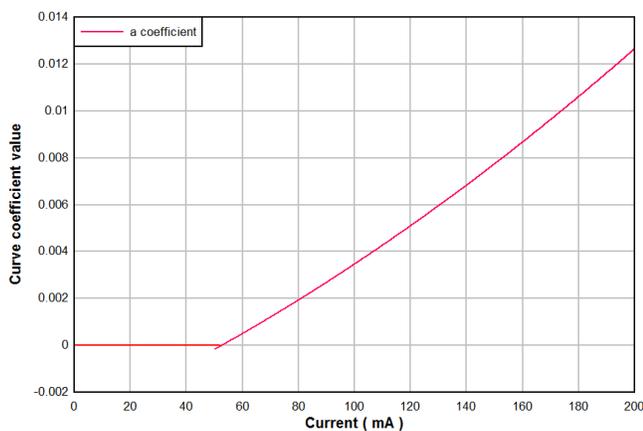


Figure 8. Coefficient a Slope

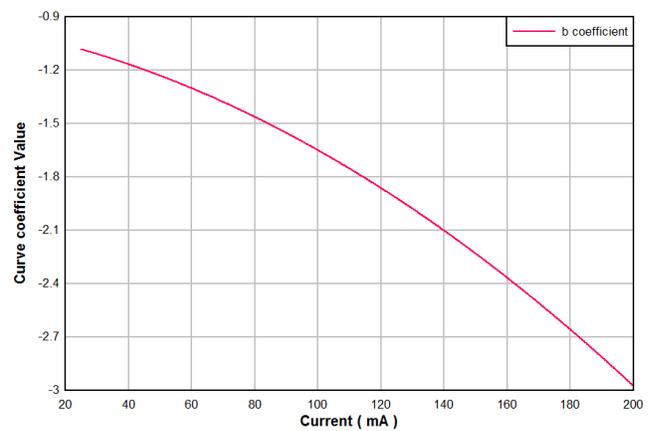


Figure 9. Coefficient b Slope

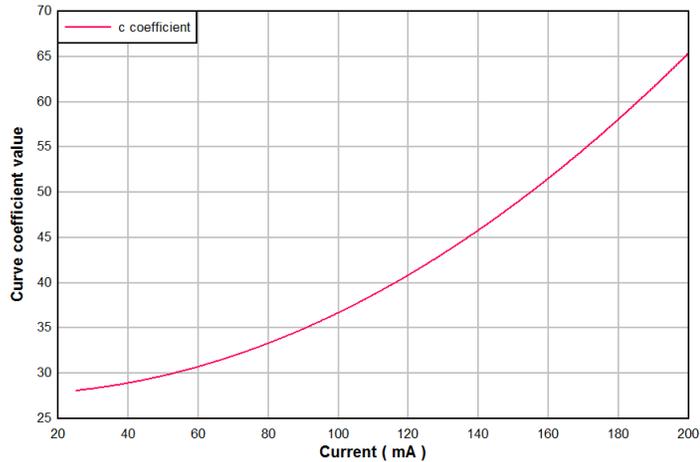


Figure 10. Coefficient c Slope

For example, if the requirement is a 120 mA drive, then the slope equation is:

$$\Delta V_f = 0.005x^2 - 1.85x + 41 \tag{4}$$

#### 4.1 PWM Current

A common way of modulating the LED current is to pulse current through the LED. Then keeping the peak current constant, varying the ON and OFF period makes the average current change. This is commonly referred to as PWM driving. The PWM frequency has to be above what the human eye can perceive. Industries usually pick a frequency between 24 Hz and 1.5 KHz.

Using PWM to drive the LED has its own influence on the Vf vs temperature.

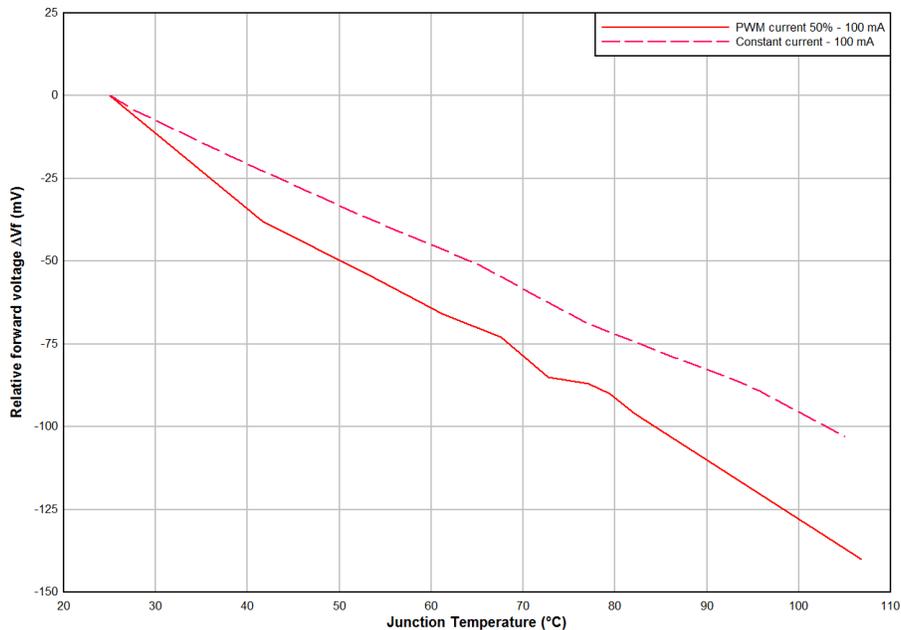
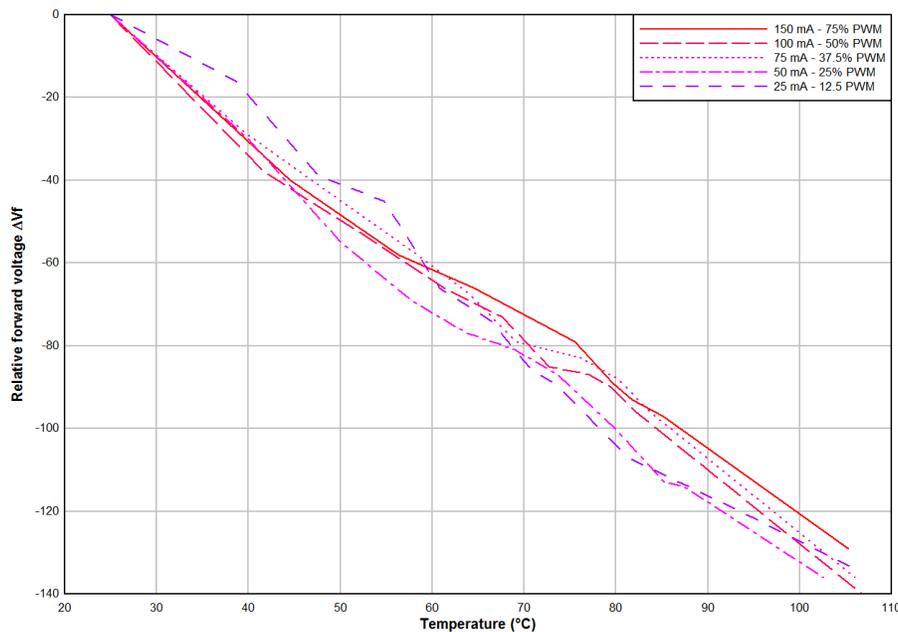


Figure 11. Relative Forward Voltage vs Temperature

In Figure 11, while using the same LED with the same average current (100 mA), the slopes are different. Notice that the PWM current (200 mA peak with 50% duty cycle) creates a bigger  $\Delta V_f$  than the 100 mA constant current.

On the other hand, once driving with PWM current, varying the duty cycle while keeping the same peak current (hence the varying the average current), the curve does not vary significantly. Once the peak current is set, the dimming does not create a significant variation as seen in [Figure 12](#).



**Figure 12. Relative Forward Voltage vs Temperature with Different Duty Cycle - 200 mA Peak Current**

In order to have better accuracy, it is recommended to perform the characterization for the application-specific dimming and peak current value.

## 5 Global Process

This section gives an overview about the suggested process in order to use the LED Vf for temperature sensing and explains which parameters are required.

The first step is to calibrate the forward voltage at the ambient temperature (25°C) with the application-specific current parameters (PWM or constant current, and current value) per LED reel, as it permits to calculate the  $\Delta V_f$  slope. Because  $(V_f - V_{f@25^\circ C}) = f(T^\circ)$  remains the same no matter what, Vf bins are received from the LED supplier for a given LED reference.

Then the next challenge is to get an accurate  $(V_f - V_{f@25^\circ C}) = f(T^\circ)$ . There are two options for this step:

- **Use the LED datasheet:** The curve provided by the datasheet can be used if the test conditions are clearly specified, namely the operating current (PWM, constant, peak current, and temperature range). It is likely less accurate but it saves the calibration experience.
- **Perform the measurement:** Take the exact  $\Delta V_f$  vs temperature slope by testing the LED in an oven or an oil bath. A suggested setup is to bias the LED with the current requirements corresponding to the application, respect thermal balance time, and measure the Vf with an accurate voltmeter.

Once the calibration point is at 25°C and the  $\Delta V_f$  vs temperature slopes are collected, Vf can be used as a temperature with an MCU able to measure the  $\Delta V_f$  vs temperature.

## 6 LED Aging Effect on the Forward Voltage

One of the main things that needs to be checked to measure the temperature using the LED forward voltage is that the behavior does not change over time due to the wear out.

In order to get an idea about how much error LED aging brings, the following test was performed. Six different LEDs from the same bin were submitted to different wear out conditions without any surface cooling, not even PCB, in order to compare the relative forward voltage vs junction temperature curve at the end of the test. The LED used was the [LR G5AP](#).

The following was the process that was used:

- Three LEDs kept as a reference to compare with the aged ones
- One LED aged during one week at 300 mA
- One LED aged during two weeks at 300 mA
- One LED aged during three weeks at 300 mA

The LEDs were driven with a constant current three times greater than the nominal current (300 mA on each LED) in order to speed up the aging. A 300 mA drive leads an LED temperature to 70°C.

Figure 13 and Figure 14 show the results of these tests.

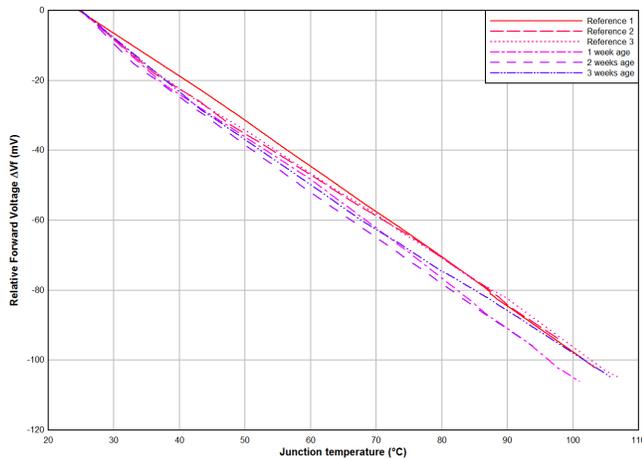


Figure 13. Vf vs Temperature-aged LED

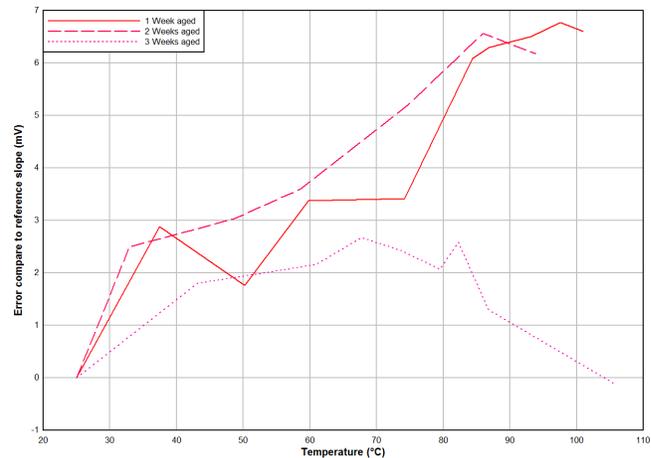


Figure 14. Aged LED  $\Delta V_f$  Error Compared to a Reference

After being aged during three, two, or even one week with three times the nominal current, they lost a significant amount of luminosity, which means they are so aged that they are no longer usable.

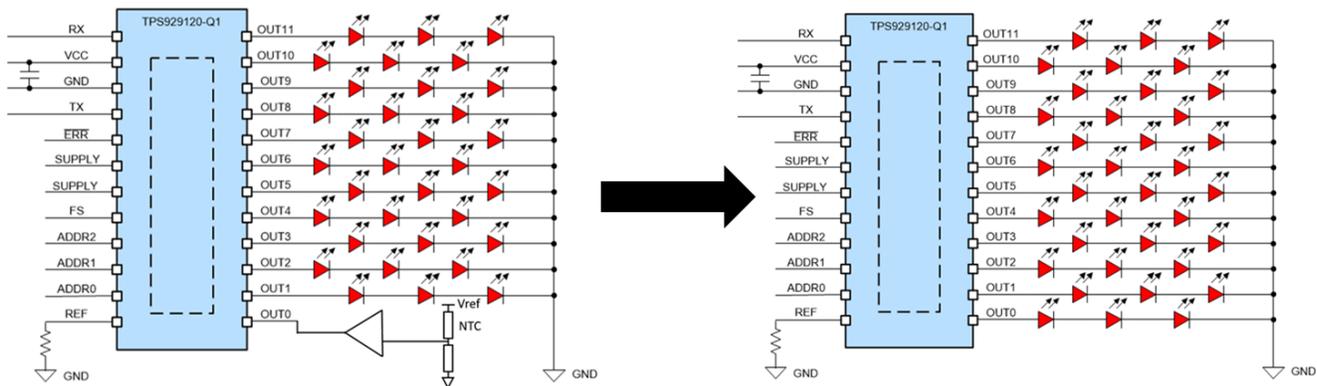
As seen in Figure 13, the slope remains the same shape, but due to wear out, it creates a small gap with the reference slope. Figure 14 shows the error of the three aged LEDs compared to the merge of the three references LED is represented. The error can go up to **6.5 mV**, which corresponds to an error of **5°C**.

For the scope of this application report, a 5°C error after severe aging is considered as acceptable, so aging is not regarded as a factor that needs to be corrected.

## 7 Using Vf as a Temperature Sensor with TPS929120-Q1

This section gives an example about how it is possible to integrate this method to a modern LED driver, the **TPS929120-Q1**. This next generation 12-channel automotive 40-V highside LED driver with FlexWire interface (UART-based) integrates an 8-bits ADC, which originally aims at LED diagnostic (LED open-circuit, LED short-circuit, and single-LED short-circuit). The FlexWire interface is designed as a robust Off board protocol to communicate with the MCU located on another board. As the MCU is not located on the same board, there may be nothing to digitize the temperature and send it to the MCU other than the TPS929120-Q1. The MCU may collect the temperature reading from different LED boards over FlexWire, and in return sends the variable PWM duty cycles.

Moreover, the TPS929120 does not have a dedicated input for NTC as other **TI LED drivers** may have, hence the following options. Using LED forward voltage to monitor temperature is a more cost-effective solution in order to save one LED driving channel as well as resistors, operational amplifier, and NTC, as shown in Figure 15.



**Figure 15. TPS929120-Q1 One Channel, Amplifier, and Resistor Saving While Using LED Vf**

This section of the application report explains how to design Vf as a temperature sensor with the TPS929120Q1.

Here are the details of the application parameters that are used for this example:

- ADC 8 bits, ADC input range = 20.5 V, which leads to a resolution of 80 mV
- LED bias constant current at 75 mA
- 10 LEDs in series (LR G5AP), forward voltage at 75 mA and 25°C = 1.98 V, leading to a 19.8 V, which is as close to the ADC range of 20.5 V as possible
- [TMP107](#) as a reference sensor, in order to compare the temperature obtained with the forward voltage of LEDs

As mentioned before, to perform temperature monitoring by Vf measurement, the first requirement is to have  $\Delta V_f = f(T^\circ)$  and the Vf at 25°C. [Section 6](#) gave a guide to calculate the equation curve for the LR G5AP, depending on the current as those equations were expressed as  $V_f = f(T)$ . Since the temperature is the desired parameter, the equation needs to be reversed, and become  $T = f(V_f)$ , which can be easily done using Excel or a calculator. The main equation becomes:

$$\text{Temperature} = 0.0009x^2 - 0.6901x + 23.836$$

where

- Temperature is in °C
- x is the relative forward voltage  $\Delta V_f = V_f - V_{f\_25^\circ\text{C}}$  (mV)

Then if temperature derating needs to be performed per [Figure 2](#), the MCU processes (every one min for instance) the Vf measured by the ADC of the TPS929120 in [Equation 5](#). Once the temperature gets above 80°C, the program starts to reduce the current (by modifying register `lout2 = 0 × 02`). As linear derating from 75 mA to 0 mA is used in this application, an offset can be applied depending on the LED current setting (-0.25 per mA), due to the linearity of the different Vf vs temperature curves as shown in [Figure 7](#). For example, instead of driving at 75 mA, the current is set at 50 mA. The offset becomes:

$$\text{Temperature} = 0.0009x^2 - 0.6901x + 23.836 + 0.25 \times (75 - 50) \quad (6)$$

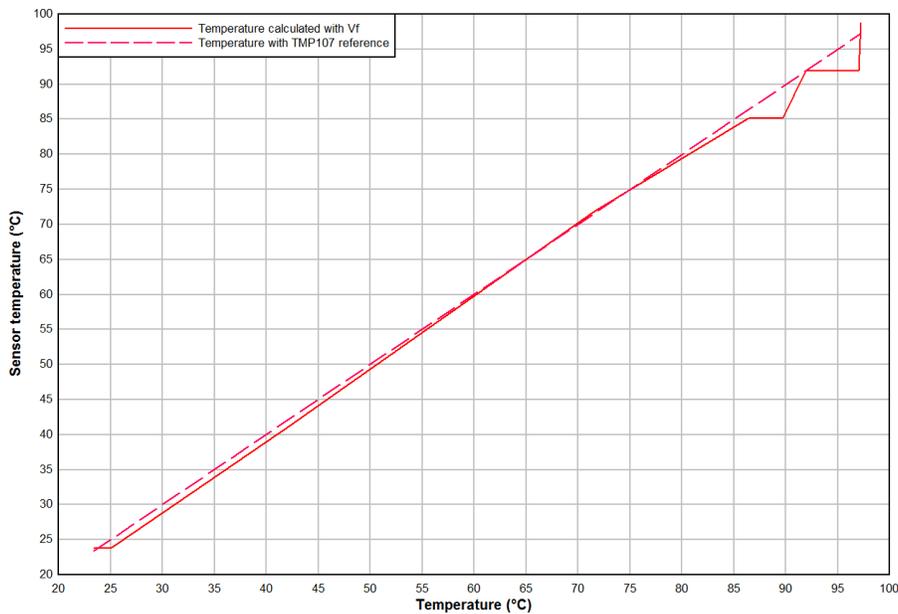
$$\text{Temperature} = 0.0009x^2 - 0.6901x + 23.836 + 6.25 \quad (7)$$

Since a 10 LED string is used, the accuracy of one LED is now  $80 \text{ mV}/10 = 8 \text{ mV}$ . For a 8 mV error, according to the curve, the temperature error must be around 7°C, depending on what temperature the measurement is taken at.

[Table 2](#) shows the data obtained after warming up the LED string and comparing the temperature calculated via the TPS929120-Q1 Vf measurement compared to the temperature measured with the [TMP107](#).

**Table 2. Result for 75 mA Drive with a 10 LED String on TPS929120**

ADC SAMPLE - 75 mA - V_supply A 20.50 V			
ADC read	ADC-based temperature (°C)	ADC Value converted (V)	Temperature TMP107 (°C)
248	23.83	20.0065	23.4
248	23.83	20.0065	25
245	41.00	19.7653	42
240	71.94	19.3633	71.65
238	85.13	19.2025	86.4
<b>238</b>	<b>85.13</b>	<b>19.2025</b>	<b>89.7</b>
<b>237</b>	<b>91.90</b>	<b>19.1221</b>	<b>91.93</b>
<b>237</b>	<b>91.90</b>	<b>19.1221</b>	<b>94.5</b>
<b>237</b>	<b>91.90</b>	<b>19.1221</b>	<b>97</b>
236	98.79	19.0417	97.26



**Figure 16. Temperature Calculated with Vf Compared to an Accurate Sensor Reference**

The error is around 7°C, which is mostly due to the ADC resolution. Nevertheless, it permits a ±3.5°C accuracy, which depends on the TMP107 accuracy (±0.4°C). From 85°C, the shape of the curve is becoming representative of the error, as the deduced temperature takes the form of steps.

**Alternative solution using NTC:**

In order to compare the results with an NTC-based method, Table 3 and Figure 17 provide a simple simulation as well as a schematic of what must be used to perform thermal foldback in the use case of the TPS929120-Q1. Here are the components used:

**Table 3. Components Used for Simulation**

Typical NTC used in automotive	<a href="#">NTCG163JF103HTDS</a>
Regulated Voltage for NTC + Resistor: 2 options	From TCAN transceiver which contain an internal LDO: <a href="#">TCAN1162x-Q1</a>
	Low-cost LDO with same input voltage than the TPS929120-Q1: <a href="#">TPS7B69xx-Q1</a> or <a href="#">LM9036Q-Q1</a> are recommended.

The simulation aims to show the output voltage range that the ADC can get depending on the resistor value. For this simulation, the temperature range is from -20°C to 100°C.

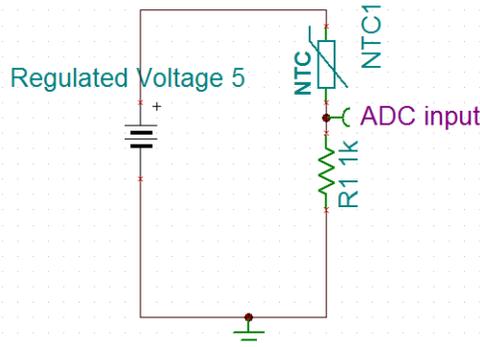


Figure 17. Simulation NTC Slope with 5 V Regulated Voltage and Resistor Divider Bridge

Figure 18 and Figure 19 show the results depending on the resistor value.

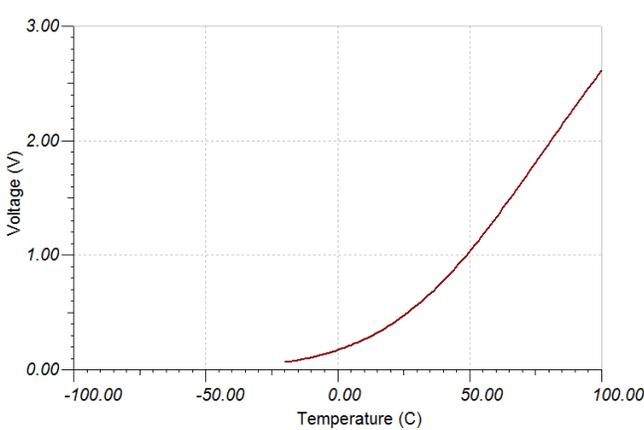


Figure 18. Slope 1 kΩ Resistor

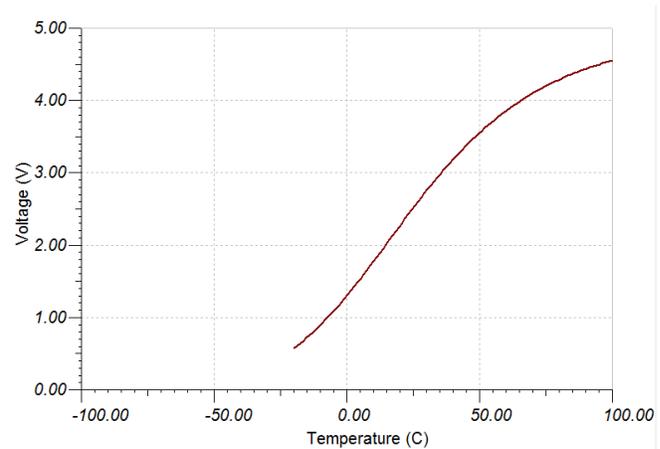


Figure 19. Slope 10 kΩ Resistor

- 1 kΩ Resistor: The curve is linear on the range of interest (50°C–100°C). Nevertheless, the ADC input voltage only goes from 60 mV to 2.61 V, which gives a maximum accuracy of **2.66°C** on this linear zone, using the internal 8-bit ADC of the TPS929120-Q1.
- 10 kΩ Resistor: The slope has a greater range of 570 mV to 4.55 V, but the linearity is not so good. This solution can be improved through better linearity or higher signal voltage variation.

Better linearity can be obtained using an additional amplifier circuit specifically to improve this aspect. Higher signal voltage variation can be improved by changing the bias voltage of the resistance divider or again by using an amplifier. A typical amplifier for this function is the [OPA377-Q1](#) or [LM2904B](#).

## 8 How to Program MCU to Perform Thermal Foldback Using Vf

This section details the general process and gives an example on how to write a simple code using a [MSP430F5529](#) to perform thermal foldback using the forward voltage of the LED or LED string.

The 12-bit ADC of the MSP430 is used to sense. It also has different reference voltage, which can be selected. In this application, the 2.5 V reference voltage is used to get as close as possible to the forward voltage of the LED used: **1.825 V at 100 mA**.

The main purpose of this section is to show that by simply entering a few parameters and using a simple program, it is possible to perform a thermal foldback by using the forward voltage of the LED.

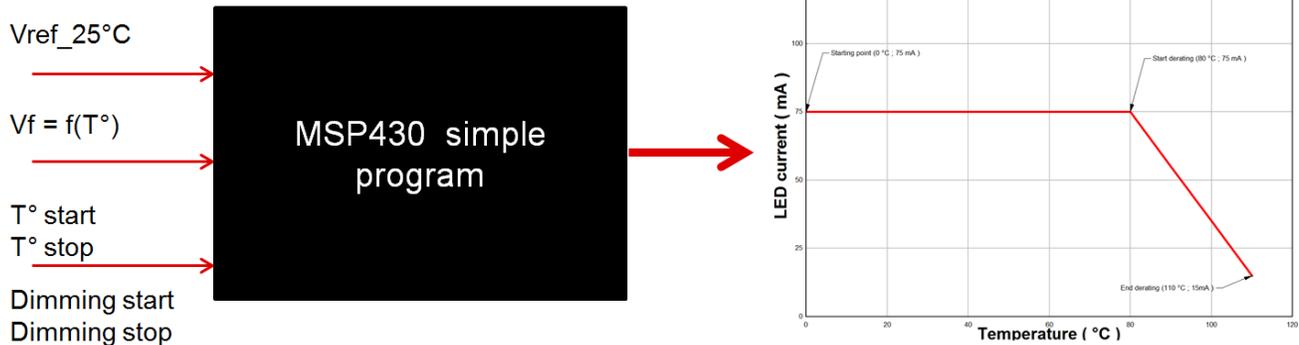


Figure 20. Basic Process: Proof of Concept with a Microcontroller

As shown in Figure 20, the parameters are:

- The calibration point value: the forward voltage at ambient temperature (25°C)
- The forward voltage = f (junction temperature) slope equation with the specific conditions (current, dimming)
- The two points of the derating slope (temperature and current):
  - Temperature starting derating, nominal current
  - Temperature stopping derating, ending current

The process can be divided in to two steps. The first one, when there is no derating, consists of monitoring the temperature only. The second one is when the derating occurs.

- No derating: during this period, the current and slope equation remain the same. As explained before, it can be determined by using the datasheet or a calibration.
- Derating: the LED driver (TPS92611-Q1) is driven by the MSP430 with the PWM dimming signal. If the application requires a linear current, an offset needs to be added depending on the current used at the moment. As seen above, the  $\Delta V_f$  vs temperature does not vary much with PWM duty cycle, but in case of linear dimming, an offset must be added, as described in Section 7.

Figure 21 shows the code flow diagram.

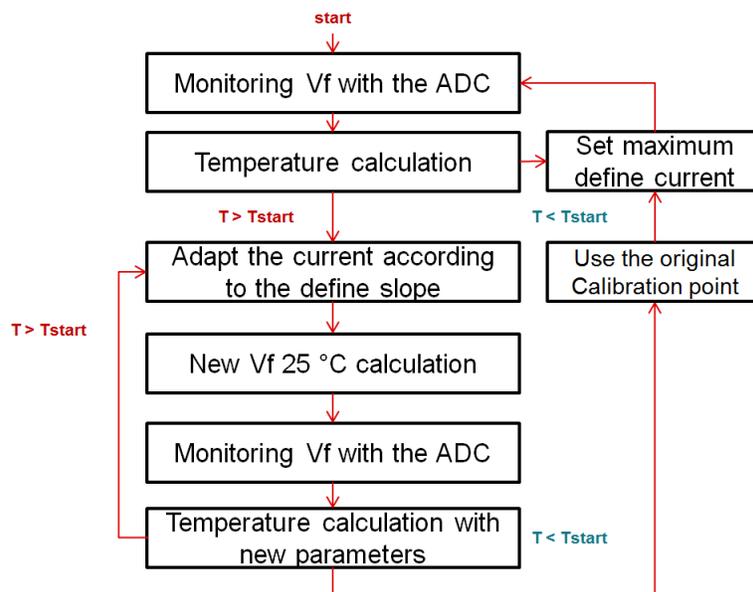


Figure 21. MSP430 Code Routine Steps for Thermal Derating

The following are the main parameters definition, routine, as well as the two important functions in C code.

### Main parameters:

```
//----- MAIN PARAMETERS-----
float Vf_25C = 1825;          //in mV

float start_dimming = 0.53 ; // in %
float start_derating = 80;   // in °C

float stop_dimming = 0;      // in %
float stop_derating = 100;   // in °C
//-----
```

The previous portion of code describes the main parameters as explained in [Figure 19](#).

### Main routine:

```
//----- ADC -----
for ( p= 0 ; p<10; p++){
    ADC12_A_startConversion(ADC12_A_BASE,ADC12_A_MEMORY_0,ADC12_A_SINGLECHANNEL);
    while (!ADC12_A_getInterruptStatus(ADC12_A_BASE,ADC12IFG0)) ;
    result = ADC12_A_getResults(ADC12_A_BASE,ADC12_A_MEMORY_0);
    volt = result * 0.0006105 * 1000;      //converting data in mV
    sum = sum + volt;                      // average of 10 datas
}
average = sum / 10;                       //Vf average in mV
//-----

*data_treatment = update_PWM_duty(current_PWM, sigma, average,
Vf_25C,start_dimming, start_derating , stop_derating, stop_dimming);

data_temp = buffer[0];                    // get the temp data
current_PWM = ( *data_treatment[0] );     // get the PWM ratio to set

//----- UPDATE PWM-----
__delay_cycles(7750);
param.dutyCycle = current_PWM ;           //update PWM (or not )
Timer_A_outputPWM(TIMER_A1_BASE, &param);
__delay_cycles(117750);
//-----
```

First, the ADC takes 10 samples of the forward voltage and then calculates the average. Afterward, the `update_PWM_duty` function updates the PWM, depending on which temperature is obtained through the Vf calculation.

### update\_PWM\_duty function:

```
float * update_PWM_duty(int current_PWM, float sigma,float Vf, float Vf_25C,float
start_dimming, float start_derating , float stop_derating,float stop_dimming ){

float PWM_cycle = 0;
float temperature = 0;
float ratio, x,y;
ratio = current_PWM / TIMER_PERIOD ;
float data[2];

temperature = convert_Vf_to_temp(Vf,Vf_25C,current_PWM);

if (temperature > start_derating && temperature < stop_derating){
    // derating slope calculation -----
    y = (start_dimming - stop_dimming) / (start_derating - stop_derating);
    x = - ( (y * start_derating) - (start_dimming) );

    PWM_cycle = temperature * y + x ; //calculate
    PWM_cycle = PWM_cycle *4000;
}
}
```

```

if (temperature < start_derating){ //start derating condition
    PWM_cycle = start_dimming * 4000 ;
}

data[0] = PWM_cycle ; // send through function
buffer[0] = temperature ; // send through pointer

return data;
}

```

The `update_PWM_duty` changes the PWM output (or not) if the temperature calculated through the Vf is higher than the limit. Then, it calculates the equation of the derating slope with the two points from the basic parameters (starting point and ending point), and adapts the PWM duty cycle. On the other hand, if the temperature is lower than the limit, the PWM duty cycle stays the same.

#### **convert\_Vf\_to\_temp function:**

```

float convert_Vf_to_temp(float Vf, float Vf_25C , int PWM) {

    float temp = 0 ;
    float facteur=0, dimming_factor =0, Vf_normalised=0, ratio=0, Vf_at_25=0, delta = 0;
    float former_temp = 0 ;

    former_temp = buffer[0]; //take the former_temp

    dimming_factor = (PWM * 0.00025) ; // dimming factor
    Vf_at_25 = 1266.2 * dimming_factor +1097; //Vf 25°C calculation
    according to the datasheet
    Vf_normalised = Vf - Vf_at_25 ; //relative Vf

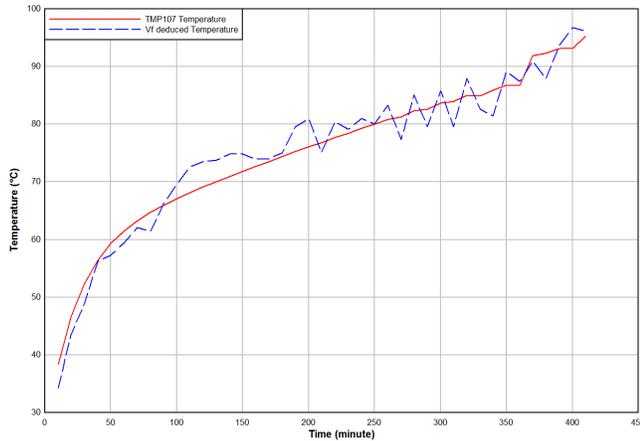
    if (former_temp > 80 ){ // if derating
        temp =(-0.0025 * Vf_normalised * Vf_normalised -
0.995*Vf_normalised + 24.45 ) ;
    }
    else {
        temp =(-0.5130 * Vf_normalised + 29 ) ; //define slope
    }
    return temp;
}

```

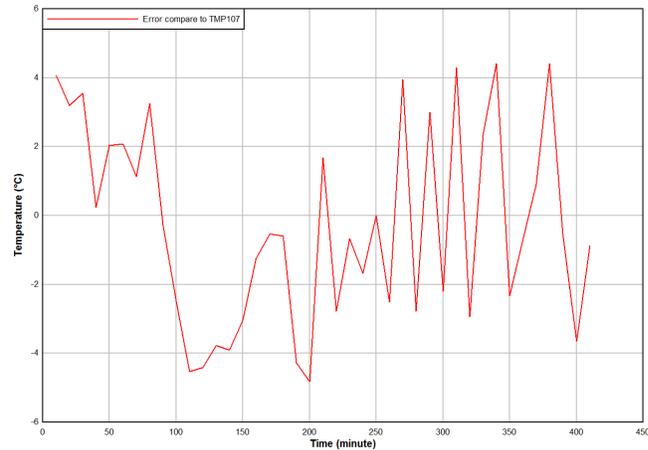
This function calculates the temperature depending on the PWM parameters. It first starts by calculating the Vf\_25°C if the PWM was modified before. It also stores the former temperature calculated. If the former temperature is above the derating threshold, the program uses another slope, more accurate to fit with the data.

#### **Results:**

In order to know the accuracy of the system, the temperature that was measured using the MSP430 code and the LED forward voltage with an accurate sensor are compared with the [TMP107](#) ( $\pm 0.4^{\circ}\text{C}$ ), while performing derating.



**Figure 22. Error Evolution Compared to the TMP107 Over Time**



**Figure 23. Error Evolution Compared to the TMP107 Over Time**

As previously shown, the monitoring is getting less accurate when the current derating is triggered. This is due to the fact that while using PWM, the equation should be changed slightly and the code does not accommodate for it as shown in [Figure 12](#). Nevertheless, notice that the accuracy is  $\pm 4.2^{\circ}\text{C}$ .

## 9 Conclusion

This method allows thermal foldback, saving the need for thermal resistance when the system requires a really low cost solution. The thermal foldback behavior is specific on each application, and the more calibration and correction that is done, the more accurate the measure is (PWM, aging, and so forth).

In this paper, the tests were performed by using a heating resistor to heat up the LEDs. In addition, thermal paste was added to increase the heat conductivity. The setup was placed inside a polystyrene box in order to avoid convection flux, and to create a thermal balance. Between each measurement, the thermal resistor was supplied with a fixed amount of power during 10 minutes to let the thermal balance happen. After those 10 minutes, the measure was taken, and the power inside the resistor was increased again to reach the next thermal step.

Better test techniques (oven, oil bath) lead to better thermal balance and, therefore, definitively increases the accuracy of the measurements. Moreover, in this paper, the tests were performed by using red LEDs. Since the blue and green LEDs have a higher forward voltage variation across temperature, the accuracy increases as well.

The aim of this experiment was to have an idea of what kind of accuracy can be reached using LED Vf as a temperature sensor. With a reasonable level of engineering, a suitable level of accuracy for most applications can be reached.

## IMPORTANT NOTICE AND DISCLAIMER

TI PROVIDES TECHNICAL AND RELIABILITY DATA (INCLUDING DATA SHEETS), DESIGN RESOURCES (INCLUDING REFERENCE DESIGNS), APPLICATION OR OTHER DESIGN ADVICE, WEB TOOLS, SAFETY INFORMATION, AND OTHER RESOURCES "AS IS" AND WITH ALL FAULTS, AND DISCLAIMS ALL WARRANTIES, EXPRESS AND IMPLIED, INCLUDING WITHOUT LIMITATION ANY IMPLIED WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE OR NON-INFRINGEMENT OF THIRD PARTY INTELLECTUAL PROPERTY RIGHTS.

These resources are intended for skilled developers designing with TI products. You are solely responsible for (1) selecting the appropriate TI products for your application, (2) designing, validating and testing your application, and (3) ensuring your application meets applicable standards, and any other safety, security, regulatory or other requirements.

These resources are subject to change without notice. TI grants you permission to use these resources only for development of an application that uses the TI products described in the resource. Other reproduction and display of these resources is prohibited. No license is granted to any other TI intellectual property right or to any third party intellectual property right. TI disclaims responsibility for, and you will fully indemnify TI and its representatives against, any claims, damages, costs, losses, and liabilities arising out of your use of these resources.

TI's products are provided subject to [TI's Terms of Sale](#) or other applicable terms available either on [ti.com](http://ti.com) or provided in conjunction with such TI products. TI's provision of these resources does not expand or otherwise alter TI's applicable warranties or warranty disclaimers for TI products.

TI objects to and rejects any additional or different terms you may have proposed.

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265  
Copyright © 2022, Texas Instruments Incorporated