AN1978

SEPIC LED Driver Demo Board for Automotive Applications

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INTRODUCTION

This application note describes a circuit developed as an LED driver solution for automotive applications. The flexible control capabilities of Microchip's PIC16F1769 8-bit microcontroller allow the LED driver to maintain constant LED current, provide enhanced dimming performance, increase the lifespan of the LEDs and add safety features.

The use of the core independent peripherals (CIP) of the PIC16F1769 permits the LED driver's power train to operate in a Fixed-Frequency Continuous Conduction mode and regulate the LED current using Peak Current mode control.

The core independent and on-chip peripherals used in this design are:

- Complementary Output Generator (COG)
- Comparator (CMP)
- Programmable Ramp Generator (PRG)
- Operational Amplifier (OPA)
- Data Signal Modulator (DSM)
- Fixed Voltage Reference (FVR)
- Digital-to-Analog Converter (DAC)
- Timers (TMR)
- Pulse-Width Modulation (PWM)
- Capture Compare PWM (CCP)
- Analog-to-Digital Converter (ADC)

These core independent peripherals are combined with other on-chip peripherals to perform functions autonomously with minimal core intervention and can alter system performance for faster response time, freeing the core to perform other tasks. Because of the PIC microcontroller CIPs that control the SEPIC power train, the current regulation is completely automatic with no software overhead and the protection features operates its tasks independently.

The solution described in this application note has the following performance specifications and key features (see Table 1).

TABLE 1: PERFORMANCE SPECIFICATION

Symbol	Parameter	Min.	Typical	Max.
V_{IN}	Operating Input Voltage Range	6V	30V	48V
V_{OUT}	LED String Voltage	3V		50V
I_{LED}	LED String Average Current	100 mA	350 mA	400 mA
h	Efficiency @ 12 V_{IN}, Full dimming		82%	
F_{SW}	Switching Frequency		350 kHz	
V_{UVLO}	Input Undervoltage Lockout Threshold	6V	—	7.5V
V_{OVLO}	Input Overvoltage Lockout Threshold	23V	—	24V
V_{OOVP}	Output Overvoltage Protection Threshold		34V	
LED_{OTW}	LED Temperature Warning	90°C	—	100°C
LED_{OTP}	LED Temperature Protection	90°C	—	124°C

Key Features

- Fully-Compensated High Bandwidth Peak Current Control
- PWM Dimming Control
- Transient and Reversed Input Voltage Protection
- Input Under- and Overvoltage Protection
- Output Overvoltage Protection
- Short-Circuit Protection
- Over Temperature Protection
- Fault Output Indicator
- Automatic BIN (Brightness Index Number) Detection

SEPIC CONVERTER

The LED driver's power train used in this application note is based on the Single-Ended Primary Inductance Converter (SEPIC). This hybrid DC/DC converter topology is an attractive LED driver solution for automotive applications because the SEPIC can provide a regulated output voltage or current even if the input supply voltage goes below or above the output voltage while providing a non-inverted output referring to the same ground potential as its input. When the automotive electrical supply voltage drops below the LED's voltage during cold crank, or rises above the LED's voltage during load dump, the SEPIC can maintain the LED current constant.

Another advantage of the SEPIC in this application is its capability to handle sustained short circuit conditions at its output without power losses, component stress or overheating as the coupling capacitor Cc (Figure 1) quasi-isolates input and output by default when the main switch Q5 is not operated.

THEORY OF OPERATION

FIGURE 1: SEPIC LED DRIVER SIMPLIFIED SCHEMATIC

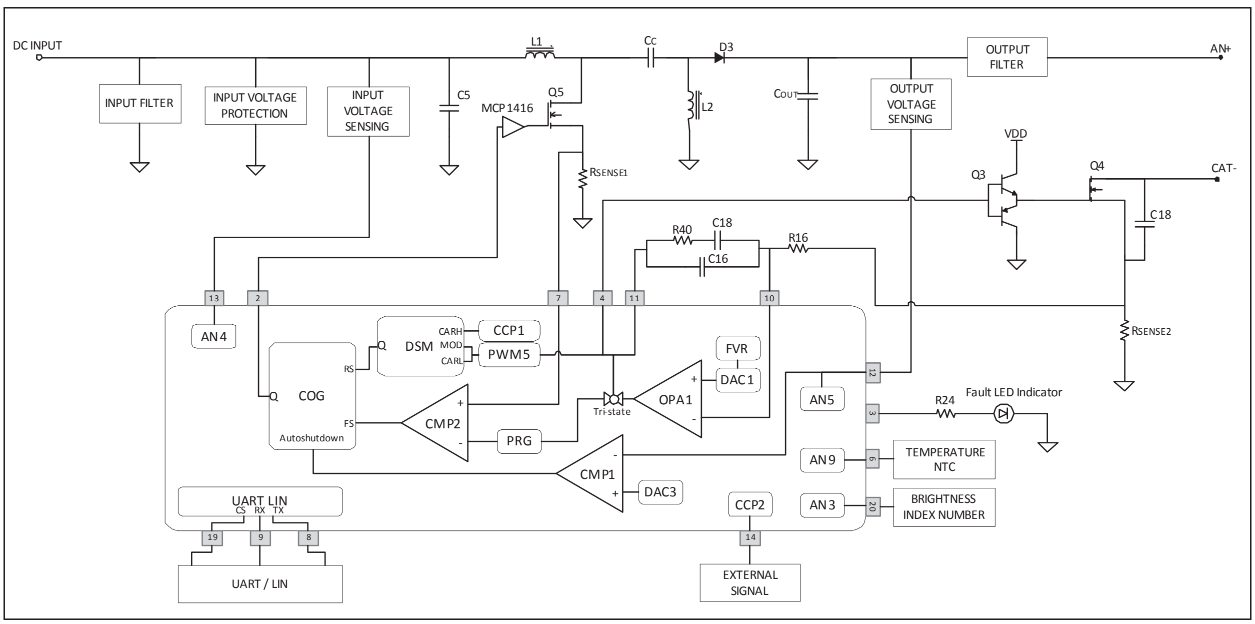
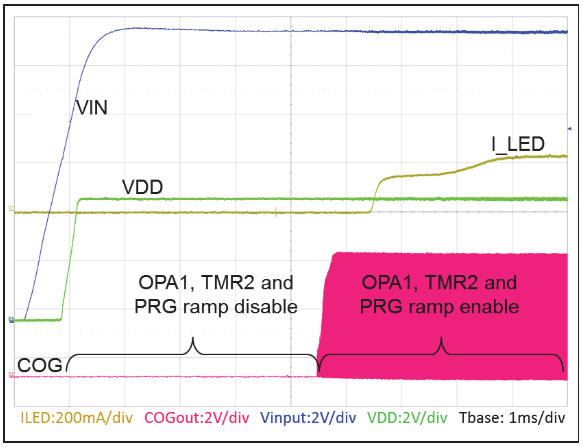


Figure 1 shows the simplified schematic of the LED driver. The whole circuit is controlled by the PIC16F1769 microcontroller, using its on-chip peripherals. The main function of the LED driver is to keep the converter output current or the LED current constant no matter how the automotive electrical supply and the LED equivalent resistance varies. The constant current provided by the LED driver maintains the color temperature of the LED.

Upon applying a positive DC voltage at the input of the LED driver to initiate the circuit start-up, the VDD voltage of PIC16F1769 is increasing. (The setup for the LED driver demo board for proper operation is discussed in **Section Appendix A: "Getting Started"**). When the VDD is high enough (usually the minimum VDD of the microcontroller) and the clock frequency of the microcontroller is stabilized, the FVR, DACs, CMPs, COG, Timers, PWM, CCPs, OPA1, ADC, EUSART, PRG and DSM peripherals are initialized and connected together. After the initialization, the OPA1 and the TMR2 are still disabled, and the PRG ramp is not started. The firmware initializes the Fault protection threshold values, the converter status and values, and the Binning class before enabling the OPA1, TMR2 and PRG ramp. Upon enabling the peripherals and the Fault thresholds are overcome, DSM and CMP2 provide an output that triggers the rising and falling source of COG. The COG delivers a PWM signal which drives the input of the MCP1416 MOSFET driver to turn On/Off Q5, repeatedly. See Figure 2 for the COG output timing during start-up.

FIGURE 2: START-UP WAVEFORM



As mentioned earlier, the LED driver, which is based on the SEPIC converter topology, operates in Continuous-Conduction mode. Just like other converter topologies, the SEPIC in Continuous Conduction mode assumes two states per switching cycle at the Steady State condition. In the On state, the COG out is high and Q5 is On; while in the Off state, the COG out is low and Q5 is Off.

During the On state, the input voltage charges the inductor L1 while the coupling capacitor CC charges L2. The output diode D3 is reverse-biased and COUT is left to supply the load current. The voltage across the L1 and L2 at this state are defined by Equation 1 and Equation 2, respectively.

EQUATION 1: VOLTAGE ACROSS L1 DURING ON STATE

$$V_{L1ON} = V_{IN}$$

EQUATION 2: VOLTAGE ACROSS L2 DURING ON STATE

$$V_{L2ON} = V_{Cc}$$

During the Off state, VIN recharges CC. The energy stored in L1 and L2 forces the current to flow through D1 and through the output while replenishing COUT. At this state, Equation 3 and Equation 4 represent the voltage across L1 and L2, respectively.

EQUATION 3: VOLTAGE ACROSS L1 DURING OFF STATE

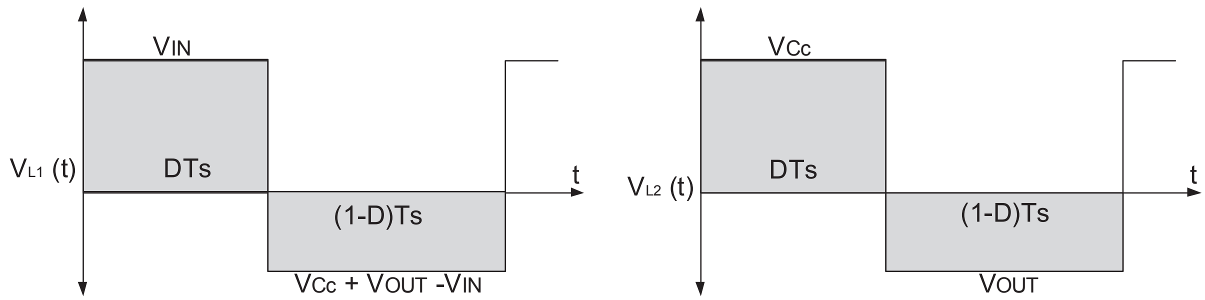
$$V_{L1OFF} = V_{CC} + V_{OUT} - V_{IN}$$

EQUATION 4: VOLTAGE ACROSS L2 DURING OFF STATE

$$V_{L2OFF} = V_{OUT}$$

To reach the Steady State condition of a converter, the net inductor voltage must be zero. Otherwise, the amplitude of the inductor's current will continuously increase until inductor saturation occurs. To ensure the zero average voltage across the inductor, the volt-second balance on the inductor must be satisfied. Figure 3 shows the volt-second balance on inductor L1 and L2 where the area (volt-second) during On state is equal to the area during Off state. At this condition, the total area produced under the inductors' voltage is equal to zero. The volt-second balance on L1 and L2 can be represented also by Equation 5 and Equation 6, respectively.

FIGURE 3: INDUCTOR VOLT-SECOND BALANCE



Note: D represents the duty ratio between on-time and off-time of main switch Q5; Ts represents the switching period.

EQUATION 5: L1 VOLT-SECOND BALANCE EQUATION

$$V_{IN}DTs = (V_{CC} + V_{OUT} - V_{IN})x(1-D)Ts$$

EQUATION 6: L2 VOLT-SECOND BALANCE EQUATION

$$V_{CC}DTs = V_{OUT}x(1-D)Ts$$

Using Equation 5 and Equation 6, voltage across CC (V_{CC}) can be solved (see Equation 7 and Equation 8).

EQUATION 7: VCC EQUATION BASED ON L1 VOLT-SECOND BALANCE

$$V_{Cc} = \frac{V_{IN} - V_{OUT}(1-D)}{(1-D)}$$

EQUATION 8: VCC EQUATION BASED ON L2 VOLT-SECOND BALANCE

$$V_{Cc} = \frac{V_{OUT}(1-D)}{D}$$

Since V_{CC} is the same during each two distinct time intervals in one switching period, Equation 7 can be equated to Equation 8. As a result, the voltage conversion ratio of the SEPIC converter in Continuous mode can be obtained (see Equation 9).

EQUATION 9: VOLTAGE CONVERSION RELATIONSHIP

$$\frac{V_{OUT}}{V_{IN}} = \frac{D}{1-D}$$

Note: Equation 9 is true when using two separate inductors or even when using a coupled inductor in a SEPIC. The magnetically coupling of the inductor does not modify the SEPIC's voltage conversion ratio.

Note: The equations are approximations which do not reflect the real signal waveforms.

Since the LED is used as a load in this application, V_{OUT} in Equation 9 is also a product of the LED current I_{LED} and the LED string total dynamic resistance R_L. Replacing V_{OUT} with this relationship and solving for I_{LED}, Equation 9 leads to Equation 10.

EQUATION 10: LED CURRENT

$$I_{LED} = \frac{V_{IN} \times D}{R_L(1-D)}$$

Equation 10 shows that I_{LED} is a function of V_{IN}, R_L and D. This result is important because it shows how the I_{LED} depends on V_{IN}, R_L and D, or how, conversely the D can be controlled based on V_{IN} and R_L in order to maintain the I_{LED} constant.

Controlling the value of D is made possible by adjusting the duty cycle of the COG's PWM output. The CCP1, which provides a fixed-frequency pulse, is modulated by PWM5 through the DSM to implement an enhanced dimming technique in this LED driver design. The modulated output signal from the DSM triggers the rising edge of the COG's PWM output while the output of the comparator C2 triggers the falling edge of the COG's PWM output. Effectively, the DSM carrier input (CCP1) determines the Q5's switching period and the output of C2 determines the Q5 switching duty cycle.

The CCP1 switching period can be calculated using Equation 11 and the output of C2 is set by the feedback circuit

EQUATION 11: Q5 SWITCHING PERIOD

$$T_S = (PR2 + 1) \times 4 \times T_{OSC} \times TMR2\ prescale\ value$$

Where: PR2 is the limit value of the TMR2 counter

T_{OSC} is the inverse of the oscillator frequency ($1/F_{OSC}$)

TMR2 prescale value is the timer multipler before TMR2 increment

FIGURE 4: FEEDBACK LOOP CIRCUIT

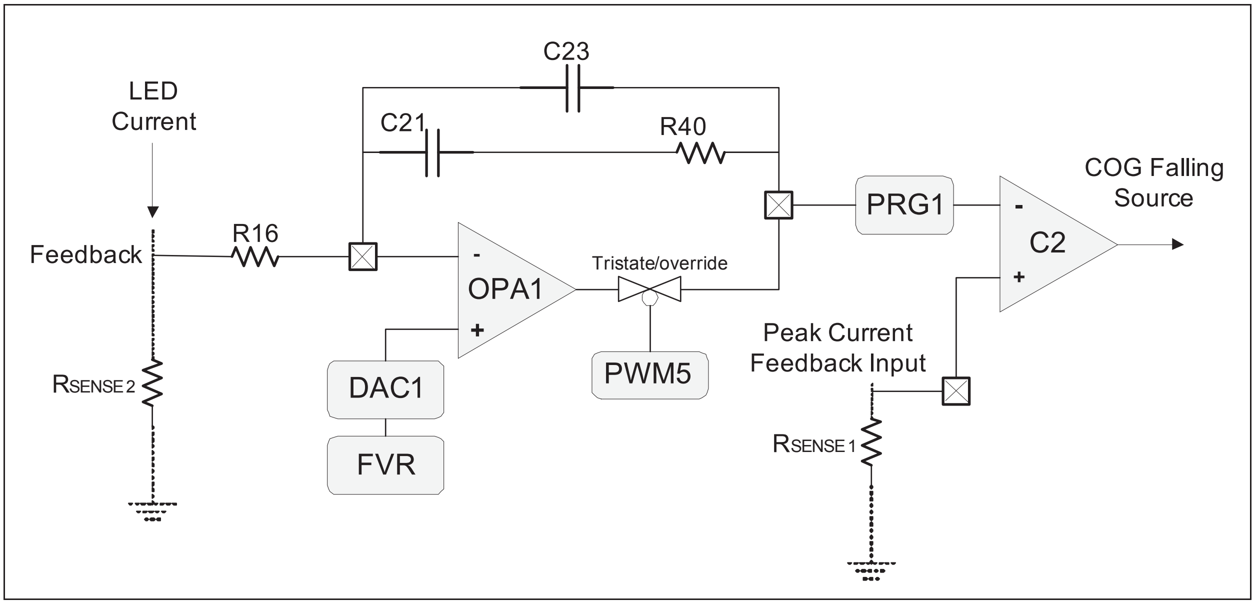
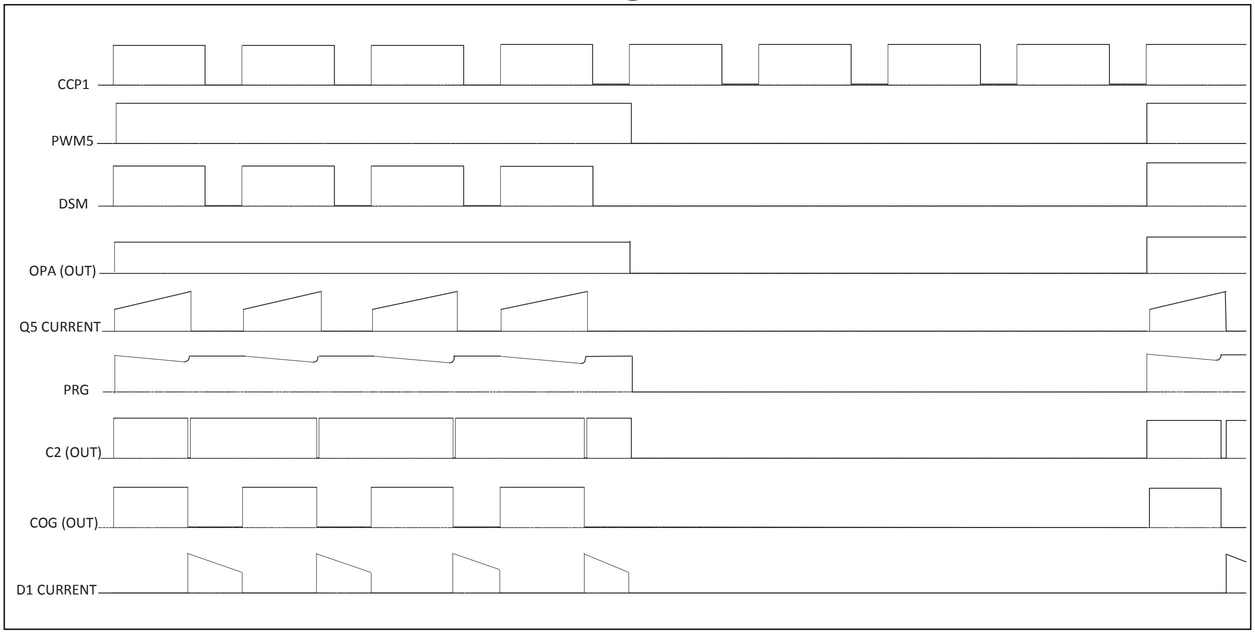


Figure 4 depicts the Type II compensator network feedback circuit based on the Peak Current mode control technique. The feedback circuit is composed of the peak current control loop and the average current control loop. In the peak current control loop, currents is translated to voltage by R_{SENSE1} and is applied to the noninverting input of C2. Likewise, in the average current control loop, the LED current is translated to voltage by R_{SENSE2} and used by OPA as a source of its inverting input. The R_{SENSE2} voltage (V_{SENSE2}) is compared with a reference voltage provided by the FVR, which can be narrowed further by the DAC. This reference voltage is chosen based on the LED constant-current required. The difference between V_{SENSE2} and the reference voltage is amplified by an OPA error amplifier gain. This gain is set by the value of the external compensation network which is composed of resistors R16 and R40, and capacitors C21 and C23. The OPA error amplifier is enabled and tri-stated by the PWM5 to eliminate high-peak current that occurs during LED dimming. To explain the importance of tri-stating the OPA, a detailed discussion is provided in **Section "PWM LED Dimming"**.

The amplified voltage error is compensated by a decaying ramp from PRG to avoid subharmonic oscillations when the duty cycle is near or above 50%. For more information about the PRG Slope Compensation mode, refer to Technical Brief, "*Programmable Ramp Generator*" (DS90003140). The slope compensated voltage is used by C2 as an inverting input. C2 compares the voltage across R_{SENSE1} from the peak current loop and the slope compensated voltage from the average current loop. While the R_{SENSE1} voltage is less than the slope compensated voltage, the C2 output remains high. The duty cycle of the COG output is increasing because the COG is still not detecting a falling event. Once the R_{SENSE1} voltage reaches the slope compensated voltage, the C2 output goes low and the duty cycle of the COG output is terminated. This is how the feedback circuit determines the response to input voltage and output current changes to maintain the LED current constant. The inductor current signal is compared with the amplified translated output current error. To visualize the control operation of the LED driver in maintaining the LED current constant, a timing diagram is provided in Figure 5.

FIGURE 5: LED DRIVER TIMING DIAGRAM @ 50% DIMMING

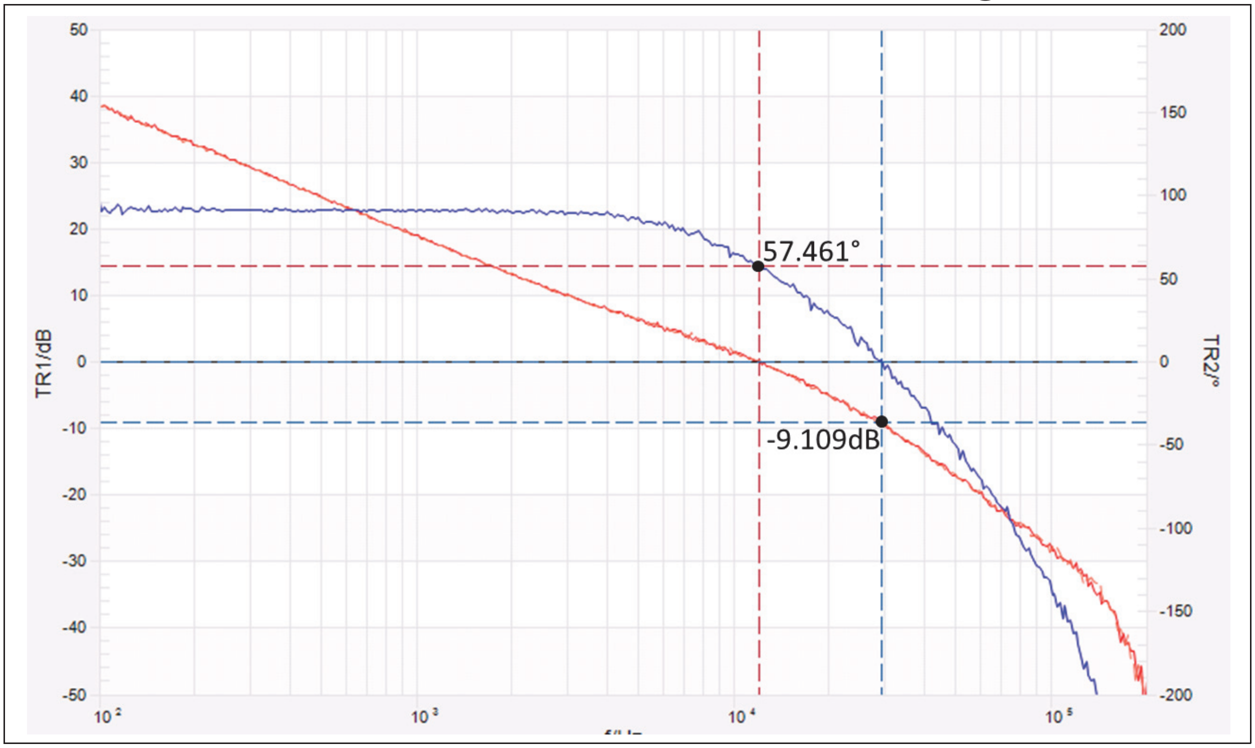


FEEDBACK STABILITY

The implementation of the feedback circuit to automatically adjust the duty cycle forms a closed-loop system. The closed-loop system requires an adequate bandwidth and stable operation under all specified operating conditions. The values of the error amplifier's external compensation network are selected to meet these requirements.

To verify the bandwidth and stable operation, open loop gain/phase measurement in a closed-loop system is usually performed to determine the phase and gain margin. Figure 6 shows the LED driver's phase and gain plot. (Refer to **Appendix C: "BODE Plot Measurement Setup"**" for the gain and phase measurement setup).

FIGURE 6: OPEN LOOP GAIN AND PHASE PLOT OF THE LED DRIVER @ 100% DIMMING



LED DRIVER PROTECTION FEATURE

To protect the driver from failure caused by abnormal input and output conditions, the following protection features are implemented in the design.

UNDERVOLTAGE LOCKOUT (UVLO)

The LED driver is designed for a specific minimum input voltage threshold only. Beyond this threshold voltage, proper operation of the LED driver is not guaranteed. To avoid operation of the LED driver outside the threshold input voltage, the operating input voltage range of the LED driver is specified in the firmware.

The input voltage is monitored from the voltage across resistor R31. This voltage is sampled and converted by the ADC and the conversion result is compared to the UVLO limit value set in the firmware.

The UVLO is set to 6.0V with hysteresis voltage band of 1.5V. The hysteresis ensures that the LED driver will not turn On and Off intermittently near the UVLO set-point and ensures a clean transition when the peak-to-peak input voltage is beyond the anticipated noise and ripple. When the input voltage goes below 6.0V, the COG, PWM5 and CCP outputs terminate and Fault detection activates. When the voltage input increases again, it must reach 7.5V to re-enable the LED driver.

OVERVOLTAGE LOCKOUT (OVLO)

The OVLO detection method is very similar to the UVLO, except that the limit is set to the maximum operating input voltage of the LED driver. The OVLO limit is set to 24V with hysteresis voltage band of 1V. When the input voltage exceeds the OVLO limit of 24V, the COG, PWM5 and CCP outputs terminate and Fault detection activates. The LED driver will be re-enabled once the input voltage becomes equal to or goes below 23V.

Just like the UVLO limit, OVLO limit can also be set in the firmware. This is one of the advantages of using a microcontroller in this application. Any limits can be simply changed in firmware, precluding the need to change external components.

INPUT VOLTAGE PROTECTION

The input voltage protection circuit is employed to protect the LED driver from reverse polarity input voltage and high input transient voltage. Supplying reverse polarity voltage usually occurs as a result of an accidental swapping of ground and the positive rail during system installation. In the input voltage protection circuit shown in Figure 7, when negative voltage is supplied to the LED driver, the body diode of the P-MOSFET Q1 blocks the negative input voltage and Q1 is prohibited from conducting (see Figure 8).

It would be easier and cheaper if a simple diode is used for the reverse polarity protection. However, during normal operation where a positive input voltage is applied, the diode will dissipate too much power. In comparison, using a P-MOSFET, the drain-source voltage drop when conducting is much lower than the voltage drop of a diode, thus reducing the power dissipation.

Aside from reverse polarity, the input protection circuit also protects the LED driver from fast high-voltage transients. This protection is achieved by employing a bidirectional transient voltage suppressor diode D1 across the input line and ground. The device operates by shunting the excess current to ground when a positive or negative applied voltage exceeds its avalanche breakdown potential. As a result, the transient energy is absorbed and is prevented from passing through the LED driver circuit. The device automatically resets when the overvoltage goes away.

In a scenario where the input voltage is removed, the stored energy on the input filter capacitor needs to be discharged to avoid the voltage of the capacitor feeds back to the input voltage source. This is made possible by implementing a PNP transistor Q2.

In normal operating condition, Q2 cease the conduction since its emitter voltage is less than the collector and base voltage. Once the input voltage is removed, Q2 conducts and connect the Q1 source to ground. The stored energy on the input filter capacitor will now be discharged to resistors R2 without affecting the input voltage source.

FIGURE 7: INPUT VOLTAGE PROTECTION

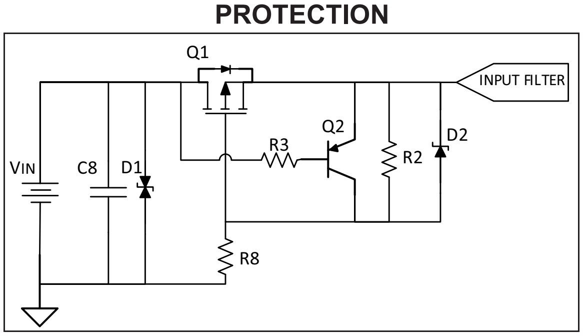
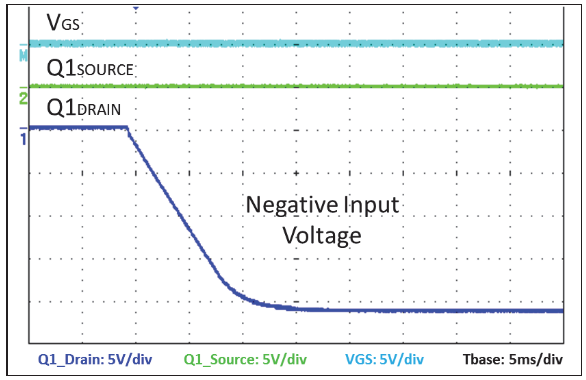


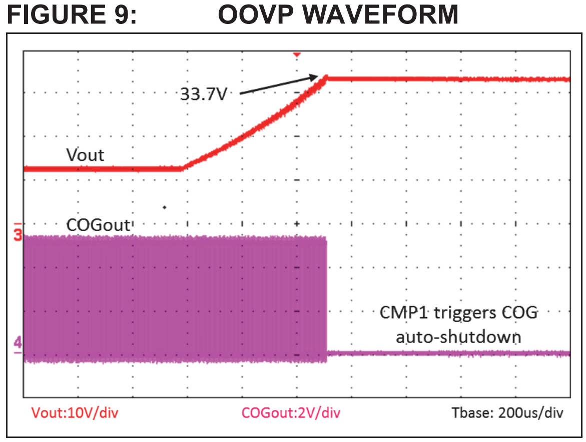
FIGURE 8: -21.5V INPUT VOLTAGE



OUTPUT OVERVOLTAGE PROTECTION (OOVP)

When the LED load is accidentally removed or one of the LEDs in the LED string fails open, the feedback loop breaks and the output voltage rises abruptly. Excessive output voltage can cause faulty performance or damage the LED driver circuit. To protect the LED driver from this Fault event, OOVP is implemented. The OOVP detection feature is implemented by comparing the derived output voltage across R41 with the OOVP voltage limit provided by the DAC3. When the voltage across R41 reaches the voltage limit, the C1 triggers the COG's auto-shutdown feature that stops the PWM switching. As Figure 9 shows, when the output voltage reaches the OOVP limit of approximately 34V, the COG's PWM output terminates and the Fault detect indicator activates.

FIGURE 9: OOVP WAVEFORM

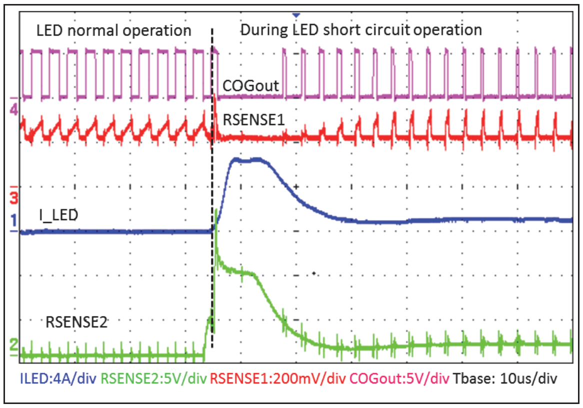


SHORT CIRCUIT PROTECTION

As mentioned earlier, the LED driver control operates based on Peak Current mode control to regulate the LED current. Since the inductors' current is monitored and limited, cycle by cycle, when under Peak Current mode control, the LED driver has inherent short circuit protection.

When the LED driver output is shorted or the LED string is shorted, the output draws excessive current. This large current causes the inductors' peak current to rise abruptly. The steep slope of the inductor current is translated to a voltage by RSENSE1. When the voltage across RSENSE1 reaches the slope compensated OPA error voltage, the COG PWM output duty cycle also decreases causing an output current drop. This is how the LED driver prevents the excessive increase of output current during a short-circuit condition. The COG's PWM output duty cycle remains at minimum percentage as long as the short circuit exists (see Figure 10). The LED driver will return to normal operation once the short circuit is removed.

FIGURE 10: OCP WAVEFORM



OVER TEMPERATURE PROTECTION

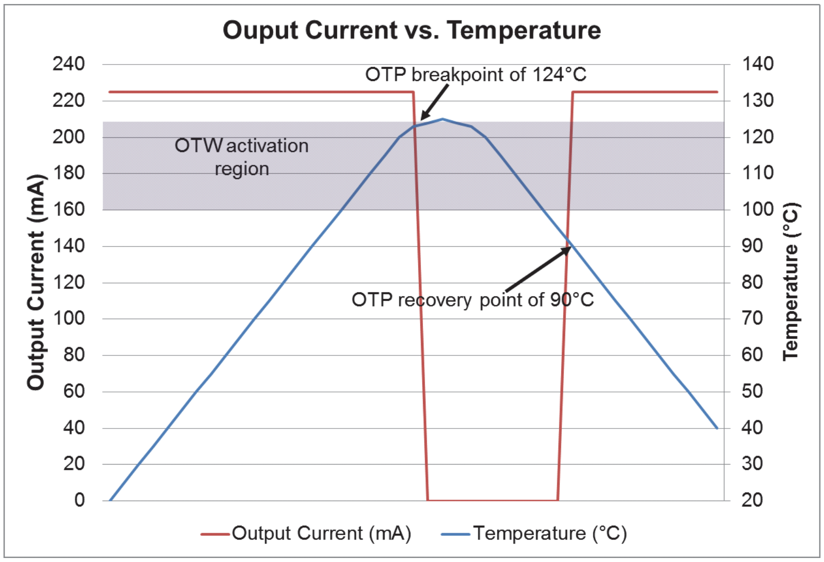
Because of the heat generated by the LEDs, the LED driver requires proper thermal management. This will increase the LEDs' lifespan and protect them from potential damage due to excessive heat.

In the LED driver circuit, an NTC thermistor is employed to monitor precisely the LED case temperature. This type of NTC thermistor exploits the resistance-versus-temperature characteristics of the thermistor. Its non-linear resistance change-over temperature characteristic can be linearized by implementing a look-up table in the firmware. The thermistor voltage output is sampled and converted by the ADC and the conversion result becomes the table index of the look-up table without any further calculation. Each index of the look-up table provides a temperature in °C for each value of the 10-bit ADC.

In Figure 11, as the LEDs continuously emit lights, the LED case temperature increases while the LED driver maintains the effective average LED current. When the temperature reaches the over temperature warning (OTW) trip point of 100°C, the LED driver alerts the user with an indicator in the Graphical User Interface (GUI). Once the temperature reaches the temperature breakpoint of 124°C, the COG, PWM5 and CCP outputs terminate and Fault detection activates until the LED case temperature goes below the thermal breakpoint of 90°C.

Power de-rating can be an option for LED driver thermal management. This method can provide the LED driver the intelligence to trim down the initial effective average LED current once the LED case temperature reaches the temperature breakpoint. When the temperature goes below the thermal breakpoint, the reduced dimming ratio gradually increases until the effective average LED current returns to its initial value.

FIGURE 11: OVER TEMPERATURE DETECTION RESULT



AUTOMATIC BIN DETECTION

Like all manufactured products, LEDs have manufacturing process variations that lead to variation in LED performance. These variations can be alleviated through the binning process. Binning is manufacturers' process to categorize LEDs depending on its color temperature output and lumen output. For this application the type of LED used is a high-power LED with full white color temperature range that provides high brightness illumination.

The on-board LEDs on this LED driver demo board provide a luminous flux between 71 and 140 lm at a nominal current rating of 350 mA. The LED manufacturer categorizes luminous flux into five brightness classes as shown in Table 2. Since LEDs are current-controlled devices and the luminous flux of an LED is directly proportional to the current, the desired light output can be achieved by regulating the current.

TABLE 2: LED BRIGHTNESS CLASSES

Group	Luminous Flux ϕ_V (lm)	Luminous Intensity I_V (cd)
KX	71 to 82	19
KY	82 to 97	22
KZ	97 to 112	26
LX	112 to 130	30
LY	130 to 140	35

The binning class of the LED can be categorized using a binning resistor. The voltage across the binning resistor is sampled and converted by the ADC. The ADC result determines the binning class of the LED. Once the binning class has been identified, the firmware calculates the DAC value to set the LED current abruptly. With the use of the PIC microcontroller, automatic binning detection can be easily implemented.

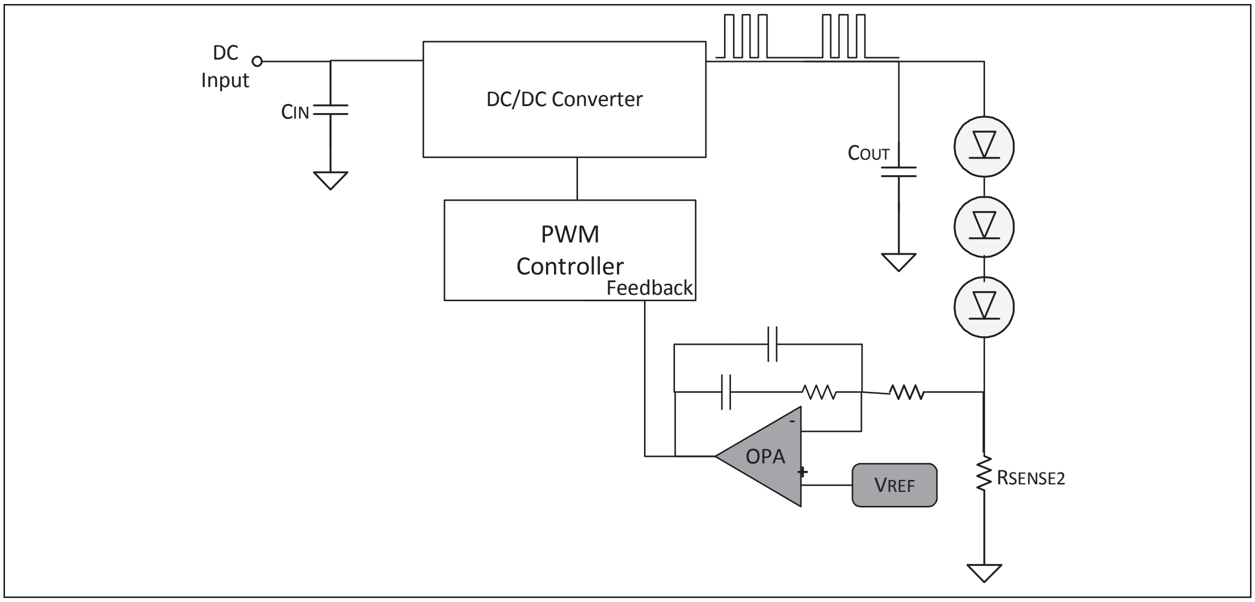
PWM LED DIMMING

One way of achieving LED dimming is by varying the LED forward current. However, this dimming method can cause the LED color temperature to change. In comparison, LED dimming based on PWM keeps the forward current constant, which makes the color temperature stable, while using a PWM signal to rapidly cycle the LED On and Off.

In a Basic-Switched mode PWM LED driver, as shown in Figure 12, the DC/DC converter transfers energy at high-switching frequency to provide current to the LED.

The DC/DC converter controller monitors the derived voltage across LED current sense resistor R_{SENSE2} through the feedback circuit to increase or decrease the duty cycle of the PWM output signal that drives the DC/DC converter switch. This linear change of the PWM duty cycle maintains the LED's current at a constant value. The dimming is achieved by turning On and Off the controller's PWM output at much slower than its switching frequency. (A dimming signal that turns On and Off the PWM output can be internal or external to the controller). This produces a frequency-modulated PWM output signal that turns the LED On and Off. The perceived brightness of the LED is proportional to the modulated PWM duty cycle.

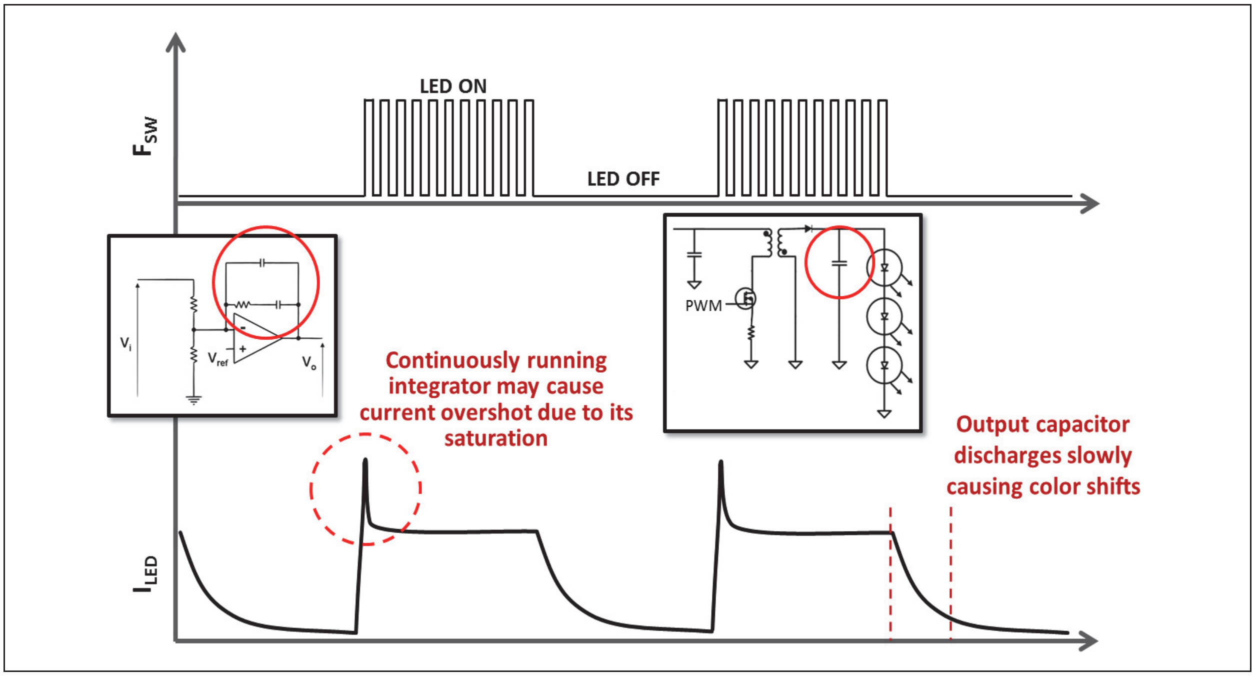
FIGURE 12: BASIC PWM LED DIMMING CIRCUIT



Although Figure 12 provides dimming control, there are two drawbacks that must be carefully considered when using this scheme. These drawbacks occur instantaneously during LEDs On/Off switching (see Figure 13). The first drawback happens when the LED is off. During this period, the LED output current is gradually diminishing due to the slow discharging of the output capacitor. This can lead to a change in color temperature and higher dissipation of the LED. The second drawback lies in the driver's feedback circuit.

When the LED is on, a current is delivered to the LED and the voltage across RSENSE2 is fed to the error amplifier (EA). When the LED turns off, no current flows to the LED and the RSENSE2 voltage becomes zero. During this dimming off-time, EA output increases to its maximum and overcharges the EA compensation network. When the modulated PWM turns on again, it takes several cycles before it recovers while high-peak current is driven to the LED. This current overshoot overdrives, and can shorten the life time of the LED.

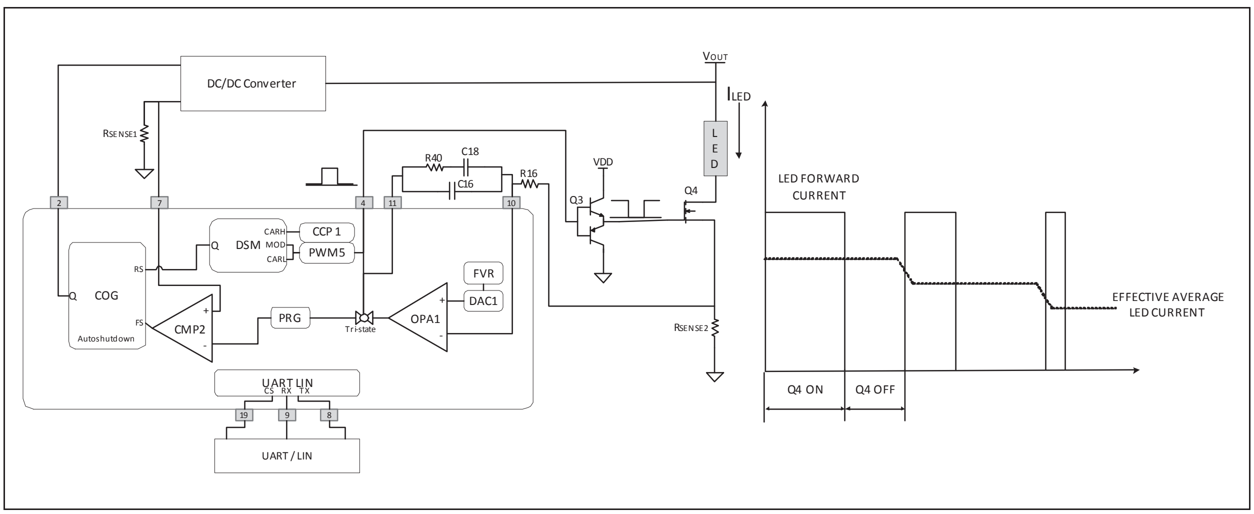
FIGURE 13: BASIC PWM LED DIMMING WAVEFORM



To provide more visually attractive dimming and protect the LEDS from over-current, an enhanced dimming technique is employed in this LED driver design. This technique involves firmware and additional components.

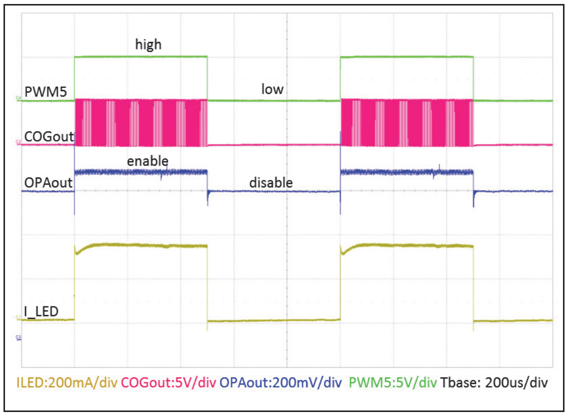
The effect of the slow discharging of the output capacitor is eliminated by adding a load switch Q4 between the LED string and the sensing resistor RSENSE2 (see Figure 14). The COG output and Q4 are synchronously turned off to cut the path of the decaying current and allow the LED to turn off faster.

FIGURE 14: LED DIMMING CIRCUIT



On the other hand, the high-peak current that occurs during LED transition from Off to On can be eliminated by using the override control of the OPA that activates during LED off time. The override control of the OPA completely disconnects the output of the OPA from the GPIOs in tri-state. In this manner, the compensation network is completely disconnected from the feedback loop and holds the last point of the stable feedback as charge stored in the compensation capacitor. When the LED turns on again, the compensator network reconnects and the OPA output voltage immediately jumps to the previous stable state (before the LED was off) and restores the LED current set value almost instantly (see Figure 15).

FIGURE 15: PWM DIMMING OPERATION

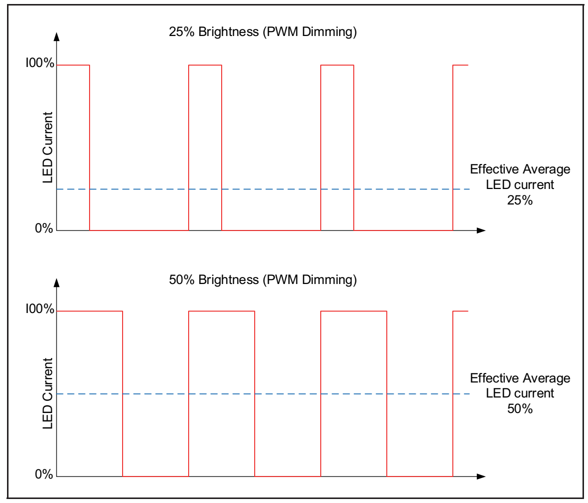


The PWM signal that controls the switching of Q4 is PWM5. PWM5, running at 1 kHz frequency, switches the MOSFET driver Q3 to drive the gate of Q4 and turns the LED on and off. PWM5 also controls the state of the OPA1 and the COG output. Effectively, the COG PWM output and OPA1 operation are disabled by PWM5. When the PWM5 output is high, the COG PWM output and OPA1 operation are enabled, and the gate of Q4 is pulled to V_{DD}. This permits the LED driver to maintain the output voltage and to switch on Q4. When Q4 is on, there is a current path between the LED and ground, which allows current to flow, turning on the LED. When the PWM5 output goes low, the gate of Q4 is pulled to ground to cease it from conducting. When Q4 is Off, the LED is disconnected from ground, thus, the LED turns off. Also, when PWM5 is low, the OPA output is tri-stated and DSM output becomes low. When the DSM output is low, the rising source of the COG will not be triggered, which keeps the COG output low (see Figure 15). Keeping the COG output low when Q4 is Off avoids continuous increase of the voltage at the LED driver output that will eventually trigger the OOVP. The frequency of PWM5 is chosen in such a way that a human eye cannot perceive the flickering.

Turning the LED On and Off produces an effective average LED current at the output of the LED driver. This effective average LED current can also be used as a representation of the LED brightness.

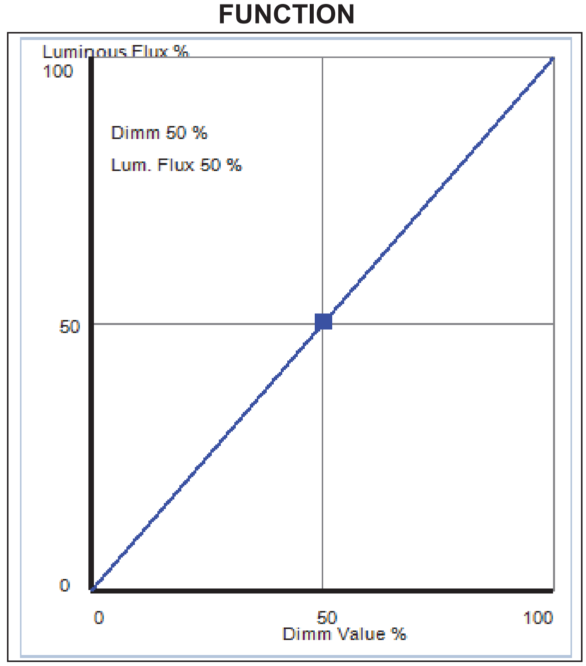
Therefore, when the duty cycle of the PWM5 output changes to control the brightness of the LED, the effective average LED current also changes as shown in Figure 16.

FIGURE 16: PWM DIMMING



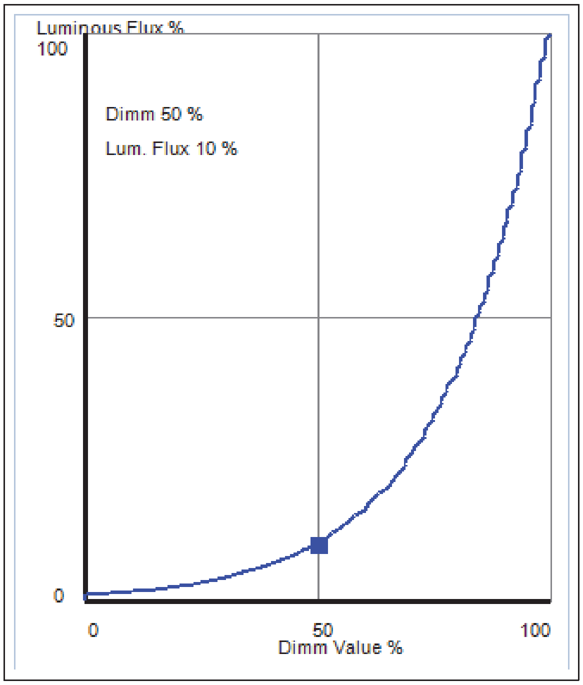
The effective average LED current can be varied linearly in the GUI by adjusting the dimming value up to 100%, (see **Appendix B: "PIC16F1769 SEPIC LED Driver Graphical User Interface"**). Since LED current determines the luminous flux of the LED, the relation between the dimming value and the luminous flux is practically linear, as shown in Figure 17.

FIGURE 17: DIMMING LINEAR FUNCTION



However, the human eye does not perceive the rate of change as constant when the LED is dimmed linearly over time. Because of this, an exponential dimming approach that applies the Weber-Fechner law can be selected in this LED driver (see Figure 18). This dimming approach approximates the logarithmic relationship between luminous flux and perceived brightness that allows the human eye to perceive a smooth and gradual dimming.

FIGURE 18: WEBER-FECHNER EXPONENTIAL DIMMING



To support the Weber-Fechner sensitivity scale in the firmware, a look-up table with values of brightness level along the exponential curve has been implemented. This look-up table translates the linear PWM dimming duty ratios into non-linear ergonomic Weber-Fechner characteristics.

FIRMWARE FLOW

FIGURE 19: FIRMWARE FLOW

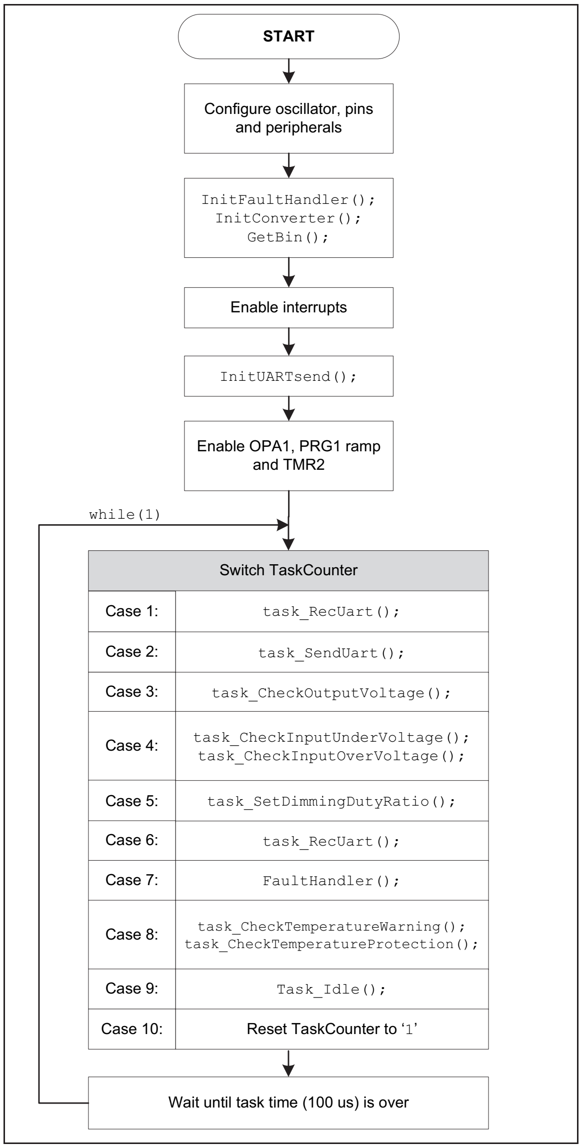


Figure 19 shows the flowchart of the LED driver firmware. When the microcontroller clock frequency is stabilized, the firmware initializes the peripherals, including the interconnections between peripherals. Likewise, the I/O pins are configured, as required. When the peripherals and I/O pins are initialized, the firmware executes the `InitFaultHandler()`, `InitConverter()` and `GetBin()` routines.

The `InitFaultHandler()` routine sets up all of the protection feature parameters while the `InitConverter()` routine sets up the dimming and the protection feature monitoring of the LED driver. These protection feature parameters are summarized in **Appendix D: "SEPIC LED Driver Protection Feature Thresholds"**.

The `GetBin()` routine measures the Brightness Index Number (BIN) resistor and sets the associated forward current of the LED driver. The firmware will then enable interrupts and execute the `InitUARTsend()`. The `InitUARTsend()` routine initializes the transmission of the data that is used in the GUI. When this routine has been executed, the firmware performs the following: enable OPA1, start the PRG ramp generation and starts the increment of TMR2 register. This event enables the operation of the LED driver.

At this stage, the LED driver is running in normal operation with the initial dimming setting while the firmware is in a continuous loop executing the following tasks depending on the value of the `TaskCounter`. Each tasks is executed every 100 µs.

1. `task_RecUart()` routine: This routine receives the data selected by the user in the GUI. The parameters that the user selected for the nominal LED current, the dimming percent and the dimming mode will be adapted by the firmware.
2. `task_SendUart()` routine: This routine sends to the GUI the information about the LED driver that can be viewed by the user every 10 ms.
3. `task_CheckOutputVoltage()` routine: This routine checks the output voltage of the LED driver. When the output voltage exceeds the predefined maximum output voltage, the OVP will be triggered.
4. `task_CheckInputUnderVoltage()` and `task_CheckInputOverVoltage()` routines: These routines check the input voltage of the LED driver. When the input voltage goes below or above the specified thresholds, the UVLO or OVLO will be triggered, respectively.
5. `task_SetDimmingDutyRatio()` routine: This routine sets the dimming of the LED according the parameters selected by the user in the GUI.
6. `FaultHandler()` routine: This routine disables or recovers the LED driver based on defined Fault conditions. The LED driver will be disabled when any of the protection features has been triggered. Likewise, the LED driver will recover from Fault detection when conditions have returned to the specification range.
7. `task_CheckTemperatureWarning()` and `task_CheckTemperatureProtection()` routine: These routines check the LED case temperature. When the temperature rises up to the predefined thresholds, the OTW or OTP will be triggered, respectively.
8. `Idle()` routine: This routine serves as a delay to achieve 1 ms execution of all the tasks.
9. After the execution of the function routines, the firmware sets the `TaskCount` to '1'. This event lets the firmware execute all of the function routines again, forming a continuous loop execution.

Notice that after initialization, no code is written for regulating the output current. This is because the CIPs, which have been combined to control the power train, do not require input from the CPU and perform the task independently. As a result, the complexity of the firmware is reduced.

Note:	The source code of this application note is available from the Microchip website (www.microchip.com).

COMPONENT SELECTIONS

This section describes the considerations on how the LED driver's major components are selected.

Duty Cycle

Selecting a proper value and rating of components begins with determining the maximum duty cycle D_{MAX} of the PWM output. The determination of D_{MAX} allows the calculation of component current ratings and the maximum voltage stress on the switching elements. D_{MAX} depends upon the minimum value of the input voltage V_{IN} and the voltage output, as determined by the desired number of LEDs. Considering these conditions in the voltage conversion relationship defined in Equation 7, D_{MAX} can be calculated as follows (see Equation 12).

EQUATION 12: MAXIMUM DUTY CYCLE

$$D_{MAX} = \frac{V_{OUT}}{V_{IN\ MIN} + V_{OUT}}$$

So far, the diode D3 forward voltage drop V_D has been ignored because of its low value. If the voltage drop of the diode is considered, D_{MAX} will be (see Equation 13):

EQUATION 13: MAXIMUM DUTY CYCLE WITH D3 DIODE VOLTAGE DROP

$$D_{MAX} = \frac{V_{OUT} + V_D}{V_{IN\ MIN} + V_{OUT} + V_D}$$

Based on the given minimum input voltage and the maximum output voltage specification of the LED driver, the calculated D_{MAX} is 82%. The COG in the microcontroller can provide much more than this required duty cycle.

INDUCTOR L1 AND L2

Solving V_{OUT} in Equation 7 and substituting its result in Equation 8 to solve V_{CC} shows that V_{CC} is equal to V_{IN} throughout the switching cycle. As discussed previously, the voltage applied to L1 is equal to V_{IN} and the voltage applied to L2 is equal to V_{CC}. Since V_{CC} is also equal to V_{IN}, therefore, the voltage applied for L1 and L2 are both equal to V_{IN}. Applying the same voltage to L1 and L2 allows these inductors to wind on the same core. These coupled inductors take up less space on the Printed Circuit Board (PCB), reduce cost and lower the inductor ripple current.

Selecting the inductance value for the coupled inductors begins with calculating the inductor's peak-to -peak ripple current. As a rule, a good approximation of the inductor's ripple current is from 20% to 40% of the maximum input current. Too much ripple increases the Electromagnetic Interference (EMI) and too little ripple results in unstable switching operation. Equation 14 shows how to calculate the inductor ripple current by choosing 20% of the maximum input current.

EQUATION 14: INDUCTOR RIPPLE CURRENT

$$\Delta I_L = 0.2 \times I_{LED} \times \frac{D_{MAX}}{1 - D_{MAX}}$$

Once the coupled inductor ripple current is determined, the inductance of coupled inductors can be calculated using Equation 15. Because the two windings of coupled inductors share the ripple current, regardless of the desired inductor peak-to-peak ripple current, the value of the inductance will be half of the individual inductors.

EQUATION 15: COUPLED INDUCTOR VALUE

$$L = L1, L2 = \frac{1}{2} \times \frac{V_{IN\,MIN} \times D_{MAX}}{\Delta I_L \bullet F_{SW}}$$

In this design solution, the calculated coupled inductors value is equal to 22.49 uH. However, 22 uH is chosen since it is the nearest standard inductance value available off-the-shelf from the manufacturer. Because of this, the inductor ripple current should be calculated again based on this chosen inductance value in order to know the actual worst-case inductor ripple current (see Equation 16).

EQUATION 16: ACTUAL COUPLED INDUCTOR RIPPLE CURRENT

$$\Delta I_{L\,ACTUAL} = \frac{1}{2} \times \frac{V_{IN} \times D_{MAX}}{L_{ACTUAL} \bullet F_{SW}}$$

Another important inductor specification that must be considered is the maximum inductor peak current. The chosen coupled inductors must have at least a 20% higher-peak current rating than this maximum inductor peak current in order to avoid saturation. The maximum peak inductor current is determined by the L1 average current ($I_{L1\,AVE}$) and the L2 average current ($I_{L2\,AVE}$). Due to the isolation provided by the coupling capacitor, $I_{L1\,AVE}$ and $I_{L2\,AVE}$ are equal to the input average current and the LED forward current, respectively (see Equation 17). Combining these two currents plus half of the actual inductor ripple current, the worst peak inductor current can be calculated (see Equation 18).

EQUATION 17: AVERAGE L1 AND L2 CURRENT

$$I_{L1AVE} = \frac{V_{OUT} \times I_{LED}}{V_{IN\,MIN} \times \eta} \quad \eta = efficiency$$

$$I_{L2AVE} = I_{LED}$$

EQUATION 18: INDUCTOR PEAK CURRENT

$$I_{LPK} = I_{L1AVE} + I_{L2AVE} + (0.5 \times I_{L\,ACTUAL})$$

MOSFET Q5

In selecting a power switch, a MOSFET with a capability to withstand peak voltage and current stress while minimizing the power dissipation must be considered. The MOSFET must have a drain-current rating higher than the current shown in Equation 18 and a drain-source voltage rating higher than the voltage shown in Equation 19. In addition, the MOSFET must have a power dissipation rating greater than the sum of conductive losses and switching losses shown in Equation 20.

EQUATION 19: Q5 DRAIN-SOURCE VOLTAGE

$$V_{Q5DS} = V_{IN\,MAX} + V_{OUT\,MAX} + V_D$$

EQUATION 20: Q5 POWER DISSIPATION

$$P_{Q5D} = I_{Q5RMS} \times r_{DSON} \times D_{MAX} \times I_{Q5D} \times (V_{IN\ MIN} + V_{OUT} + V_D) \times \frac{T_{RISE} + T_{FALL}}{2} \times F_{SW}$$

Where:

$$I_{Q5RMS} = \frac{I_{IN}}{\eta\sqrt{D_{MAX}}}$$

$$I_{Q5D} = drain\ current$$

$R_{DS\ ON}$ = drain-source on-state resistance

T_R = Rise time

T_F = Fall time

Based on the calculated value by using Equation 18, Equation 19, and Equation 20, the N-Channel MOSFET with 60V, 8.7A and 800 mW at 70°C power dissipation rating is used in the design.

OUTPUT DIODE D3

Because the same peak current flows through MOSFET Q5 and Diode D3, the selected D3 must also handle I_{LPK}, as shown in Equation 18. Also, the reverse voltage rating of D3 should be greater than Q5's maximum voltage to account for transients and ringing. Since the average D3 current is the forward LED current, D3 must be capable of handling the power dissipation shown in Equation 21.

EQUATION 21: D3 POWER DISSIPATION

$$P_{D3D} = I_{LED} \times V_D$$

In this design, a Schottky barrier diode with a reverse voltage of 60V, a forward current of 1A and a power rating of 550 mW are used.

INPUT CAPACITOR CIN

The input capacitor CIN reduces the input ripple voltage. CIN can be any value between 10 uF to 100 uF since it sees fairly low-ripple current due to the input inductor. In addition, since the current waveform is continuous and triangular, CIN should be able to handle the RMS current that flows through it. The RMS current flowing through CIN is given by Equation 22.

EQUATION 22: INPUT CAPACITOR CURRENT

$$I_{CIN\ RMS} = \frac{\Delta I_{LACTUAL}}{\sqrt{12}}$$

A 10 uF ceramic capacitor with 50V rating is used in the application due to its low-equivalent series resistance and high RMS current capability.

COUPLING CAPACITOR CC

As mentioned previously, the voltage across coupling capacitor CC is equal to VIN, therefore, CC must be selected with a voltage rating greater than the maximum input voltage specification. The capacitance value of CC can be calculated using Equation 23 where ΔVCS is the desired ripple voltage across CC.

EQUATION 23: COUPLING CAPACITOR

$$C_C = \frac{I_{LED} \times D_{MAX}}{\Delta V_{CS} \times F_S}$$

CC must be able to withstand the RMS current flowing through it. Therefore, the selected CC must have greater RMS rating than a value calculated using Equation 24.

EQUATION 24: ICC RMS CURRENT

$$I_{CC\ RMS} = I_{LED} \times \sqrt{\frac{V_{OUT}}{V_{IN\ MIN}}}$$

OUTPUT CAPACITOR COUT

The output capacitor COUT supplies the output current when Q5 is turned on, therefore COUT must have enough capacitance while maintaining the application's requirement for the output ripple voltage. Since the LED driver is using a low-ESR ceramic capacitor for COUT, ESR can be ignored in calculating COUT. COUT can be calculated using Equation 25, where the COUT ripple voltage ΔVCOUT is 1% of the maximum output voltage.

EQUATION 25: OUTPUT CAPACITOR

$$C_{OUT} \geq \frac{I_{LED} \times D_{MAX}}{\Delta V_{COUT} \times F_{SW}}$$

Similar to other capacitors in the circuit, the selected output capacitor COUT must also be capable of handling the RMS current that enters and leaves through it. The selected COUT RMS current rating must be greater than the computed RMS current expressed in Equation 26.

EQUATION 26: OUTPUT CAPACITOR CURRENT

$$I_{COUT\ RMS} = I_{LED} \times \sqrt{\frac{V_{OUT}}{V_{IN\ MIN}}}$$

Table 3 shows the summary of the selected components based on the computed values for this application.

TABLE 3: SEPIC DESIGN COMPONENT SELECTION

Design Equation	Computation	Selected Component/ Rating
Passive Components		
(19)	$D_{MAX} = \frac{31.2V + 0.7V}{7V + 31.2V + 0.7V} = 82\%$	COILCRAFT MSD1583-223MEB: 22 uH, 2.44A, 65 mA
(20)	$\Delta I_L = 0.2 \times 350mA \times \frac{0.82}{1 - 0.82} = 319\ mA$	
(21)	$L1, L2 = \frac{1}{2} \times \frac{7V \times 0.82}{319\ mA \times 400KHz} = 22.494\ \mu H$	
(22)	$I_{L\ ACTUAL} = \frac{7V \times 0.82}{22\ \mu H \times 400\ KHz} = 652\ mA$	
(24)	$I_{LPK} = 1.95A + 350mA + (0.5 \times 319mA) = 2.63A$	
(28)	$I_{CINRMS} = \frac{650mA}{\sqrt{12}} = 188\ mA$	10 µF, 50V X7R ceramic
(29)	$C_C = \frac{350\ mA \times 0.82}{312\ mV \times 400\ KHz} = 2.05\ \mu F$	2 µF, 50V X7R ceramic
(30)	$I_{CC\ RMS} = 350\ mA \times \sqrt{\frac{31.2V}{7V}} = 739\ mA$	

TABLE 3: SEPIC DESIGN COMPONENT SELECTION (CONTINUED)

Design Equation	Computation	Selected Component/ Rating
(31)	$C_{OUT} \geq \frac{350\ mA \times 0.82}{312\ mV \times 400\ KHz} = 2.29\ \mu F$	4.4 µF, 100V X7S ceramic
(32)	$I_{COUT\ RMS} = 350\ mA \times \sqrt{\frac{31.2V}{7V}} = 739\ mA$	
Active Components		
(25)	$V_{Q5DS} = 21.5V + 31.2V + 0.7V = 53.4V$	SIR878ADP with 100V drain source voltage, 13.3A drain current and maximum power dissipation of 3.2W at 70°C
(24)	$I_{Q5D} = 1.95V + 350\ mA + (0.5 \times 650mA) = 2.63A$	
(26)	$P_{Q5D} = (1.725A)^2 \times 0.036\Omega \times 0.82 \times 2.63A \times (7V + 31.2V + 0.7V) \times \frac{20\ ns + 20\ ns}{2} \times 400\ KHz = 71.83\ mW$	
(25)	$V_{D3R} = 21.5V + 31.2V + 0.7V = 53.4V$	SS2PH10-M3/84A Schottky Barrier Rectifier with 100V reverse voltage and 2A rectified forward current
(23)	$I_{D3AVE} = 350\ mA$	
(27)	$P_{D3D} = 350\ mA \times 0.7V = 245\ mW$	

MCU PERIPHERALS

Figure 20 and Table 4 summarize the configuration of the PIC16F1769 for this application.

FIGURE 20: PIC16F1769 PERIPHERAL CONFIGURATION

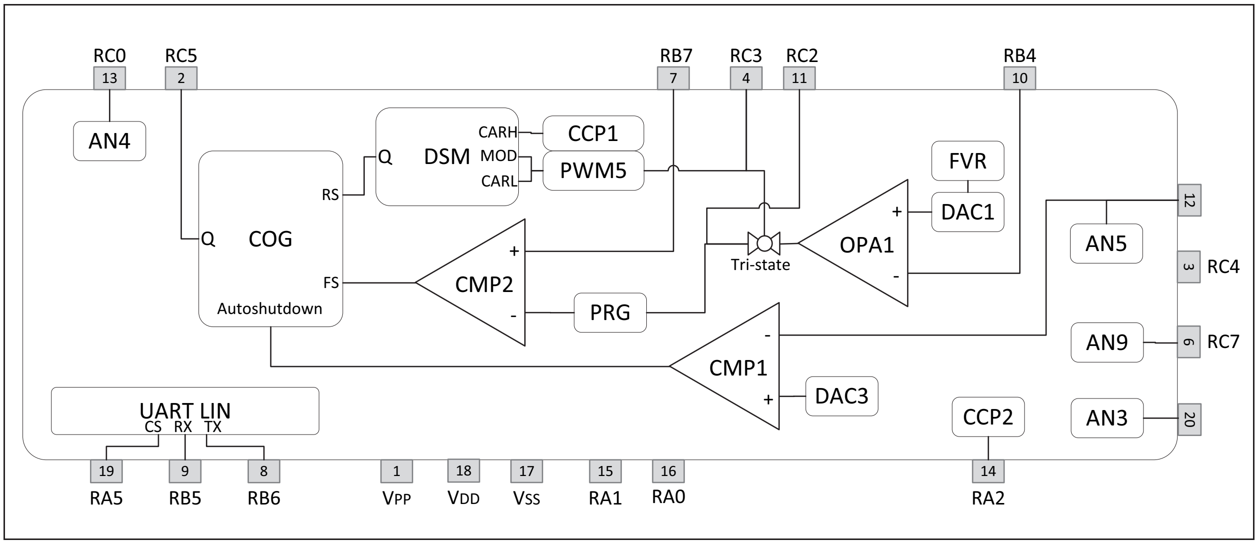


TABLE 4: PIC16F1769 PIN CONNECTION

Pin Number	Name	Function	Circuit Connection
1	VPP	VPP	
2	RC5	COG output	SEPIC MOSFET Driver
3	RC4	Fault indicator	LED Fault indicator
4	RC3	PWM5	Dimming Circuit
5	RC6	Unimplemented	
6	RC7	Analog-to-Digital (AN9)	LED case Temperature
7	RB7	Comparator 2 positive input	SEPIC Sensing Resistor (R_{SENSE1})
8	RB6	UART Transmit	
9	RB5	UART Receive	
10	RB4	OP AMP 1 negative input	LED Sensing Resistor (R_{SENSE2})
11	RC2	OPAMP1 output	Compensator circuit
12	RC1	Comparator 1 negative input	Output Voltage Sensing
13	RC0	Analog-to-Digital (AN4)	Input Voltage Sensing
14	RA2	Capture Compare PWM (CCP2)	Automotive external interface
15	RA1	CLK	
16	RA0	DAT	
17	VSS	Ground	
18	VDD	Supply Voltage	
19	RA5	CS	
20	RA4	Analog-to-Digital (AN4)	

Note 1: Please refer to **Appendix E: "Peripheral References"** for the list of technical briefs and references related to the peripherals used in this application.

PERFORMANCE

Figure 21, Figure 22 and Figure 23 show the dimming performance and efficiency of the LED driver.

FIGURE 21: DIMMING PERFORMANCE

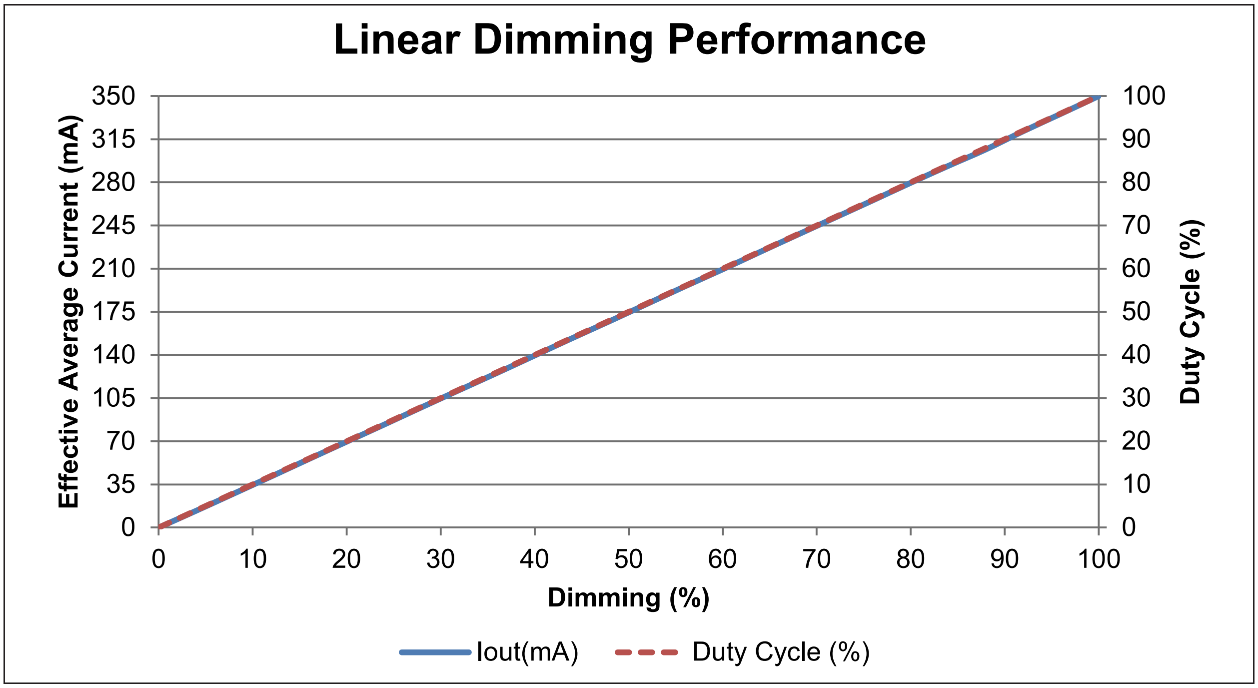


FIGURE 22: WEBER-FECHNER DIMMING PERFORMANCE

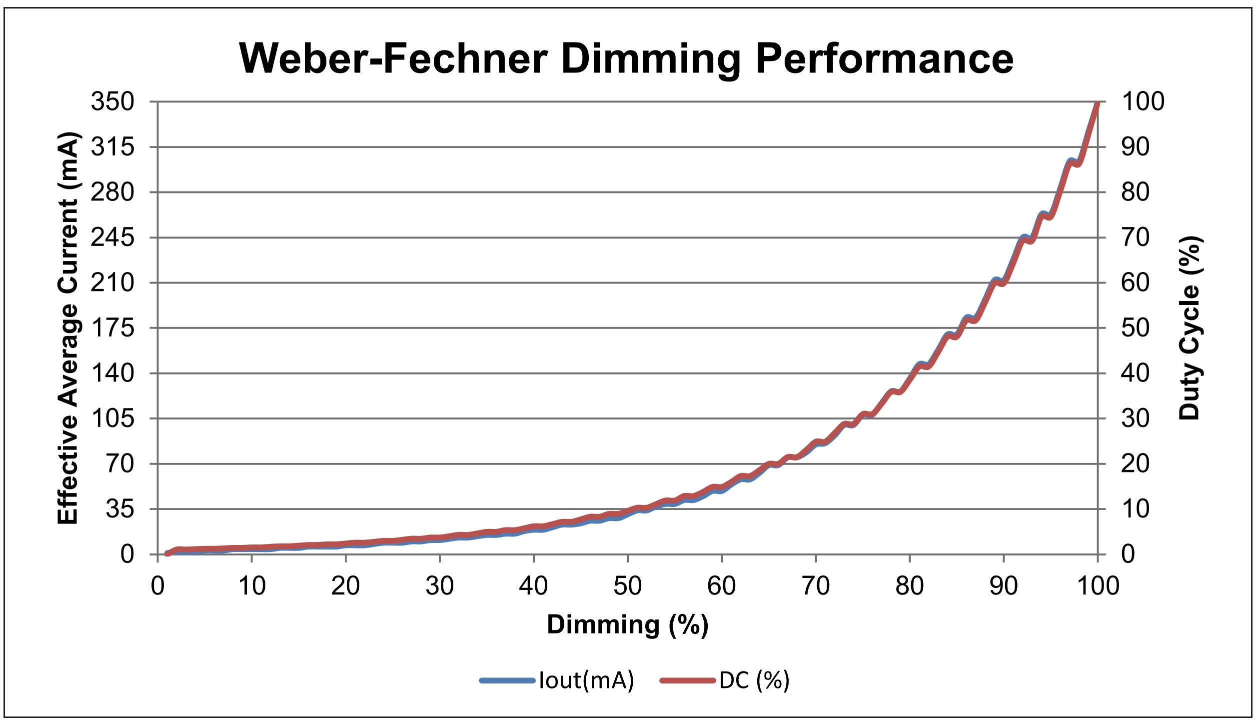
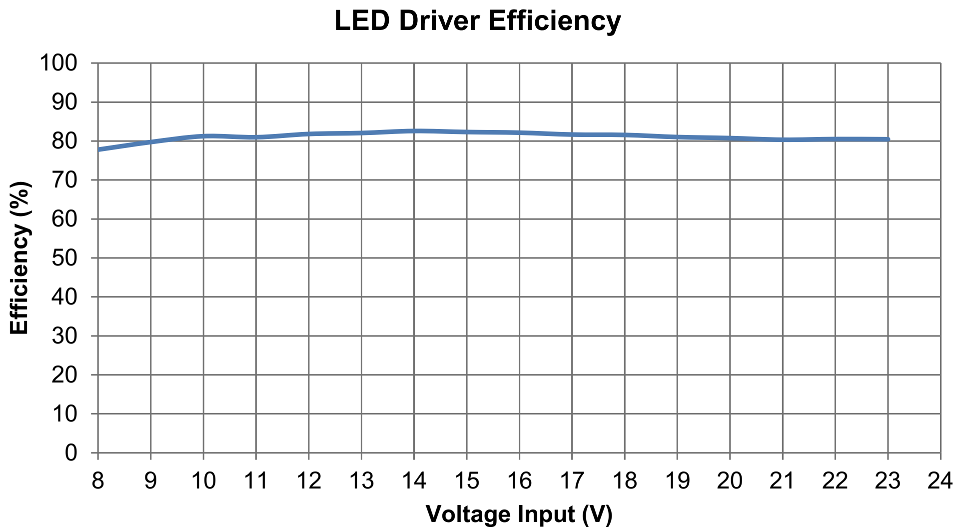


FIGURE 23: LED DRIVER EFFICIENCY



CONCLUSION

In a harsh usage environment such as an automotive application, an intelligent and reliable LED driver is essential. This application note describes an LED driver solution that meets this demand. By utilizing the flexibility of the PIC16F1769 microcontroller, an LED driver can maintain the consistency of the LED color temperature, increase the LED's lifespan, enhance the dimming method and impose safety features.

APPENDIX A: GETTING STARTED

FIGURE A-1: ACTUAL PIC16F1769 SEPIC LED DRIVER

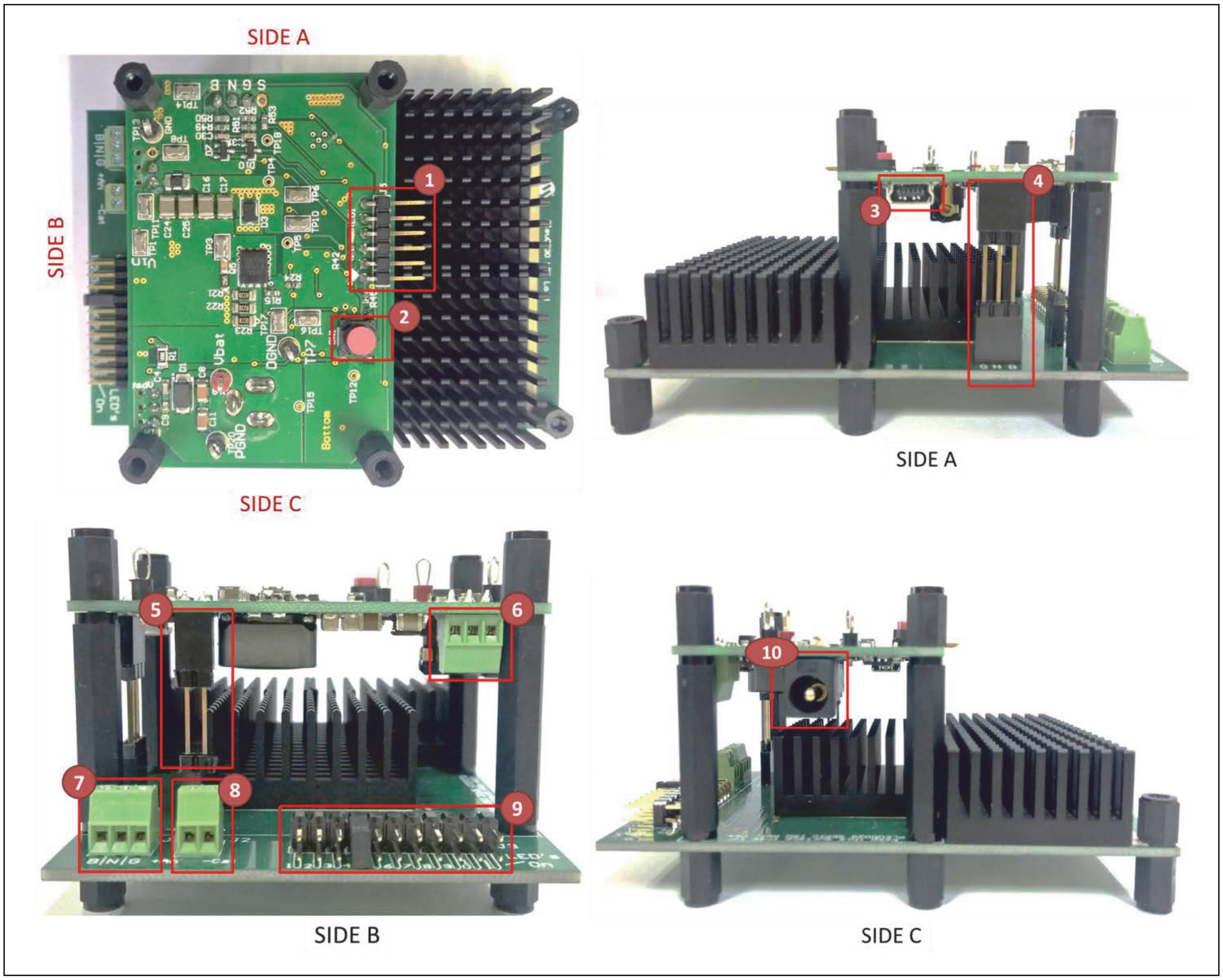


TABLE A-1: CONNECTOR DESCRIPTION

Number	Name	Description
1	J5	Debugger / Programmer Interface
2	SW1	Reset Button
3	USB	USB to UART Interface for GUI
4	J7	Terminal for Binning and NTC
5	J4	Terminal for On Board LEDs
6	LIN	LIN connector support
7	J1	External Binning and NTC support
8	J2	External LED support
9	J3	Jumpers for On Board LED selection
10	POWER	Power Supply connector

Powering the PIC16F1769 SEPIC LED Driver

Apply the input voltage to the input terminal block, J1. The input voltage source should be limited to the 0V to +45V range at 1A current limit. For nominal operation, the input voltage should be between +7V to +23V.

Applying Load to the PIC16F1769 SEPIC LED Driver

The LED driver has up to twelve on-board LEDs that can be selected in J3 connector. A jumper must be placed to the desired number of LEDs.

To drive external LEDs, connect the cathode side of the LED(-) to -Cat of J2, and the anode side of the LED(+) to +An of J2. Make sure that the jumper LED_ON is open.

Status LED

The PIC16F1769 LED driver has an LED to indicate the occurrence of Fault detection during operation. The turning On of the LED indicator states the following faults:

- UVLO detection
- OVLO detection
- OOVP detection

Graphical User Interface

A Graphical User Interface has been provided to the user for the selection of the desired current, dimming method and dimming percentage. A display for Fault protection, current temperature, input and output voltage is also provided. Refer to **Appendix B: "PIC16F1769 SEPIC LED Driver Graphical User Interface"**.

BODE PLOT MEASUREMENT

A bode connector is provided for power supply feedback loop measurement. Refer to the **Appendix C: "BODE Plot Measurement Setup"**.

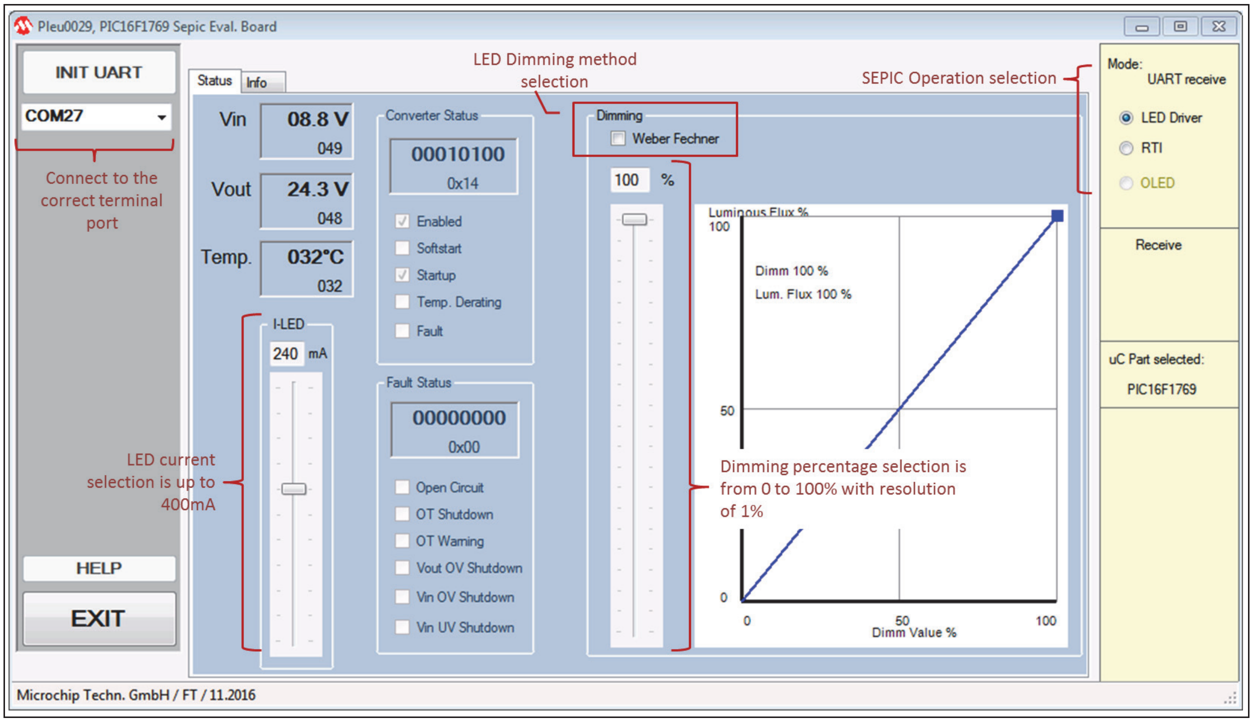
PROGRAMMING

Header J5 is provided for In-Circuit Serial Programming™. Use MPLAB® X IDE to program the LED driver. Refer to the "*MPLAB® X IDE User's Guide*" (DS52027) for more information on how to use MPLAB® X IDE with a Microchip debugger/ programmer.

Note:	Disconnect the programmer before enabling the LED driver demo board operation (www.microchip.com).

APPENDIX B: PIC16F1769 SEPIC LED DRIVER GRAPHICAL USER INTERFACE

FIGURE B-1: LED DRIVER GUI



This LED driver GUI is a PC utility designed to visualize the real-time LED driver status, voltages and temperature. The dimming and the LED current of the LED can also be controlled in the GUI.

In order to use the LED driver GUI, the user needs a mini-USB cable as a tool to establish the connection between the PC and the LED driver board. The LED driver board must be powered on before running the GUI. On the GUI, select the correct terminal port used and click the “INIT UART” button to initiate the communication.

APPENDIX C: BODE PLOT MEASUREMENT SETUP

FIGURE C-1: PLANT MEASUREMENT

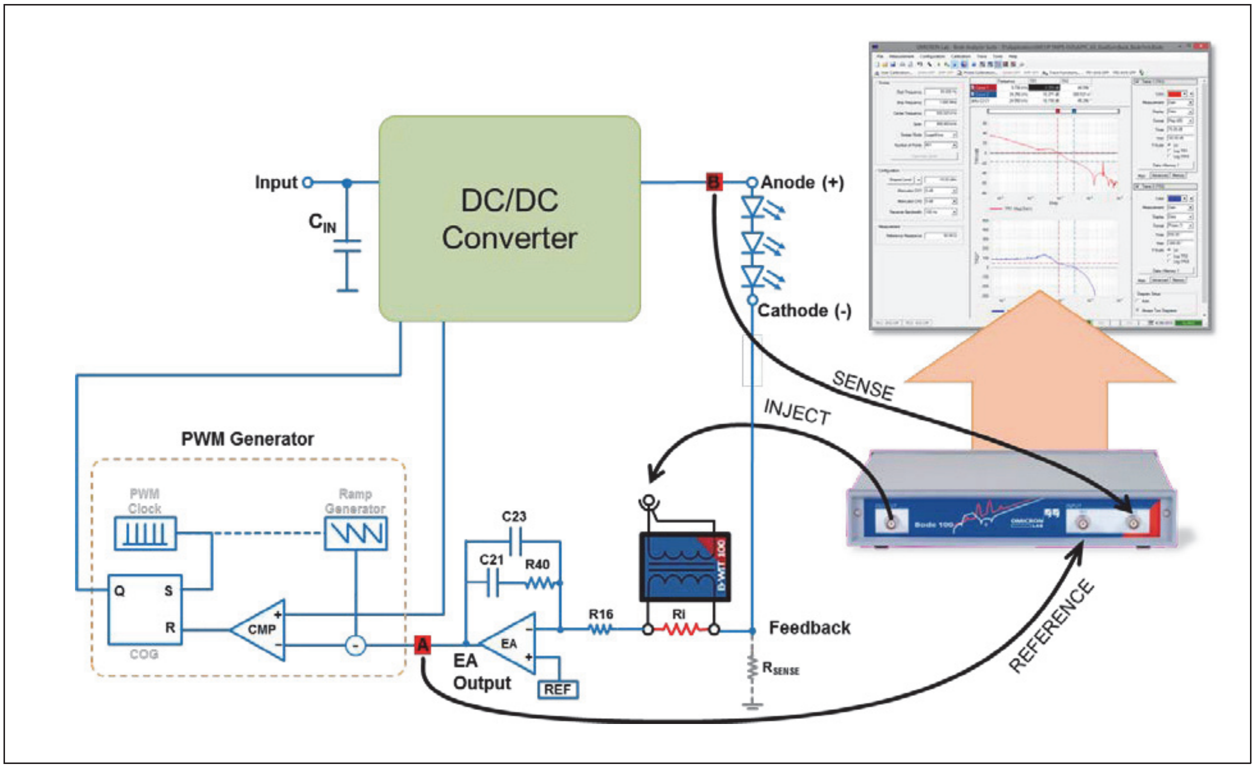


FIGURE C-2: COMPENSATION MEASUREMENT

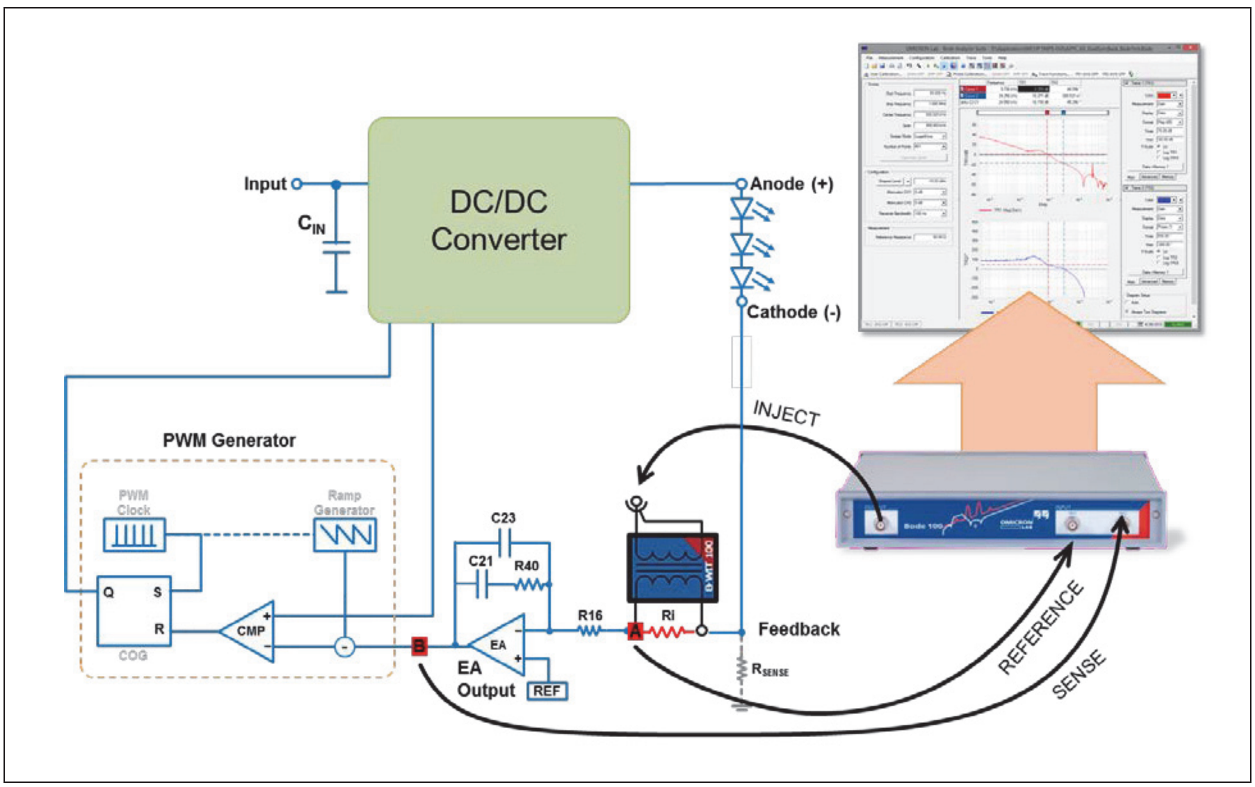


FIGURE C-3: OPEN LOOP MEASUREMENT

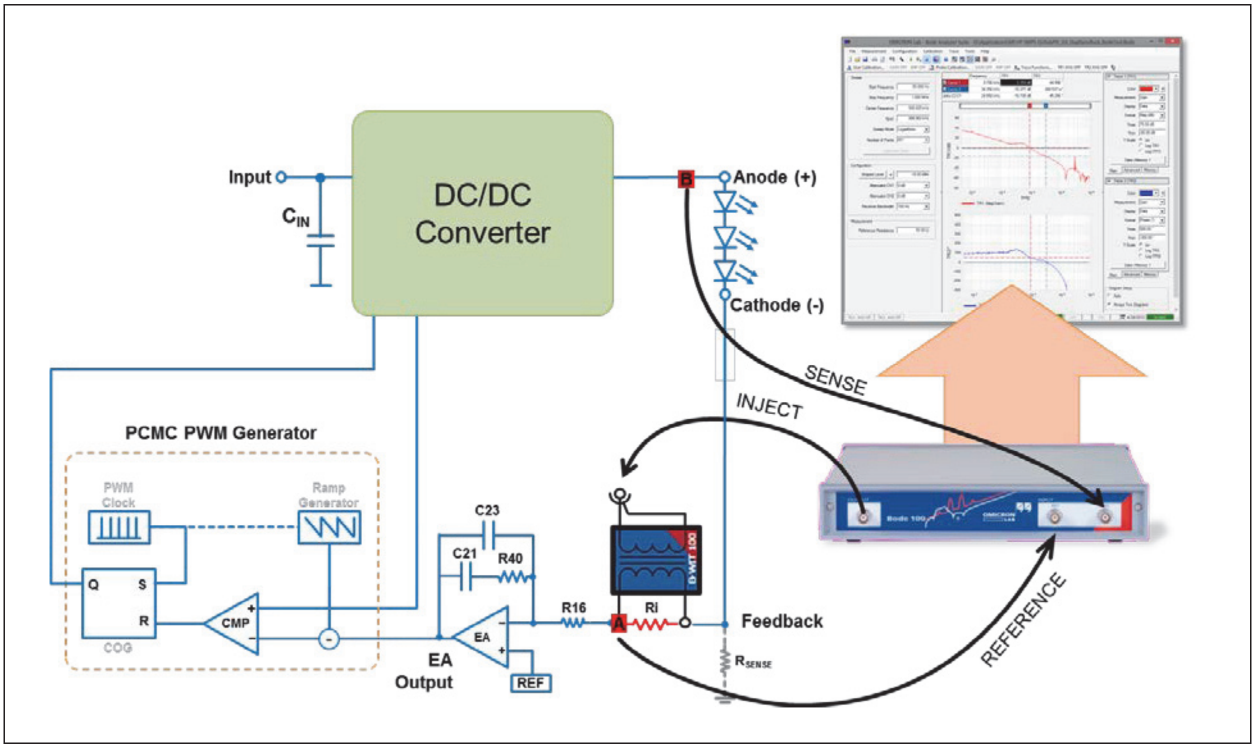
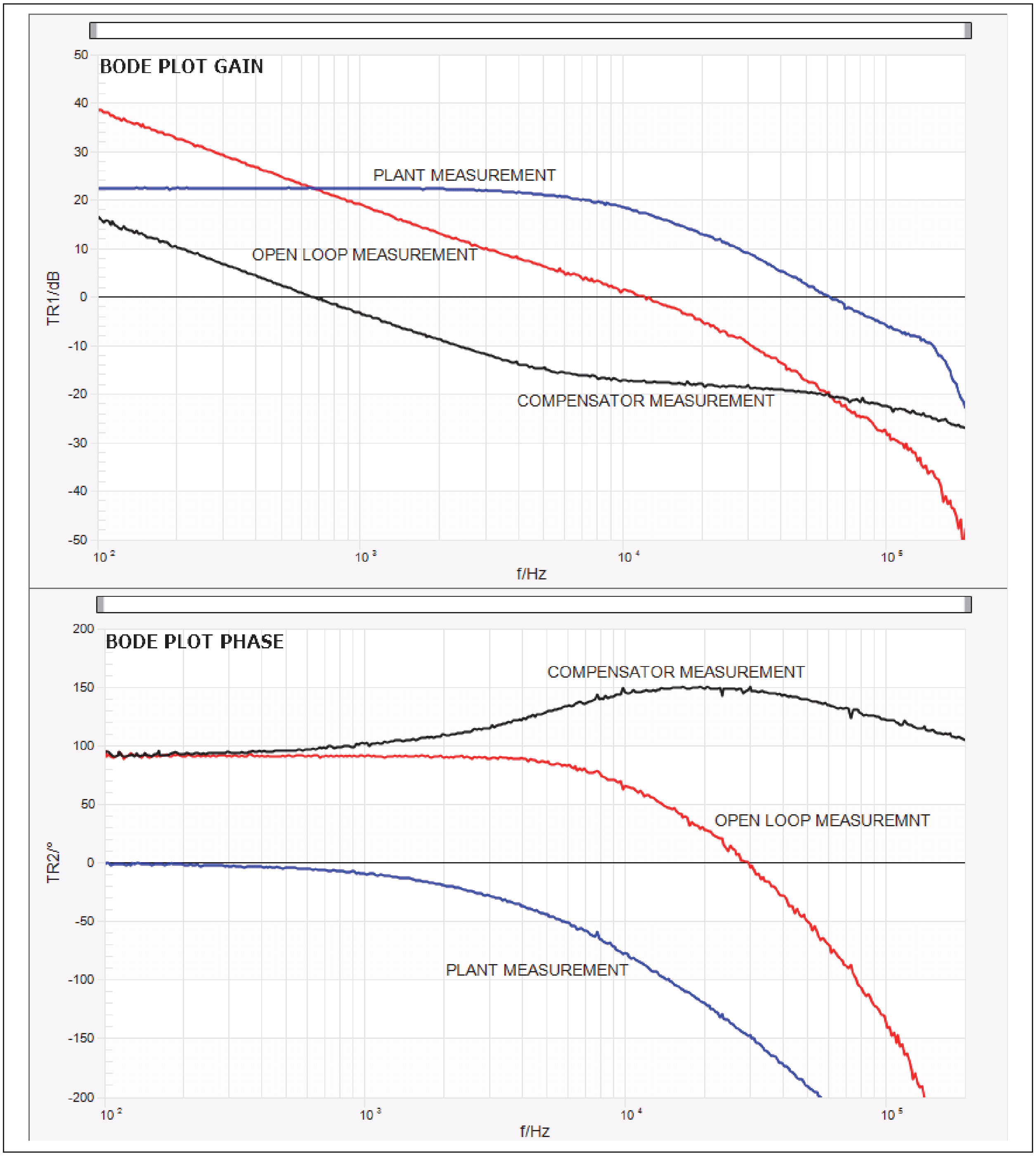


FIGURE C-4: BODE MEASUREMENT RESULT



APPENDIX D: SEPIC LED DRIVER PROTECTION FEATURE THRESHOLDS

TABLE D-1: PROTECTION FEATURE FIRMWARE THRESHOLDS

Constant Variable	Value	Description
OutputVoltageClamping	50	Desired Output Overvoltage Clamping in V
OutputVoltageClampRecovery	48	Desired Output Overvoltage Clamping Recovery Threshold in V
InputUVLOTrip	6	Desired Input Undervoltage Lockout Threshold in V
InputUVLORecovery	7.5	Desired Input Undervoltage Lockout Recovery Threshold in V
InputOVLOTrip	24	Desired Input Overvoltage Lockout Threshold in V
InputOVLORecovery	23	Desired Input Overvoltage Lockout Recovery Threshold in V
LED_OTWTrip	100	Desired Over Temperature Warning Threshold in °C
LED_OTWRecovery	90	Desired Over Temperature Warning Recovery Threshold in °C
LED_OTPTrip	124	Desired Over Temperature Protection Threshold in °C
LED_OTPRecovery	90	Desired Over Temperature Protection Recovery Threshold in °C

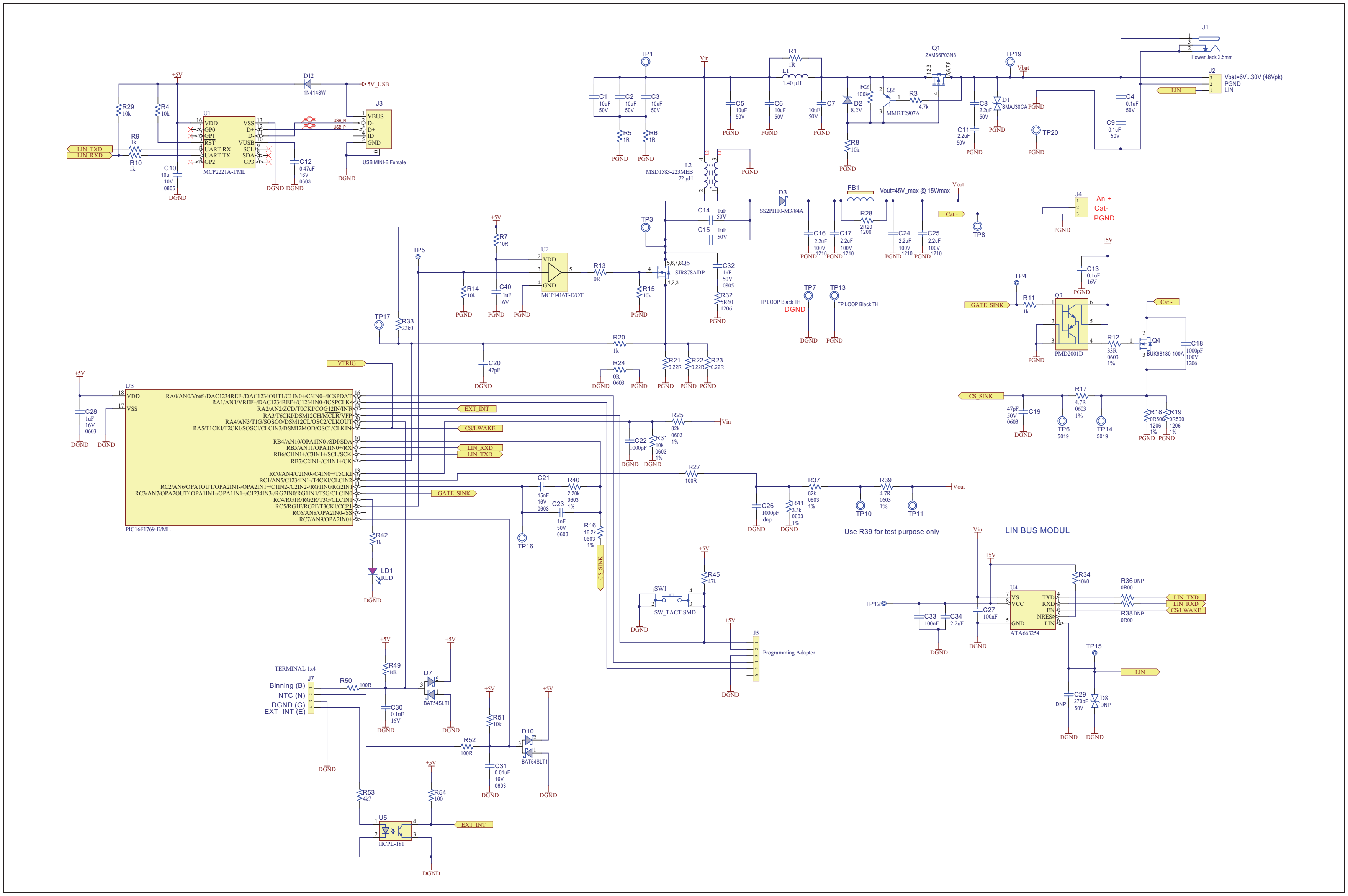
APPENDIX E: PERIPHERAL REFERENCES

TABLE E-1: SUMMARY OF PERIPHERALS REFERENCES

Peripherals	References
Analog-to-Digital Conversion	Application Note AN840, *PIC16F7X/PIC16C7X Peripherals Configuration and Integration* (DS00008400)
Capture/Compare/PWM	Application Note AN594, *Using the CCP Module(s)* (DS00594)
Timer1	Technical Brief TB3100, *Timer1 Timer Mode Interrupt Latency* (DS90003100)
Complementary Output Generator	Technical Brief TB3119, *Complementary Output Generator Technical Brief* (DS90003119)
Slope Compensation	Technical Brief TB3120, *Slope Compensator on PIC® Microcontrollers* (DS90003120)
Fixed Voltage Reference	Technical Brief TB3104, *Boost Converter Using the PIC16F753 Analog Features* (DS90003104)
Operational Amplifier	Technical Brief TB3132, *Operational Amplifier Module of 8-bit PIC® Microcontrollers* (DS90003132)
Comparators	Application Note AN1104, *Capacitive Multibutton Configurations* (DS01104)
Digital-to-Analog Conversion	Application Note AN823, *Analog Design in a Digital World Using Mixed Signal Controllers* (DS00823)

APPENDIX F: SCHEMATIC OF THE LED DRIVER

FIGURE F-1: BOARD SCHEMATIC



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