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 (CIPs) 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 CIPs are combined with other on-chip peripherals to perform functions autonomously with minimal core intervention. They 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 operate 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

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Min.</th>
<th>Typical</th>
<th>Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{IN}$</td>
<td>Operating Input Voltage Range</td>
<td>6V</td>
<td>30V</td>
<td>48V</td>
</tr>
<tr>
<td>$V_{OUT}$</td>
<td>LED String Voltage</td>
<td>3V</td>
<td>—</td>
<td>50V</td>
</tr>
<tr>
<td>$I_{LED}$</td>
<td>LED String Average Current</td>
<td>100 mA</td>
<td>—</td>
<td>400 mA</td>
</tr>
<tr>
<td>$h$</td>
<td>Efficiency at 12 $V_{IN}$, Full dimming</td>
<td>82%</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>$F_{SW}$</td>
<td>Switching Frequency</td>
<td>—</td>
<td>350 kHz</td>
<td>—</td>
</tr>
<tr>
<td>$V_{UVLO}$</td>
<td>Input Undervoltage Lockout Threshold</td>
<td>6V</td>
<td>—</td>
<td>7.5V</td>
</tr>
<tr>
<td>$V_{OVP}$</td>
<td>Input Overvoltage Lockout Threshold</td>
<td>23V</td>
<td>—</td>
<td>24V</td>
</tr>
<tr>
<td>$V_{POVP}$</td>
<td>Output Overvoltage Protection Threshold</td>
<td>34V</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>LED$_{TW}$</td>
<td>LED Temperature Warning</td>
<td>90°C</td>
<td>—</td>
<td>100°C</td>
</tr>
<tr>
<td>LED$_{OTP}$</td>
<td>LED Temperature Protection</td>
<td>90°C</td>
<td>—</td>
<td>124°C</td>
</tr>
</tbody>
</table>

### 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
- Overtemperature Protection
- Fault Output Indicator
- Automatic BIN (Brightness Index Number) Detection

The solution described in this application note has the following performance specifications and key features (see Table 1).
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 $C_c$ (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 V_{DD} voltage of PIC16F1769 increases. (The setup for the LED driver demo board for proper operation is discussed in Section Appendix A: “Getting Started”). When the V_{DD} is high enough (usually the minimum V_{DD} 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.

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 C_C charges L2. The output diode D3 is reverse-biased and C_{OUT} 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.

\[
V_{L1ON} = V_{IN}
\]

\[
V_{L2ON} = V_{CC}
\]

During the Off state, \(V_{IN}\) recharges \(C_C\). The energy stored in L1 and L2 forces the current to flow through D1 and through the output while replenishing \(C_{OUT}\). At this state, Equation 3 and Equation 4 represent the voltage across L1 and L2, respectively.

\[
V_{L1OFF} = V_{CC} + V_{OUT} - V_{IN}
\]

\[
V_{L2OFF} = V_{OUT}
\]

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.

\[
V_{L1ON} = V_{IN}
\]

\[
V_{L2OFF} = V_{OUT}
\]
Using Equation 5 and Equation 6, voltage across C (VCC) can be solved (see Equation 7 and Equation 8).

EQUATION 7: \( V_{CC} \) EQUATION BASED ON L1 VOLT-SECOND BALANCE

\[
V_{CC}DT_s = (V_{CC} + V_{OUT} - V_{IN})x(1 - D)Ts
\]

EQUATION 8: \( V_{CC} \) EQUATION BASED ON L2 VOLT-SECOND BALANCE

\[
V_{CC}DT_s = V_{OUT}x(1 - D)Ts
\]

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

\[
\frac{V_{OUT}}{V_{IN}} = \frac{D}{1 - D}
\]

Using Equation 5 and Equation 6, voltage across C (VCC) can be solved (see Equation 7 and Equation 8).

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

EQUATION 10: LED CURRENT

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

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

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

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.
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**

\[ T_s = (PR2 + 1) \times 4 \times T_{OSC} \times \text{TMR2 prescale value} \]

Where: PR2 is the limit value of the TMR2 counter
Tosc is the inverse of the oscillator frequency (1/Fosc)
TMR2 prescale value is the timer multiplier 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 to 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 increases because the COG still does not detect 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 AT 50% DIMMING

FEEDBACK STABILITY

The implementation of the feedback circuit to automatically adjust the duty cycle forms a closed-loop system. This 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, the 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 D: “BODE Plot Measurement Setup” for the gain and phase measurement setup).
FIGURE 6: OPEN LOOP GAIN AND PHASE PLOT OF THE LED DRIVER AT 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 only for a specific minimum input voltage threshold. 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 a 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. It also 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 needs to 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 a 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 for change in the 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 during 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 the 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 disappears.

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 ceases 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**

![Input Voltage Protection Diagram](image)

**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 to 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 is activated.

**FIGURE 9: OOVP WAVEFORM**

![OOVP Waveform](image)
SHORT-CIRCUIT PROTECTION

As mentioned previously, 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 or the LED string are 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 an 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

OVERTEMPERATURE 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 correctly monitor 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 overtemperature warning (OTW) trip point of 100°C, the LED driver alerts the user through an indicator in the Graphical User Interface (GUI). Once the temperature reaches the 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 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.
AUTOMATIC BIN DETECTION

Like all manufactured products, LEDs have manufacturing process variations that lead to variation in their performance. These variations can be alleviated through a binning process. Binning is the manufacturers’ process that categorizes LEDs depending on their 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.

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 Rsense2 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 the controller’s PWM output On and Off at much slower than its switching frequency. (A dimming signal that turns the PWM output On and Off 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 the 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 lifetime of the LED.
To provide more visually attractive dimming and protect the LEDs from overcurrent, 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.

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).
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 VDD. 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 stop it from conducting. When Q4 is Off, the LED is disconnected from ground and it turns off. Also, when PWM5 is low, the OPA output is tristated 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 OOV. The frequency of PWM5 is chosen in such a way that the 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.

The effective average LED current can be varied linearly in the GUI by increasing the dimming value up to 100%, (see Appendix C: “PIC16F1769 SEPIC LED Driver Graphical User Interface”). Since the 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.

The diagram shows the relationship between the dimming value and the luminous flux of the LED.
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 levels 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**

![Flowchart](image)

To support the Weber-Fechner sensitivity scale in the firmware, a look-up table with values of brightness levels 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.

**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 E: “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 task is executed every 100 µs.

1. `task_Recurt()` 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 to 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.

### COMPONENT SELECTIONS

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

### Peripheral Configuration for SEPIC LED Driver using MCC SMPS Library

The SEPIC LED Driver incorporates the PIC16F1769 as a freely programmable power supply management integrated circuit that can be programmed with the code generated using the MPLAB® Code Configurator (MCC) Switched Mode Power Supply (SMPS) Library. The MCC SMPS Library allows quick and easy configuration, and code generation for 8-bit PIC MCU SMPS applications. This library contains a set of modules for generic fundamental SMPS building blocks and topologies.

For more information about the MCC SMPS Library and the step by step procedure on how to configure it to run the SEPIC LED Driver, refer to ‘MPLAB Code Configurator Switch Mode Power Supply Library User’s Guide’ (DS50002835) and “MCC SMPS Library Configuration for SEPIC LED Driver Demo Board” (DS00003343), respectively.

### Duty Cycle

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

---

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

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

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

\[ \Delta I_{L\ ACTUAL} = \frac{1}{2} \times \frac{V_{IN} \times D_{MAX}}{L_{ACTUAL} \cdot F_{SW}} \]
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**

$\begin{align*}
I_{L1 \, AVE} &= \frac{V_{OUT} \times I_{LED}}{V_{IN \, MIN} \times \eta} \quad \eta = \text{efficiency} \\
I_{L2 \, AVE} &= I_{LED}
\end{align*}$

**EQUATION 18: INDUCTOR PEAK CURRENT**

$\begin{align*}
I_{LPK} &= I_{L1 \, AVE} + I_{L2 \, AVE} + (0.5 \times I_L \, \text{ACTUAL})
\end{align*}$

**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**

$V_{Q5\, DS} = V_{IN \, MAX} + V_{OUT \, MAX} + V_D$

**EQUATION 20: Q5 POWER DISSIPATION**

$P_{Q5D} = \left(\frac{I_{Q5\, RMS} \times R_{DS\, ON} \times D_{MAX} \times I_{Q5D} \times (V_{IN \, MIN} + V_{OUT} + V_D)}{\eta} \times \frac{T_{RISE} + T_{FALL}}{2} \times F_{SW} \right)$

Where:

$I_{Q5\, RMS} = \frac{I_{IN}}{\eta \times D_{MAX}}$

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

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

$T_R = \text{Rise time}$

$T_F = \text{Fall time}$

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 $C_{IN}$**

The input capacitor $C_{IN}$ reduces the input ripple voltage. $C_{IN}$ can have 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, \( C_{\text{IN}} \) should be able to handle the RMS current that flows through it. The RMS current flowing through \( C_{\text{IN}} \) is given by Equation 22.

\[
I_{\text{CIN RMS}} = \frac{\Delta I_{\text{LACTUAL}}}{\sqrt{2}}
\]

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

**COUPLING CAPACITOR \( C_C \)**

As mentioned previously, the voltage across coupling capacitor \( C_C \) is equal to \( V_{\text{IN}} \), therefore, \( C_C \) must be selected with a voltage rating greater than the maximum input voltage specification. The capacitance value of \( C_C \) can be calculated using Equation 23 where \( \Delta V_{\text{CS}} \) is the desired ripple voltage across \( C_C \).

\[
C_C = \frac{I_{\text{LED}} \times D_{\text{MAX}}}{\Delta V_{\text{CS}} \times F_S}
\]

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

\[
I_{\text{CM RMS}} = I_{\text{LED}} \times \sqrt{\frac{V_{\text{OUT}}}{V_{\text{IN MIN}}}}
\]

**EQUATION 22: INPUT CAPACITOR CURRENT**

**EQUATION 23: COUPLING CAPACITOR**

**OUTPUT CAPACITOR \( C_{\text{OUT}} \)**

The output capacitor \( C_{\text{OUT}} \) supplies the output current when Q5 is turned on, therefore \( C_{\text{OUT}} \) 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 \( C_{\text{OUT}} \), ESR can be ignored in calculating \( C_{\text{OUT}} \). \( C_{\text{OUT}} \) can be calculated using Equation 25, where the \( C_{\text{OUT}} \) ripple voltage \( \Delta V_{\text{COUT}} \) is 1% of the maximum output voltage.

\[
C_{\text{OUT}} \geq \frac{I_{\text{LED}} \times D_{\text{MAX}}}{\Delta V_{\text{COUT}} \times F_S}
\]

Similar to other capacitors in the circuit, the selected output capacitor \( C_{\text{OUT}} \) must also be capable of handling the RMS current that enters and leaves through it. The selected \( C_{\text{OUT}} \) RMS current rating must be greater than the computed RMS current expressed in Equation 26.

\[
I_{\text{COUT RMS}} = I_{\text{LED}} \times \sqrt{\frac{V_{\text{OUT}}}{V_{\text{IN MIN}}}}
\]

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

**EQUATION 25: OUTPUT CAPACITOR**

**EQUATION 26: OUTPUT CAPACITOR CURRENT**

Table 3 shows the summary of the selected components based on the computed values for this application.
### TABLE 3: SEPIC DESIGN COMPONENT SELECTION (CONTINUED)

<table>
<thead>
<tr>
<th>Design Equation</th>
<th>Computation</th>
<th>Selected Component/ Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>(19) $D_{MAX} = \frac{31.2V + 0.7V}{7V + 31.2V + 0.7V} = 82%$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(20) $\Delta I_L = 0.2 \times 350mA \times \frac{0.82}{1 - 0.82} = 319 mA$</td>
<td></td>
<td>COILCRAFT MSD1583-223MEB: 22 µH, 2.44A, 65 mA</td>
</tr>
<tr>
<td>(21) $L_{1, 2} = \frac{i}{2} \times \frac{7V \times 0.82}{319 mA \times 400 KHz} = 22.494 \mu H$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(22) $I_{L \text{ ACTUAL}} = \frac{7V \times 0.82}{22 \mu H \times 400 KHz} = 652 mA$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(24) $I_{LPK} = 1.95A + 350mA + (0.5 \times 319mA) = 2.63A$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(28) $I_{CINRMS} = \frac{650mA}{\sqrt{2}} = 188 mA$</td>
<td></td>
<td>10 µF, 50V X7R ceramic</td>
</tr>
<tr>
<td>(29) $C = \frac{350mA \times 0.82}{312 mV \times 400 KHz} = 2.05 \mu F$</td>
<td></td>
<td>2 µF, 50V X7R ceramic</td>
</tr>
<tr>
<td>(30) $I_{CC RMS} = 350 mA \times \sqrt{\frac{31.2V}{7V}} = 739 mA$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**TABLE 3: SEPIC DESIGN COMPONENT SELECTION (CONTINUED)**

<table>
<thead>
<tr>
<th>Design Equation</th>
<th>Computation</th>
<th>Selected Component/ Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>(31)</td>
<td>( C_{OUT} \geq \frac{350 \text{ mA} \times 0.82}{312 \text{ mV} \times 400 \text{ KHz}} = 2.29 \mu\text{F} )</td>
<td>4.4 ( \mu\text{F}, 100\text{V} ) X7S ceramic</td>
</tr>
<tr>
<td>(32)</td>
<td>( I_{COUT \ RMS} = 350 \text{ mA} \times \sqrt{\frac{31.2V}{7V}} = 739 \text{ mA} )</td>
<td></td>
</tr>
</tbody>
</table>

**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)             | \( I_{Q5D} = 1.95V + 350 \text{ mA} + (0.5 \times 650\text{mA}) = 2.63A \) | |
| (26)             | \( P_{Q5D} = (1.725A)^2 \times 0.036\Omega \times 0.82 \times 2.63A \times (7V + 31.2V + 0.7V) \times \frac{20 \text{ ns} + 20 \text{ ns}}{2} \times 400 \text{ KHz} = 71.83 \text{ mW} \) | |
| (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)             | \( I_{D3AVE} = 350 \text{ mA} \) | |
| (27)             | \( P_{D3D} = 350 \text{ mA} \times 0.7V = 245 \text{ mW} \) | |

**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

<table>
<thead>
<tr>
<th>Pin Number</th>
<th>Name</th>
<th>Function</th>
<th>Circuit Connection</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>VPP</td>
<td>VPP</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>RC5</td>
<td>COG Output</td>
<td>SEPIC MOSFET Driver</td>
</tr>
<tr>
<td>3</td>
<td>RC4</td>
<td>Fault Indicator</td>
<td>LED Fault Indicator</td>
</tr>
<tr>
<td>4</td>
<td>RC3</td>
<td>PWM5</td>
<td>Dimming Circuit</td>
</tr>
<tr>
<td>5</td>
<td>RC6</td>
<td>Unimplemented</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>RC7</td>
<td>Analog-to-Digital (AN9)</td>
<td>LED Case Temperature</td>
</tr>
<tr>
<td>7</td>
<td>RB7</td>
<td>Comparator 2 Positive Input</td>
<td>SEPIC Sensing Resistor (RSENSE1)</td>
</tr>
<tr>
<td>8</td>
<td>RB6</td>
<td>UART Transmit</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>RB5</td>
<td>UART Receive</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>RB4</td>
<td>OP AMP 1 Negative Input</td>
<td>LED Sensing Resistor (RSENSE2)</td>
</tr>
<tr>
<td>11</td>
<td>RC2</td>
<td>OPAMP1 Output</td>
<td>Compensator Circuit</td>
</tr>
<tr>
<td>12</td>
<td>RC1</td>
<td>Comparator 1 Negative Input</td>
<td>Output Voltage Sensing</td>
</tr>
<tr>
<td>13</td>
<td>RC0</td>
<td>Analog-to-Digital (AN4)</td>
<td>Input Voltage Sensing</td>
</tr>
<tr>
<td>14</td>
<td>RA2</td>
<td>Capture Compare PWM (CCP2)</td>
<td>Automotive External Interface</td>
</tr>
<tr>
<td>15</td>
<td>RA1</td>
<td>CLK</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>RA0</td>
<td>DAT</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>VSS</td>
<td>Ground</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>VDD</td>
<td>Supply Voltage</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>RA5</td>
<td>CS</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>RA4</td>
<td>Analog-to-Digital (AN4)</td>
<td></td>
</tr>
</tbody>
</table>

**Note 1:** Refer to Appendix F: “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

![Linear Dimming Performance Graph](image)

FIGURE 22: WEBER-FECHNER DIMMING PERFORMANCE

![Weber-Fechner Dimming Performance Graph](image)
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 several safety features.
## APPENDIX A: GETTING STARTED

**FIGURE A-1: ACTUAL PIC16F1769 SEPIC LED DRIVER**

![Actual PIC16F1769 SEPIC LED Driver](image)

### TABLE A-1: CONNECTOR DESCRIPTION

<table>
<thead>
<tr>
<th>Number</th>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>J5</td>
<td>Debugger/Programmer Interface</td>
</tr>
<tr>
<td>2</td>
<td>SW1</td>
<td>Reset Button</td>
</tr>
<tr>
<td>3</td>
<td>USB</td>
<td>USB to UART Interface for GUI</td>
</tr>
<tr>
<td>4</td>
<td>J7</td>
<td>Terminal for Binning and NTC</td>
</tr>
<tr>
<td>5</td>
<td>J4</td>
<td>Terminal for On Board LEDs</td>
</tr>
<tr>
<td>6</td>
<td>LIN</td>
<td>LIN Connector Support</td>
</tr>
<tr>
<td>7</td>
<td>J1</td>
<td>External Binning and NTC Support</td>
</tr>
<tr>
<td>8</td>
<td>J2</td>
<td>External LED Support</td>
</tr>
<tr>
<td>9</td>
<td>J3</td>
<td>Jumpers for On Board LED Selection</td>
</tr>
<tr>
<td>10</td>
<td>POWER</td>
<td>Power Supply Connector</td>
</tr>
</tbody>
</table>

**Note 1:** The schematic for this board can be found in Appendix F: “Peripheral References”
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 and +23V.

Applying Load to the PIC16F1769 SEPIC LED Driver

The LED driver has up to 12 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
- OVP 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 C: “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 D: “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” (DS0002027) 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: APPENDIX B: SEPIC LED DRIVER WITH FOUR ON-BOARD LEDS
DEMO BOARD

FIGURE B-1: ACTUAL PIC16F1769 SEPIC LED DRIVER WITH FOUR ON-BOARD LEDS

TABLE B-1: CONNECTOR DESCRIPTION

<table>
<thead>
<tr>
<th>Number</th>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CON1</td>
<td>Power Supply Connector</td>
</tr>
<tr>
<td>2</td>
<td>CON2</td>
<td>Communication Connector Support</td>
</tr>
<tr>
<td>3</td>
<td>CON3</td>
<td>External LED Support</td>
</tr>
<tr>
<td>4</td>
<td>CON4</td>
<td>USB to UART Interface for GUI</td>
</tr>
<tr>
<td>5</td>
<td>CON5</td>
<td>Terminal for Binning and NTC</td>
</tr>
<tr>
<td>6</td>
<td>CON6</td>
<td>Debugger/Programmer Interface</td>
</tr>
<tr>
<td>7</td>
<td>J1</td>
<td>Jumpers for On-Board LED selection</td>
</tr>
<tr>
<td>8</td>
<td>LED</td>
<td>Four LEDs</td>
</tr>
</tbody>
</table>

Note 1: The schematic for this board can be found in Appendix H: “SIMPLIFIED SCHEMATIC OF THE SEPIC LED DRIVER WITH FOUR ON-BOARD LEDs”
APPENDIX C: PIC16F1769 SEPIC LED DRIVER GRAPHICAL USER INTERFACE

FIGURE C-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, a Mini-USB cable is needed 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 D:  BODE PLOT MEASUREMENT SETUP

FIGURE D-1:  PLANT MEASUREMENT

FIGURE D-2:  COMPENSATION MEASUREMENT
FIGURE D-3: OPEN LOOP MEASUREMENT
FIGURE D-4: BODE MEASUREMENT RESULT
## APPENDIX E: SEPIC LED DRIVER PROTECTION FEATURE THRESHOLDS

### TABLE E-1: PROTECTION FEATURE FIRMWARE THRESHOLDS

<table>
<thead>
<tr>
<th>Constant Variable</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>OutputVoltageClamping</td>
<td>50</td>
<td>Desired Output Overvoltage Clamping in V</td>
</tr>
<tr>
<td>OutputVoltageClampRecovery</td>
<td>48</td>
<td>Desired Output Overvoltage Clamping Recovery Threshold in V</td>
</tr>
<tr>
<td>InputUVLOTrip</td>
<td>6</td>
<td>Desired Input Undervoltage Lockout Threshold in V</td>
</tr>
<tr>
<td>InputUVLORecovery</td>
<td>7.5</td>
<td>Desired Input Undervoltage Lockout Recovery Threshold in V</td>
</tr>
<tr>
<td>InputOVLOTrip</td>
<td>24</td>
<td>Desired Input Overvoltage Lockout Threshold in V</td>
</tr>
<tr>
<td>InputOVLORecovery</td>
<td>23</td>
<td>Desired Input Overvoltage Lockout Recovery Threshold in V</td>
</tr>
<tr>
<td>LED_OTWTrip</td>
<td>100</td>
<td>Desired Overtemperature Warning Threshold in °C</td>
</tr>
<tr>
<td>LED_OTWRecovery</td>
<td>90</td>
<td>Desired Overtemperature Warning Recovery Threshold in °C</td>
</tr>
<tr>
<td>LED_OTPTrip</td>
<td>124</td>
<td>Desired Overtemperature Protection Threshold in °C</td>
</tr>
<tr>
<td>LED_OTPRecovery</td>
<td>90</td>
<td>Desired Overtemperature Protection Recovery Threshold in °C</td>
</tr>
</tbody>
</table>
APPENDIX F: PERIPHERAL REFERENCES

### TABLE F-1: SUMMARY OF PERIPHERALS REFERENCES

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

FIGURE G-1: BOARD SCHEMATIC
Appendix H: SIMPLIFIED SCHEMATIC OF THE SEPIC LED DRIVER WITH FOUR ON-BOARD LEDS

FIGURE H-1: SIMPLIFIED SCHEMATIC OF THE SEPIC LED DRIVER WITH FOUR ON-BOARD LEDS
Note the following details of the code protection feature on Microchip devices:

- Microchip products meet the specification contained in their particular Microchip Data Sheet.
- Microchip believes that its family of products is one of the most secure families of its kind on the market today, when used in the intended manner and under normal conditions.
- There are dishonest and possibly illegal methods used to breach the code protection feature. All of these methods, to our knowledge, require using the Microchip products in a manner outside the operating specifications contained in Microchip’s Data Sheets. Most likely, the person doing so is engaged in theft of intellectual property.
- Microchip is willing to work with the customer who is concerned about the integrity of their code.
- Neither Microchip nor any other semiconductor manufacturer can guarantee the security of their code. Code protection does not mean that we are guaranteeing the product as “unbreakable.”

Code protection is constantly evolving. We at Microchip are committed to continuously improving the code protection features of our products. Attempts to break Microchip’s code protection feature may be a violation of the Digital Millennium Copyright Act. If such acts allow unauthorized access to your software or other copyrighted work, you may have a right to sue for relief under that Act.

Information contained in this publication regarding device applications and the like is provided only for your convenience and may be superseded by updates. It is your responsibility to ensure that your application meets with your specifications. MICROCHIP MAKES NO REPRESENTATIONS OR WARRANTIES OF ANY KIND WHETHER EXPRESS OR IMPLIED, WRITTEN OR ORAL, STATUTORY OR OTHERWISE, RELATED TO THE INFORMATION, INCLUDING BUT NOT LIMITED TO ITS CONDITION, QUALITY, PERFORMANCE, MERCHANTABILITY OR FITNESS FOR PURPOSE. Microchip disclaims all liability arising from this information and its use. Use of Microchip devices in life support and/or safety applications is entirely at the buyer’s risk, and the buyer agrees to defend, indemnify and hold harmless Microchip from any and all damages, claims, suits, or expenses resulting from such use. No licenses are conveyed, implicitly or otherwise, under any Microchip intellectual property rights unless otherwise stated.

Trademarks

The Microchip name and logo, the Microchip logo, Adaptec, AnyRate, AVR, AVR logo, AVR Freaks, BesTime, BitCloud, chipKIT, chipKIT logo, CryptoMemory, CryptoRF, dsPIC, FlashFlex, flexPWR, HELDO, IGLOO, JukeBox, KeeLoq, Kleer, LANcheck, LinkMD, maxSTylus, maXTouch, MediaLB, megaAVR, Microsemi, Microsemi logo, MOST, MOST logo, MPLAB, OptoLyzer, PackeTime, PIC, picooPower, PICSTART, PIC32 logo, PolarFire, Prochip Designer, QTouch, SAM-BA, SenGenuity, SpyNIC, SST, SST Logo, SuperFlash, Symmetricom, SyncServer, Tachyon, TempTrackr, TimeSource, tinyAVR, UNI/O, Vectron, and XMEGA are registered trademarks of Microchip Technology Incorporated in the U.S.A. and other countries.

APT, ClockWorks, The Embedded Control Solutions Company, EtherSynch, FlashTec, Hyper Speed Control, HyperLight Load, IntelliMOS, Libero, motorBench, mTouch, Powermate 3, Precision Edge, ProASIC, ProASIC Plus, ProASIC Plus logo, Quiet-Wire, SmartFusion, SyncWorld, Temux, TimeCesium, TIMEhub, TimePictra, TimeProvider, Vite, WinPath, and ZL are registered trademarks of Microchip Technology Incorporated in the U.S.A.


SQTP is a service mark of Microchip Technology Incorporated in the U.S.A. The Adaptec logo, Frequency on Demand, Silicon Storage Technology, and Symmcom are registered trademarks of Microchip Technology Inc. in other countries. GestIC is a registered trademark of Microchip Technology Germany II GmbH & Co. KG, a subsidiary of Microchip Technology Inc., in other countries. All other trademarks mentioned herein are property of their respective companies.

© 2015-2020, Microchip Technology Incorporated, All Rights Reserved.

ISBN: 978-1-5224-5581-3

For information regarding Microchip’s Quality Management Systems, please visit www.microchip.com/quality.
## AMERICAS

**Corporate Office**  
2355 West Chandler Blvd.  
Chandler, AZ 85224-6199  
Tel: 480-792-7200  
Fax: 480-792-7277  
Technical Support: http://www.microchip.com/support  
Web Address: www.microchip.com

**Atlanta**  
Duluth, GA  
Tel: 678-957-9614  
Fax: 678-957-1455

**Austin, TX**  
Tel: 512-257-3370

**Boston**  
Westborough, MA  
Tel: 774-760-0087  
Fax: 774-760-0088

**Chicago**  
Itasca, IL  
Tel: 630-285-0071  
Fax: 630-285-0075

**Dallas**  
Addison, TX  
Tel: 972-818-7423  
Fax: 972-818-2924

**Detroit**  
Novi, MI  
Tel: 248-848-4000

**Houston, TX**  
Tel: 281-894-5983

**Indianapolis**  
Noblesville, IN  
Tel: 317-773-8323  
Fax: 317-773-5453  
Tel: 317-536-2380

**Los Angeles**  
Mission Viejo, CA  
Tel: 949-462-9523  
Fax: 949-462-9608  
Tel: 951-273-7800

**Raleigh, NC**  
Tel: 919-844-7510

**New York, NY**  
Tel: 631-435-6000

**San Jose, CA**  
Tel: 408-735-9110  
Tel: 408-436-4270

**Canada - Toronto**  
Tel: 905-695-1980  
Fax: 905-695-2078

## ASIA/PACIFIC

**Australia - Sydney**  
Tel: 61-2-9886-6733

**China - Beijing**  
Tel: 86-10-8569-7000

**China - Chengdu**  
Tel: 86-28-8665-5511

**China - Chongqing**  
Tel: 86-23-8980-9588

**China - Dongguan**  
Tel: 86-769-8702-9880

**China - Guangzhou**  
Tel: 86-20-8755-8029

**China - Hangzhou**  
Tel: 86-571-8792-8115

**China - Hong Kong SAR**  
Tel: 852-2943-5100

**China - Nanjing**  
Tel: 86-25-8473-2460

**China - Qingdao**  
Tel: 86-532-8502-7355

**China - Shanghai**  
Tel: 86-21-3326-8000

**China - Shenyang**  
Tel: 86-24-2334-2829

**China - Shenzhen**  
Tel: 86-755-8864-2200

**China - Suzhou**  
Tel: 86-186-6233-1526

**China - Wuxi**  
Tel: 86-21-3347-1920

**China - Xian**  
Tel: 86-29-8833-7252

**China - Xiamen**  
Tel: 86-592-2386138

**China - Zhuhai**  
Tel: 86-756-3210040

**India - Bangalore**  
Tel: 91-80-3090-4444

**India - New Delhi**  
Tel: 91-11-4160-8631

**India - Pune**  
Tel: 91-20-4121-0141

**Japan - Osaka**  
Tel: 81-3-6880-3770

**Japan - Tokyo**  
Tel: 81-3-6880-3770

**Korea - Daegu**  
Tel: 82-53-744-4301

**Korea - Seoul**  
Tel: 82-2-554-7200

**Malaysia - Kuala Lumpur**  
Tel: 60-3-7651-7906

**Malaysia - Penang**  
Tel: 60-4-227-8870

**Philippines - Manila**  
Tel: 63-2-634-9065

**Singapore**  
Tel: 65-6334-8870

**Taiwan - Hsin Chu**  
Tel: 886-3-577-8366

**Taiwan - Kaohsiung**  
Tel: 886-7-213-7830

**Taiwan - Taipei**  
Tel: 886-2-2588-8600

**Thailand - Bangkok**  
Tel: 66-2-694-1351

**Vietnam - Ho Chi Minh**  
Tel: 84-28-5448-2100

## EUROPE

**Austria - Wels**  
Tel: 43-7242-2244-39  
Fax: 43-7242-2244-393

**Denmark - Copenhagen**  
Tel: 45-4450-2828  
Fax: 45-4485-2829

**Finland - Espoo**  
Tel: 358-9-4520-820

**France - Paris**  
Tel: 33-1-69-53-63-20  
Fax: 33-1-69-30-90-79

**Germany - Garching**  
Tel: 49-8931-9700

**Germany - Haan**  
Tel: 49-2129-3766400

**Germany - Heilbronn**  
Tel: 49-7131-72400

**Germany - Karlsruhe**  
Tel: 49-721-625370

**Germany - Munich**  
Tel: 49-89-627-144-0  
Fax: 49-89-627-144-44

**Germany - Rosenheim**  
Tel: 49-8031-354-560

**Israel - Ra’anana**  
Tel: 972-9-744-7705

**Italy - Milan**  
Tel: 39-0331-742611  
Fax: 39-0331-466781

**Italy - Padova**  
Tel: 39-049-7625286

**Netherlands - Drunen**  
Tel: 31-416-690399  
Fax: 31-416-690340

**Norway - Trondheim**  
Tel: 47-7288-4388

**Poland - Warsaw**  
Tel: 48-22-3325737

**Romania - Bucharest**  
Tel: 40-21-407-87-50

**Spain - Madrid**  
Tel: 34-91-708-08-90  
Fax: 34-91-708-08-91

**Sweden - Gothenburg**  
Tel: 46-31-704-60-40

**Sweden - Stockholm**  
Tel: 46-8-5090-4654

**UK - Wokingham**  
Tel: 44-118-921-5800  
Fax: 44-118-921-5820