AN1047

Buck-Boost LED Driver Using the PIC16F785 MCU

Author: *Stephen Bowling*
Microchip Technology Inc.

INTRODUCTION

This application note presents the design equations, schematics and source code for a 5.5W power LED driver using the PIC16F785 MCU. The application, as shown, can be connected to operate as a buck-boost converter or a boost converter.

The PIC16F785 makes a great choice for this application because it combines a MCU with many on-chip analog peripherals. This application is similar to the circuit described in Microchip's application note AN874 and you can refer to this document for more design information. This application note builds on the application described in AN874 and adds the following features:

- The on-chip op amp of the PIC16F785 is used to amplify the voltage across the current sensing resistor. This allows a much smaller sensing resistor to be used and reduces power dissipation.
- The PIC16HV785 device can be used, which eliminates the requirement for an external 5V regulator when operating from higher supply voltages.
- This application has unused analog resources which could be used to control another LED driver, power supply, or battery charging circuit.

LED BACKGROUND

LEDs have emerged in recent years as viable sources of light. They are no longer used solely as 'status light' indicators for electronic equipment. Advances in technology have provided LEDs that are typically 3 times more efficient than incandescent bulbs. LEDs are also extremely durable and have lifetimes exceeding tens of thousands of hours.

LEDs are designed to be driven with a constant current source. It is common to see standard current drive levels among different LED manufacturers. Current drive levels of 350 mA and 700 mA are common for power LEDs. The forward voltage across the LED can vary depending on the type and number of junctions connected in series. Many manufacturers of power LEDs will provide multiple junctions integrated into a single module.

A simple method that can be used to drive an LED is to install a resistor in series to limit the current. A linear voltage regulator or op amp circuit can also be connected in a constant current source configuration. However, these methods will not have enough efficiency at the typical power levels required for LEDs. As a 'rule-of-thumb', a linear solution will generally become impractical above 1W.

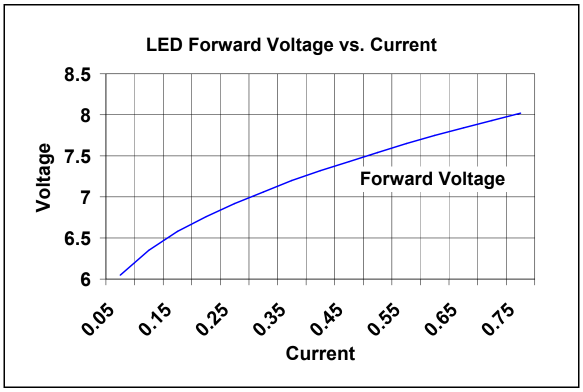
A switch-mode power supply (SMPS) provides a more efficient solution for driving a high power LED. An SMPS supply can buck or boost the input voltage to the correct level to provide the desired LED current. The system input voltage range and the required LED forward voltage will determine the SMPS topology that is selected.

The circuit and software presented in this application note are compatible with a wide variety of power LEDs. A selection of power LED sources can be found in **Appendix B: "Bill of Materials (BOM)"**. The LED module chosen for this application is the Lamina BL-4000 series White 5500K LED Light Engine. The module was chosen for the power rating and accessories that were useful for evaluation. These accessories include a PCB with wiring harness, heat sink, and lenses that provide different light patterns.

In particular, the heat sink is an important component of any power LED. Even though LEDs are much more efficient than other types of light sources, they still dissipate heat. Most of this heat must be conducted away from the LED junction to avoid damage. In contrast, incandescent light sources will radiate heat from the filament. One advantage of LED lighting is the absence of this radiated heat, which helps to keep the illuminated area cool.

The Lamina module was driven with a laboratory power supply with an adjustable current limit to determine the characteristics of the device. Figure 1 shows a plot of the LED forward voltage drop vs. current. The maximum current limit for the device is 700 mA, which results in a forward voltage drop of approximately 8V. The module can produce usable light output down to currents as low as 50 mA. Within the forward conduction range shown in Figure 1, the LED has almost resistive characteristics. This can be used to our advantage in the circuit design.

FIGURE 1: LAMINA BL-4000 TRANSFER CHARACTERISTICS

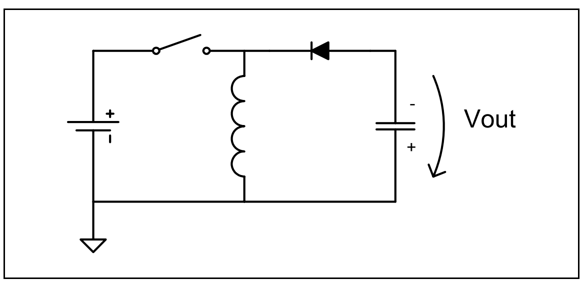


THE BUCK-BOOST CONVERTER

The Buck-Boost converter is used when the supply voltage may be above or below the required output voltage. The Buck-Boost converter is especially useful for battery applications. The Buck-Boost topology is also known as a fly-back or inverting regulator.

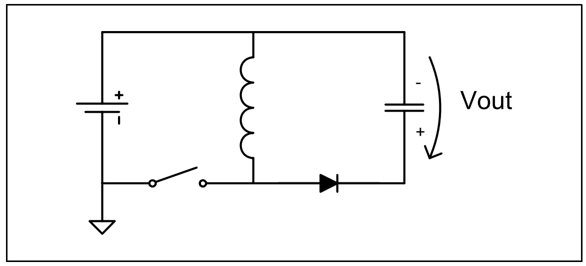
A simplified schematic of a Buck-Boost converter is shown in Figure 2. The converter has a single switch, inductor, diode, and capacitor. As shown, the buck-boost converter produces a negative output voltage with respect to the circuit common.

FIGURE 2: BUCK-BOOST CONVERTER SIMPLIFIED SCHEMATIC



The Buck-Boost converter can also be implemented as shown in Figure 3. This implementation has the advantage that a low-side switch can be used. This allows a simple MOSFET driver circuit to be used. The topology shown in Figure 3 will generate a positive voltage referenced to the input voltage rail. The down-side of this Buck-Boost implementation is that the load is not referenced to 0 volts.

FIGURE 3: ALTERNATE BUCK-BOOST CONVERTER CIRCUIT TOPOLOGY



Buck-Boost Design Equations and Component Selection

This section provides a 'cookbook' that you can use to select the component values for the Buck-Boost converter.

The output voltage of the buck-boost circuit is a function of the input voltage, duty cycle, and is given by the following formula:

EQUATION 1:

$$V_{OUT} = -V_{IN} \bullet \left(\frac{k}{1-k}\right)$$

At 0 duty, there will be 0 volts across the load. At 50% duty, the output voltage will have the same magnitude as the input voltage but will be inverted. The maximum duty cycle should be limited to avoid high peak currents and to prevent instability.

Equation 2 can be used to relate the inductor ripple current to the input voltage, duty cycle, inductor value, and switching frequency:

EQUATION 2:

$$\Delta I = \frac{V_{IN} \bullet k}{f \bullet L}$$

Equation 3 relates the output voltage ripple to the output current, duty cycle, capacitor value, and switching frequency:

EQUATION 3:

$$\Delta V_{OUT} = \frac{I_{OUT} \bullet k}{f \bullet C}$$

These are all of the basic equations that we need to calculate component values. Now we just need to set the range of some of the variables.

We know that the LED is designed for 5.5W power at 700 mA. This would mean that V_{OUT} should be 7.86V for full power LED drive. The actual LED data that was obtained using the laboratory power supply confirms this value. For convenience, we'll set V_{OUT} = 8V for the component value calculations.

A 9V power supply was used to power the demonstration circuit shown in the **Appendix A: "Schematics"**. But, for this discussion, let's assume that the LED will be powered from an auto battery. So, V_{IN} might range from a minimum of 6V to a maximum of 14V. Solving Equation 1 for k, the minimum duty cycle will be 36% (V_{IN} = 14V) and the maximum duty cycle will be 57% (V_{IN} = 6V).

Next, Equation 2 and Equation 3 can be used to determine the inductor ripple current and output ripple voltage. The switching frequency, f, is set to 250 kHz to reduce the size of the inductor. An inductor value of 100 µH was chosen for this design. The ripple will increase with reduced input voltage and increased duty cycle. At 57% duty and V_{IN} = 6V, The ripple current will be 137 mA under these conditions.

A capacitor must be used to supply current to the load while the inductor is charging. Equation 3 provides the ripple voltage value based on the switching frequency and capacitor value. A value of 47 µF will provide 36 mV voltage ripple for this design.

CIRCUIT IMPLEMENTATION

A simplified circuit design for the LED driver is shown in Figure 4. The topology of the Buck-Boost circuit has been changed so that a low-side transistor can be used to drive the inverter. Note that the output of this circuit is referenced to the battery voltage, not to ground. The output of the inverter is connected to the LED anode and produces a voltage that is greater than the input voltage.

The op amp, comparator, and PWM module are all contained within the PIC16F785 device. All pins of the op amps and comparators are externally accessible so that any circuit configuration can be implemented.

CURRENT SENSING CIRCUIT

This circuit has a current sensing resistor located at the negative connection of the power supply input. A low value resistor is used to avoid excessive power dissipation in the resistor. The voltage across the resistor is amplified by using an op amp on the PIC16F785. You may have noticed that this circuit does not sense the LED current directly. You may be wondering why the current is sensed in this location.

The best location for current sensing would be at the terminals of the power LED itself. However, a sense resistor installed at this location would have a high common-mode voltage on its terminals that would exceed the limits of the PIC16F785 op amp.

Another possible place to measure the current is in the source leg of the MOSFET. This is a good place to install a current sense resistor, because there will not be a common-mode voltage present. This measurement would provide the inductor current, which is the same as the LED current. However, the MOSFET current is not continuous. The sense resistor would only indicate the LED current when the MOSFET is on.

If current was sensed in the source of the MOSFET, the voltage across the sense resistor would look similar to the signal shown in Figure 5. A fast op amp is required to amplify this signal to a usable value.

FIGURE 4: PIC16F785 LED DRIVER SIMPLIFIED SCHEMATIC

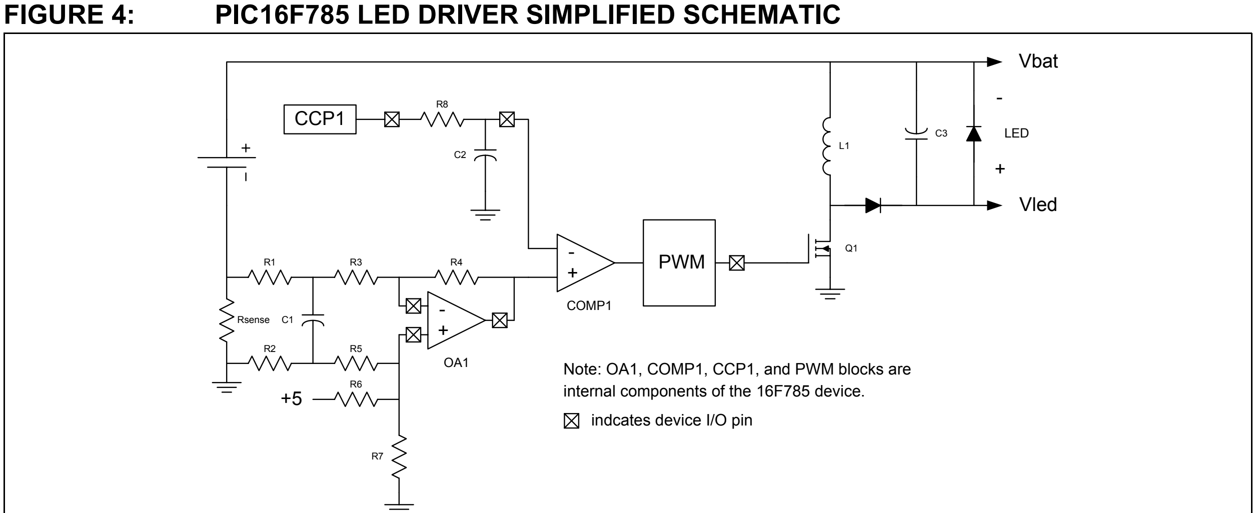
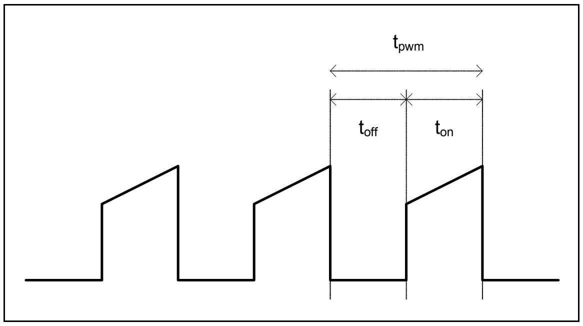


FIGURE 5: CURRENT WAVEFORM MEASURED AT SOURCE OF MOSFET



The current sensing circuit for this application is a design compromise that actually provides some useful benefits. The power supply current will be a DC current with a small amount of ripple current that results from charging and discharging the inductor. This current signal is much easier to measure using an op amp to amplify the sense resistor voltage. Secondly, this same sense circuit could be used to monitor battery current for a charging application.

Ultimately, we want to control the LED current and the total amount of power going into the LED. If the power supply voltage is measured along with the current, then the total power going into the system is a known quantity. Furthermore, the forward voltage drop across the LED is a function of current as shown in Figure 1.

The input supply voltage and the LED anode voltage can be measured periodically using the PIC16F785 ADC. These two voltages can be used to calibrate the reference voltage that is used to regulate the supply current. The LED presents a constant load, so the current reference voltage does not need to be set frequently.

The current sensing op amp is connected as a differential amplifier to obtain an accurate measurement of the voltage across the current sense resistor. R1, R2, and C1 form a low-pass filter to reduce any switching noise that may be present. However, the cutoff frequency of this filter must be chosen above the converter switching frequency to avoid limiting the control loop response.

R6 and R7 are sized to provide a 1.75V offset at the output terminal of the op amp. This offset value is chosen to provide the maximum possible positive and negative current sensing range, based on the maximum common mode input voltage of the comparator.

Current Regulator Circuit

This application uses the Two-Phase PWM module, an internal comparator, and a voltage reference to regulate the amount of LED current. The Two-Phase PWM module is an ‘analog’ style PWM module that works on the set/reset principle. First, a clock signal derived from the system clock is used to periodically turn on the PWM output. The PWM clock signal sets the fundamental PWM frequency. Second, a reset signal from one of the on-chip comparators turns off the PWM output when a specified reference level has been reached.

The amplified current signal is internally routed to the positive input of Comparator 1 of the PIC16F785. Each of the on-chip comparators has a 4 input multiplexer to select different input options. The negative input of the comparator can be connected to 2 different locations. First, the negative input can be connected internally to an on-chip voltage reference with 16 adjustable levels. Second, the negative input can be connected to an external input pin. For this application, the second option is chosen.

The Capture-Compare Peripheral (CCP1) on the PIC16F785 is used in the PWM mode to generate the voltage reference for the comparator. Using the PWM allows finer control of the comparator reference voltage. The PWM signal is filtered with a RC filter to produce an analog voltage and is connected to the negative comparator input pin.

Software Implementation

The software for this application is very simple since the LED current control function is accomplished in the analog domain. After all peripherals have been enabled and a current reference level has been set, the LED will continue to illuminate without software intervention. There are two main components of the software. The first is the setup code and the second is the main software loop.

SETUP CODE

The setup code simply enables all of the resources associated with the LED driver function:

- The Two-Phase PWM module is enabled with an input clock frequency of 250 kHz and is configured to receive a shutdown signal from Comparator 1.
- OpAmp 2 is enabled to amplify the current sensing resistor.
- Comparator 1 is enabled with OpAmp 1 connected to the negative input. The positive (reference) input is connected to an external I/O pin.
- Timer2 and the CCP1 module are enabled to produce a voltage reference.
- The ADC is enabled to monitor the input voltage and the LED forward voltage.

Note:	Either op amp or comparator could be used for this application, with minor changes in software.

MAIN SOFTWARE LOOP

The main software loop has two functions:

1. Measure the value of the DC bus voltage and the LED forward voltage using the ADC. These voltages are used to select the appropriate current reference level so that constant power will be delivered to the LED.
2. Respond to user input to set the brightness of the LED.

As stated earlier, this application measures the supply current instead of the actual LED current. This simplifies the current sensing circuit requirement and allows the same circuit to be used for LED current control and battery charge current measurement. However, this means that the current reference level must change as the input voltage changes.

One way to derive the desired current reference level is to measure the DC input voltage and perform a division operation to calculate a current reference level that will maintain a constant power input to the LED. The PIC16F785 does not have specific hardware to support divide operations, so the divide operation would be time consuming. Instead of performing the divide calculation, a lookup table has been used that selects a current reference level based on the measured voltage values. As the battery input voltage changes, the lookup table provides a new duty cycle value for the CCP1 peripheral that will adjust the current reference level.

Setting the LED Brightness Level

There are two ways that the LED light level can be adjusted using this circuit and software.

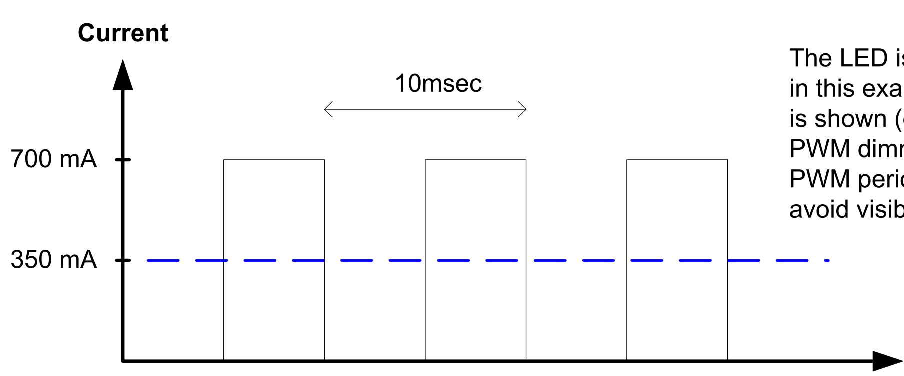
The LED brightness can be controlled by simply adjusting the current reference voltage that is connected to the comparator input. This is accomplished by writing a different duty cycle to the CCP1 peripheral that generates the reference voltage. As another solution, the internal voltage reference could be used to provide up to 16 current levels for dimming.

The first technique relies on the principle that the brightness of the LED will change with the drive current. In fact, an approximate linear control of the LED brightness can be accomplished using this method.

However, variable-current dimming is not the most efficient way to set the LED brightness level. The LED achieves its best efficiency at the maximum drive current level specified by the manufacturer.

A low frequency PWM signal can be used to modulate the LED drive current. Instead of reducing the current drive level, the LED is always driven at maximum current during the on-time. The duty cycle of the PWM signal sets the average amount of time that the LED is energized. The PWM frequency is chosen high enough so that the LED current is turned on and off at a rate that will not cause the human eye to detect flickering. The PWM frequency is also chosen low enough so that the current regulation circuit has enough time to stabilize during the PWM on time. If these conditions are met, the human eye will average the light output from the LED over time. The frequency of the PWM dimming signal is usually between 60 Hz and 1000 Hz. Figure 6 shows block diagrams that compare variable-current and PWM dimming techniques.

FIGURE 6: A COMPARISON OF VARIABLE CURRENT DIMMING AND PWM DIMMING



The LED is driven at 1/2 current in this example. Current dimming is shown (dotted line) versus PWM dimming (solid line). The PWM period is small enough to avoid visible flicker.

Software Implementation of LED Dimming Function

The interrupt signal from Timer2 is used to implement the PWM dimming function in software. This allows efficient use of hardware and software resources since Timer2 is already used along with the CCP1 module to generate the current reference level.

The system clock is provided by the internal RC oscillator, which is 8 MHz. The system clock is divided by 4 to generate a 2 MHz instruction cycle clock, Fcy. Timer2 is clocked by the device instruction clock. The period register for Timer2 is set to 0xFF, which provides an interrupt frequency of 2 MHz/256 = 7.8 kHz.

A software state machine is used to generate a 100 Hz PWM dimming signal from the Timer2 interrupt events. A software variable, PerCount, is used to count the number of Timer2 interrupts. When PerCount = 78, a new period of the dimming signal is started. At each interrupt event, the value of PerCount is compared to a second variable, Duty, to determine when the dimming signal should be turned off. The dimming signal is turned on at the start of each period, unless Duty = 0.

The software generated dimming signal is used to directly control the output of the Two-Phase PWM module. When the dimming signal is on, the PWM output is enabled. When the dimming signal is off, the PWM output is disabled.

Voltage Measurement and Current Reference Calibration

For a typical application, the supply voltage will not change rapidly. For example, you could expect the battery voltage to decay slowly as the battery discharges. For this reason, the supply voltage is only sampled by the ADC once per PWM dimming cycle (100 Hz rate). The ADC conversion is started one software count period before the LED is to be turned off (Duty – 1). This ensures that the supply voltage is at a stable value after the LED has been energized. If the duty cycle for the PWM dimming is 0, then the ADC conversion is performed at the beginning of the dimming signal period.

When the ADC conversion is complete, a new current reference value is read from the lookup table. The lookup value is a duty cycle that is written to the CCP1 module. The software can also do voltage range checks at this time.

User Interface

The application has two input buttons that are sampled once per PWM dimming period (100Hz). One button increases the duty cycle of the PWM dimming signal and the other decreases it. A software routine is provided for each button that performs de-bouncing.

OPERATION IN BOOST MODE

Depending on the supply voltage range, it may be more efficient to use a boost circuit instead of the buck-boost circuit shown in Figure 4. This decision can be made based on the LED forward voltage and the supply voltage. The LED used for this application has a forward voltage of approximately 8V when driven at maximum current. (See Figure 1) The LED can provide usable illumination with forward voltages as low as 6V.

If the supply voltage is always less than the forward voltage range of the LED, then the boost mode can be used. For example, the boost configuration would be appropriate when the circuit is powered by three 1.5V cells. The boost configuration provides greater efficiency because the duty cycle is smaller for a given output voltage and the conduction losses in the inductor and other components are smaller.

The circuit can be rewired for boost mode by connecting the LED and capacitor C3 to ground instead of the supply voltage rail. No other hardware or software modifications are necessary.

SUMMARY

This application note shows how a LED drive application can be implemented using the PIC16F785. The drive circuit can be configured for boost operation or Buck-Boost operation depending on the input voltage range. The application uses 7 bytes of RAM out of 128 bytes and 293 words of Flash out of 2048 words, leaving plenty of room for other user code. In fact, there are enough unused peripherals on the PIC16F785 to implement a second LED driver, battery charger, or other switch-mode circuit.

REFERENCES

“Power Electronics – Circuits, Devices and Applications”, Muhammad Harunur Rashid, Prentice Hall, ©1988.

PIC16F785/HV785 Data Sheet, *“20-Pin Flash-Based, 8-Bit CMOS Microcontroller with Two-Phase Asynchronous Feedback PWM Dual High-Speed Comparators and Dual Operational Amplifiers”*, DS41249, ©2006, Microchip Technology Inc.

Application Note AN874, *“Buck Configuration High-Power LED Driver”*, DS00874, ©2006, Microchip Technology Inc.

APPENDIX A: SCHEMATICS

FIGURE A-1: PIC16F785 LED DRIVER BOARD

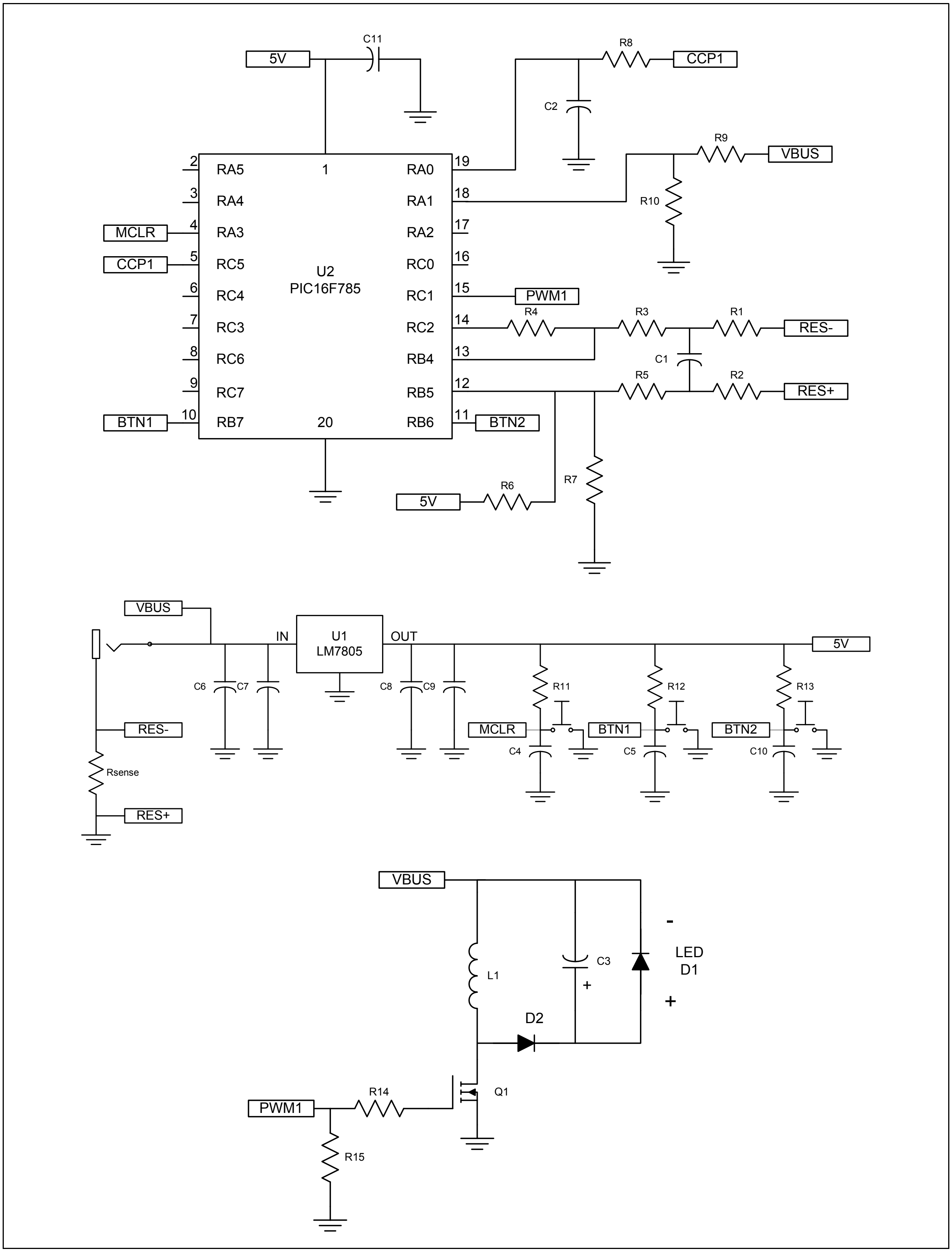
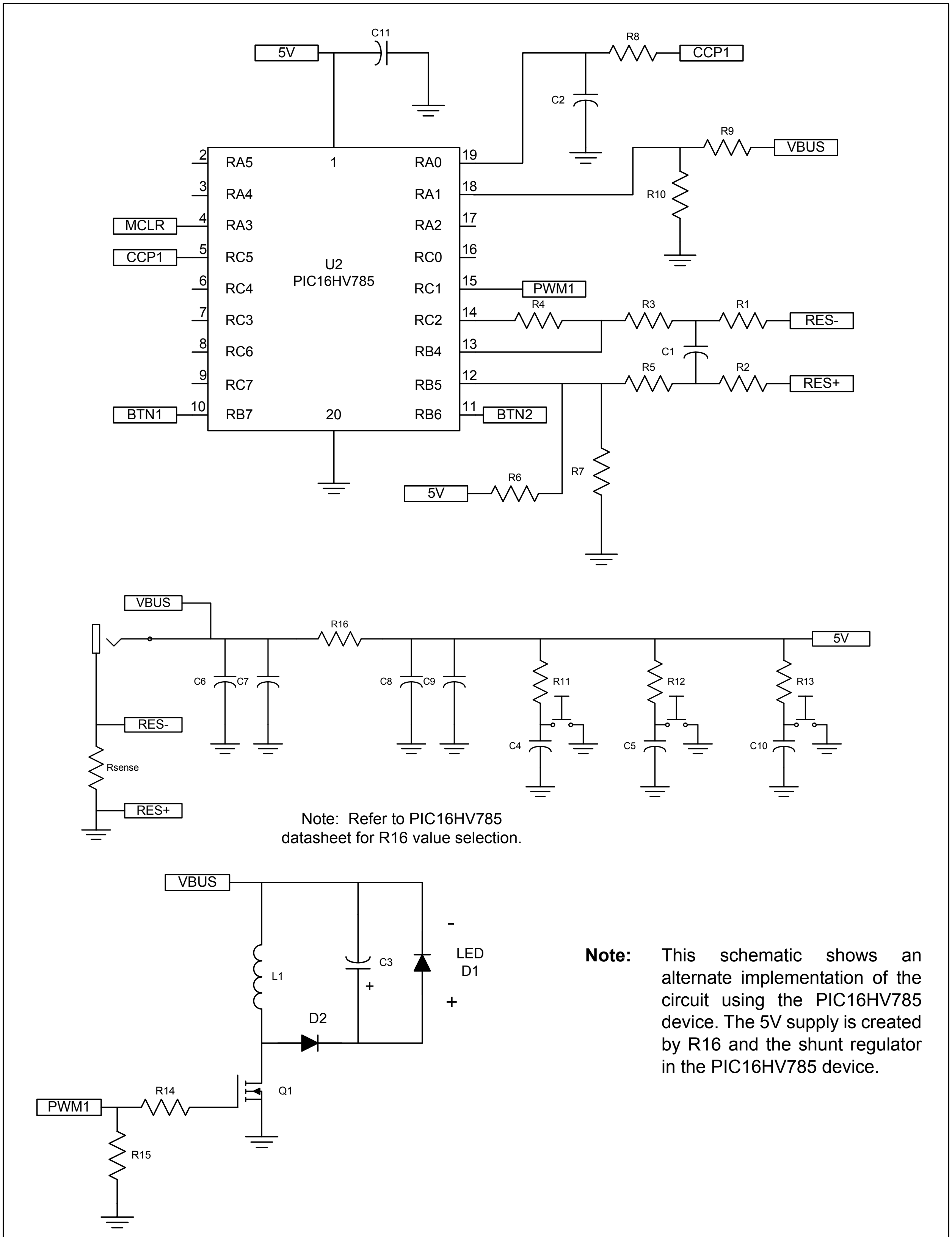


FIGURE A-2: PIC16HV785 LED DRIVER BOARD



Note: This schematic shows an alternate implementation of the circuit using the PIC16HV785 device. The 5V supply is created by R16 and the shunt regulator in the PIC16HV785 device.

APPENDIX B: BILL OF MATERIALS (BOM)

TABLE B-1: BILL OF MATERIALS (BOM)

Qty	Reference	Description	Manufacturer	Part Number
1	C1.C3	Cap 1 µF		
6	C2,C4,C5,C9, C10, C11	Cap 0.1 µF		
1	C3	Cap 47 µF, Panasonic TE-L Series, Tantalum, Low ESR	Panasonic®	EEJL1CD476R
1	C6	Cap 100 µF		
1	C7	Cap 0.1 µF		
1	C8	Cap 22 µF		
1	D1	White LED, EZ-Connect Board, EZConnect Wiring Harness	Lamina Ceramics Lamina Ceramics	EZ-4000 EZ-46WH-0354
1	D2	Shottky Diode	ON Semiconductor®	MBRA130LT3
1	J1	2.1 mm power connector jack		
1	L1	100 µH	Coilcraft	DO5010H Series
1	Q1	Power MOSFET SuperSOT-6 pkg	Fairchild Semiconductor®	NDC651N
2	R1,R2	47 ohms		
1	R3	1 kohms		
2	R4, R5	10 kohms		
1	R6	27 kohms		
2	R7, R10	1 kohms		
1	R8	100 kohms		
4	R9, R11, R12, R13	4.7 kohms		
1	R14	10 ohms		
1	R15	4.7 kohms		
1	Rsense	0.08 ohms	Vishay® Intertechnology	WSL1206R0800FEA
3	SW1, SW2, SW3	Normally Open Push Button		
1	U1	LM7805 (Optional when PIC16HV785 is used)		
1	U2	PIC16F785	Microchip Technology Inc.	

TABLE B-2: SOURCES FOR POWER LEDS

Manufacturer	Power LED Products	Web Address
CREE Inc.	XLamp 7090	www.cree.com
Lamina Ceramics, Inc.	BL-2000, BL-3000, BL-4000	www.laminaceramics.com
Optek Technologies.	Leonium Series 1 watt and 10 watt	www.optekinc.com

APPENDIX C: CURRENT REFERENCE TABLE CALCULATIONS

This Appendix describes how to calculate the values for the current reference lookup table that is used in the software. The table values are chosen based on three criteria. First, the values provide constant power input to the LED as the supply voltage changes. Secondly, the values are chosen to limit the power supplied to the LED when the supply voltage decreases below a certain threshold. The efficiency of the buck-boost circuit drops significantly when the supply voltage is low and the circuit is operating at higher boost ratios. This efficiency drop occurs because of increased conduction losses in the inductor and MOSFET at high duty cycles. Finally, an offset value is added to the values to account for the offset voltage present in the current feedback circuit.

The value of the current sensing resistor is 0.08 and the differential gain of the op amp circuit is 10. Therefore, the effective value of the current sense resistor is 0.8. This provides a current feedback sensitivity of 1.25A/V.

The CCP1 module is used to generate the voltage reference for the current control loop. At the chosen PWM frequency, 10 bits of duty cycle resolution are available. For convenience, only the upper 8 bits of the duty cycle register are used. The adjustment resolution of the current reference is given by the following calculation:

$$\frac{5V}{2^8 bits} \bullet \frac{1.25A}{V} = (24mA)/(bit)$$

The bus voltage is sampled using a resistor divider network that provides an attenuation of 0.175. Only the upper 8 bits of the ADC result is used in this application. So, the voltage scaling of the ADC is given by this calculation:

$$\frac{5V}{2^8 bits} \bullet \frac{1}{0.175} = (112mV)/(bit)$$

The next step is to decide the power level as a function of the bus input voltage. The relationship shown in Figure 7 (solid trace) was chosen based on testing of the actual application circuit. The LED power is limited at input voltages less than 6 volts. The profile shown allows the LED to produce usable light levels at low input voltages while conserving power.

The dotted trace in Figure 7 shows the supply current required to produce the desired amount of power at a given supply voltage. These values were calculated using the power profile and supply voltage. It was assumed that the switch-mode power supply is 80% efficient for the calculations.

Using the data shown in Figure 7, the duty cycle required for the CCP1 module then can be calculated as follows:

$$CCP\ Duty = \frac{I_{Supply}}{K_{Current}} + Offset$$

$$K_{Current} = \frac{24mA}{bit}$$

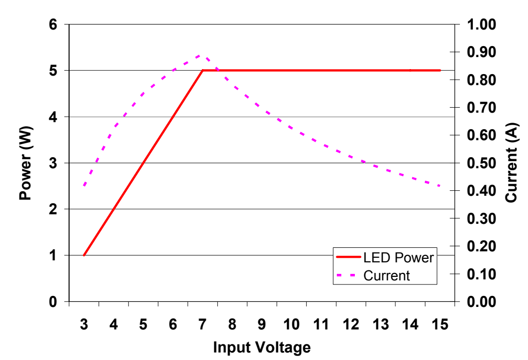
$$Offset = \frac{1.75V}{5V} \bullet 256 = 90$$

$$I_{Supply} = \frac{P_{LED}}{V_{IN} \bullet \eta}$$

$$\eta = 0.8$$

The offset value is calculated from the offset voltage that is implemented in the current amplifier circuit.

FIGURE 7: LED POWER AND SUPPLY CURRENT VS. INPUT VOLTAGE



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