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Application Note

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# Automotive High Brightness LED Control

## Based on the MC9S08MP16 microcontroller

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## 1 Overview

This document describes the implementation of a lighting control for high-brightness LED strings based on the MC9S08MP16 family of microcontrollers and a low-cost discrete solution. The embedded closed-loop control algorithm that is implemented ensures the optimal flow of current through the high-brightness LED strings, maximizing their life and avoiding undesirable visual blemishes.

The microcontroller implements a closed-loop PID control, along with some features required for automotive lighting applications including dimming, indicating over-temperature, and open-load protections.

The right combination of high performance, analog-to-digital converters, FlexTimer module, and connectivity make the MC9S08MP16 the ideal solution for this application.

**Contents**

# 2 Introduction

High-brightness light emitting diodes (HBLEDs) are taking the lighting industry by storm. Brilliant colors, long life, and energy efficiency are only three reasons why high-brightness LEDs are gaining rapid popularity in the automotive, consumer, and industrial markets. With improved output intensities, drive circuitry and packaging technologies, high-brightness LED systems offer tremendous opportunities for dazzling new lighting applications.

In the automotive industry, the HBLED technology differentiates vehicles in terms of styling, safety, and fuel economy, going from simple switch illumination and LCD backlighting through very high-brightness headlamp applications.

Some of the potential applications for HBLEDs in a vehicle include:

- Exterior LED lighting
  - Daytime running lamps (DRL)
  - Headlamps
  - Center high-mounted stop lamps (CHMSL)
  - Rear stop/turn/tail lamps
  - Adaptive brake lamps
  - Indicators
  - License plate illumination
  - Fog lamps
  - Cornering lamps
  - Static bending lights
- Interior LED lighting
  - Map lamps
  - Dome lamps
  - Puddle lamps
  - Reading lamps
  - Accent lighting
  - Ambient lighting
  - Dashboard lighting
- LED backlighting
  - Infotainment system (navigation, entertainment) displays
  - HVAC backlighting
  - Gear indicators
  - Switches
  - Instrument clusters

# 3 Background information

## 3.1 LED basics

Figure 1 shows the basic symbol of a common LED; when polarized, the current flowing through the LED is commonly called forward current and the voltage drop across it forward voltage. In the next paragraphs, the basic implications of these parameters in system behavior are described.

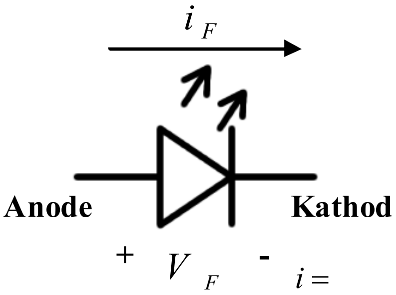

Figure 1. LED symbol

### 3.1.1 Forward current ($I_F$)

High-power LED systems require a constant current to maintain color integrity and provide luminosity.

The typical forward current for HBLEDs ranges from 100 mA up to 1000 mA; in automotive systems the control also needs to compensate low or high operational battery conditions to maintain a constant current through the LED.

### 3.1.2 Forward voltage ($V_F$)

LEDs with the same part number and same specification will not have exactly the same forward voltage. If the current $I_F$ flowing in two LEDs is the same, their forward voltages $V_F$ will not be identical. Controlling the LEDs intensity by means of a constant voltage might result in variations in intensity from LED to LED. A current control is required to ensure the same luminosity for all LEDs.

### 3.1.3 Dimming an LED

Not only does LED luminous intensity depend on the current flowing in the LED, but LED chromaticity also depends on the LED current (Figure 2). To make sure not to change LED color, it is necessary to drive the LED with constant current. By using PWM, the average current in the LED (light intensity) can be changed without changing the real LED current (color).

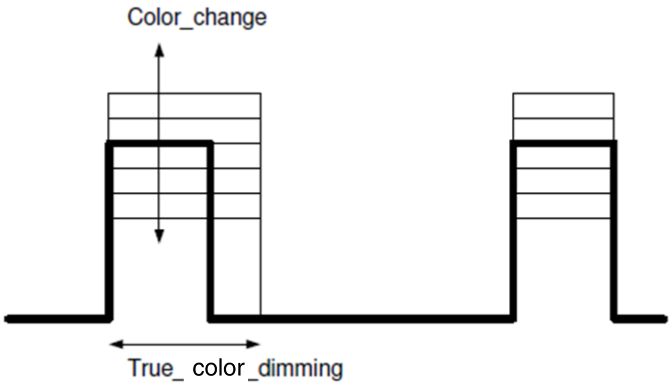

Figure 2. True color dimming example

### 3.1.4 Thermal design

LED luminous intensity is inversely proportional to LED junction temperature — emitter colors can go to higher wavelengths as temperature ($T_J$) increases. Thermal design of LED lighting systems is of primary importance.

## 3.2 Driving LEDs

There are several strategies for driving an LED, each with pros and cons in terms of cost, functionality, efficiency, and reliability; below you can find a comparison for each of these strategies:

### 3.2.1 Parallel vs. LED strings

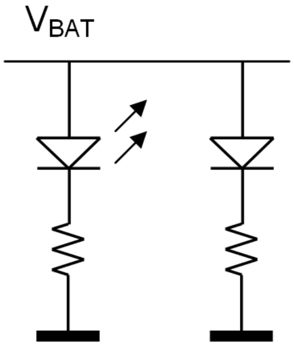

Figure 3. Parallel LED driving

Using resistors to limit LED current is very common for low-intensity LEDs, but in the case of HBLEDs the resistors must be rated for higher power, resulting in an inefficient system.

When driving LEDs in parallel, LED current variations are lower in case of $V_{BAT}$ variations. Differences in light output between LEDs are due to mismatches in the LED forward voltage and resistance variations.

If a control loop is chosen, each LED will require dedicated control, driver, and sense circuitry. This solution would be expensive if there are a large number of LEDs.

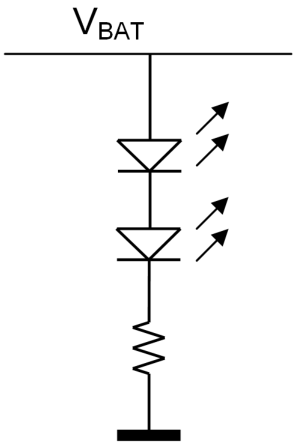

**Figure 4. LED strings**

When using LED strings, the resistors can be rated for lower power. Compared to parallel driving, power dissipation is lower, but LED current variations are higher in case of $V_{BAT}$ variations.

In a series string only one driver is needed per string — all of the LEDs in the series have the same current flowing through them to give a relatively constant brightness, and each string requires only a single sense circuit.

On LED strings, differences in light output are lower than in the parallel driver, because all LEDs have the same forward current; variations in light output remain proportional to $V_{BAT}$.

### 3.2.2 Linear regulator vs. switched-mode power supply

There are two strategies to regulate LED current with closed-loop control:

- Linear regulation
- Switched regulation

When using linear regulators, HBLED current can be set by using a resistor — the feedback loop regulates the current linearly. In case of large $V_{BAT} – V_{OUT}$ delta and/or high LED current, the power dissipation in the transistor is large.

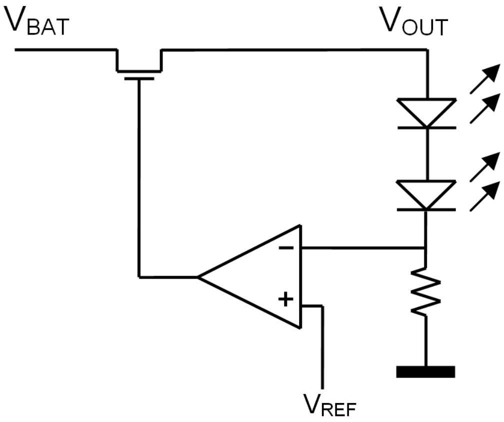

Figure 5. LED driving example using a linear regulator

Differences in light output between LEDs are due only to mismatch in light intensity between the LEDs.

When using switched-mode power supplies, the LED current can be also set by using a resistor. The feedback loop regulates the current, but in this case, the transistor is being driven in the cutoff and saturation regimes, switching $V_{BAT}$ voltage on and off. This solution is the most energy-efficient because there is very low power dissipation on the transistor.

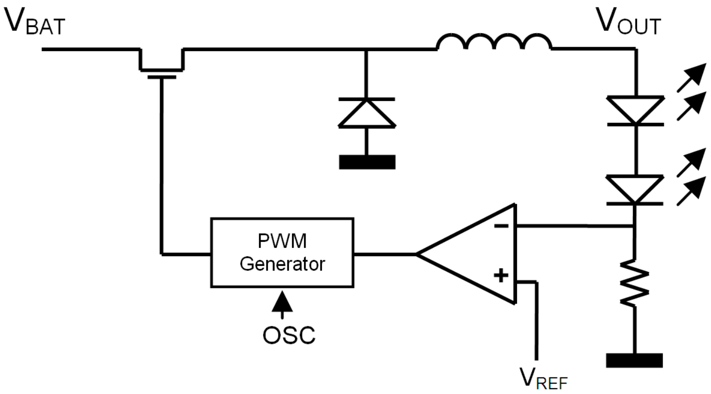

Figure 6. LED driving example using a switched-mode power supply

Depending on the SMPS topology (buck, boost, buck-boost), $V_{OUT}$ can be below and/or above $V_{BAT}$, allowing a large number of LEDs.

In terms of cost, switched-mode power supplies are usually more expensive because of the need for energy storage components (inductors and capacitors); also, switched-mode power supplies might create noise or EMI problems.

## 3.3 Switched-mode power supply basics

A switched-mode power supply regulates the output voltage as a proportion of the input voltage, controlling the average current by means of the duty cycle or on-time. When the load requires a higher current, the percentage of on time is temporarily increased to accommodate the voltage required to adapt to that change; after enough energy is stored in the inductor the on time will then be back to its previous value. This results in an average DC current flowing through the inductor that depends on the on time or the duty cycle, with a ripple current proportional to the switching frequency ($F_{Switch}$). The higher the frequency, the smaller the ripple, and the smaller the inductor can be. The maximum inductor current will depend on the switching frequency $F_{Switch}$ .

There are basically three types of switched-mode power supplies: buck, boost, and buck-boost.

### 3.3.1 Buck converter

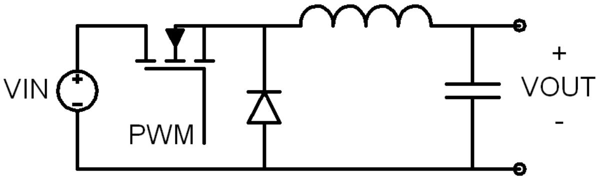

**Figure 7. Common topology for a buck converter**

- A buck (or step-down) converter changes DC voltage from a higher to a lower level.
- The transfer function of a buck converter is given by Equation 1, where D is the duty cycle of the PWM switching frequency.

$$D \approx \frac{V_{OUT}}{V_{IN}}$$ [1]

***Eqn. 1***

### 3.3.2 Boost converter

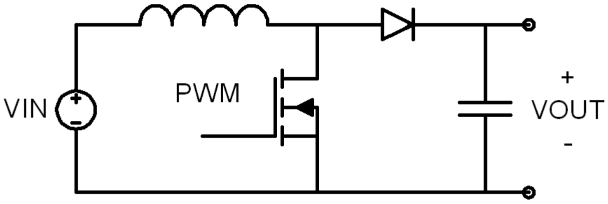

**Figure 8. Common topology for a boost converter**

- A boost (or step-up) converter changes DC voltage from a lower to a higher level.
- The transfer function of a buck converter is given by Equation 2. D is the duty cycle of the PWM switching frequency.

$$D \approx \frac{V_{OUT} - V_{IN}}{V_{OUT}}$$ [2]

***Eqn. 2***

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[1] Equation 1 is only valid for continuous conduction mode.
[2] Equation 2 is only valid for continuous conduction mode.

- Input current $I_{IN}$ will be larger than the actual output current $I_{OUT}$. The relationship is given by the equation $I_{IN} = \varepsilon \times I_{OUT} / (1-D)$, where ε is the power supply efficiency (ideally = 1).

### 3.3.3 Buck-boost converter

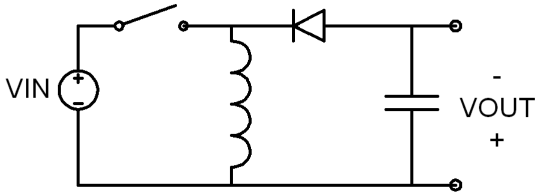

Figure 9. Negative topology for a buck-boost converter

- Depending on the duty cycle of the switching signal, in a buck-boost converter $V_{OUT}$ can be lower or greater than VIN.
- Given the fact that output power $P_{OUT}$ should ideally be equal to input power $P_{IN}$, the output current can be greater or lower than $I_{IN}$.

Several topologies can be used for buck-boost converters. It is important to have in mind that some provide a negative output voltage, like the CUK converter.

The transfer function for the buck-boost converter shown in Figure 9 (negative topology for a buck-boost converter) is given by Equation 3.

$$\frac{Vout}{Vin} \approx -\left(\frac{D}{1-D}\right) \qquad \textbf{Eqn. 3}$$

### 3.3.4 Power supply selection

Depending on the battery voltage $V_{BAT}$ and on the number and type of LEDs composing the string, the output voltage $V_{OUT}$ can be lower or greater than $V_{BAT}$.

Output voltage for an LED string is given by the sum of the forward voltage of the LEDs that it contains, resulting in Equation 4.

$$V_{OUT} = V_F 1 + V_F 2 + \ldots + V_F N \approx N \times (V_F) \qquad \textbf{Eqn. 4}$$

Where:

- *N* is the number of LEDs in the string
- $V_F$ is the typical forward voltage of the LED

# 4 Demo application overview

The present demo application is a dual string HBLED lighting control based on the MC9S08MP16 microcontroller. The microcontroller is in charge of measuring the current feedback coming from the LED strings, processing it with a control algorithm and, as a result, controlling the operation of a discrete buck-boost switched-mode power supply. This ensures the optimal flow of current through the HBLED strings, maximizing HBLED life and avoiding undesirable visual blemishes.

The microcontroller is also responsible for monitoring user inputs, battery voltage and temperature sensors, and diagnosing the status of the LED power supply in real time; extra communication features, such as LIN, can be also implemented with the same microcontroller.

The switched-mode power supply used to provide power to the HBLEDs is a discrete buck-boost topology, designed to manage from one to eighteen LED strings (from 0 V to ~65 V continuous) and up to 500 mA of output current. The design block diagram is found in Figure 10.

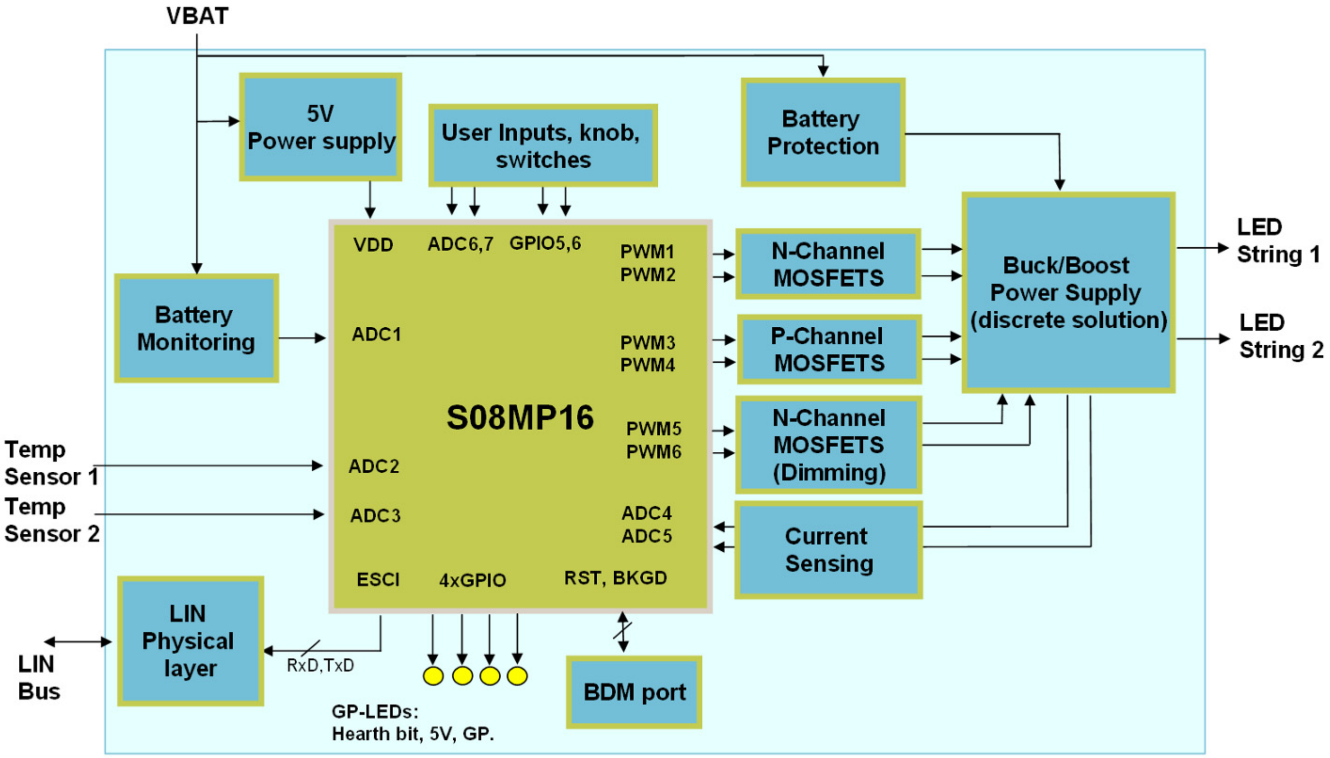

**Figure 10. Application block diagram**

# 5 Hardware design

This section describes the main hardware design considerations for the demo application, including the switched-mode power supply and microcontroller blocks.

## 5.1 Buck-boost switched-mode power supply design

As described in section Section 3.3, “Switched-mode power supply basics,” a buck-boost power supply is capable of supplying an output voltage $V_{OUT}$ either lower or greater than battery voltage $V_{BAT}$.

In the same manner, the output current capability can be lower or higher than the input current; if the module is designed to keep a constant current at the output, then the power supply’s current consumption will be variable as well.

The simple buck-boost topology shown in Figure 9 might look like an easy and cheap solution, but as stated in its transfer function (Equation 3), the output voltage is negative and referenced to $V_{BAT}$. Because of this, the application requires a complex and expensive current feedback strategy to ensure proper voltage to the microcontroller’s ADC.

The same issue can be found in other buck-boost topologies, for example the CUK converter shown in the left side of Figure 11. An alternative solution could be to use a SEPIC configuration (right side of Figure 11) in which LEDs are always connected directly to ground and have no need for differential current feedback measurements. However, this solution does have the disadvantage of added cost because it requires one extra inductor and one extra capacitor.

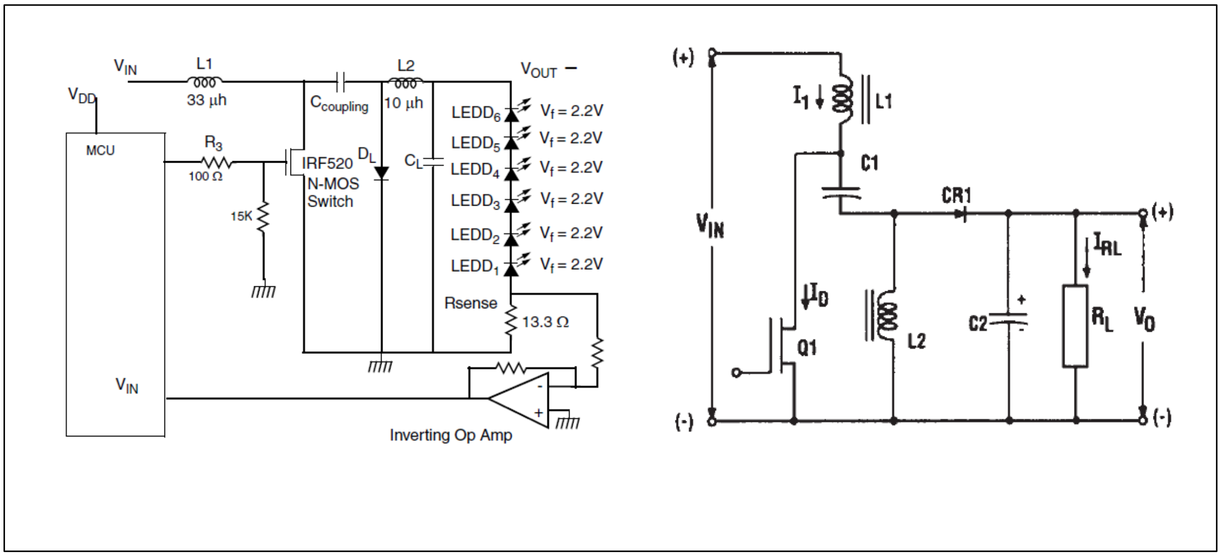

Figure 11. Alternative Buck-Boost topologies

For this demo application we explored a different topology, the one shown in Figure 12. This is a combination of a buck converter and a boost converter sharing the same inductor and capacitor.

This circuit works as a buck or boost converter depending on the status of the transistors Q1 and Q2.

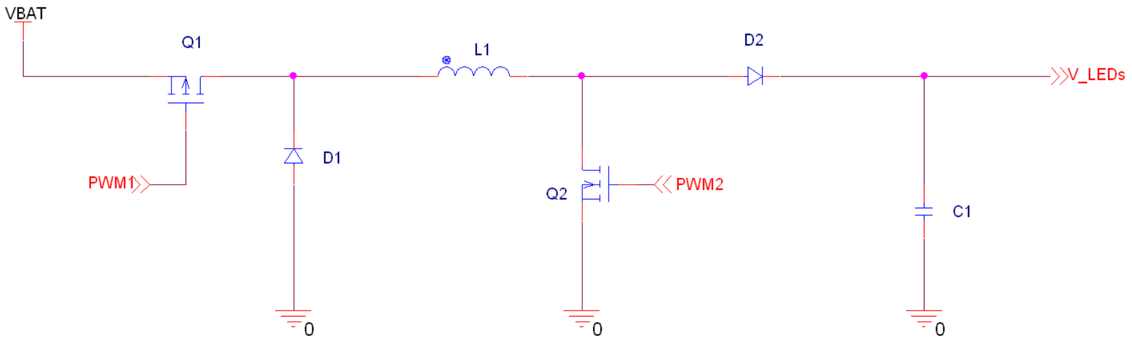

Figure 12. Buck-Boost converter used in the application

For example, if Q1 is switching and Q2 is always open, D2 would be always conducting, resulting in a common buck converter (see Figure 7); on the other hand, if Q1 is always closed and Q2 is switching, D1 will always be open and the topology is simplified to that of a boost converter (see Figure 8).

This topology reduces the cost of having an extra inductor and an extra capacitor. Also, the transfer function is reduced to that of a common buck or boost converter depending on the mode at which the switched-mode power supply is working. This simplifies the design from the standpoint of control.

## 5.2 Component value calculation

Before doing any component value calculation it is necessary to establish the electrical and functional conditions for the module to operate. The module considers these operational parameter specifications:

Table 1. Operational demo application parameters

| | Symbol | Unit | Minimum | Typical | Maximum |
|---|---|---|---|---|---|
| Forward current of LEDs | $I_F$ | mA | 100 | 350 | 500 |
| Input voltage | $V_{BAT}$ | V | 8 | 12 | 18 |
| LEDs per string | LED_# | — | 1 | 7 | 18 |
| Forward voltage of LEDs | $V_F$ | V | 2.7 | 3.2 | 3.7 |
| Buck-boost switching frequency | $F_{Switch}$ | kHz | — | 350 | — |
| Dimming frequency | $F_{Dim}$ | Hz | — | 100 | — |

From the parameters described in Table 1 we can infer that the maximum output voltage $V_{OUT\_MAX}$ for the switched-mode power supply (based on Equation 4) is given by:

$$V_{OUT\_MAX} = LED\_\#\,(\max) \times V_F\,(\max) = 66.6 \qquad \textbf{\textit{Eqn. 5}}$$

Given the chosen buck-boost topology from Figure 12, the component value can be determined in the same way typically done for a common buck converter and boost converter separately; in the same manner, the transfer function for the whole circuit depends on the mode at which it is operating.

A switching frequency of about 350 kHz is initially considered. However, this value can be changed, and the component calculation can be modified accordingly if a different switching frequency is chosen.

In the next subsections the basic formulas and procedures for component calculation are described.

### 5.2.1 Buck transistor (Q1)

Using the circuit shown in Figure 12, Q1 will be switching at 350 kHz in buck mode, and remain closed in boost mode. Therefore this component must sustain at least the maximum input voltage $V_{BAT}$ (~18V).

In terms of current consumption, in buck mode the maximum current flowing through Q1 is nothing more than the output current or the HBLED string current; however, it is important to consider that in boost mode the output current is always lower than input current. In other words, if the output current is constant then the input current will increase as a proportion of the output voltage.

Equation 6 illustrates this behavior:

$$I_{IN} = I_{\_OUT} \times D/(1\text{-}D) \qquad \textbf{Eqn. 6}$$

From Equation 6 we can infer that the maximum input current $I_{In\_max}$ is a function of the maximum output current and the maximum duty cycle.

$$I_{IN\_MAX} = I_{\_OUTMAX} \times D_{MAX} / (1 - D_{MAX}) \qquad \textbf{Eqn. 7}$$

You can derive the maximum duty cycle, $D_{MAX}$, from the boost mode transfer function (Equation 2). Substituting $V_{In\_min}$ as the minimum input voltage and $V_{OUT\_MAX}$ as the maximum output voltage, the expression yields:

$$D \approx \frac{V_{OUT} - V_{IN}}{V_{OUT}} \therefore D_{MAX} \approx \frac{V_{OUT\_MAX} - V_{IN\_MIN}}{V_{OUT\_MAX}} = \frac{66.6v - 8v}{66.6v} = 0.87 \qquad \textbf{Eqn. 8}$$

From Equation 8 we must rate the components, considering an operational range with a maximum 87% duty cycle.

**NOTE**

It is important for the application software to limit the maximum duty cycle to avoid exceeding hardware maximum limits.

Substituting $D_{max}$ in Equation 7, the maximum input current results in:

$I_{IN\_MAX} = I_{\_OUTMAX} \times D_{MAX} / (1 - D_{MAX}) = 0.5A \times (0.87) / (1 - 0.87) = 3.3\ A$

Please consider that, even though the output current for the LEDs is 500 mA maximum, the switched-mode power supply components must be rated to sustain 3.3 A.

### 5.2.2 Boost transistor (Q2)

Q2 will always be open in buck mode, so the most important electrical considerations for this component are when the switched mode power supply is working in the boost mode.

When the circuit is in boost mode, the boost transistor Q2 is used to charge the inductor during the positive duty cycle. We previously calculated that the maximum duty cycle for the PWM is 87%, and that for this range, the maximum input current $I_{IN\_MAX}$ is 3.3 A; this same spec applies for the boost transistor Q2.

In terms of voltage, during the off time the inductor will conduct its charged current to the output by polarizing D2. Therefore the drain to source voltage ($V_{DS}$) for the boost transistor is even higher than the maximum $V_{OUT}$ of the power supply (LED string maximum voltage), considering the voltage drop at boost diode D2.

Summarizing, the specification for the maximum voltage is 66.6 V + 0.7 V (output diode D2 voltage drop) = 67.3 V.

It is recommended that the boost transistor have a value of at least 50% of this limit, to avoid the possibility of voltage spikes created during commutation from damaging the device.

### 5.2.3 Buck diode (D1)

When in buck mode, D1 is open during on time, then acts as a free-wheel diode during off time.

The specification for this diode is recommended to be:

- Forward current > output current +50%
- Breakdown voltage > $V_{BAT}$

In boost mode, this diode always has an inverse polarity, resulting in a voltage approximating $V_{BAT}$ across its terminals.

### 5.2.4 Boost diode (D2)

In either mode of the power supply, the boost diode D2 will be in series with the load. Therefore its ratings must be:

- Forward current > $I_{F\_MAX}$ = 500 mA
- Reverse Voltage > $V_{OUT\_MAX}$ = 66.6 V

### 5.2.5 Inductor (L1)

The inductor’s simplified calculation for the power supply is given in Equation 9.

$$L = \frac{(Vin\_\max - Vo)(Vo)}{(Vin\_\max) * f * LIR * Iout\_\max} \qquad \textbf{Eqn. 9}$$

Where:

- *Vin_max* — Maximum input voltage = 18 V

- $Vo$ — Typical output voltage, given by the multiplication of the typical amount of LEDs per string times the forward voltage for each = 16.8 V
- $f$ — Switching frequency = 350 kHz
- $LIR$ — Inductor current ratio given in percentage — typically 0.1
- $I_{out\_max}$ — Maximum output current = 0.5 A

Substituting all these values into Equation 9 results in an inductor value of 22 µH.

It is important to consider a saturation current for the inductor of at least 50% of its maximum current. For this specific case that would be 3.3 A.

Also notice that the higher the switching frequency of the power supply, the lower will be the value for the inductor.

### 5.2.6 Capacitor (C1)

The capacitor complements the output filter. The capacitor is important for keeping the output voltage level as regulated as possible.

The calculation for the output filter capacitor is described in Equation 10.

$$C = \frac{L(I_{out\_\max} + \frac{\Delta I_{inductor}}{2})^2}{(\Delta V + V_{out})^2 - V_{out}^{\;2}} \qquad \textbf{\textit{Eqn. 10}}$$

Where:

- $L$ — Calculated inductor = 22 µH
- $I_{out\_\max}$ — Maximum output current = 0.5 A
- $\Delta I_{inductor}$ — Given by LIR × Iout_max = 0.05
- $\Delta V$ — Maximum output voltage overshoot — typically allowed to be no more than 100 mV; in this case we are choosing 50 mV
- $V_{OUT}$ — Typical output voltage for the power supply

Substituting all values into Equation 10 results in approximately 4.4 µF.

Please notice that the higher the capacitor value, the lower the output ripple will be — if possible choose a larger capacitor value than the one calculated. Also, it is recommended to choose a ceramic capacitor because such capacitors have lower ESR. This provides better frequency response.

## 5.3 Current-sense circuitry

In the application, a current-sense resistor monitors the LED current by measuring the voltage drop across it. The measured value is used by the MCU to calculate, with the control algorithm, the proper duty cycle for adjusting the current supplied to the LED(s).

The current sense resistor should be small enough not to dissipate a large amount of power, but large enough to provide adequate voltage to the analog input of the controller.

On this application, we are measuring a maximum current of 500 mA and a typical current of 350 mA; given these parameters, a 1 Ω resistor would have a maximum drop of 0.5 V in the resistor, with a dissipation of 250 mW (1/4 W). With this size resistor, the measurements can have a resolution of 1.22 mA.

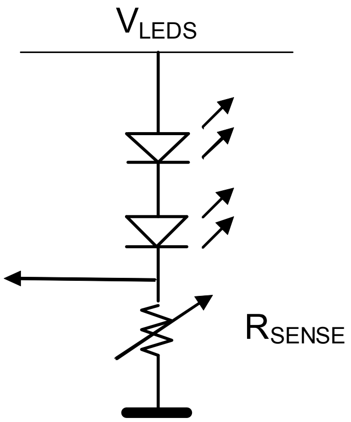

**Figure 13. Current-sense resistor array**

## 5.4 Dimming circuitry (special considerations)

Dimming is a must in today's automotive lighting applications; it allows different light intensities and smooth transitions when turning a light source on and off. Dimming also enlarges a lighting source's life by reducing thermal and electrical stress.

As explained in Section 3.1, "LED basics," dimming an LED is not as simple as merely driving less current through it, because chromaticity also depends on LED current. Pulse width modulation (PWM) is required to change the average current in the LED without changing the LED color.

Dimming HBLEDs might look simple, but when using a variable switched-mode power supply, several challenges arise, such as boosting the output voltage during dimming signal off time. Also, the current feedback measurements must be synchronized with the PWM signal to avoid measuring during off time or state transitions.

### 5.4.1 Boosting output voltage

If the power supply is commutating, and the load is simply disconnected, because of either an open load condition, a broken LED, or the load being intentionally switched on and off when dimming, then the output of the switched-mode power supply will consequently create a larger voltage on the output capacitor. While the switched-mode power supply continues commutating, this voltage continues increasing, up to a point that can damage the power supply components.

This phenomenon occurs because energy is stored on the power supply inductor and then delivered to the load, but this energy cannot be delivered to any load when the LED string is disconnected. Therefore the energy is transformed into a large output voltage.

The output voltage boosting behavior can be observed in Figure 14.

To avoid this phenomenon, the switched-mode power supply must stop switching each time the load is disconnected (open load) or during the off period of the dimming PWM signal.

The output voltage boosting can be solved using several methods. For example, it is possible to have a parallel on-board load that is always connected to the output, limiting the voltage boosting when the main load is disconnected. This method is not recommended because it makes the power supply inefficient, dissipating energy on the alternative load at all times.

Hardware protections such as Zener diodes can also be used in a more efficient manner, but this adds cost to the module. The solution proposed here is a software solution, done by means of an open load detection routine and synchronization between the power supply switching signal and the PWM dimming signal.

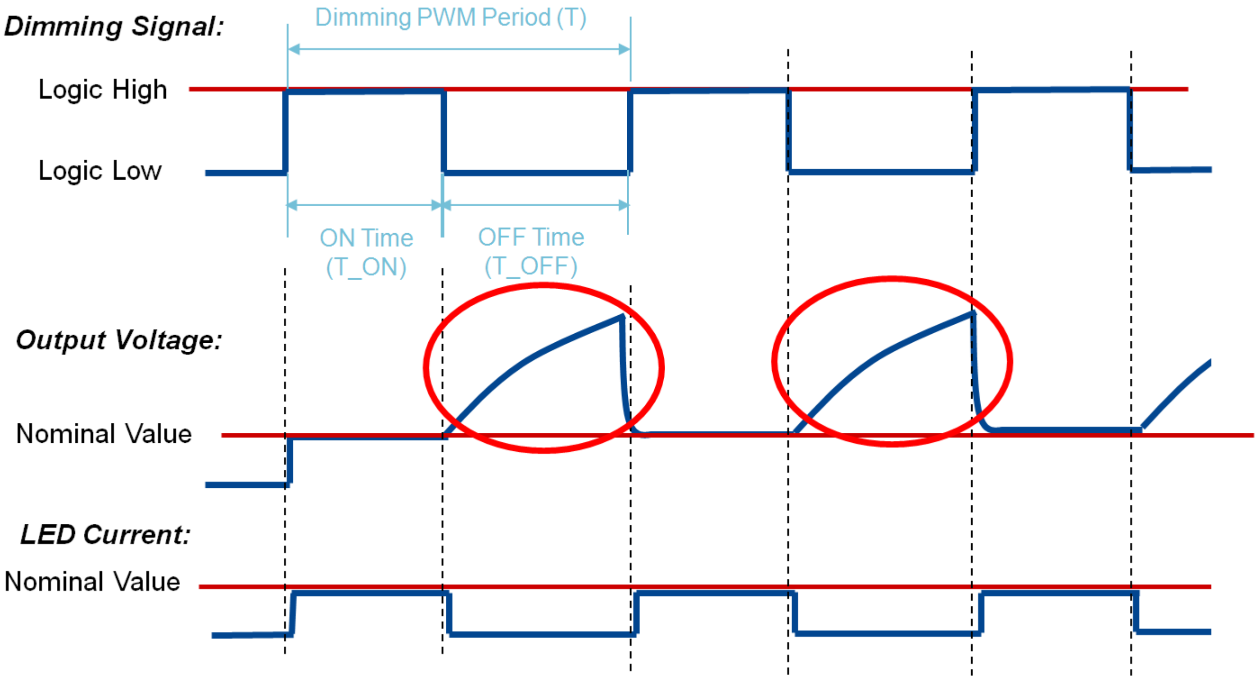

**Figure 14. Output voltage boosting during off time of dimming signal**

## 5.4.2 PWM synchronization

It is important to consider that, if the load is continuously connected and disconnected, and consequently the current is going to be switching from zero to its nominal value, the current feedback measurement must be synchronized with the PWM signal. Synchronization is necessary for taking accurate measurements after the LED current is stabilized and only during the positive PWM duty cycle.

The PWM synchronization is shown in Figure 15.

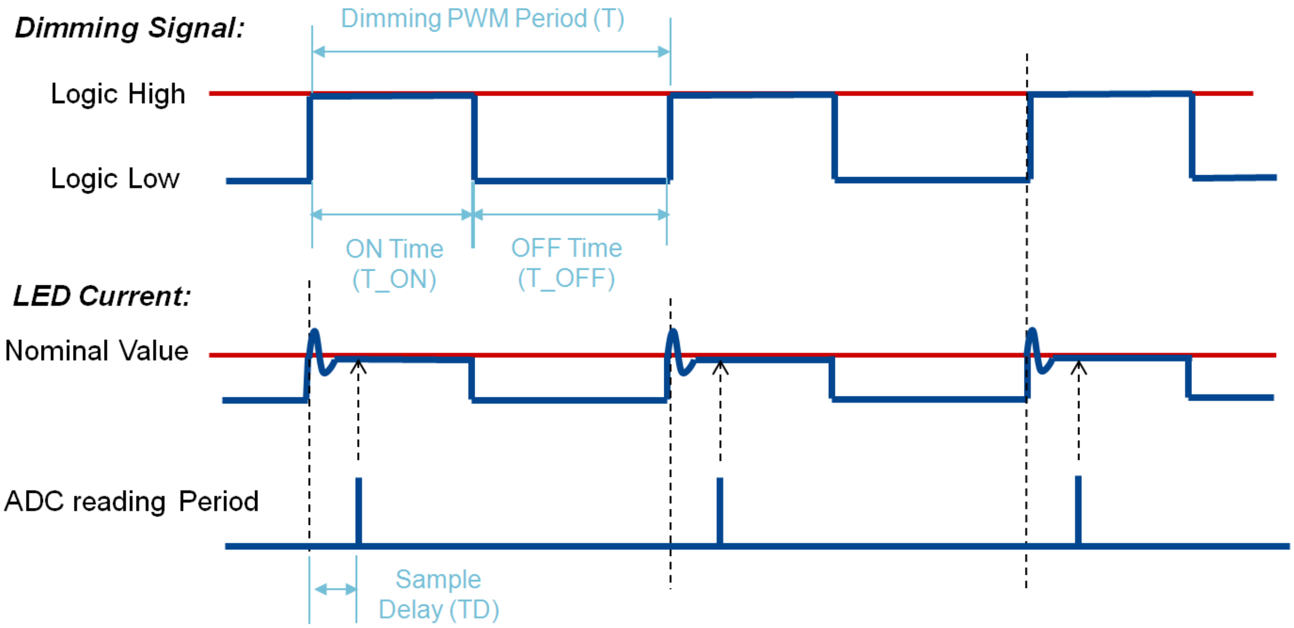

Figure 15. Current feedback measurement synchronization

**NOTE**

For the PWM synchronization, the MC9S08MP16 analog-to-digital converter module includes a hardware trigger function to synchronize ADC readings with either real time counter (RTC), high speed comparators (HSCMPx) or the FlexTimer modules (FTMx).

In addition, any delay for this ADC trigger can also be programmed with the programmable delay block built into the MC9S08MP16.

## 5.5 Protections

Almost every lighting automotive module requires that any output be protected against conditions such as:[1]

- Open load
- Short circuit
- Over-current
- Output over-voltage
- Voltage clamping

Also, to ensure safe operation of the switched-mode power supply, it is necessary to protect against battery over-voltage, battery under-voltage, output voltage boosting, and high-current operation.

In the next subsections you will find a brief description of how the main protections implemented in this example module work.

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[1] This list is not intended to list every such condition, but only to offer examples.

### 5.5.1 Open load

An open load condition occurs whenever an attempt is made to turn the load on and no current feedback is detected; this condition is monitored by the microcontroller approximately every 1 ms by reading the result from the analog-to-digital converter corresponding to the current feedback. If the current feedback value is lower than 10% of its nominal value and the voltage (also monitored by the microcontroller ADC) is above the operational limit, an open load flag is asserted and the power supply is disconnected immediately.

When an open load condition occurs, an open load retry period starts so as to periodically check the condition and attempt turning the load back on. The open load flag is also cleared when the load is manually turned off, so next time it is set on again, the module will try to turn it on normally.

The open load condition is monitored only in the positive period of the dimming signal. In other words, an open load condition is ignored when the load is intentionally disconnected by the dimming circuitry. In the off time for the PWM dimming signal, the switched-mode power supply stops switching to avoid output voltage boosting.

### 5.5.2 Output short circuit/over current

If a short circuit occurs, the output must be protected (off) to avoid excessive current flowing through the components of the switched-mode power supply.

This condition is also monitored with the microcontroller by reading the analog voltage across the current feedback resistor. If the value exceeds the one corresponding to the maximum operational current, then the power supply is disconnected.

### 5.5.3 Over-voltage (battery)

The battery voltage is monitored to make sure that the control algorithm and its result values are applied to the power supply only if the battery voltage is valid ($18\ V > V_{BAT} > 8\ V$).

The battery voltage is monitored using a resistor divider; the resistor divider output is connected to an analog-to-digital converter (ADC) channel of the microcontroller.

If the battery voltage value is lower than nominal, the control algorithm tries to increase the duty cycle so as to have accurate output voltage to supply the LEDs at a constant current. However, if it’s below the lower limit (8 V), the power supply duty cycle would increase above the maximum hardware limits, overstressing the components.

On the other hand, if the voltage is high the control algorithm compensates the output voltage by decreasing the duty cycle for the switched-mode power supply. However, the excessive input voltage could damage the components in the module, so it is recommended to stop the module’s operation.

### 5.5.4 Over-voltage (output)

The output of the switched-mode power supply is monitored by means of a resistor divider; the resistor divider voltage is tied to an ADC channel which is read periodically to make sure that the output voltage is within limits.

In case of over-voltage, the switched-mode power supply period will be decreased to the point at which the condition is removed.

This over-voltage information is also used to determine the open load condition.

### 5.5.5 Power supply over-current

The over-current protection is implemented to ensure that the power supply components are not driving a current higher than the maximum specified, thus ensuring proper power supply operation.

This protection makes sure that regardless of the operating conditions and the internal limitations in the power supply duty cycle, the switched-mode power supply components are not driving higher current than expected. This protection monitors, using a current-sense resistor, the main power supply loop that is created by the buck transistor, boost transistor, and inductor. This protection works only in boost mode where the input current is higher than the output current.

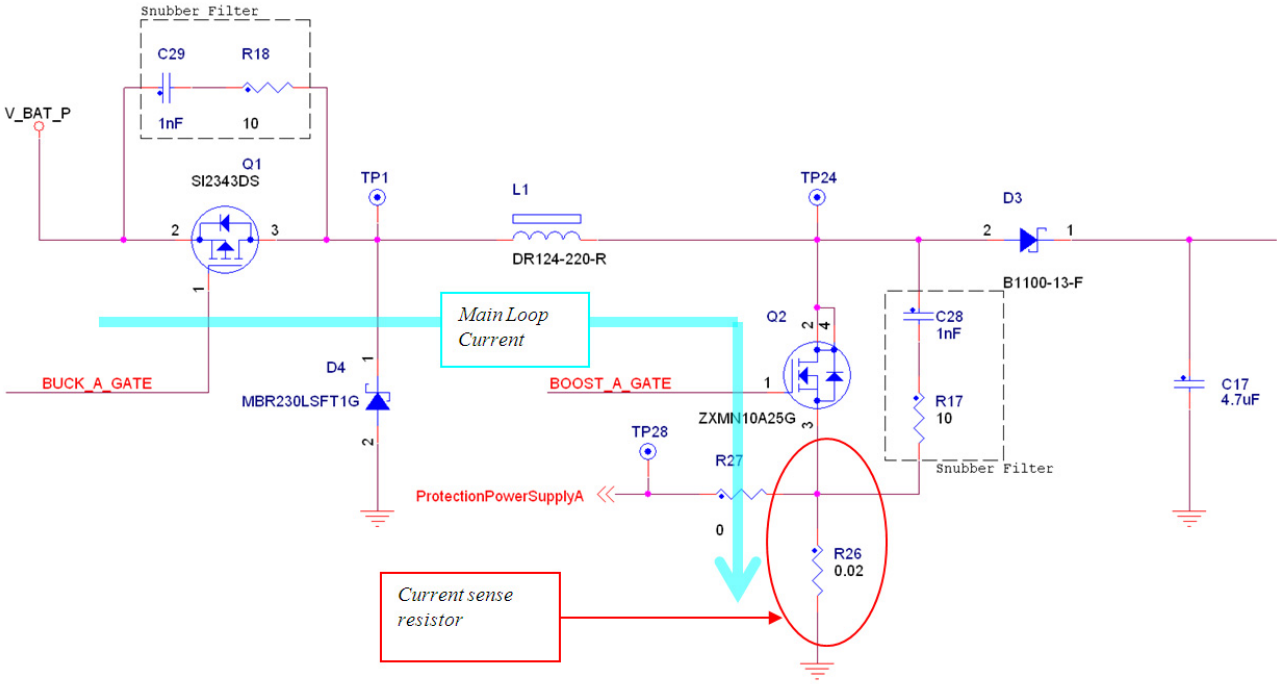


Figure 16. Power supply over-current protection

### 5.5.6 Over-temperature

Not only is it important to design a proper heat sink for the board to dissipate the energy generated by the LEDs, but it is also necessary to have temperature feedback to ensure that the module is working within a safe temperature region.

In this application, an analog-to-digital converter channel is dedicated to reading the information coming from a temperature sensor; the temperature sensor is strategically placed in the center of the LED daughter card, where the heat concentration is typically larger.

The sensor is rated from –55 °C to 130 °C and its main function is to protect LEDs working out of their operational range. If the LEDs are at a high temperature (in this case, > 85° C) the module dims the string of HBLEDs to 50% intensity to avoid damaging the LEDs.

## 5.6 Microcontroller

The MC9S08MP16 is a low-cost, high-performance HCS08 microcontroller available with a variety of modules, memory sizes, memory types, and package types.

The characteristics that make this device the ideal solution for this application are described in Table 2.

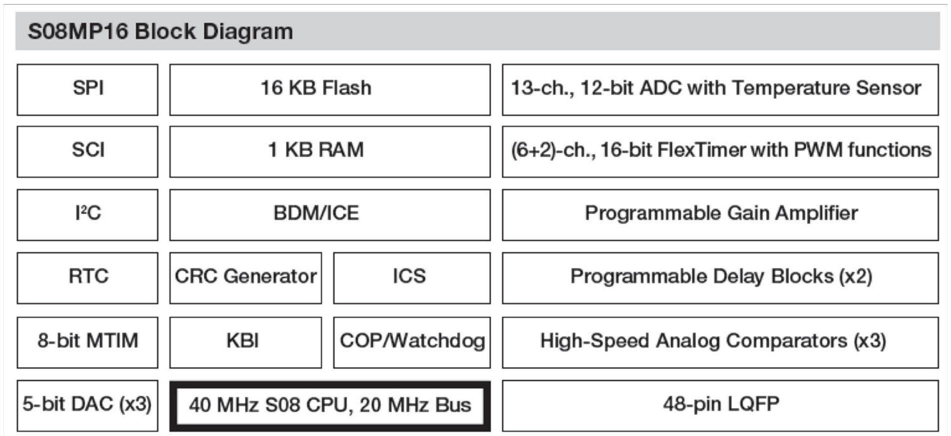
**Table 2. Special features of MC9S08MP16 used in HBLED applications**

| Module | Channels available | Special characteristics for HBLED applications |
|---|---|---|
| Analog-to-digital converter (ADC) | 13 | 12-bit ADC with hardware trigger from PWM module allows conversion at any point in the PWM cycle. |
| FlexTimer (FTM) | 6 PWM | 16-bit resolution and up to 40 MHz clock speed enables high-frequency and high-resolution PWM generation. |
| High speed analog comparator (HSCMP) | 3 | Analog comparator works in conjunction with the PWM to enable quick LED current regulation.<br>Rail to rail, selectable for rising or falling edge or both. |
| Programmable gain amplifier (PGA) | 1 | Allows the use of a very small external sense resistor.<br>Differential readings, triggered by software or hardware, programmable gain from 1× to 32×. |
| Programmable delay block (PDB) | 2 | Dead time insertions, trigger synchronization for PGA or ADC. |

### NOTE

> The modules described here are only some of the modules available in the MC9S08MP16; the modules highlighted there are special features useful in the HBLED control applications. To see the full device description and features please refer to device reference manual and datasheet.

The MC9S08MP16 block diagram is found in Figure 17.



S08MP16 Block Diagram

| | | | |
|---|---|---|---|
| SPI | 16 KB Flash | | 13-ch., 12-bit ADC with Temperature Sensor |
| SCI | 1 KB RAM | | (6+2)-ch., 16-bit FlexTimer with PWM functions |
| I²C | BDM/ICE | | Programmable Gain Amplifier |
| RTC | CRC Generator | ICS | Programmable Delay Blocks (x2) |
| 8-bit MTIM | KBI | COP/Watchdog | High-Speed Analog Comparators (x3) |
| 5-bit DAC (x3) | 40 MHz S08 CPU, 20 MHz Bus | | 48-pin LQFP |

**Figure 17. MC9S08MP16 block diagram**

## 5.7 Thermal management for HBLEDs

Thermal management is a very important design consideration in applications involving HBLEDs — not only for ensuring a module's operating temperature and therefore its safety and reliability, but also from the lighting perspective. A thermally oriented design is important to ensure the reduction of temperature impact to LED luminosity.

The optical performance of HBLEDs also depends on temperature; proper thermal design will guarantee not only the best optical performance in the application but its long term reliability as well.

It is important to consider the thermal resistance parameters in the LED's datasheet, then design the proper heat dissipation methodology via either PCB area or external heatsink.

A basic thermal design starts with the estimation of the temperature increase at a given power dissipation. This relation is defined in the thermal resistance model described in Figure 18.

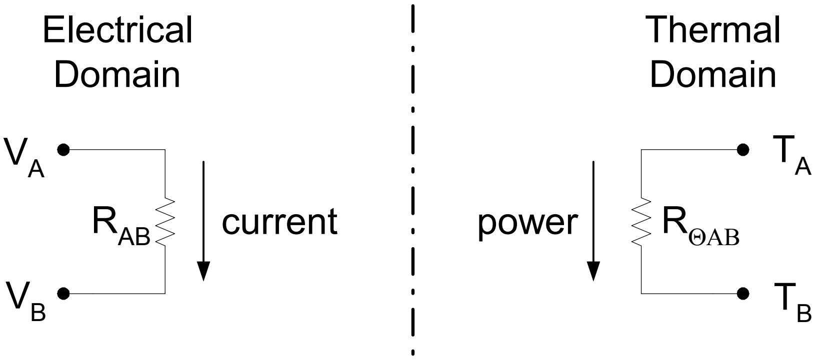


**Figure 18. Basic thermal resistance model**

As observed in Figure 18, $R(\theta)_{AB}$, called thermal resistance, is defined as the ratio of temperature difference at a given power dissipation. This dependence is defined by Equation 11.

$$R(\theta)_{AB} = \frac{\Delta T}{P_D}$$

***Eqn. 11***

Where:

- $R(\theta)_{AB}$ = thermal resistance [°C/W or K/W]
- T = Temperature increase [°C or K]
- $P_D$ = Power dissipated [W]

If thermal resistance is reduced, the increment of temperature will be lower at the same power dissipation. Power dissipation can only be reduced by proper component selection.

In the case of HBLEDs, the power dissipated by an HBLED is defined as the product of $V_F$ (forward voltage) and $I_F$ (forward current). For example, if an HBLED is specified at nominal values of $V_F = 3.2$ V and $I_F = 350$ mA, then the power dissipated by a single LED would be 1.12 W.

The total power dissipation to consider will be the sum of the power dissipation generated by all LEDs in the string.

As power dissipation increases, the temperature will increase proportionally. Increasing the junction temperature in an LED will impact the light output; typically, there is a loss of light as LED junction temperature ($T_j$) increases. Electrically, the temperature increment also affects the forward voltage and forward current in the LED.

For HBLEDs, the thermal resistance value (junction to case, typically) is given in the device datasheet; depending on the heatsink strategy, the thermal resistance can go lower as illustrated in Figure 19, resulting in a smaller temperature increase at a given power dissipation.

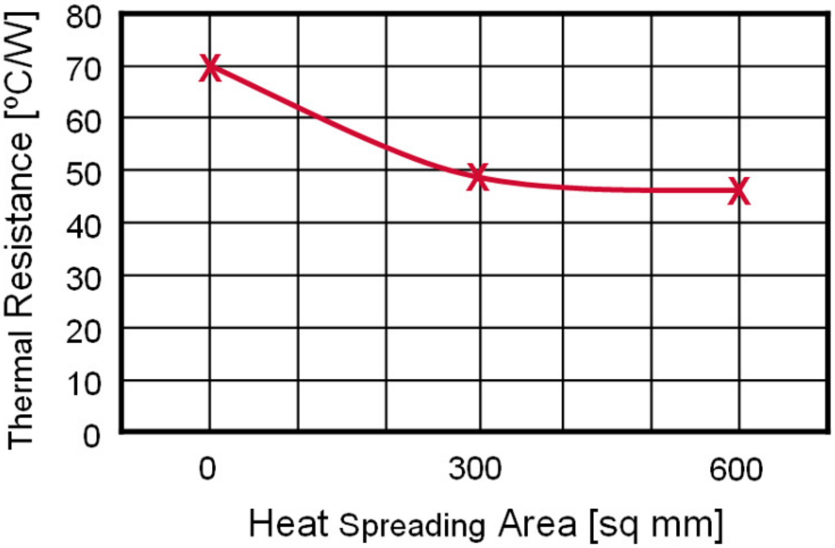


**Figure 19. Thermal resistance vs. dissipation area example**

As observed in Figure 19, the larger the dissipation area, the lower the thermal resistance.

The heatsink area is not the only parameter that can help lower thermal resistance; the parameters listed here must be considered as well for a proper LED board design:

- Intended heatsink (PCB, finned)
- The board’s thermal characteristics

  - Copper thickness
  - Pad area
  - Number of layers
- Location and number of vias
- Air speed
- Board orientation
- Board-to-ambient thermal path
- Heat flux in adjacent elements

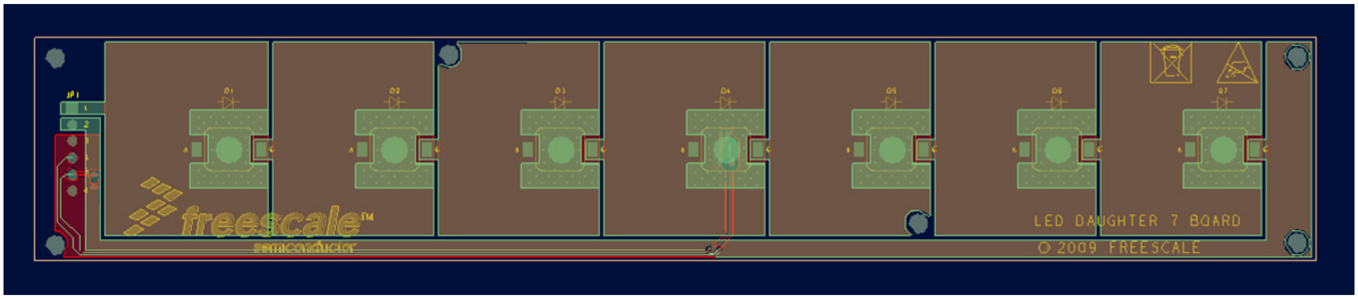


Figure 20. Thermally enhanced LED string board design example

# 6 Software design considerations

In this section some of the main considerations in terms of software design for the application are described.

## 6.1 Pulse width generation for a switched-mode power supply

Switched-mode power supplies require a fine and accurate switching frequency and duty cycle; jitter in the PWM signal implies variations in the output voltage. For this application, these variations could result in flickering of the light source.

Also, because a closed-loop control is used for light intensity, if the PWM resolution is poor a PWM step increment will be reflected in a large control action. This could cause instability or visible light intensity changes.

The FlexTimer module (FTM) is an enhanced version and compatible with the previous timer module (TPM) available in Freescale microcontrollers. The FlexTimer module includes:

- Selectable clock source
- 16-bit counter register
- Input capture
- Output compare edge-aligned or center-aligned PWM
- Channel combinations with:
  - Dead time insertion
  - Hardware and software triggering

- Configurable polarity
- Interrupt generation

The FlexTimer module brings several configurability advantages, but talking specifically about the resolution, it doubles the PWM resolution by means of working at 2× the bus speed.

For example, if the bus speed at which the module is operating is 20 MHz, the FlexTimer frequency could go up to 40 MHz; the PWM duty cycle resolution will be dependent on the chosen PWM frequency. For the example application described herein, the chosen switching frequency for the switch mode power supply is 350 kHz. Therefore the resolution is 40 Mhz / 350 kHz 114 steps, or 0.87%.

## 6.2 Analog-to-digital conversion resolution

We already know that luminosity control will depend on the resolution of the PWM signal controlling the switched-mode power supply; however, the control algorithm also requires a fine and accurate current feedback measurement for performing the proper duty cycle calculations.

The analog-to-digital converter module on the MC9S08MP16 microcontroller can work at up to twelve bits; and given the current-sense circuitry described in Section 5.3, “Current-sense circuitry,” the voltage drop in the 1 Ω resistor would be 500 mV at 500 mA (maximum operational current) while at the minimum current of 100 mA the drop will be 100 mV.

The given step resolution for twelve bits at 5 V is 5 V / $2^{12}$ = 1.22 mV; so, in the operational range of 400 mV (500 mV–100 mV) for the current sense circuitry, there are 327 steps of resolution or 0.3% resolution.

As an alternative, if the resolution is not enough or if a lower current measurement resistor is used, the programmable gain amplifier, also available on the MC9S08MP16, can be used to increase the reading resolution.

## 6.3 Analog reading synchronization

It is important to synchronize current feedback readings with the dimming PWM signal and with the open load protection, making sure that current feedback measurements take place only when the load is connected and only when the current for the LEDs is in a steady state condition.

In this situation, the programmable delay block (PDB) can be used to synchronize the ADC reading with the rising edge of the PWM dimming frequency, adding also a programmable time delay so that the ADC reading will not start until the current in the LEDs has reached a steady state value.

This hardware trigger process to get the ADC data is described in Figure 21.

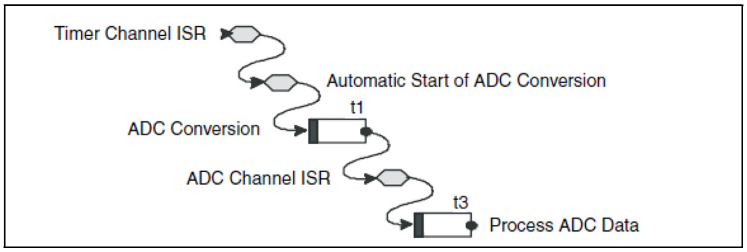


Figure 21. Obtaining ADC sample with hardware trigger

As an alternative, the interrupt service routines of the FlexTimer can be used to trigger the ADC readings, having a synchronization either in the timer overflow or in the timer channel interrupt service routines (see Figure 22). In this scenario, an alternative time base variable can be used to trigger ADC readings (software trigger).

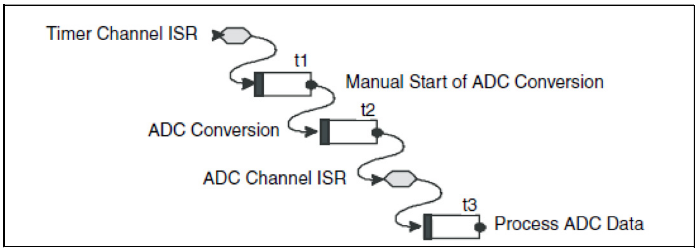


**Figure 22. Obtaining ADC sample with software trigger**

The solution used for this demo application was the software trigger synchronization, using the timer interrupt service routines.

The interrupt service routes, both for timer overflow and for channel value, were enabled so as to disable the switched-mode power supply frequency during off dimming times, avoiding output voltage boosting (Figure 14).

## 6.4 Constant current control algorithm

A simple control loop is usually enough to ensure the proper driving of HBLEDs; with closed-loop control the module compensates for fluctuations in battery voltage, out-of-range temperatures, or any other parameter variations that might affect the LED current in an open loop.

If performing constant current control, the module will provide the required voltage to keep the LED string at the proper current; this also allows a flexible number of LEDs per string without any further calibration or hardware changes.

The proposed control architecture for this example application is a software proportional-integral-derivative (PID) control. A block diagram is shown in Figure 23.

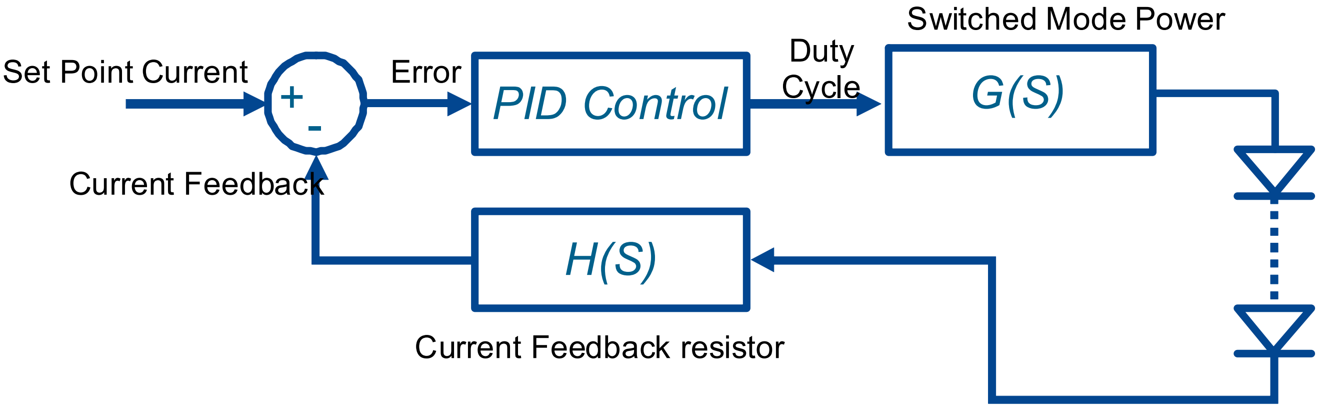


**Figure 23. Proposed control-loop block diagram**

From the block diagram above:

Error = Set Point Current – Current Feedback

The output of the PID control is given by Equation 12:

$$\text{DutyCycle}[i] = \text{DutyCycle}[i-1] + Kp \times \text{ProportionalFactor}[i] + Ki \times \text{IntegralFactor}[i] + Kd \times \text{DerivativeFactor}[i] \qquad \textbf{Eqn. 12}$$

Where:

- $\text{ProportionalFactor}[i] = \text{Error}[i]$
- $\text{IntegralFactor}[i] = \{\text{Error}[i] + \text{Error}[i-1]\} \times T/2$
- $\text{DerivativeFactor}[i] = \{\text{Error}[i]-\text{Error}[i-1]\} \times T$

And:

- Kp is the proportional constant
- Ki is the integral constant
- Kd is the derivative constant
- i is present time value
- i–1 is the previous time value
- T is the sampling period (this value is considered = 1 to simplify calculations)

The control loop is integrated into the 8-bit microcontroller without using floating-point mathematics. 16-bit variables were used to perform the calculations.

Also, because Kp, Kd, and Ki are typically fractional numbers, the control loop operates on the integer-division results of the reciprocals (1/Kp, 1/Kd, and 1/Ki).

The control algorithm constants used for the implementation are:

- $1/Kp = 45 \rightarrow Kp = 0.022$
- $1/Ki = 80 \rightarrow Ki = 0.0125$
- $1/Kd = 100 \rightarrow Kd = 0.01$

# 7 Implementation results

This section shows some basic oscilloscope graphs from the HBLED controller described in this document. It was implemented on the MC9S08MP16 8-bit microcontroller using a low-cost switched-mode power supply.

Results are shown for a single LED string of 7 LEDs, rated at a programmable value of 350 mA.

No matter what the input battery voltage or number of LEDs in the string, the switched-mode power supply duty cycle is automatically adapted to keep an output voltage that ensures constant current in the string.

The graphs below depict the basic behavior of this controller running with a PID control algorithm.

In Figure 24, the power-on response for the module can be observed. The bright green scope trace (scope trace 1) shows the input battery voltage (~12 V), the turquoise channel (channel 2) shows the LED current measured at the 1 Ω current sense resistor (350 mV correspond to 350 mA flowing in the LED string); the violet scope trace (scope trace 3) shows the output voltage generated by the switched mode power supply.

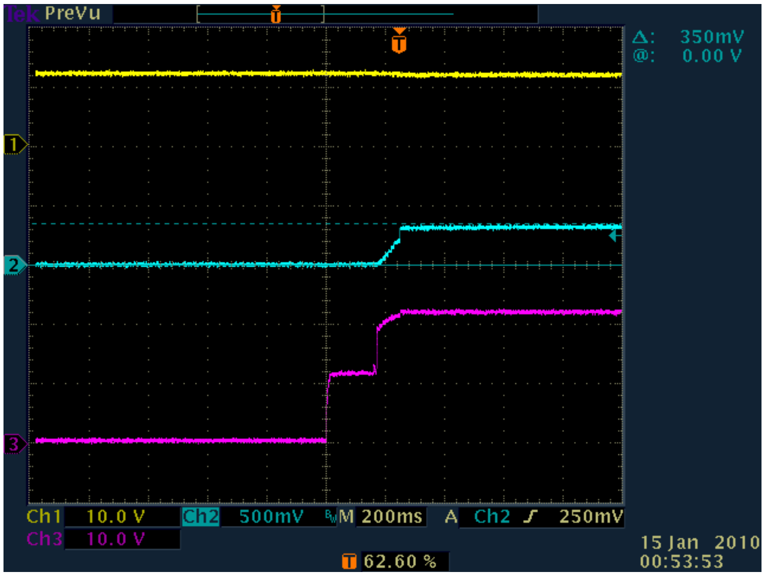


Figure 24. LED string power-on response

For Figure 24 and Figure 25:

- Bright green (CH 1) — battery voltage
- Turquoise (CH 2) — LED current (measured at 1 Ω current-sense resistor)
- Violet (CH 3) — output voltage

Figure 24 also shows a delay of about 250 ms for the LEDs to reach their nominal value. The length of this time varies depending on the number of LEDs in the string. This delay is determined by the time it will take for the control to reach the proper current value.

Also, in the output voltage scope trace (violet), a discontinuity in the rising slope can be observed. This is caused by:

- The non-linearity inherent in the switched-mode power supply
- The operational mode switching from buck to boost mode

In Figure 25, the control response to a battery voltage change (bright green, scope trace 1) is seen; in this case, the battery voltage changed from ~8 V to ~17 V. However, the output voltage (violet, scope trace 3) and the LED string current (turquoise, scope trace 2) remain constant.

The control algorithm latency used in this example application is 10 ms; this latency and/or the control algorithm constants can be modified for faster response times.

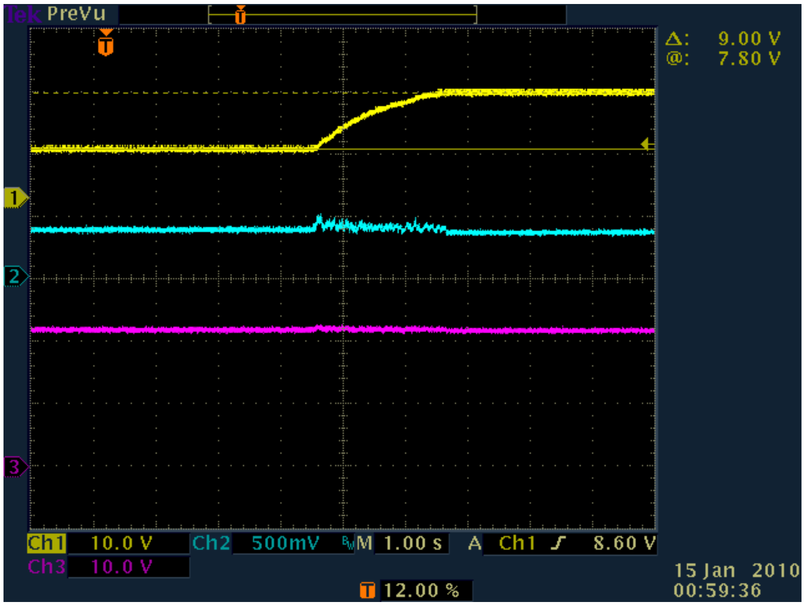


Figure 25. Control response to a battery voltage variation

Figure 26, Figure 27, and Figure 28 illustrate the control algorithm operation by automatically modifying the switched-mode power supply duty cycle so as to keep the output current constant. As can be seen in these three figures, the current flowing through the LED is, on average, the nominal value regardless of the input battery voltage. It can also be observed that the duty cycle of the switched-mode power supply is modified to maintain this behavior.

Figure 26, Figure 27, and Figure 28:

- Bright green (CH 1) — Switching frequency output generated by the MCU as a result of the PID control
- Turquoise (CH 2) — LEDs current (measured at 1 Ω current sense resistor)
- Violet (CH3) — Output voltage of the switched-mode power supply

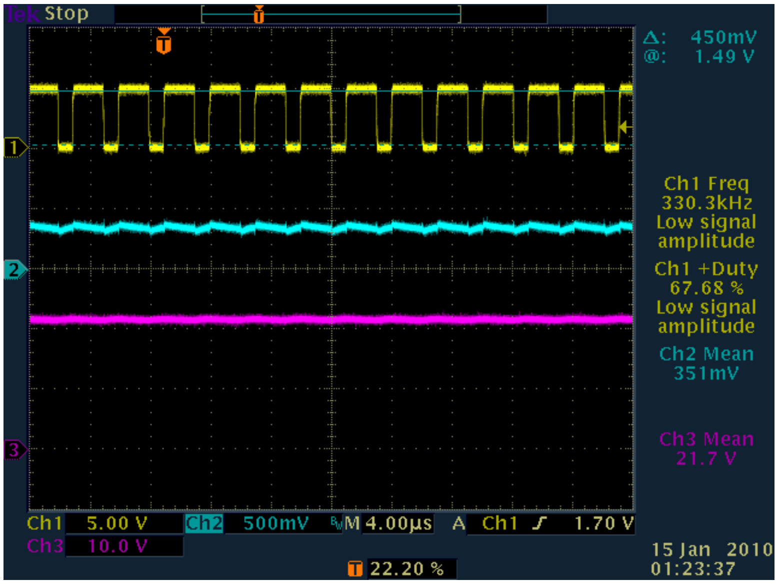


Figure 26. Control operation at input voltage of ~8V (duty cycle ~67.68% and LED current ~351 mA)

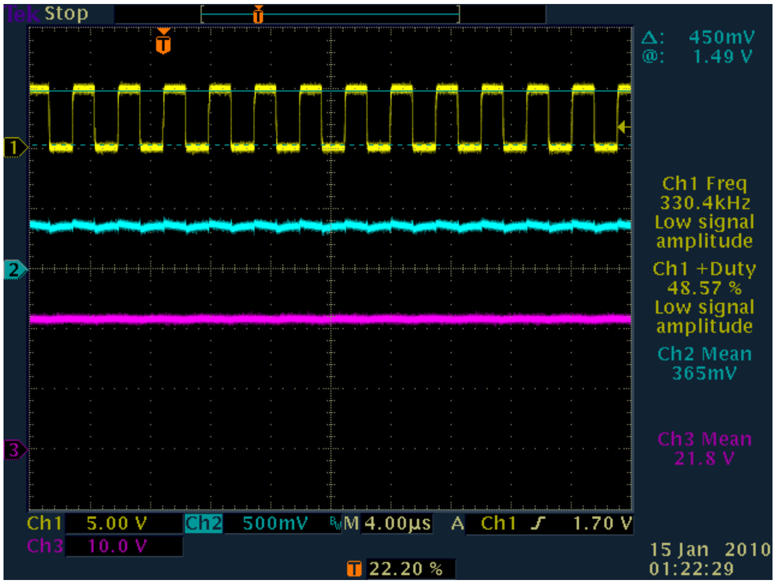


Figure 27. Control operation at input voltage ~12V (duty cycle ~48.7% and LED current ~365 mA)

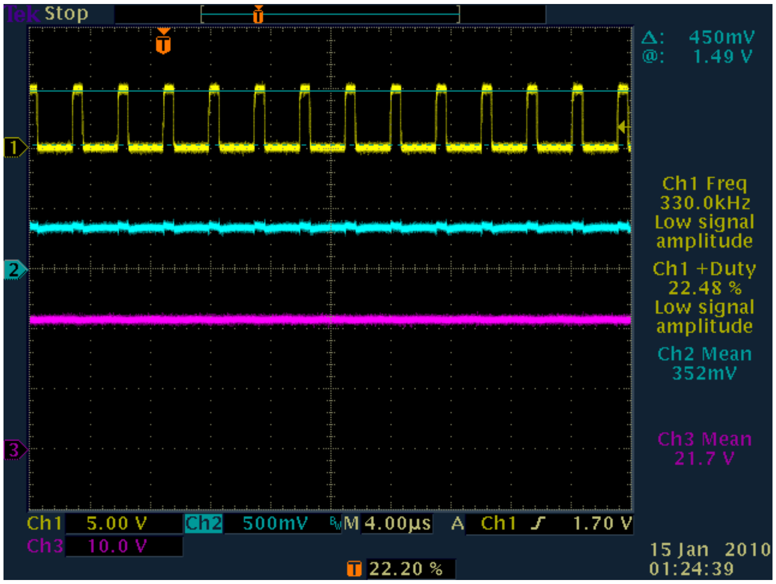


Figure 28. Control operation at input voltage ~18
(duty cycle ~22.48% and LED current ~352 mA)

Finally, in Figure 29 the operation of the dimming function is shown; the average current flowing in the LED is given by switching the LED output on and off.

For Figure 29:

- Bright green (CH 1) — Dimming signal from the MCU
- Turquoise (CH 2) — LED current (measured at 1 Ω current sense resistor)
- Violet (CH3) — Output voltage of the switched-mode power supply

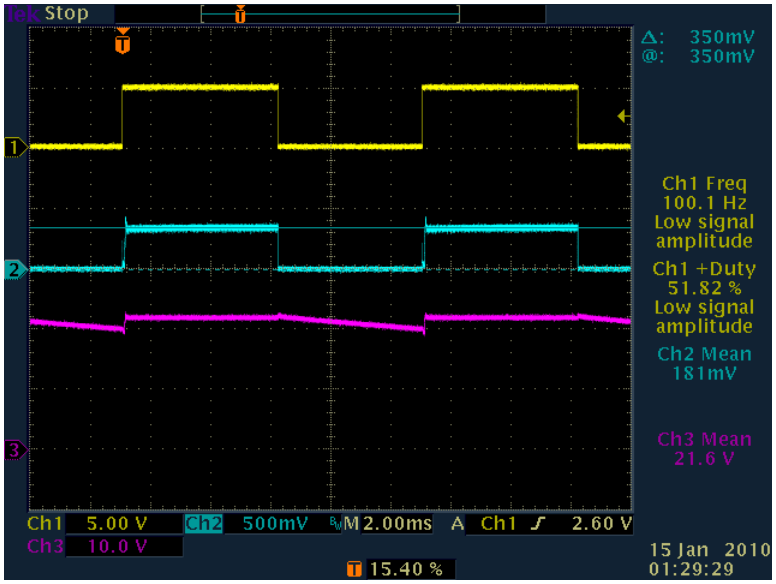


Figure 29. LED string dimming function

In Figure 29 we can see that the average LED current is 181 mA. However, this is accomplished by switching LEDs on and off at a nominal current of 350 mA, thus avoiding chromatic changes. Also, we can see that there is no output voltage boosting, because the power supply output is disconnected during dimming off period.

# 8 Conclusions

This application note has explained the implementation of High Brightness LED control based on an embedded PID algorithm implemented on the MC9S08MP16 8-bit microcontroller. Examples of dimming, switched-mode power supply control, and many other lighting features were described in the document.

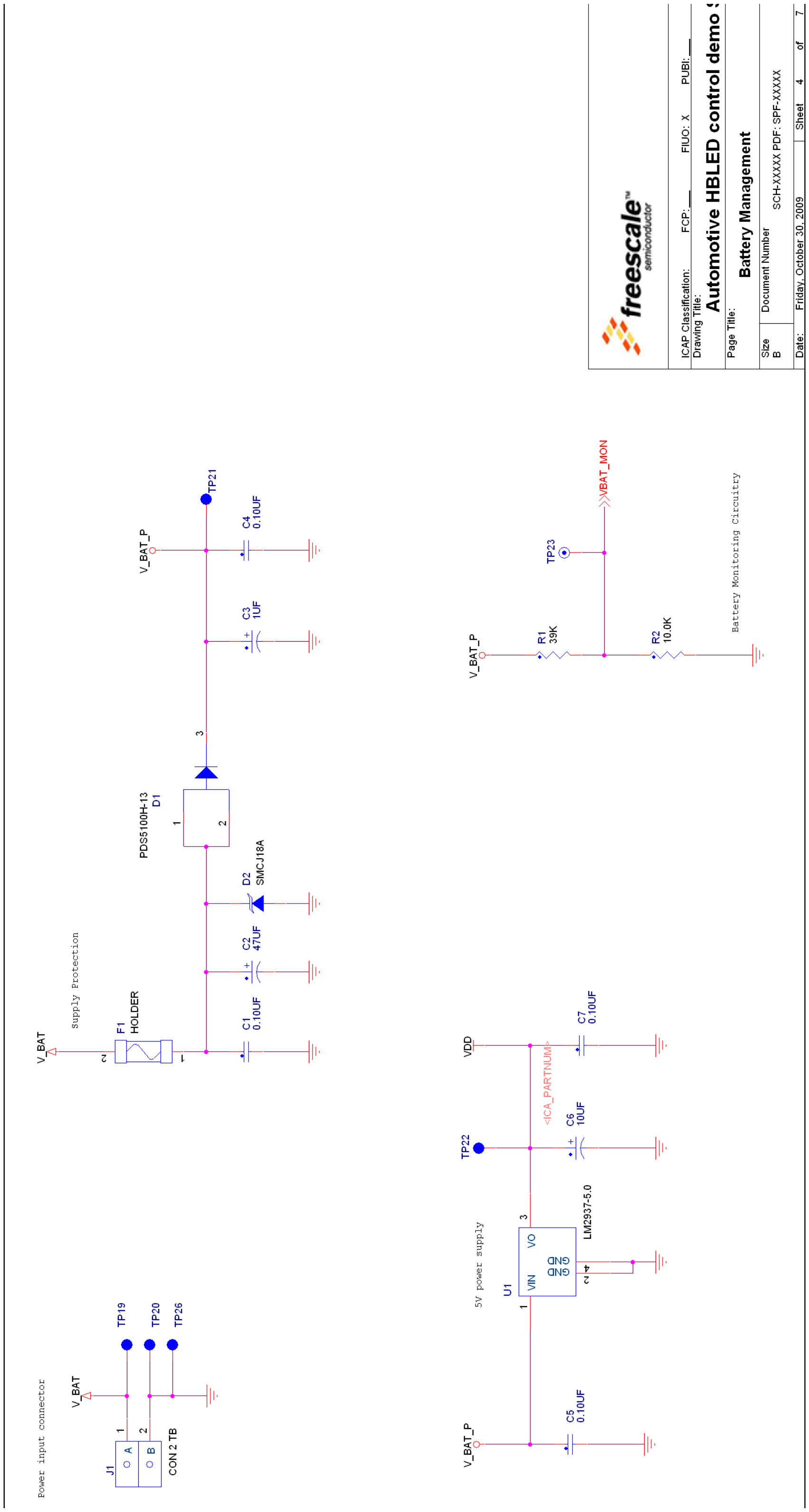
Even though this demonstration is intended for automotive applications, the concepts and solution described herein can be applied to many other industrial and consumer applications that use HBLEDs.

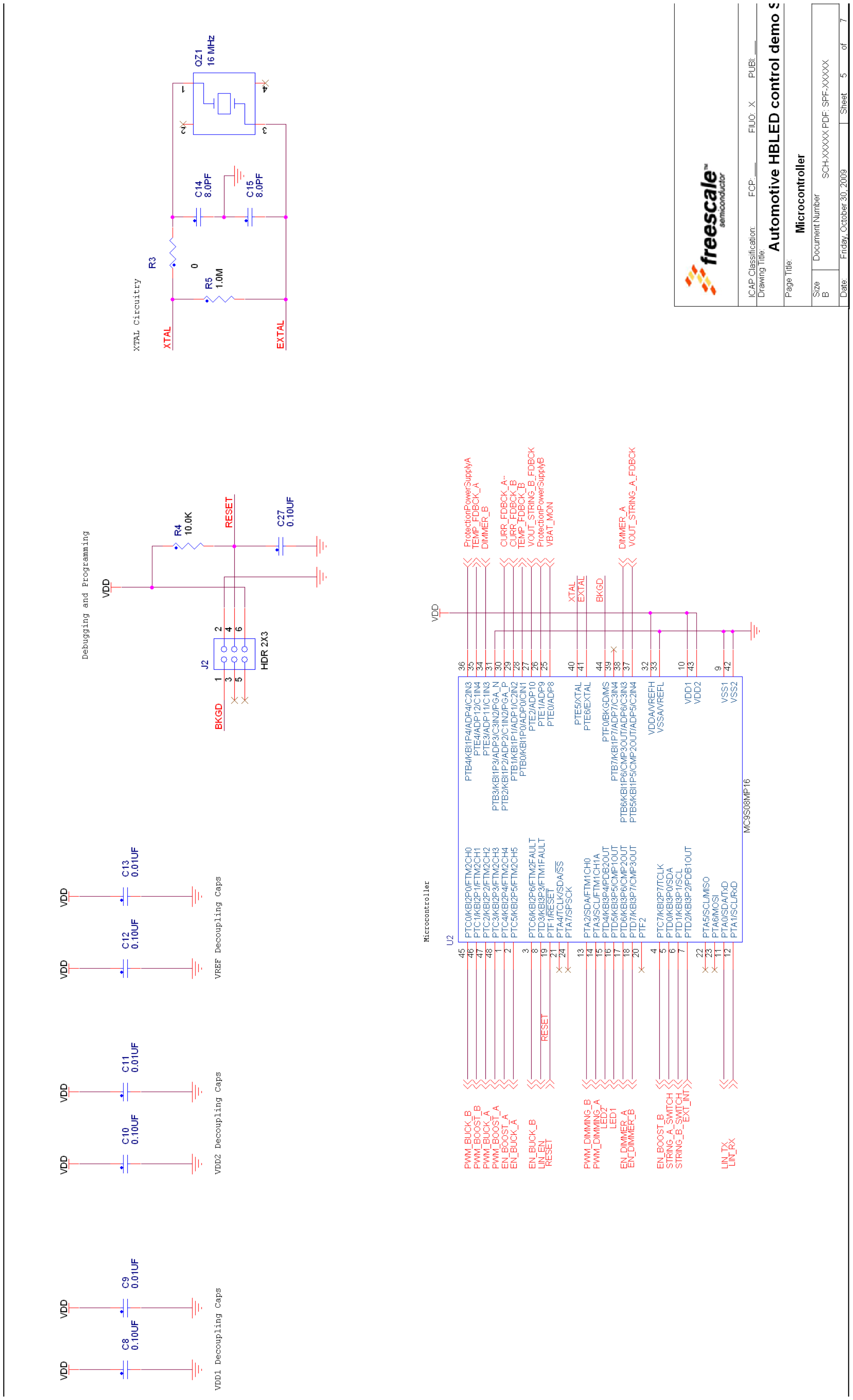
Freescale provides a wide range of products supporting automotive lighting applications — the specific device used in this demonstration is only one possible solution for these types of applications. For further information about Freescale solutions for lighting please visit www.freescale.com/lighting.

# 9 References

- Lighting page at Freescale website:
  www.freescale.com/lighting
- Freescale document AN3321, “High-Brightness LED Control Interface”
  www.freescale.com/files/microcontrollers/doc/app_note/AN3321.pdf?fsrch=1
- Freescale’s S08MP product summary page:
  www.freescale.com/webapp/sps/site/prod_summary.jsp?code=S08MP&tid=m8Hp

# Appendix A Schematics

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XTAL
EXTAL
R3
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R5
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C14
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Debugging and Programming
VDD
R4
10.0K
RESET
C27
0.10UF
J2
BKGD
HDR 2X3
Microcontroller
U2
MC9S08MP16
PTB4/KBI1P4/ADP4/C2IN3
PTE4/ADP12/C1IN4
PTE3/ADP11/C1IN3
PTB3/KBI1P3/ADP3/C3IN2/PGA_N
PTB2/KBI1P2/ADP2/C1IN2/PGA_P
PTB1/KBI1P1/ADP1/C2IN2
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PTE1/ADP9
PTE0/ADP8
PTE5/XTAL
PTE6/EXTAL
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PTB6/KBI1P6/CMP3OUT/ADP6/C3IN3
PTB5/KBI1P5/CMP2OUT/ADP5/C2IN4
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VSSA/VREFL
VDD1
VDD2
VSS1
VSS2
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PTC1/KBI2P1/FTM2CH1
PTC2/KBI2P2/FTM2CH2
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PTC5/KBI2P5/FTM2CH5
PTC6/KBI2P6/FTM2FAULT
PTD3/KBI3P3/FTM1FAULT
PTF1/RESET
PTA4/TCLK/SDA/SS
PTA7/SPSCK
PTA2/SDA/FTM1CH0
PTA3/SCL/FTM1CH1A
PTD4/KBI3P4/PDB2OUT
PTD5/KBI3P5/CMP1OUT
PTD6/KBI3P6/CMP2OUT
PTD7/KBI3P7/CMP3OUT
PTF2
PTC7/KBI2P7/TCLK
PTD0/KBI3P0/SDA
PTD1/KBI3P1/SCL
PTD2/KBI3P2/PDB1OUT
PTA5/SCL/MISO
PTA6/MOSI
PTA0/SDA/TxD
PTA1/SCL/RxD
ProtectionPowerSupplyA
TEMP_FDBCK_A
DIMMER_B
CURR_FDBCK_A-
CURR_FDBCK_B
TEMP_FDBCK_B
VOUT_STRING_B_FDBCK
ProtectionPowerSupplyB
VBAT_MON
XTAL
EXTAL
BKGD
DIMMER_A
VOUT_STRING_A_FDBCK
PWM_BUCK_B
PWM_BOOST_B
PWM_BUCK_A
PWM_BOOST_A
EN_BOOST_A
EN_BUCK_A
EN_BUCK_B
LIN_EN
RESET
PWM_DIMMING_B
PWM_DIMMING_A
LED2
LED1
EN_DIMMER_A
EN_DIMMER_B
EN_BOOST_B
STRING_A_SWITCH
STRING_B_SWITCH
EXT_INT
LIN_TX
LIN_RX
VDD
C8
0.10UF
C9
0.01UF
VDD1 Decoupling Caps
C10
0.10UF
C11
0.01UF
VDD2 Decoupling Caps
C12
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C13
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freescale semiconductor
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Drawing Title:
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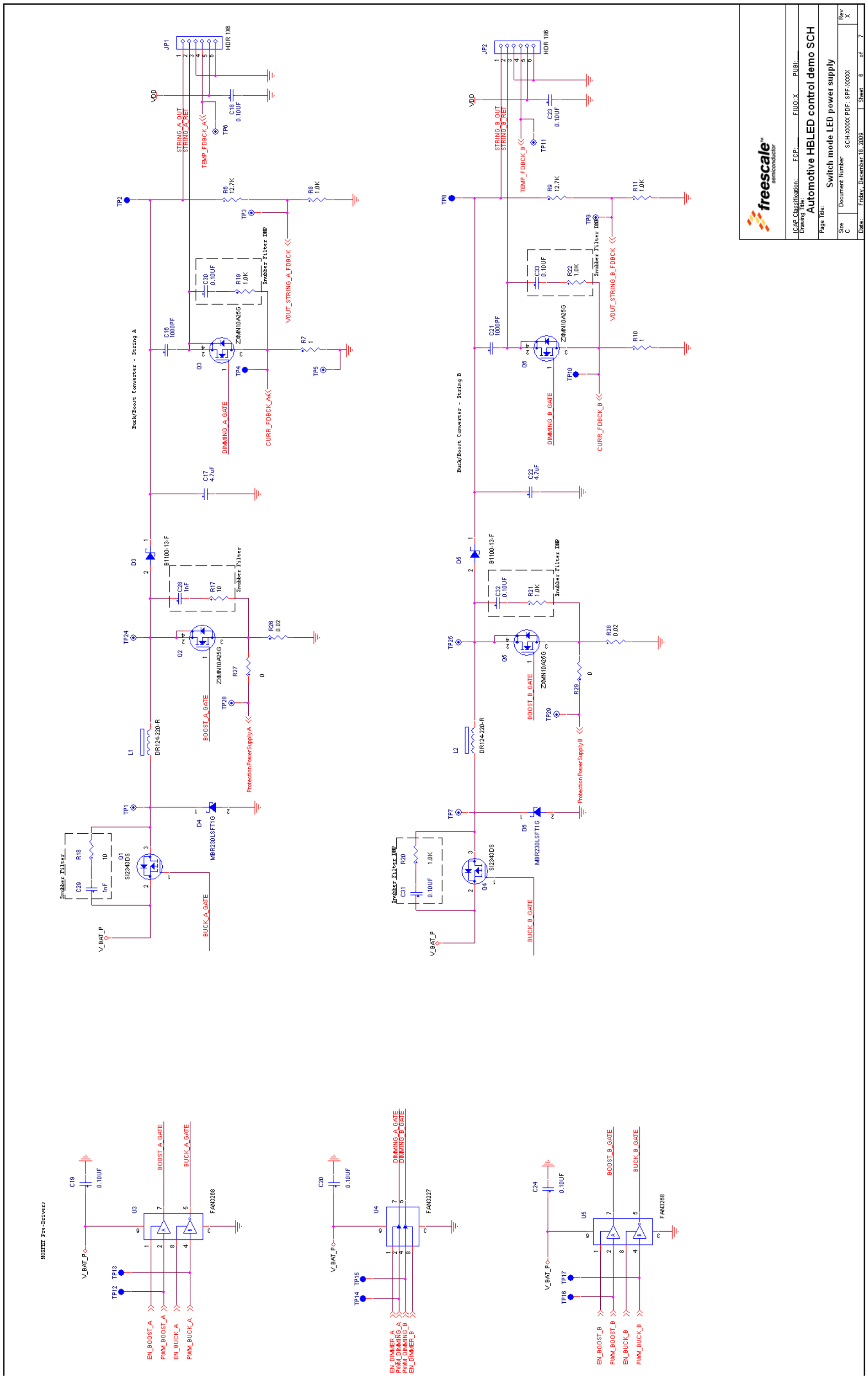
Page Title:
Microcontroller
Size
B
Document Number
SCH-XXXXX PDF: SPF-XXXXX
Date: Friday, October 30, 2009
Sheet 5 of 7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Rev X
Date: Friday, December 18, 2009
Sheet 6 of 7
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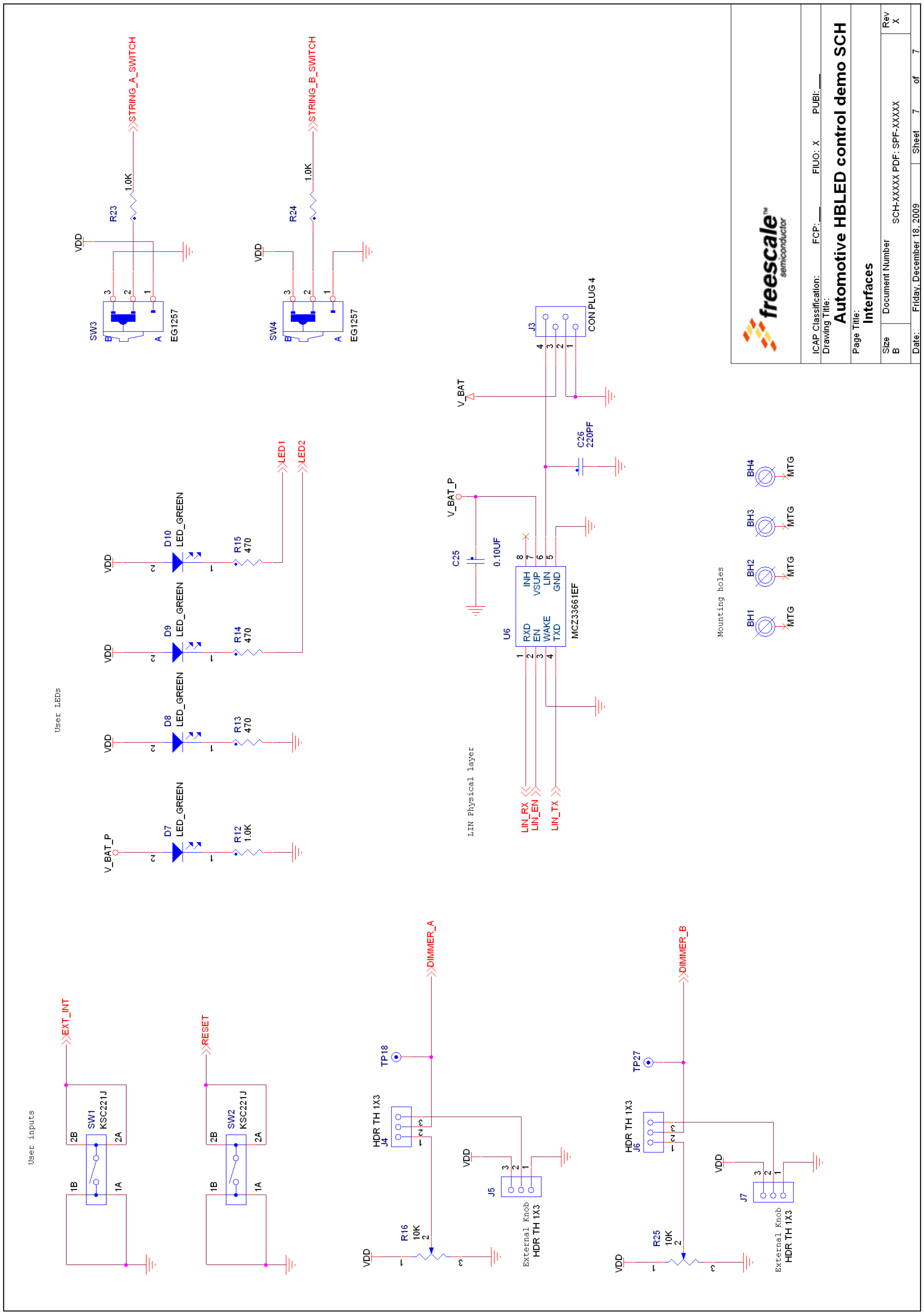
Buck/Boost Converter - String B
MOSFET Pre-Drivers
JP1 HDR 1X6
JP2 HDR 1X6
VDD
STRING_A_OUT
STRING_A_RET
STRING_B_OUT
STRING_B_RET
TEMP_FDBCK_A
TEMP_FDBCK_B
C18 0.10UF
C23 0.10UF
R9 12.7K
R8 1.0K
R11 1.0K
C30 0.10UF
R19 1.0K
C33 0.10UF
R22 1.0K
Snubber Filter
VOUT_STRING_A_FDBCK
VOUT_STRING_B_FDBCK
C16 1000PF
C21 1000PF
Q3 ZXMN10A25G
Q6 ZXMN10A25G
R7 1
R10 1
DIMMING_A_GATE
DIMMING_B_GATE
CURR_FDBCK_A
CURR_FDBCK_B
C17 4.7uF
C22 4.7uF
D3 B1100-13-F
D5 B1100-13-F
C28 1nF
R17 10
C32 0.10UF
R21 1.0K
Q2 ZXMN10A25G
Q5 ZXMN10A25G
R26 0.02
R28 0.02
R27 0
R29 0
BOOST_A_GATE
BOOST_B_GATE
ProtectionPowerSupplyA
ProtectionPowerSupplyB
L1 DR124-220-R
L2 DR124-220-R
D4 MBR230LSFT1G
D6 MBR230LSFT1G
Q1 SI2343DS
Q4 SI2343DS
R18 10
C29 1nF
R20 1.0K
C31 0.10UF
V_BAT_P
BUCK_A_GATE
BUCK_B_GATE
TP1 TP2 TP3 TP4 TP5 TP6 TP7 TP8 TP9 TP10 TP11 TP12 TP13 TP14 TP15 TP16 TP17 TP24 TP25 TP28 TP29
C19 0.10UF
C20 0.10UF
C24 0.10UF
U3 FAN3268
U4 FAN3227
U5 FAN3268
EN_BOOST_A
PWM_BOOST_A
EN_BUCK_A
PWM_BUCK_A
EN_DIMMER_A
PWM_DIMMING_A
PWM_DIMMING_B
EN_DIMMER_B
EN_BOOST_B
PWM_BOOST_B
EN_BUCK_B
PWM_BUCK_B


User inputs
SW1 KSC221J
SW2 KSC221J
1B 2B 1A 2A
EXT_INT
RESET
User LEDs
D7 LED_GREEN
D8 LED_GREEN
D9 LED_GREEN
D10 LED_GREEN
R12 1.0K
R13 470
R14 470
R15 470
V_BAT_P
VDD
LED1
LED2
SW3 EG1257
SW4 EG1257
R23 1.0K
R24 1.0K
STRING_A_SWITCH
STRING_B_SWITCH
TP18
TP27
J4 HDR TH 1X3
J6 HDR TH 1X3
DIMMER_A
DIMMER_B
R16 10K
R25 10K
J5
J7
External Knob HDR TH 1X3
LIN Physical layer
U6 MCZ33661EF
RXD EN WAKE TXD
INH VSUP LIN GND
LIN_RX
LIN_EN
LIN_TX
C25 0.10UF
C26 220PF
V_BAT_P
V_BAT
J3 CON PLUG 4
Mounting holes
BH1 MTG
BH2 MTG
BH3 MTG
BH4 MTG
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ICAP Classification: FCP: ___ FIUO: X PUBI: ___
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Automotive HBLED control demo SCH
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Interfaces
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Date: Friday, December 18, 2009
Sheet 7 of 7

# Appendix B Bill of materials

Table B-1. Bill of materials

| Item number | Quantity | Reference designator | Value | Description | Manufacturer | Manufacturer part number |
|---|---|---|---|---|---|---|
| 1 | 4 | BH1, BH2, BH3, BH4 | MTG | Mounting hole 0.130 inch, no part to order | N/A | N/A |
| 2 | 20 | C1, C4, C5, C7, C8, C10, C12, C18–C20, C23–C25, C27–C33 | 0.10 μF | Cap cer 0.10 μF 25 V 10% X7R 0805 | Any | Any |
| 3 | 1 | C2 | 47 μF | Cap alel 47 μF 50 V SM 6.3 × 6.3 × 5.3 | Any | Any |
| 4 | 1 | C3 | 1 μF | Cap alel 1 μF 50 V 20% X5R SMT | Any | Any |
| 5 | 1 | C6 | 10 μF | Cap tant 10 μF 10 V 10% — 3216-18 | Any | Any |
| 6 | 3 | C9, C11, C13 | 0.01 μF | Cap cer 0.01 μF 16 V 10% X7R 0603 | Any | Any |
| 7 | 2 | C14, C15 | 8 pF | Cap cer 8.0 pF 50 V 0.5 pF C0G 0603 | Any | Any |
| 8 | 2 | C16, C21 | 1000 pF | Cap cer 1000 pF 100 V 10% X7R 0603 | Any | Any |
| 9 | 2 | C17, C22 | 4.7 μF | Cap cer 4.7 μF 100 V 10% X7R 2220 | Any | Any |
| 10 | 1 | C26 | 220 pF | Cap cer 220 pF 50 V 10% C0G 0603 | Any | Any |
| 11 | 1 | D1 | PDS5100H-13 | Diode SCH 5 A 100 V PowerDI 5 | Diodes Inc | PDS5100H-13 |
| 12 | 1 | D2 | SMCJ18A | Diode TVS 18 V 1500 W DO-214AB | Any | Any |
| 13 | 2 | D3, D5 | B1100-13-F | Diode SCH rect 1 A 100 V SMA | Diodes Inc | B1100-13-F |
| 14 | 2 | D4, D6 | MBR230LSFT1G | Diode SCH RECT 2 A 30 V SMT SOD-123 | On Semiconductor | MBR230LSFT1G |
| 15 | 4 | D7, D8, D9, D10 | LED_GREEN | LED GRN SGL 30 mA SMT 0603 | Any | Any |
| 16 | 1 | F1 | Holder | Fuse holder SMT for 5 mm fuse RoHS compliant | Any | Any |
| 17 | 1 | J1 | CON 2 TB | CON 1 × 2 TB TH 5.08 MM SP 740H SN | Any | Any |
| 18 | 1 | J2 | HDR 2X3 | HDR 2 × 3 TH 100 mil CTR 335H AU 95L | Any | Any |

### Table B-1. Bill of materials (continued)

| Item number | Quantity | Reference designator | Value | Description | Manufacturer | Manufacturer part number |
|---|---|---|---|---|---|---|
| 19 | 1 | J3 | Con plug 4 | Con 2 × 2 plug shrd RA TH 4.2 mm SP 396H SN 140L | Any | Any |
| 20 | 2 | JP1, JP2 | Hdr 1X6 | Hdr 1 × 6 TH RA 100 mil SP 268H AU | Any | Any |
| 21 | 2 | L1, L2 | 22 µH | Ind pwr shield 22 µH@100 kHz 3.2 A 20% SMT | Bussmann | DR124-220-R |
| 22 | 2 | Q1, Q4 | SI2343DS | Tran PMOS pwr 3.1 A 30 V SOT23 | Vishay Intertechnology | SI2343DS-T1-E3 |
| 23 | 4 | Q2, Q3, Q5, Q6 | ZXMN10A25G | Tran NMOS gen 3.7 A 100 V SOT223 | Zetex Inc | ZXMN10A25GTA |
| 24 | 1 | QZ1 | 16 MHz | XTAL 16 MHz — 2520 SMD | Any | Any |
| 25 | 1 | R1 | 39 kΩ | Res MF 39.0 kΩ 1/10 W 1% 0603 | Any | Any |
| 26 | 2 | R2, R4 | 10.0 kΩ | Res MF 10.0 kΩ 1/10 W 1% 0603 | Any | Any |
| 27 | 1 | R3 | 0 Ω | Res MF 0 Ω 1/10 W — 0603 | Any | Any |
| 28 | 1 | R5 | 1.0 mΩ | Res MF 1.0 mΩ 1/10 W 1% 0603 | Any | Any |
| 29 | 2 | R6, R9 | 12.7 kΩ | Res MF 12.7 kΩ 1/10 W 1% 0603 | Any | Any |
| 30 | 2 | R7, R10 | 1 Ω | Res MF 1 Ω 1/2 W 1% 1206 | Any | Any |
| 31 | 11 | R8, R11, R12, R17—R24 | 1.0 kΩ | Res MF 1.00 kΩ 1/10 W 1% 0603 | Any | Any |
| 32 | 3 | R13, R14, R15 | 470 Ω | Res MF 470 Ω 1/10 W 1% 0603 | Any | Any |
| 33 | 2 | R16, R25 | 10 kΩ | Res pot 10.0 kΩ 1/2 W 20% TH | Any | Any |
| 34 | 2 | SW1, SW2 | KSC221J | Sw SPST SMT 32 V 50 mA J-BEND | Any | Any |
| 35 | 12 | TP1, TP3, TP5—TP7, TP9, TP11, TP18, TP23—TP25, TP27 | TP | Test point 36 × 20 mils TH, not part to order | N/A | Not part to order |
| 36 | 1 | U1 | LM2937-5.0 | IC VREG LDO 5 V 500 mA 26V SOT-223 | Any | Any |

## Table B-1. Bill of materials (continued)

| Item number | Quantity | Reference designator | Value | Description | Manufacturer | Manufacturer part number |
|---|---|---|---|---|---|---|
| 37 | 1 | U2 | MC9S08MP16 | IC MCU 8-bit 16 K flash 1 K RAM 2.7–5.5 V LQFP48 | Freescale Semiconductor | MC9S08MP16 |
| 38 | 2 | U3,U5 | FAN3268 | IC PMOS-NMOS bridge DRV 2 A 4.5–18 V SOIC 8 | Fairchild | FAN3268TMX |
| 39 | 1 | U4 | FAN3227 | IC DRV NON INV TTL IN DUAL 4.5—18 V SOIC8 | Fairchild | FAN3227TMX |
| 40 | 1 | U6 | MCZ33661EF | IC XCVR LIN 10–20 Kbit/s 6.0–18 V SO8 | Freescale Semiconductor | MCZ33661EF |
| 41 | 4 | J4, J5, J6, J7 | HDR TH 1 × 3 | HDR 1 × 3 TH 100 mil SP 339H AU 118L | Any | Any |
| 42 | 2 | SW3, SW4 | EG1257 | SW slide SM right angle 0.3A | Any | Any |
| 43 | 5 | TP2, TP8, TP19, TP21, TP22 | Test point red | Test point red 40 mil drill 180 mil TH | Any | Any |
| 44 | 8 | TP4, TP10, TP12–TP17 | Test point white | Test point white 40 mil drill 180 mil TH | Any | Any |
| 45 | 2 | TP20, TP26 | Test point black | Test Point Black 40 mil drill 180 mil TH | Any | Any |

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