# High-Brightness LED Control Interface

## MCU-Based LED Drivers Using DC-to-DC Converters: Buck, Boost, and Buck-Boost

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High-brightness LED control requires a constant current, maintained over temperature and voltage. The driver and control system must be designed to deliver a constant current to optimize reliability and constancy. Integration of high-brightness LED control with a low-cost microcontroller (MCU) affords a control system increased functionality and flexibility for tomorrow's lighting application needs. LED luminosity and reliability rely on thermal control achieved with an MCU. Wired and wireless protocols such as DALI, DMX512, and ZigBee™ can be implemented at a very low cost with an MCU. Multi-color mixing is practical with the use of an MCU control device.

The analog subsystem configuration has several options. In most applications, a DC-to-DC converter is needed to supply the voltage and constant current that the high-power or high-brightness LED needs. And in other applications, the DC-to- DC converter supplies a constant voltage tot he LED string and the current is controlled through an active switch in the LED string. Multi-output buck-boost constant current drivers

**Contents**

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optimized for interface with high-brightness LEDs and the MCU are available and cost-effective. The features of many of the HCS08 MCUs, such as the analog comparator interface, the ADC inputs, timer channels, and digital I/O options, offer a variety of control and interface options for applications driving high-brightness LEDs.

DC-to-DC converters for LED drivers come in several varieties: buck, boost, buck-boost, and several other variants of these circuits. All are inductor-based switch mode power converters with various features. The buck circuit reduces the supply voltage to a lower output voltage. The boost circuit increases the output voltage and the buck-boost circuit can either increase or decrease the output voltage over the input voltage or supply.

# 1 Overview

## 1.1 Terminology

The amount of light that a standard incandescent light bulb gives off is traditionally given in watts (W). The unit of light strength is the lumen (lm). Watt ratings are based on electrical consumption ($I_{FWD}$ x $V_{FWD}$), but they are not equivalent to incandescent bulb ratings. A typical light output of an incandescent light bulb is approximately 10 lm/W or for a 75 W bulb, about 750 lm. The efficiency of the LED is improving, typically showing 25–40 lm/W in production devices. If we used the low end of the scale, 25 lm/W as an example using the 5 W LED rating below the output is 125 lm. A set of six high-power LEDs of this type consumes only 30 watts and give off the equivalent amount of light of that 75 W incandescent light bulb

1-Watt — 350 mA operation at ~3.5 V = ~1.2 Watt electrical power

2-Watt — 700 mA operation at ~3.5 V = ~2.4 Watt electrical power

3-Watt — 1000 mA operation at ~3.5 V = ~3.5 Watt electrical power

5-Watt — 700 mA operation at ~6.8 V = ~4.8 Watt electrical power

- – Incandescent 75 W @ 10 lm/W = 750 lm
- – High-brightness LED 5W @ 25 lm/W = 125 lm
- – Six high-brightness LEDs 5-Watts (30 electrical watts) ~ 75W incandescent ~(6 x 125 lm = 750 lm)

## 1.2 LED Specifics

### 1.2.1 LED Intensity and Flux

There is no direct conversion between millicandela (mcd) and lumens. Luminous intensity, measured in candela or millicandela, is the light output in a particular direction. Luminous Flux, measured in lumens, is the total light output in all directions.

## 1.2.2    LED Forward Voltage

The forward voltage ($V_{FWD}$) of high-brightness and high-power LEDs are not identical. The colors have different technologies (1.4 V for GaAs, 2 V for GaAsP, 3 V for GaP) and there are differences from part to part. The perceived color intensity for a uniform field of LEDs of different colors is not uniform either.

An example of forward voltages versus brightness is given below:

- Red: 1400 mcd @ 20 mA @ $V_{FWD} = 2.4$ V
- Green: 1000 mcd @ 20 mA @ $V_{FWD} = 3.4$ V
- Blue: 300 mcd @ 20 mA @ $V_{FWD} = 3.4$ VB

This presents a challenge that can be solved with the use of color mixing algorithms executing on an MCU. This aspect of control is not addressed in this application note. Refer to the presentation, "HB LED Color Mixing and LCD Backlight," on Freescale's web site.

## 1.3    Interface and Control Options

In addition to color control options, the MCU offers these interface and control options:

- Control system interface implemented via standard MCU interfaces such as RS232, SPI, DMX, DALI, and ZigBee.
- High-speed A/D used to sense input level (slider) settings, current sensing voltages, or other circuit levels such as ambient light and temperature.
- Comparators are used to sense input voltage level changes relative to either internal reference or external set level.
- Temperature sensors are used for circuit protection of high-brightness LED.
- Push button interface is used for user inputs and inter-network control settings.
- Multiple timer outputs can be used for brightness and color control.
- Display drivers are used for user interface.

# 2    MCU Control of LEDs

A number of sophisticated MCU peripherals can enable the use in the LED lighting applications market. When the circuit requires a user display with backlighting, an input key or buttons and communication with another master/slave unit the microcontroller shows its advantages. The brightness of the LED can be controlled by the pulse-width modulator (PWM). The current control circuit can use the internal analog comparator integrated into the MCU. If multiple strings of LED need to be controlled, consider using an MCU per string to control the current drive of the string with the on-chip comparator and control the brightness and color of each string with PWM outputs of the same MCU. A good reference to help you decide which MCU to use can be found in AN3325, "Designing for Migration Among 8-Pin, 8-Bit MCUs." It compares three devices: the MC9S08QG8, the MC9S08QD4, and the MC9RS08KA2.

## 2.1 MCU Control of the DC-to-DC Convertor

As demonstrated in the circuits in this application note, MCU control of the LED's current can be achieved in several ways. This control can be direct or indirect. You can use an external power mosfet switch to control the current to the LED and use an on-chip comparator or ADC modules to monitor that current. When control is incorporated into a software loop, flexibility, and optional features are easily integrated into a expandable control solution.

Outputs can adjust the duty cycle of the switch in the converter in response to the load current as measured across the sense resistor. Adjustment of the duty cycle of the control waveform can be made depending on the intensity or color of the LED string being controlled so that true color generation can be achieved.

A comparator that measures the effective LED current against a set reference voltage can be used to control the switch of the converter in a buck converter. A timer output can be used to modulate the comparators current control which in turn controls the brightness of the LED string.

# 3 Current Control for LEDs

High-brightness and high-power LEDs require precise control over the current to maintain efficient, reliable, and output color wavelength of the LED. 1 W high-brightness LEDs typically require 350 mA and the 3 to 5 W ultra-bright LEDs typically require higher than 700 mA with a forward voltage ($V_{FWD}$) of 3.4 V. Forward voltage varies between different manufacturers and colors of LEDs. If color control is desired, separate control over the current for each color LED is required. This is accomplished with a sensing circuit on the output to control the on-time of the transistor to regulate the output current through the load.

Systems using high or ultra-bright LEDs often have many LEDs connected. A series connection has several advantages: only one driver is needed per string, all of the series LEDs have the same current flowing through them to give a relatively constant brightness, and each string requires only one sense circuit for each string.

A switching regulator regulates the current flow by dividing the input voltage and controlling the average current by means of the duty cycle or the on-time. When a higher current is required by the load, the percentage of on time is increased to accommodate the change. This results in a nominal DC current with a ripple current proportional to the switching frequency ($f_{Switch}$) of the control circuit. The higher the frequency, the smaller the ripple, and the smaller the inductor can be. The current that the inductor circuit must provide is inversely probational to the $f_{Switch}$. Much smaller inductors are needed when frequencies above 1 MHz are used.

A pure linear solution is simple and quick. It has the drawback of being inefficient and creates more heat. But if those factors are not important in your circuit, consider the option. A series current limiting resistor does the job of limiting the current to the LED. It must be sized and meet the power requirements of the load.

## 3.1    Buck, Boost, or Buck-Boost

Depending on the needs of the system, a DC-to-DC converter is available to meet those needs. As mentioned, the LED needs constant current. There are three general categories of switching drivers:

- Buck is used when the LED voltage is always lower than the supply voltage. This is typical of a simple 3 to 5 V system with one LED to drive.
- Boost is used when the LED voltage is always higher than the supply voltage. This is typical of a simple 3 to 5V system with more than one LED in series are being driven.
- Buck-boost or cuk (pronounced chook) is used when the LED voltage can be higher or lower than the supply voltage or the supply voltage varies significantly, as it does in an automobile. The typical lighting application in the vehicle for high brightness led is the tail lights or interior lighting where there are LEDs in series driven from the nominal 12 V battery supply. The battery supply actually varies from 9 to 18 V depending upon the conditions.

Each driver can be designed with a single inductor, a fast-switching diode, and a load capacitor. The higher the switch frequency, the smaller the current maintained by the inductor, and the smaller the inductor can be. Typically the switch frequency is in the range of 50 kHz to 250 kHz but higher frequency circuits are becoming available. The load capacitor supplies current in some of the circuits and aids the circuit in reducing EMI and smoothing the current surges.

### 3.1.1    DC-to-DC Converters as Constant Voltage Source

DC-to-DC converters can be used as in their standard configuration, as a constant voltage source instead of a current source for the LED. If the voltage was maintained just higher than the need forward voltage Vf drop of the LED, or string of LEDs, a linear control approach of the LED is possible. The switch in the control path of the LED could switch the LED on and off at much higher rates improving control granularity thereby increasing the number of dimming steps possible or accuracy of the color wavelength of the LED.

Other more efficient converters circuits are available, but are not discussed in this application note. The topologies mentioned above are considered non-synchronous. For more efficient design a synchronous topology replaces the catch diode in these circuits by a low-drop power mosfet. When the diode is supposed to conduct, the mosfet is switched on and when the diode is not conducting, you switch the diode off. Because the drop across this mosfet is much lower than across a diode, you would significantly reduce the conduction loss in the circuit.

## 3.2    Buck Topology

The buck circuit, used to reduce the input voltage to a lower level, turns on the voltage to control the current to the load current when the FET turns on, driving current into and charging the capacitor. While the FET is off, the current flows through the inductor, but also through the diode. A voltage-sensing circuit on the load can be used to adjust the switch duty or frequency to maintain a set current within a desired tolerance. Figure 1 shows a version of the buck converter with a sense resistor providing feedback to the MCU control system.
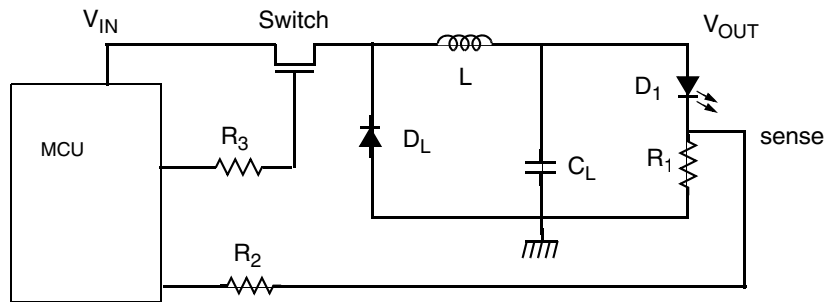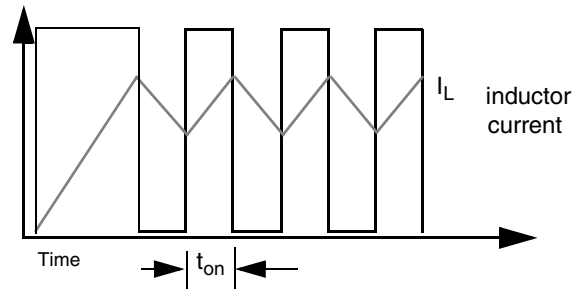
**Figure 1. Buck Converter Configuration**



**Figure 2. Current Changes**

The operation of this regulator topology has two distinct time periods. The first one occurs when the series switch is on. The input voltage ($V_{IN}$) is connected to the input of the inductor (L). The output of the inductor is the output voltage ($V_{OUT}$), and the rectifier, or catch diode, is reverse-biased. Because there is a constant voltage source connected across the inductor during this period, the inductor current begins to linearly ramp upwards, as described by Equation 1.

$$I_L(on) = [(V_{IN} - V_{OUT}) \times t_{ON}] / L \qquad \textit{Eqn. 1}$$

During the on period, energy is stored within the core material in the form of magnetic flux. If the inductor is properly designed, there is sufficient stored energy to carry the requirements of the load during the off period.

The next period is the off period of the power switch. When the power switch turns off, the voltage across the inductor reverses its polarity and is clamped at one diode voltage drop below ground by the diode. The current now flows through the diode, maintaining the load current loop. This removes the stored energy from the inductor. The inductor current during this time is:

$$I_L (off) = [(V_{OUT} - V_D) \times t_{off}] / L \qquad \textit{Eqn. 2}$$

This period ends when the power switch is turned on again. Regulation of the converter is accomplished by varying the duty cycle of the power switch according to the loading conditions. To achieve this, the power switch requires electronic control for proper operation. It is possible to describe the duty cycle as:

$$D = ton / T \qquad \textit{Eqn. 3}$$

where T is the switching period.

For the buck converter with ideal components, the duty cycle can also be described as:

$$D = V_{OUT} / V_{IN} \qquad \textit{Eqn. 4}$$

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## 3.2.1    Simplified Buck Converter

In a previous promotional tool developed by Freescale, the PROMOTORCH, a simplified version of of
the buck converter was used effectively. The buck circuit shown in Figure 3 eliminates the capacitor and
maintains the LED current by turning on the switch to charge the inductor until the current reaches the
desired level in the LED and then turning it off until the lower current threshold is reached. Refer to the
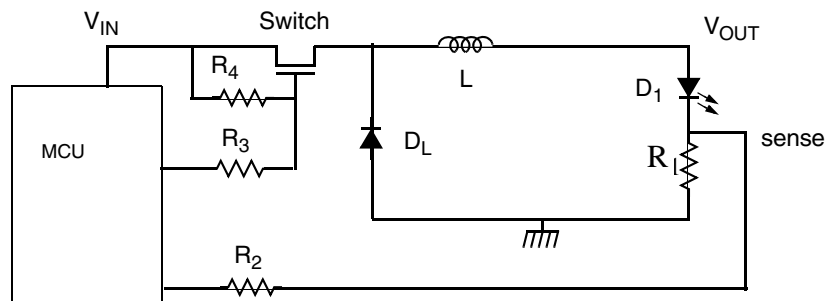full demonstration of this circuit on the Freescale website.

**Figure 3. Buck Converter Configuration**

# 3.3    Boost Topology

The boost circuit, used to increase the input voltage to a higher level, shunts the voltage on the output of
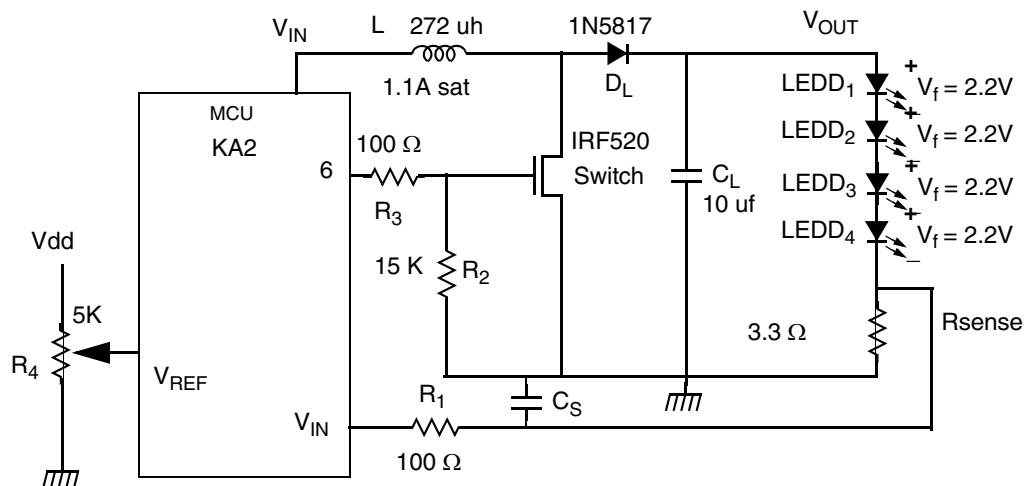the inductor, increasing the current through the inductor and stopping the charging of the capacitor.

**Figure 4. Boost Converter Configuration**

### 3.3.1    Circuit Operation

While the switch is on, the supply drives current charging the inductor. While the switch is off, the inductor current flows through the diode to the capacitor and the load. The equation for the output voltage is given here.

$$V_{OUT} / V_{IN} = 1/ (1-D) \hspace{4cm} \textbf{\textit{Eqn. 5}}$$

where D is the duty cycle of the switching waveform.

### 3.3.2    Boost Circuit Control

To use this circuit with an MCU, you must control the switch with a output pin of the MCU and monitor the current by sensing the voltage across the sense resistor. If a simple on/off function is needed for the LED, the comparator inside the MCU can be the monitor. The input voltage is set by selecting an appropriate resistor value for the current needed. For a 350 mA LED current and a voltage equivalent to the internal bandgap threshold of 1.218 V, a resistor value of 3.45 Ω can be chosen. The output frequency and duty cycle can be designed to provide nominal 350 mA current with the comparator adjusting the duty cycle of the output PWM up and down as the sense voltage dictated. If the sense voltage was higher than the reference the PWM duty cycle is adjusted to decrease the current supplied by the inductor. If the sense voltage is lower than the bandgap reference, the PWM duty cycle is adjusted to increase the current supply.

The value of the resistor ($R_{sense}$) can be selected to keep the power consumed by the resistor to a minimum. The power dissipated by the 3.45 Ω resistor above is about a 1/2 W, which decreases the efficiency of the drive circuit. It can be sized as an over-current protection for the LED string. If you need to maintain a lower power, for example, a standard 1/4 W resistor, then the reference voltage gets much smaller and you cannot use the internal bandgap voltage as a reference. A separate external reference can be provided by a resistor divider circuit source for the comparator.

### 3.3.3    Boost Circuit Power Mosfet Use

The boost circuit requires the use of an N-channel power mosfet switch. An N-channel device turns off with the input gate at ground. Because the circuit's purpose is to boost the voltage at the inductor, there are no restrictions for drain to gate voltage. If a P-channel device was used, the source of the mosfet would have to be connected to the boosted inductor. The voltage at the source cannot be more than a diode step above the input gate voltage, which is high at 5 V typically.

## 3.4    Buck-Boost Topology

The buck-boost is a versatile circuit allowing the most dynamic changes in source voltage. The output can be higher or lower than the supply voltage and is opposite to that of the input voltage. The switch does not have a reference to ground. Other very similar topologies, the SEPIC and cuk, offer advantages over the single-inductor buck-boost design. A single-ended primary inductance converter (SEPIC) is also able to step-up or step-down the voltage. A typical buck-boost converter is shown in Figure 5. A typical cuk converter is shown in Figure 6. In the cuk converter ,the input current is continuous, resulting in lower peak values, and the drive circuit requirements are simplified due to the switch location and the possible use of a coupled inductor, thereby reducing the cost and layout area of these designs.
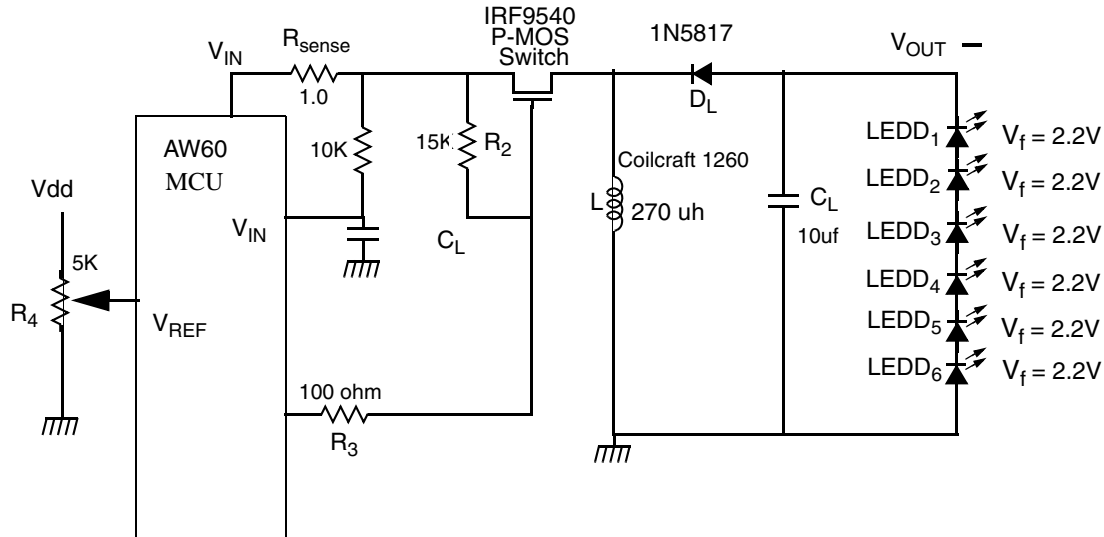
**Figure 5. Buck-Boost Converter**

## 3.4.1    Buck-Boost Circuit Operation

In the buck-boost converter, while the switch is on, the voltage across the inductor $V_L$ is equal to $V_{IN}$.

$$I_L(on) = (V_I * D * T) / L \qquad \textbf{\textit{Eqn. 6}}$$

While the switch is off, the current flows through the diode and forms an opposite polarity voltage across the load.

$$I_L(off) = (-V_{OUT} *(1-D) * T) / L \qquad \textbf{\textit{Eqn. 7}}$$

When you prototype this circuit you will be able to make it boost the voltage negative enough to drive the LEDs. Like the buck converter, the use of a P-MOS power mosfet was chosen.

The supply voltage to the microcontroller must be stabilized with a 7805 type voltage regulator that can provide the 5 V Vdd with an input voltage between 8 and 18 V. The buck-boost converter can accept the unregulated input voltage and reduce or increase the output current to the LED string as needed to source the LED's.

The size of the sense resistor in the control path can be selected to provide a full scale voltage input to the AD converter when the maximum current is reached. If you have a MCU ADC power level of 5 V and a current of 350 ma, then a nominal 2 W precision resistor value of 14.2 Ω can be used. Figure 5 shows a 1 Ω 1/5 watt precision resistor. It provides a fairly accurate representation of the current to the ADC input of an MCU.

A MC9S08AW60 was used in this test. This device can be powered by a 5 V supply, has 12 channels of ADC input and up to eight timer channels, and a possible 20 MHz bus rate. This combination is well suited to drive multiple strings of LED, while monitoring the current on each string, the temperature of the LEDs, variable control voltage inputs to control brightness of each string, and have enough I/O for a keyboard interface and a communications control interface.

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The timer control registers in the S08 have a feature to use a center-aligned positive or negative true PWM output. For the P-MOS power device, the timer output must be active low with an external pull-up resistor to disable the switch when the MCU control logic is not active. If you are mixing converter types that require both P-MOS and N-MOS power devices care should be taken to properly select the polarity of the timer output and pull devices. A current isolation resistor in series with the MCU outputs to the switch, which is necessary to minimize injection current into the MCU pin. ADC channel input protection is provided by a high impedance resistor to minimize injection current into the ADC input pin.

## 3.5 Cuk Converter Topology

Figure 6 depicts an example circuit of a cuk current controlled source. The cuk converter, like the buck-boost also provides a negative output voltage and can increase or decrease the output voltage.
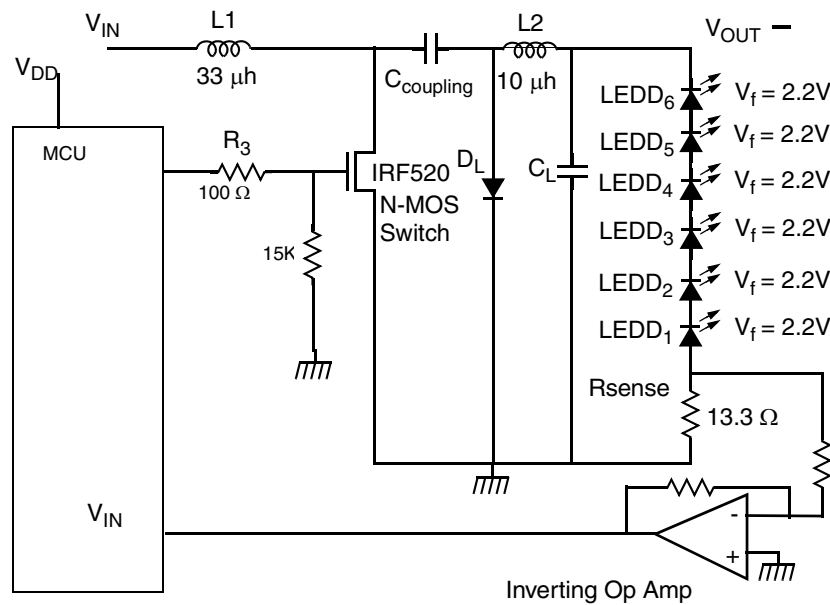


**Figure 6. Cuk Converter**

### 3.5.1 Cuk Circuit Operation

The output voltage for the Cuk converter ($V_{OUT}$) is given in Equation 8.

$$D = V_{OUT}/(V_{OUT} + V_{IN})$$ *Eqn. 8*

where D is the duty cycle of the switching frequency.

Use an N-channel power mosfet switch in this instance. The inductors should be the same value. In the schematic, different values were used without any bad effects.

The use of the inverting operation amplifier is needed in this circuit to ensure the MCU sees a positive voltage from the sense circuit.

## 3.6    Example of Buck Current Control With a Simple Comparator

Figure 7 is an example of how you could generate a control signal based upon an analog input from the voltage generated across a sense resistor at the base of the LED. If the design does not need brightness control, adjust the sense resistor size to give a voltage equivalent to the typical voltage of the internal bandgap of the part. The comparator input can be used to compare to either the internal bandgap or an external analog reference. The output of the comparator is isolated from the power mosfet with a 1 KΩ resistor to limit damaging current injection currents that can enter the MCU from the power mosfet. If you want to program the part in-circuit you must provide a way to disconnect the power mosfet from the pin since the ACMP output is shared with the BKGD pin on the KA2. Also, because the power mosfet is a P-channel device, it turns on when the comparator output is driven low. The reference input voltage is fed into the V- of the comparator and the VSense is feed back to the V+ letting the comparator to turn off (high output) when the current through the sense resistor is above limit. The addition of the capacitor on the sense input smooths out the signal as seen in Figure 7. This hook up avoids a potential issue with the KA2 when PTA0 pin is pulled up (refer to KA2 errata for details).
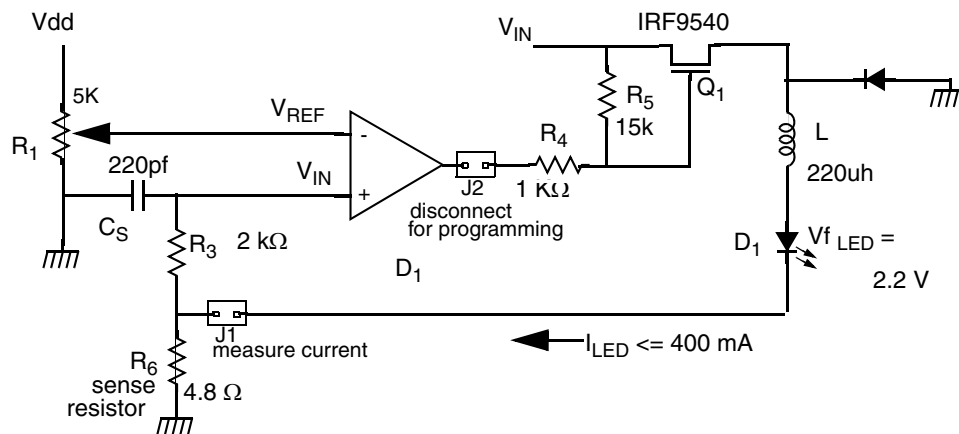


**Figure 7. LED Drive with Comparator from a KA2**

```
;*******************************************************************
;* This code drives a single high brightness led with the        *
;*   comparator on the MCU.                                       *
;*   no special set up of clock will be done.                     *
;*   for this demonstration the cop will be disabled.             *
;* The initialization is done followed by a main program          *
;* The main program doesn't need to do anything and just          *
;*   goes into stop.                                              *
;*******************************************************************
; export symbols
     XDEF _Startup, main
     ; we export both '_Startup' and 'main' as symbols. Either can
     ; be referenced in the linker .prm file or from C/C++ later on
; Include derivative-specific definitions
     INCLUDE 'derivative.inc'
; variable/data section
TINY_RAM_VARS: SECTION  RS08_SHORT ; Insert here your data definition
tmp: DS.B   1
; code section
MyCode:   SECTION
```

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```
main:
_Startup:
;init the acmp
      mov    #HIGH_6_13(SRS),PAGESEL

      mov #(mSOPT_COPT|mSOPT_STOPE|!mSOPT_BKGDPE), MAP_ADDR_6(SOPT)
; BKGD disabled,COP disabled, STOP enabled

      mov #(mACMPSC_ACME|mACMPSC_ACBGS|mACMPSC_ACO|mACMPSC_ACOPE),ACMPSC
;acmp enabled - output pin enabled - no interrupt

mov #(mSPMSC1_LVDE|mSPMSC1_LVDRE), MAP_ADDR_6(SPMSC1)
; LVI enable

      stop
      nop
      bra *
```

**Figure 8. Assembly Language Code for Comparator Circuit**

Figure 10 depicts the resulting control output of the comparator. The comparator output changes the output frequency and duty cycle when the current through the LED is adjusted. The control signal is on to the P-MOS device when the signal is low. The circuit is design to have a peak current of less than the LED maximum current of 400 mA when the switch is on all the time.
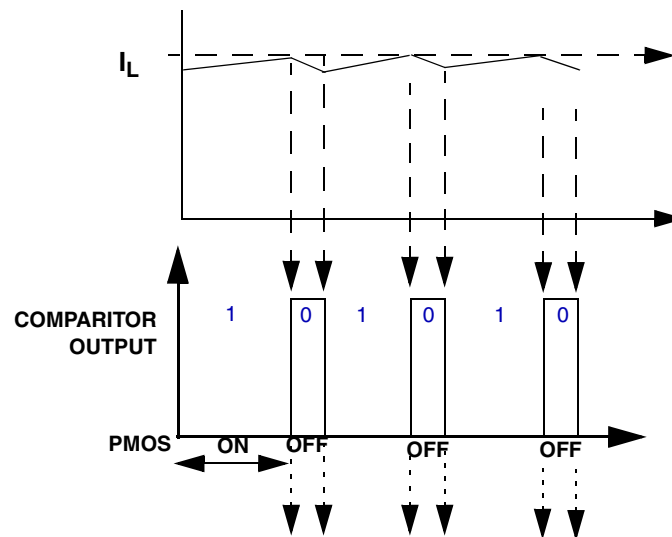


**Figure 9. Comparator Control Waveform**

## 3.7    Component Selection Guidelines

This section describes the function of each of the main components of the DC converter power stage. To meet the performance requirements of the circuit, each of the application's specific needs must be studied. For high-brightness LEDs, constant current and reduced current for dimming control with minimum ripple current drove each drive component selection.

### 3.7.1 Inductor Selection

The inductor is functioning as an energy storage device in these circuits. Figure 9 shows us that the inductor has AC and DC components. The AC component is at a high frequency and will flow through the output capacitor because it has a low impedance at high frequencies. For a reasonable compromise between inductor and capacitor size, a ripple current of 10 to 30 percent of the maximum inductor current can be chosen. However, the maximum ratings of the high-brightness LED can be as little as 7% higher than nominal and the circuit should be constrained to stay within the LED specification.

### 3.7.2 Inductor Saturation Current

As the current in an inductor increases, the inductance decreases. How much the inductor decreases is important. If it decreases too much, the converter circuit will not function properly. The current at which the inductor does not work properly is the saturation current and is a fundamental parameter of the inductor. Practically, the change in inductance is not a drastically changing parameter, the inductance gradually trails off. The specified saturation current for most inductors is often a soft parameter. Given this soft parameter is usually adequate to select a inductor with a saturation current greater than your average plus the max ripple current. The maximum DC current if the switch is turned on continuously dictates the saturation current you specify for the inductor. Typically a 1A saturation current is sufficient for a 350 mA high-brightness LED.

### 3.7.3 Buck Converter Inductor Selection

In a buck converter, while the switch is on, the current in the inductor current ramps up and energy is stored. When the switch turns off, this energy is released into the LED string. The assumption is that the current is continuous for the circuit. The amount of energy stored by the inductor is given by:

$$\text{Energy} = 1/2\ L I_L{}^2 - \text{(Joules)} \qquad\qquad \textbf{\textit{Eqn. 9}}$$

where L is the inductance and I is the peak value of inductor current. The amount the current changes during switching is called the ripple current. The ripple current is given by the equation:

$$V_L = L\ di/dt \qquad\qquad \textbf{\textit{Eqn. 10}}$$

where $V_L$ is the voltage across the inductor, di is the ripple current, and dt is the amount of time the voltage is applied. Therefore the ripple current is dependent upon the inductor value.

The parameters needed to determine the inductance are the input voltage ($V_{IN}$), output voltage ($V_{OUT}$), maximum DC and ripple currents ($I_{MAX}$ percent of ripple), duty cycle (D), and switching frequency ($F_S$=1/T).

$$L = (V_{IN} - V_{OUT})\ X\ (D\ x\ T)/I_{Ripple} \qquad\qquad \textbf{\textit{Eqn. 11}}$$

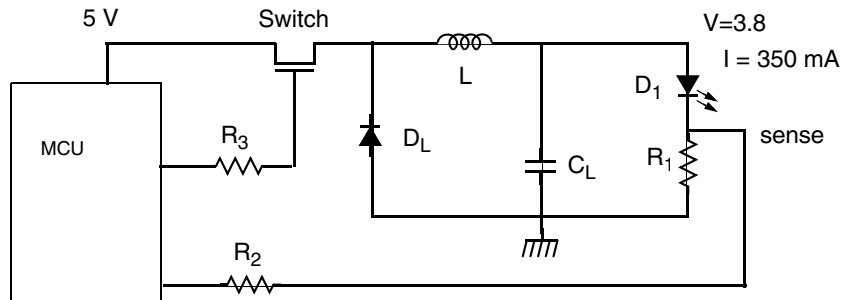**Figure 10. Buck Converter Components**

For example, for a buck converter with an input voltage range of 5 V $\pm$ 10% ($V_{IN}$) – input voltage of 5 + .5 or 5.5, and an output voltage of 3.8 V ($V_{OUT}$), the duty cycle needed is:

$$D = V_{OUT}/V_{IN} = 3.8/5.5 = 0.69 \qquad \textit{Eqn. 12}$$

The voltage across the inductor:

$$V_{L\text{-}on} = V_{IN} - V_{OUT} = 5 - 3.8 = 1.2 \text{ V while the switch is on} \qquad \textit{Eqn. 13}$$

$$V_{L\text{-}off} = V_{OUT} = 3.8 \text{ while the switch is off} \qquad \textit{Eqn. 14}$$

With a switching frequency (F) of 200 KHz and a max ripple current of 30 mA, gives a inductor value of:

$$L = (V_{L\text{-}on} \text{ x } D/F)/I_{Ripple\ Max} \qquad \textit{Eqn. 15}$$

$$L = (1.2 \text{ x } 0.69/200 \text{ x } 10^3)/.030 = 138 \text{ uH (50uH)} \qquad \textit{Eqn. 16}$$

## 3.7.4 Boost Converter Inductor Selection

For a boost converter, the process is different in the equations for duty cycle and inductor voltage.

This example uses a maximum input voltage of 5.5 V, a switching frequency of 70 KHz, and a maximum ripple current of 350 mA $\times$ 25% or 87.5 mA.

For an output voltage of 22 V, the duty cycle is:

$$D = 1-(V_{IN} / V_{OUT}) = 1 - (5.5/22) = 0.25 \qquad \textit{Eqn. 17}$$

The voltage across the inductor is:

$$V_L = V_{IN} = 5.5 \text{ V while the switch is on} \qquad \textit{Eqn. 18}$$

$$V_L = V_{OUT} - V_{IN} = 22 - 5.5 = 16.5 \text{ V while the switch is off} \qquad \textit{Eqn. 19}$$

Using Equation 15, the inductance is:

$$L = V_L \text{ (dt/di)} = (16.5 \text{ x } 0.25/70 \text{ x } 10^3)/.0875 = 673.5 \text{ uH} \qquad \textit{Eqn. 20}$$

For a buck-boost converter, consider the use of two inductors of equal size. For example, if we have an output voltage of 36 V, a maximum input voltage of 18 V, a switching frequency of 200 KHz, and a maximum ripple current of 700 mA × 30 percent or 210 mA, we have

Duty cycle:

$$\text{or } D = V_{OUT}/(V_{OUT} + V_{IN}) = 36/(36+18) = .666 \qquad \textbf{\textit{Eqn. 21}}$$

Inductor voltage of:

$$V_L = V_{IN} = 18 \text{ V while the switch is on} \qquad \textbf{\textit{Eqn. 22}}$$

$$V_L = V_{OUT} = 36 \text{ V while the switch is off} \qquad \textbf{\textit{Eqn. 23}}$$

Resulting in inductor values of:

$$L = V_L (dt/di) = (36 \times 0.666/200 \times 10^3)/.210 = 571.4 \text{ uH} \qquad \textbf{\textit{Eqn. 24}}$$

## 3.7.5 Output Capacitor

The function of the output capacitor is to store energy, and to maintain a constant voltage. The value is usually selected to minimize the ripple current of the converter. For our discussion, consider only continuous inductor current mode of operation. To determine the capacitance needed, we use Equation 25 and our knowledge of the inductor current ($I_L$), switching frequency ($F_S$), and the desired output voltage ripple ($V_{Ripple}$). The typical output ripple is between 25 and 30 percent.

$$C >= I_L / 8 \times F_S \times V_{OUT} \qquad \textbf{\textit{Eqn. 25}}$$

Consideration of the capacitor's equivalent series resistance (ESR) and equivalent series inductance (ESL) guides the selection a bit further. The ripple current in the circuit causes a temperature increase internally in the capacitor. Excessive temperatures result in a long-term reliability issue. To limit the effects of the ESR and ESL of the capacitor, a value much larger than described in Equation 11 is required to maintain the ripple current. Tantalum capacitors offer low ESR and ESL and are available in various packages.

## 3.7.6 Power Switch

For good switching performance, a N or P-channel MOSFET device with a low on-state resistance, and low gate charge must be used. Typically the current rating must be 20% larger than the maximum load current or the LED string and the drain-to-source breakdown voltage should be at least 25 percent larger than the maximum input voltage. N-channel power mosfets are required for all boost or buck-boost circuits due to the inherent gate to drain limits of the P-channel device. The voltage on the drain of the P-channel device is typically a diode drop above the driving gate voltage so it is not possible to control the gate with logic levels and expect the output voltage to boost. For the purpose of demonstration, IRF9540, and IRF520 devices were used in our circuits.

### 3.7.7　Current Sense Resistor

In our control circuit, a current sense resistor monitors the LED current by monitoring the voltage across the sense resistor. This enables the MCU to change the duty cycle in the control loop to adjust the current to the LED(s). The resistor should be small enough not to dissipate a lot of power, but large enough to provide an adequate voltage to the analog input of the controller. If we want maintain a standard 1/4 W precision resistor a value of 1 to 5 $\Omega$ can achieve our design goals. If the resistor is used as a current limiting element, then a .5 to 2 W resistor must be used, but a lot of energy will be lost and heat generated by the resistor.

## 3.8　Integrated MCU and Analog Power Solutions

Integrated high-power analog sub-systems can be used to drive single or multiple LED strings. The control of these high-power current drivers can incorporate sophisticated serial channel controls. For example, the MM908E625 is Quad Half H-Bridge with P/S + HC08 + LIN. The 908E625 is a highly integrated single-package solution that includes a high-performance HC08 MCU with a SMARTMOS$^{TM}$ analog control IC. The HC08 includes flash memory, a timer, enhanced serial communications interface (ESCI), an analog-to-digital converter (ADC), serial peripheral interface (SPI), and an internal clock generator module. The analog control die provides fully protected quad H-Bridge/high-side outputs, voltage regulator, watchdog, and local interconnect network (LIN) physical layer.

The MM908E625 has current regulators built into each of its four half-bridge low-side outputs. Current limit circuitry turns off the mosfet when programmed limit is reached. Current trip points levels are programmable at six different levels: 55, 260, 370, 550, and 740 mA. The circuitry regulates the duty cycle of the switching frequency. The switching frequency is a maximum of 25 kHz provided by a timer output of the MCU.

When the control of the LED is combined in an MCU-based system, other options for control and interface arise. Simple button inputs can be used to set the mode of the high-power LED to improve marketability of a simple device or allow unassisted safety alarm systems.

### 3.8.1　LED Lighting Control Using the MC9S08AW60

Refer to a reference design of a multi-color LED lighting control solution using the MC9S08AW60 microcontroller, available on the Freescale website.

Using an MCU to control the red/green/blue (RGB) color LEDs increases system flexibility and functionality for the next generation of lighting applications, architectural/entertainment lighting, or LCD back lighting, that require a smart and adaptive control methodology to ensure optimized color space rendering for various display contents, excellent color contrast for realistic display scene and a consistent color setting in manufacturing. In many cases, these new applications are controlled by a central control unit that requires a connectivity interface that can be implemented at a low cost using an MCU-based lighting controller.

In general, LEDs have a nonlinear I-V behavior and current limitation is required to prevent the power dissipation to exceed a maximum limit. Therefore, the ideal source for LED driving is a constant current source. As mentioned earlier the major advantage of linear driver is fast turn ON and OFF response times

to support high frequency PWM dimming method and wide range control on dimming level. An integrated DC-to-DC boost converter (MC34063) generates the high voltage required for LED driving in series and is shared with RGB channels, but the drawback id the power loss on R channel is higher than G or B channels. Individual DC-to-DC blocks must be used for each channel in power sensitive applications.

## 3.9 Serial and Parallel Interface Options

Because most Freescale MCUs have hardware modules that support serial interfaces, you have several options for implanting control interfaces.

### 3.9.1 The SCI Interface

The SCI is an asynchronous serial interface similar to a UART using two wires, a TxD and RxD. The SCI allows full-duplex, asynchronous, NRZ serial communication between the MCU and remote devices, including other MCUs.

### 3.9.2 The SPI

The SPI is a 4-wire synchronous high-speed interface. The SPI module pins are master in–slave out (MISO), master out – slave in (MOSI), SPI synchronous clock (SPSCK) and slave select (SS). The most common uses of the SPI system include connecting simple shift registers for adding input or output ports or connecting small peripheral devices, such as serial A/D or D/A converters. Although a system can exchange data between two MCUs, many practical systems involve simpler connections where data is unidirectionally transferred from the master MCU to a slave or from a slave to the master MCU.

### 3.9.3 The Inter-Integrated Circuit—IIC

The inter-integrated circuit (IIC) provides a method of communication between a number of devices. The interface is designed to operate up to 100 kb/s with maximum bus loading and timing. The device is capable of operating at higher baud rates, up to a maximum of clock/20, with reduced bus loading. The maximum communication length and the number of devices that can be connected are limited by a maximum bus capacitance of 400 pF.

The IIC bus system uses a serial data line (SDA) and a serial clock line (SCL) for data transfer and are bidirectional. All devices connected to it must have open drain or open collector outputs. A logic AND function is exercised on both lines with external pull-up resistors.

## 3.10 DALI Lighting Protocol

Digital Addressable Lighting Interface (DALI) protocol is set out in the technical standard IEC 60929 for the controlling of lighting in buildings. DALI is a bidirectional, digital protocol developed by lighting manufacturers for the control of light source levels. A DALI controller can query and set the status of each light by the bidirectional data exchange. DALI can be operated as a subsystem or as a stand alone system with maximum of 64 devices. The DALI web site provides for detailed specification and overview presentations. The interface has been standardized by IEC (EN) 60929 E4 AC Supplied Electronic Ballasts for Tubular Fluorescent Lamps — Performance Requirements Annex E, "Control Interface for

Controllable Ballasts." The logo is registered by AG-DALI, the international supporter of this standard. Freescale Semiconductor has created a DALI reference design using the MC68HC908KX8. Documentation for the design is found in "Digitally Addressable Lighting Interface (DALI) Unit Using the MC68HC908KX8." This is a good starting point to learn more about DALI.

## 3.11    DMX Lighting Protocol

DMX512 is designed around the industry standard EIA485 interface. The system is based on balanced transmission down a twisted pair of shielded conductors. Data transmission is based on an 8-bit asynchronous serial protocol with one start bit (low), two stop bits (high), and no parity. This gives a data frame of 11 bits. Because each bit is 4s wide it takes 44s to send a frame. If the line were to transmit a continuous data stream this would result in a data rate of 250,000 bits per second, or 250k baud. For more information on the implementation of this protocol refer to "DMX512 Protocol Implementation Using MC9S08GT60 8-Bit MCU" (document number AN3315).

## 3.12    ZigBee Communication

ZigBee technology, a network layer protocol designed to use the IEEE 802.15.4 standard. is a wireless solution available to LED control systems. The 802.15.4 standard is a specification for a cost-effective, low-data rate (<250 kbps), 2.4 GHz or 868/928 MHz wireless technology designed for personal-area and device-to-device wireless networking. ZigBee technology is designed to replace costly and complicated proprietary solutions currently existing in the market and is targeted at applications that already use an MCU. ZigBee technology requires a smaller stack size than Bluetooth™ wireless technology. It occupies less memory on a chip, keeping costs low. Because they are standard-based, 802.15.4 and ZigBee technologies help reduce development time for the OEM and offer reliability, security, inter-operability and certification. ZigBee can be used with the standard lighting control protocols, DMX, or DALI, if desired.

### 3.12.1    Integration Brings Reduced Size and Cost

The latest edition to the ZigBee family of ICs, the MC1321x system in package (SiP) integrates the MC9S08GT MCU with the MC1320x transceiver into a single 9x9 mm LGA package. This reduces the external component count up to 40 percent, lowers the solution size up to 33 percent, and reduces the overall cost by up to 29 percent. The platform provides for scalable flash memory size from 16 K to 60 K, providing solutions for wireless sensing and control applications that require networks that support simple point-to-point solutions, to complete ZigBee compliant mesh networks.

For example, the MC13192 is an ultra low cost 2.4 GHz transceiver designed for low-power proprietary wireless applications. Its features include:

- Low cost with printed antenna options, programmable output clock, 5x5 QFN-32 package
- Ideal for simple networks with multiple-end devices linked to one controller
- Compatible to any processor that provides a 4-wire SPI and three GPIO
- Packet mode used for post data processing in non-timing critical applications
- Sixteen channels, 250 kbps over the air data rate
- DSSS O-QPSK spreading and modulation

- Sensitivity of –91 dBm and output power of –16.6 dBm to +3.6 dBm
- Low-power modes include hibernate 3 μA and doze 40 μA

SMAC is a software layer used to control the MC13192. It resides on the application processor. The SMAC:

- Supports simple star and point-to-point networks
- Requires low-memory footprint, less than 2.5 k
- Includes only 16 primitives
- Provides in source code and developed in ANSI C
- Is easily portable to any MCU

# 4　User Interfaces Displays and Buttons

Lighting solutions are becoming more sophisticated as designers differentiate their products. The incorporation of MCU-based lighting systems are becoming the standard rather than the exception due to the expanding need for more features such as button or slider inputs, status or control output state information, color and brightness control, ambient condition feedback, and interface protocols.

## 4.1　LCD Display

Several MCUs have LCD hardware interfaces that suit the needs of lighting control systems. The MC68HC908LJ24 has device circuitry to driver to 4/3 backplanes and static with maximum 32/33 front planes for liquid crystal display (LCD). The MC689S08LC60 is offering an integrated LCD controller with the low-power and feature-rich capabilities of the S08 family. It is the first LCD S08 8-bit microcontroller for battery-powered and handheld applications. It is specifically crafted to provide high segment count that is easy on the batteries. A larger segment display of up to 160 segments offers total flexibility with a graphical display and sufficient memory to act as application and LCD controller without added cost of a dot matrix or chip-on-glass, fulfilling the need for a broad spectrum of applications with displays.

## 4.2　Button and Slider Switch Interface

Keyboard interrupt inputs and A/D inputs of the MCU provide the direct sensing of user controls. The typical slider input is a variable resistor that can provide a variable voltage input to an ADC channel. Capacitive touch sensors and resistive touch screens interfaces to the MCU are already present with most of Freescale's MCU selection.

# 5　Conclusion

The realm of high-brightness LED drivers is sometimes a daunting task for an MCU designer. These designs cross over into a mix of power analog and MCU software/digital control design. With the tips and direction given in this application note, the digital MCU designer can design and test any number of applications that use the higher voltage and currents to drive high-brightness and high-power LEDs.

# 6    References

Jim Holdahl, "Simple Inductors, Simple Solutions." *ECN Magazine*, May 1, 2001,
http://www.ecnmag.com/article/CA82608.html

Freescale Semiconductor, "MR16 Form Factor Lighting Module Design Example."
http://www.freescale.com/webapp/sps/site/application.jsp?nodeId=02430Z904043388501

Dugald Campbell and Oliver Jones. "Connecting with High Brightness LEDs." Presentation, Freescale
Technology Forum, Orlando, Florida, June 20–23, 2005.

Freescale Semiconductor, "ZigBee Standards Overview."
http://www.freescale.com/webapp/sps/site/overview.jsp?nodeId=01J4Fs25657725

Wikipedia - DC to DC converters:
http://en.wikipedia.org/wiki/DC_to_DC_converter#Switched-mode_conversion

Power Electronics—Converters, Applications, and Design, 2nd Edition.
by Mohan, Undeland and Robbins

MM908E625: Quad Half H-Bridge with P/S + HC08 + LIN device specification.
http://www.freescale.com

AN3315 "DMX512 Protocol Implementation Using MC9S08GT60 8-Bit MCU"
http://www.freescale.com

HB LED Color Mixing and LCD Backlight presentation at FTF America by John Suchyta
http://www.freescale.com

LED Lighting Control Using the MC9S08AW60 Designer Reference Manual
www.freescale.com

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