INTRODUCTION

The proliferation of portable electronic devices with Liquid Crystal Displays (LCDs), such as smart phones, handheld games and portable computers, has increased the demand for using white LEDs as a backlight source for the LCDs. The white LEDs are used as a light source because of their high efficiency, small size, lower cost and long operating life. Series string clusters of LEDs are usually used for higher brightness and better brightness matching between LEDs; therefore, a high-efficiency DC-DC boost converter is used to drive the LEDs in series for the LCD backlight in these battery-powered handheld electronic devices. In this application note, some external soft start and dimming control circuits for simple DC-DC boost LED drivers will be discussed.

SOFT START CIRCUIT

In DC-DC boost converters, the inrush current is approximately double, or more than the nominal input current level during start-up, to set up the output voltage on the output capacitor and LED string load. High inrush current will drain excessive power from the battery, cause output voltage overshoot, generate more heat dissipation and power loss, which reduces the battery usable operating time. To reduce the inrush current, prevent output voltage overshoot and save the battery power, a soft start circuit should be used to limit the inrush current. For some simple DC-DC boost converters, which may not have sufficient soft start or a longer soft start time is required, the soft start circuit in Figure 1 can be implemented.

FIGURE 1: MIC2289 Boost Converter LED Driver Application Circuit with External Soft Start.
The circuit uses a soft start capacitor, C_{SS}, to control the output voltage rise time by providing extra feedback from the output to the FB pin. The output voltage starts to rise when the boost converter starts switching. The dV/dt of the output voltage forces a current through the soft start capacitor C_{SS} and lower resistor R_{SS}. This action provides an overdrive voltage to the FB pin through the diode D1 during start-up. This increased voltage on the FB pin reduces the switching duty cycle of the boost converter, limiting the turn-on time of the boost switch and the inductor switching current. As the C_{SS} capacitor is charging up, the overdrive voltage on the FB pin is slowly reducing, and this results in an initial reduced switching duty cycle and then gradual increase of the switching duty cycle, up to the final nominal value in regulation steady state, and limited inrush current and slow ramping up of output voltage.

Increasing the value of the C_{SS} capacitor causes the output voltage to rise more slowly and increases the soft start time. The increased C_{SS} capacitor value causes the C_{SS} capacitor to charge up more slowly and the overdrive voltage on the FB pin to decay more slowly. This results in a more gradual increase of switching duty cycle, up to nominal value and longer output voltage ramp-up time. The lower resistor, R_{SS}, together with C_{SS}, controls the RC decay time of the overdrive voltage seen by the FB pin and R_{SS} ensures the D1 is reverse-biased after soft start. It also provides a discharge path for C_{SS} when the boost converter turns off. The value of R_{SS} should be in the range of kOhm for most applications, while the C_{SS} should be in the range of a few nF to a few µF.

Diode D1 provides a conduction path for the overdrive voltage to the FB pin during soft start. D1 is reverse-biased in normal operation after soft starting the output and prevents C_{SS} from appearing in parallel with normal feedback, which would affect the stability and transient response. A signal diode should be used for the D1 since a signal diode has very small reverse leakage current. Using a Schottky diode is not recommended for D1, as it would have larger reverse leakage current which will affect the normal feedback voltage signal after soft start. The optional Zener diode, D2, clamps the voltage seen by the FB pin below the FB pin’s maximum rating and provides a discharge path for C_{SS} when the boost converter is turned off. The soft start time can be approximated by the following equation:

**EQUATION 1:**

\[
t_{SS} \approx 2 \times C_{SS} \times R_{SS} \times \ln\left(\frac{V_{OUT}}{V_{REF}}\right)
\]

Where:
- \(C_{SS}\) = External Soft Start Capacitor
- \(R_{SS}\) = Resistor of the Soft Start Circuit
- \(V_{OUT}\) = Output Voltage
- \(V_{REF}\) = Internal Reference Voltage

**Design Example 1**

Let’s consider a practical application for driving six white LEDs with the MIC2289 supplied by a single-cell Li-ion battery.

The design parameters are given as below:

- Input Voltage (V_{IN}): 3.6V
- Output: Six LEDs in Series
- Reference (V_{REF}): 95 mV
- Forward Voltage (V_F): 3.6V (single LED)
- Number of LEDs (N): 6
- Soft Start Time (t_{SS}): 200 µs

\[
V_{OUT} = N \times V_F + V_{REF}
\]
\[
V_{OUT} = 6 \times 3.6V + 0.095V
\]
\[
V_{OUT} = 21.695V
\]

10 kΩ is selected as R_{SS} for convenience.

The value of C_{SS} can be calculated from **Equation 1** as follows:

**EQUATION 2:**

\[
C_{SS} = \frac{t_{SS}}{2 \times R_{SS} \times \ln\left(\frac{V_{OUT}}{V_{REF}}\right)}
\]

\[
C_{SS} = \frac{200\mu s}{2 \times 10k\Omega \times \ln\left(\frac{21.695V}{0.095V}\right)}
\]
\[
C_{SS} \approx 1.84nF
\]

Therefore, 2200 pF is chosen for C_{SS} to ensure the target soft start time can be achieved.
Figure 2 shows the turn-on of the MIC2289 boost LED driver, driving six white LEDs in series, without the external soft start circuit. Figure 3 shows the turn-on of the same LED driver with the external soft start circuit using $C_{SS} = 2200 \, \text{pF}$ and $R_{SS} = 10 \, \text{k}\Omega$. It shows that the soft start circuit has reduced the inrush current and prevents output voltage overshoot.

**DIMMING CONTROL**

Adjusting LED brightness is usually required in the actual end product application, such as increasing the brightness of the LCD in brighter environments to improve the readability of the display content. There are two types of dimming methods: one method is PWM dimming and another one is continuous analog dimming.

### PWM Dimming

PWM dimming control is implemented by applying a PWM signal at the EN pin of the boost LED driver device, as shown in Figure 4.

The boost LED driver device is turned on and off by the PWM signal and this is the simplest way commonly used for dimming or adjusting the brightness of the LEDs. With the PWM dimming method, the LEDs operate in either zero or full current. The average LED current is proportional to the duty cycle of the PWM dimming signal. This EN pin PWM dimming method consumes no current during the off cycle of the PWM dimming signal. However, most of the simple boost LED driver outputs are discharged when the dimming signal is low and have to go through the soft start every time the PWM signal at the EN pin changes from low-to-high. Therefore, the period of the PWM dimming signal has to be significantly longer than the soft start time of the boost LED driver; otherwise, the average LED current will not be proportional to the duty cycle of the PWM dimming signal. Therefore, the maximum PWM frequency of this dimming method is limited by the soft start time. On the other hand, the PWM dimming frequency cannot be too low; otherwise, the flicking of LED brightness will be percepted by the human eye, so the dimming frequency should be between 100 Hz to 10 kHz. The maximum LED current at 100% PWM duty at the EN pin is set by Equation 3:

**EQUATION 3:**

$$I_{LED(MAX)} = \frac{V_{REF}}{R_{FB}}$$

Where:

- $V_{REF}$ = Internal Reference Voltage
- $R_{FB}$ = Lower Feedback Resistor
The average LED current of this EN pin PWM dimming method is approximately changed according to the PWM duty cycle and can be calculated as below:

**EQUATION 4:**

\[
I_{\text{LED}} \approx \frac{V_{\text{REF}}}{R_{\text{FB}}} \times D_{\text{PWM}}
\]

Where:
- \(V_{\text{REF}}\) = Internal Reference Voltage
- \(R_{\text{FB}}\) = Lower Feedback Resistor
- \(D_{\text{PWM}}\) = Duty Cycle of PWM Dimming Signal

For EN pin PWM dimming method, the minimum PWM dimming pulse width has to be sufficiently longer than the soft start time of the boost LED driver. The frequency of the PWM dimming signal can be estimated by the following equation:

**EQUATION 5:**

\[
f_{\text{PWM}} \leq \frac{1}{4 \times I_{SS} \times D_{\text{PWM(MIN)}}}
\]

**Design Example 2**

Let’s consider a practical application example for using the EN pin PWM signal dimming method shown in Figure 4.

The design parameters are given as below:
- Input Voltage \((V_{\text{IN}})\): 3.6V
- Output: Six LEDs in Series
- Reference \((V_{\text{REF}})\): 95 mV
- Max. LED Current: 40 mA
- Dimming Method: PWM
- Dimming Range: 5% to 100%

Since the maximum LED current at 100% PWM duty is 40 mA, the value of \(R_{\text{FB}}\) can be calculated from Equation 3 as below:

**EQUATION 6:**

\[
R_{\text{FB}} = \frac{V_{\text{REF}}}{I_{\text{LED(MAX)}}} = \frac{95\text{mV}}{40\text{mA}} = 2.375\Omega
\]

Where:
- \(R_{\text{FB}} = 2.37\Omega\) Selected for Available Value

For MIC2289, the soft start time is about 100 µs without an external soft start circuit. The frequency of the PWM dimming signal can be calculated as below:

**EQUATION 7:**

\[
f_{\text{PWM}} \leq \frac{1}{4 \times 100\mu s} \times 0.05 = 125\text{Hz}
\]

Since the EN pin logic level high is 1.5V, as shown in the “MIC2289 Data Sheet”, a PWM dimming signal with 100 Hz frequency and 2V pulse amplitude should be used. Some bench test results are shown in Figure 5 through Figure 9.
Continuous Analog Dimming

Continuous analog dimming control is implemented by applying an analog DC control voltage through a series resistor, R1, to the FB pin of the boost LED driver, as shown in Figure 10.

Since the voltage at the FB pin is regulated at the internal reference voltage in steady state, the voltage difference between the DC control voltage and the FB pin voltage across the R1 generates a programmable current flowing through another series resistor, R2, between the FB pin and the LED current setting resistor RF. This current generates an effectively adjustable regulated voltage across the LED current setting resistor RF. The values of R1 and R2 should be in kΩ range. The LED current of this continuous analog dimming method can be programmable by the following equation:

**EQUATION 8:**

\[ I_{LED} = \frac{V_{REF} - V_{DC} \cdot V_{REF}}{R_{FB}} \times R_{2} \]

or

\[ I_{LED} = \frac{V_{REF}}{R_{FB}} \times \left(\frac{R_{2}}{R_{1}} + 1\right) \times V_{DC} \times \frac{R_{2}}{R_{1}} \]

Where:
- \( V_{REF} \) = Internal Reference Voltage
- \( R_{FB} \) = Lower Feedback Resistor
- \( V_{DC} \) = DC Dimming Control Voltage
- \( R_{1} \) = Series Resistor between \( V_{DC} \) and FB Pin
- \( R_{2} \) = Series Resistor between FB pin and \( R_{FB} \)

As shown in Equation 8, the LED current is just equal to the undimmed maximum when the \( V_{DC} \) is equal to \( V_{REF} \) or the DC input is floating, while the LED current decreases linearly as the amplitude of the DC control voltage increases above the \( V_{REF} \). On the other hand, the LED current increases linearly as the amplitude of the DC control voltage decreases below the \( V_{REF} \). However, if the \( V_{REF} \) is a very low voltage and \( V_{DC} \) must be a positive voltage, this section of the \( V_{DC} \) is less useful for continuous dimming purposes.

For positive DC control voltage, the \( V_{DC} \) is bounded by the following inequality condition:

**EQUATION 9:**

\[ V_{DC} \leq V_{REF} \times \left(\frac{R_{1}}{R_{2}} + 1\right) \]

Therefore, the maximum DC control voltage which dims the LED current to zero is given by the equation below:

**EQUATION 10:**

\[ V_{DC(MAX)} = V_{REF} \times \left(\frac{R_{1}}{R_{2}} + 1\right) \]
In most applications, \( V_{DC} \) is in the range of a few volts, while the \( V_{REF} \) is just less than 0.1V. Therefore, the value of \( R_1 \) should be more than ten times larger than the value of \( R_2 \), as indicated by Equation 10. Then, the maximum LED current can be approximated by:

**EQUATION 11:**

\[
I_{LED(MAX)} = \frac{V_{REF}}{R_{FB}} \times \left( \frac{R_2}{R_1} + 1 \right)
\]

When \( R_1 >> R_2 \):

\[
I_{LED(MAX)} \approx \frac{V_{REF}}{R_{FB}}
\]

In fact, not every application needs to dim the LED current to zero. Then, the following more general equation can be used:

**EQUATION 12:**

\[
V_{DC} = (V_{REF} - I_{LED} \times R_{FB}) \times \frac{R_1}{R_2} + V_{REF}
\]

The value of the \( R_2 \) resistor is in the range of kOhm and the value of \( V_{DC(MAX)} \) is in the range of a few volts. When the value of \( R_2 \) and \( V_{DC(MAX)} \) is selected, the value of \( R_1 \) can be calculated by:

**EQUATION 13:**

\[
R_1 = \frac{R_2 \times (V_{DC(MAX)} - V_{REF})}{V_{REF} - I_{LED(MIN)} \times R_{FB}}
\]

The LED current and brightness can be dynamically varied by applying a DC voltage through the series resistor \( R_1 \) to the FB pin. The DC voltage can be from a DAC signal or RC filtered PWM signal. For an RC filtered PWM signal applied to the DC terminal, the LED current can be programmed by the below equation:

**EQUATION 14:**

\[
I_{LED} = \frac{V_{REF}}{R_{FB}} \times \left( \frac{R_2}{R_1} + 1 \right) - \frac{V_{PWM} \times D_{PWM}}{R_{FB}} \times \frac{R_2}{R_1}
\]

Where:

\( V_{PWM} \) = Amplitude of PWM Signal
\( D_{PWM} \) = PWM Duty Cycle

For the RC filter used for the filtered PWM signal to generate the equivalent DC control voltage, the value of \( R \) should be selected with the condition that it will not cause a significant voltage drop to the DC control voltage, as the current is drawn into the \( R_1 \) and \( R_2 \) network, passing through the resistor \( R \) of the filter. Therefore, the resistance of the RC filter can be chosen by the following inequality, as shown in Equation 15.

**EQUATION 15:**

\[
R_f \leq \frac{0.01 \times V_{DC(MAX)} \times R_1}{V_{DC(MAX)} - V_{FB}}
\]

Then, the capacitance of the RC filter can be estimated by the equation below:

**EQUATION 16:**

\[
C_f \approx \frac{5}{\pi \times R_f \times f_{PWM}}
\]

Where:

\( R_f \) = Resistance of the RC Filter
\( f_{PWM} \) = Frequency of the PWM Signal

The advantage of this continuous analog dimming approach is that the boost LED driver does not need to go through a soft start repeatedly and a high-frequency PWM signal larger than 10 kHz can be used to control LED brightness.

**Design Example 3**

Let’s consider another practical application example for using the analog DC voltage continuous dimming method, as shown in Figure 10.

The design parameters are given as below:

| Input Voltage (\( V_{IN} \)) | 3.6V |
| Output | Six LEDs in Series |
| Reference (\( V_{REF} \)) | 95 mV |
| Max. LED Current | 40 mA |
| Dimming Method | Analog DC Voltage |
| Dimming Range | 0% to 100% |

The \( I_{LED(MAX)} \) is 40 mA at 100% LED current. The value of \( R_{FB} \) is calculated from Equation 11 as below:

**EQUATION 17:**

\[
R_{FB} \approx \frac{V_{REF}}{I_{LED(MAX)}} = \frac{95mV}{40mA} = 2.375\Omega
\]

Where:

\( R_{FB} \) = 2.37\Omega Selected for Available Value

The \( I_{LED(MIN)} \) is 0 mA at 0% LED current. Since the recommended \( R_2 \) is in kOhm and the recommended \( V_{DC(MAX)} \) is in the range of a few volts, then \( R_2 = 1 \) kΩ and \( V_{DC(MAX)} = 2V \) are chosen, respectively, for convenience. Then, the value of \( R_1 \) is calculated from Equation 13 as follows:

**EQUATION 18:**

\[
R_1 = \frac{1k\Omega \times (2V - 95mV)}{95mV - 0mA \times 2.37\Omega} = 20.05k\Omega
\]

Where:

\( R_1 \) = 20 kΩ Selected for Commonly Available Value
Some bench test results are shown in Figure 11 through Figure 16.

**FIGURE 11:** Analog Continuous Dimming with $V_{DC} = 2V$, $I_{LED} = 0 mA$ (0%).

**FIGURE 12:** Analog Continuous Dimming with $V_{DC} = 1.9V$, $I_{LED} = 2 mA$ (5%).

**FIGURE 13:** Analog Continuous Dimming with $V_{DC} = 1.8V$, $I_{LED} = 4 mA$ (10%).

**FIGURE 14:** Analog Continuous Dimming with $V_{DC} = 1V$, $I_{LED} = 21 mA$ (50%).

**FIGURE 15:** Analog Continuous Dimming with $V_{DC} = 0.1V$, $I_{LED} = 40 mA$ (95%).

**FIGURE 16:** Analog Continuous Dimming with $V_{DC} = 0V$, $I_{LED} = 42 mA$ (100%).
Design Example 4

The same conditions as in the previous “Design Example 3”, but a filtered PWM signal is used to generate the equivalent DC control voltage.

The extra design parameters are given as below:

- PWM Signal Frequency ($f_{PWM}$): 20 kHz
- PWM Signal Amplitude ($V_{PWM_{MA}}$): 2V
- $V_{DC(MAX)} \approx V_{PWM_{MA}}$ at 100% PWM duty.

Using Equation 15, the value of $R_f$ of the filter can be chosen by the below calculated result:

**EQUATION 19:**

$$R_f < \frac{0.01 \times 2V \times 20k\Omega}{2V - 95mV}$$

$$R_f < 210\Omega$$

$R_f = 100\Omega$ is selected to minimize the voltage drop to the DC control voltage.

From Equation 16, the value of $C_f$ of the filter can be chosen by the following calculated result:

**EQUATION 20:**

$$C_f > \frac{5}{\pi \times 100\Omega \times 20kHz}$$

$$C_f > 0.796\mu F$$

$C_f = 10 \mu F$ is selected for obtaining better filtered resulting DC control voltage.

The bench test results are shown in Figure 17 through Figure 21.
CONCLUSION

In this application note, an external soft start circuit, EN pin PWM LED dimming circuit and continuous analog DC voltage LED dimming circuit for a simple boost LED driver, such as MIC2289, are discussed. Also, the related design equations are introduced and design examples are demonstrated with test results to assist the implementation of the circuits.

REFERENCE

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### EUROPE

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