AN-9744

Smart LED Lamp Driver IC with PFC Function

Introduction

The FL7701 is a PWM peak current controller for a buck converter topology operating in Continuous Conduction Mode (CCM) with an intelligent PFC function using a digital control algorithm. The FL7701 has an internal self-biasing circuit that is a current source using a high-voltage switching device. When the input voltage is applied to the HV pin is over 25 V to 500 V, the FL7701 maintains a 15.5 V DC at the VCC pin. The FL7701 also has a UVLO block for stable operation. When the VCC voltage reaches higher than VCCST+, the UVLO block starts operation. When the VCC drops below the VCCST-, IC operation stops. Please note that this application note could also be used for FLS0116, which is a Smart LED Lamp driver IC with the same features and functions as FL7701 but includes built-in 1 A, 500 V MOSFET.

Internal Digital Reference by ZCD

Hysteresis is provided for stable operation of the IC when the input voltage is in noisy circumstances or unstable conditions. The FL7701 has a “smart” internal block for AC input condition. If an AC source with 50 Hz or 60 Hz is applied, the IC automatically changes the internal reference to adjust to input conditions with an internal fixed transient time.

When a DC source connects to the IC, the internal reference immediately changes to DC waveform. The internal DAC_OUT reference signal is dependent on the VCC voltage. Using the DAC_OUT signal and internal clock, CLK_GEN; the FL7701 automatically makes a digital reference signal, DAC_OUT. If too high of a capacitor value is connected to VCC, the VCC voltage may not drop enough during the AC input voltage valley region. The ZCD_OUT signal does not trigger correctly and the IC will have an abnormal internal reference signal, see Figure 2 for a normal trigger sequence. This abnormal internal reference signal causes LED light flicker.

Soft-Start Function

The FL7701 has an internal soft-start to reduce inrush current at IC startup. When the IC starts operation, the internal reference of the IC slowly increases up to a fixed level for around seven cycles. After this transient period, the internal reference is fixed at a certain DC level, see Figure 3. In this transient time, the IC continually tries to find input phase information from the VCC pin. If the IC succeeds in detecting phase information from the VCC input, the IC automatically follows a similar shape to the AC input voltage, see Figure 4. If not, the IC has a DC reference level.
Internal Power Factor (PF) Function

The FL7701 application circuit does not use the input electrolytic capacitor for voltage rectification after a bridge diode because this system design results in a high pulse shape input current. This pulse shape current contains many harmonic components, so the total system cannot have high PF. To get high PF performance, the FL7701 uses a different approach.

The FL7701 has an intelligent internal PFC function that does not require additional detection pins or other components. The IC does not need a bulk capacitor on the VCC pin for supply voltage stabilization.

The FL7701 detects the VCC changing point for generating the Zero Crossing Detection (ZCD) signal, which is an internal timing signal for generating DAC_OUT. Normally, a capacitor connected to the VCC pin is used for voltage stabilization and acts as a low-pass filter or noise-canceling filter. This increases the ability to get a stable timing signal at the VCC pin, even though there may be noise on other pins.

To precisely and reliably calculate the input voltage phase on the VCC pin, the FL7701 uses a digital technique (sigma/delta modulation/demodulation). After finishing this digital technique, the FL7701 has new reference that is the same phase as input voltage, as shown in Figure 6.

Output Frequency Programming

The FL7701 can program output frequency using an RT resistor or with the RT pin in open condition. The FL7701 can have a fixed output frequency around 45 kHz when the RT pin is left open. For increasing system reliability, a small-value capacitor is recommended below 100 nF in RT-open condition. The relationship between output frequency and the RT resistor is:

\[
f_{\text{osc}} = \frac{2.02 \times 10^6}{RT} \text{[Hz]}\]  

Output Open-Circuit Protection

The recommended connection method is shown in Figure 7. The FL7701 has a high-voltage power supply circuit, which self-biases using a high-voltage process device. If the LED does not connect to the chip, the IC cannot start.
Inductor Short-Circuit Protection

The FL7701 has an Abnormal Over-Current Protection (AOCP) function. If the voltage of the LED current-sensing resistor is higher than 2.5 V, even within Leading Edge-Blanking (LEB) time of 350 ns; the IC stops operation.

Analog Dimming Function

The Analog Dimming (ADIM) function adjusts the output LED current by changing the voltage level of the ADIM pin.

Application Information

The FL7701 is an innovative buck converter control IC designed for LED applications. It can operate from DC and AC input voltages without limitation and its input voltage level can be up to 308 VDC.

Table 1 shows one example of a design target using the FL7701 device.

<table>
<thead>
<tr>
<th>Item</th>
<th>Specification</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>45 kHz</td>
<td></td>
</tr>
<tr>
<td>Output Voltage</td>
<td>35 Vf=3.5 V, n=10</td>
<td></td>
</tr>
<tr>
<td>Output LED Current</td>
<td>0.3 ILED(rms)</td>
<td></td>
</tr>
<tr>
<td>Output LED Peak</td>
<td>0.5 ILED(peak)</td>
<td></td>
</tr>
<tr>
<td>Input Voltage (Max.)</td>
<td>220 VAC(rms)</td>
<td></td>
</tr>
</tbody>
</table>

Step 1: Minimum Duty Ratio

The FL7701 has a fixed internal duty ratio range between 2% and 50%. This range depends on the input voltage and the number of LEDs in the string.

\[ D_{\min} = \frac{nV_f}{\eta \times V_{\text{in(max)}}} \]  

(2)

where \( \eta \) is efficiency of system; \( V_{\text{in(max)}} \) is maximum input voltage; \( V_f \) is forward-drop voltage of LED; and \( n \) is LED number in series connection.

For example, if \( V_{\text{in(max)}} = 220 \text{ V} \), \( \eta = 85\% \) and ten LEDs are in series connection, the minimum duty ratio is:

\[ D_{\min} = \frac{10 \times 3.5}{0.85 \times \sqrt[2]{220}} = 0.132 \]

Step 2: Maximum Duty Ratio

Similar to Step 1, calculate maximum duty ratio as:

\[ D_{\max} = \frac{nV_f}{\eta \times V_{\text{in(min)}}} \]

(3)

Figure 9. Duty Variation vs. Time

The FL7701 has a 50% maximum duty cycle to prevent sub-harmonic instability. Assume the minimum input voltage enters 50% duty ratio. Using Equation (2), re-calculate the minimum input voltage for CCM operation:

\[ V_{\text{in(min)}} = \frac{nV_f}{\eta \times D_{\max}} = \frac{35}{0.85 \times 0.5} = 82.35[V] \]

(4)
Step 3: Maximum On/Off Time
The FL7701 has internally fixed maximum duty ratio around 0.5 to prevent sub-harmonic instability. Assume the maximum on/off time at 45 kHz operation condition is:

\[ t_{on} = t_{off} = \frac{1}{2f_s} = \frac{1}{90000} = 11.11 \text{ [μs]} \]

Step 4: Calculate the LED Current Ripple, \( Δi \)
Figure 11 shows the typical LED current waveforms of a FL7701 application. For more stable or linear LED current, operate in CCM.

\[ I_{LED(peak)} = I_{LED(ave) + Δi/2} \quad \text{or} \quad I_{LED(min)} = I_{LED(average) - Δi/2} \]

\[ Δi = 2(I_{LED(peak)} - I_{LED(average)}) \quad \text{or} \quad Δi = 2(I_{LED(average)} - I_{LED(min)}) \]

\[ I_{LED(rms)} = \frac{I_{LED(average)}}{\sqrt{2}} \]

In Table 1, the desired LED current average is always located between LED peak current value, \( I_{LED(peak)}=500 \) mA, which is limited by the IC itself, and the LED minimum current. Using this characteristic, the inductor value for the desired output current ripple range (\( Δi \)) is:

\[ Δi = 2(I_{LED(peak)} - I_{LED(average)}) \quad \text{or} \quad Δi = 2(I_{LED(average)} - I_{LED(min)}) \]

\[ I_{LED(rms)} = \frac{I_{LED(average)}}{\sqrt{2}} \]

Step 5: Inductance
Derive one more formula for the minimum inductance value of the inductor using the Step 4 results:

\[ L = \frac{(V_i \times n)[1 - D_{\text{min}}]}{f_s \times Δi} = \frac{3.5 \times 10 \times (1 - 0.132)}{45000 \times 0.1516} = 4.5 \text{[mH]} \]

(7)

Step 6: Sensing Resistor
The current sensing resistor value can be determined by:

\[ R = \frac{V_{CC}}{I_{LED(peak)}} = \frac{0.5}{0.5} = 1 \text{[Ω]} \]

(8)

The power rating is under 0.25 W even when considering power consumption at peak-current condition.

Step 7: Frequency Set Resistor
\[ R_f = \frac{1}{f_{sw}} \cdot 2.0213 \cdot 10^9 = 44.919 \text{[kΩ]} \]

(9)

If the frequency setting resistor \( R_f \), is not connected, the system operates at the IC’s default switching frequency which is 45 kHz.
System Verification

Figure 14 shows the recommended circuit of a FL7701 system with just a few components.

Figure 14. Test Circuit

Figure 15 and Figure 16 show the startup waveforms from a FL7701 application in DC and AC input conditions at 220 V with ten LEDs.

Figure 15. Soft-Start Performance in DC Input Condition

Figure 16. Soft-Start Performance in AC Input Condition

Figure 17 and Figure 18 show performance of FL7701 following the input source changes from high-line frequency, to lower frequency, then to higher frequency.

Figure 17. Input Source Changing: 45 Hz to 100 Hz

Figure 18. Input Source Changing: 100 Hz to 45 Hz

Figure 19 shows the analog dimming performance with changing $V_{\text{ADM}}$. The output LED current changes according to the control voltage.

Figure 19. $V_{\text{ADM}}$ vs. LED Current
Figure 20 shows the typical function of AOCP performance. The FL7701 limits output LED current pulse-by-pulse with Leading-Edge Blanking (LEB), ignoring current noise. Even though the IC limits the output LED current pulse-by-pulse, it cannot prevent inrush current during an inductor short. To prevent this kind of abnormal situation, the IC has an AOCP function to protect the system.

**Design Tips**

**LED Current Changing**

Figure 22 shows the recommended circuit for achieving high PF. In this condition, the LED current goes to 0 every half cycle period.

**LED Current Changing**

To design around this, add an electrolytic capacitor in parallel to the LED load, as shown in Figure 23. This added capacitor provides a truer DC LED current.

**LED Current Changing**

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Preventing LED Flicker Due to ZCD Error During Analog Dimming

HV pin of FL7701 is usually connected behind the EMI filter components. Waveform of HV pin has distortion due to L-C resonance of the EMI filter and discharging of EMI capacitor. This could lead to VCC waveform distortion as well as ZCD detection error as shown in Figure 25. The abnormal waveform could cause LED light flicker to happen.

![Figure 25. LED Flicker at Analog Dimming](image)

The reasons for the LED flickering are as follow;

1. EMI filter is optimized for the rated output power. When analog diming is used, the output power is decreased. As the output power decreases, the EMI filter capacitor is not fully discharged.
2. When the EMI filter capacitor is fully discharged, VCC voltage does not have a drop point and this causes ZCD error.
3. When ZCD error happens, FL7701 changes to DC mode operation for the next 6 rectified line cycles LED string has a flicker due to current deviation.

In order to prevent ZCD error when FL7701 is used for analog dimming, HV connection point must change from the drain side to the input side via series connected diodes as shown in Figure 26.

![Figure 26. FLS0126 Application with Analog Dimming](image)

Minimum Dimming Range

Operating range of analog dimming pin is 0.5 V ~ 3.5 V. If a dc signal is not injected into the ADIM pin, this pin is internally pulled high to 3.5 V and the system operates at full brightness.

When voltage of ADIM pin is below 0.5 V, FL7701 operates with minimum turn on time which decides the minimum dimming current as shown in Figure 27.

![Figure 27. Example of Analog Dimming Curve](image)

Increasing System Reliability

To increase system reliability in noisy conditions, add a small capacitor with below 100 pF to the RT and ADIM pins. In normal conditions, these components are unnecessary.

PCB Layout Guidelines

The PCB layout is important because a common application would be to retrofit a lamp application, which requires a small product size. The IC could be affected by noise, so carefully follow the PCB layout guide lines:

- Locate the IC on the external powering path.
- Separate power GND and signal GND.
- VCC capacitor should be located close to the VCC pin.

![Figure 28. Example LED Layout](image)
Related Datasheets

**FL7701 - Smart LED Lamp Driver IC with PFC Function**

**FLS0116 - MOSFET Integrated Smart LED Lamp Driver IC with PFC Function**