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 25V to 450V, the FL7701 maintains a $15.5V_{DC}$ at the VCC pin. The FL7701 also has a UVLO block for stable operation. When the V_{CC} voltage reaches higher than V_{CCST+}, the UVLO block starts operation.hen the V_{CC} drops below the V_{CCST-}, IC operation stops.

Hysteresis is provided for stable operation of the IC when input the voltage is in noisy circumstances or unstable conditions. The FL7701 has a "smart" internal block for AC input condition. If an AC source with 50Hz or 60Hz 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.

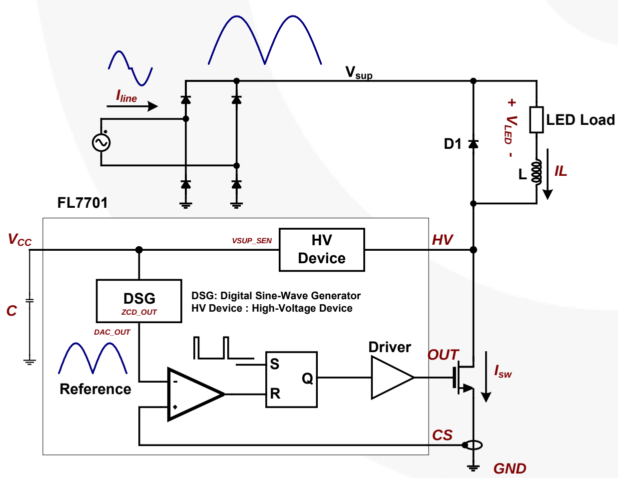


Figure 1. Basic Block of FL7701

The internal DAC_OUT reference signal is dependent on the V_{CC} voltage. Using the DAC_OUT signal and internal clock, CLK_GEN; the FL7701 automatically makes a digital reference signal, DAC_OUT. If the FL7701 cannot detect the ZCD_OUT signal, the IC has an abnormal internal reference signal. In this situation, this phenomenon causes a lighting flicker.

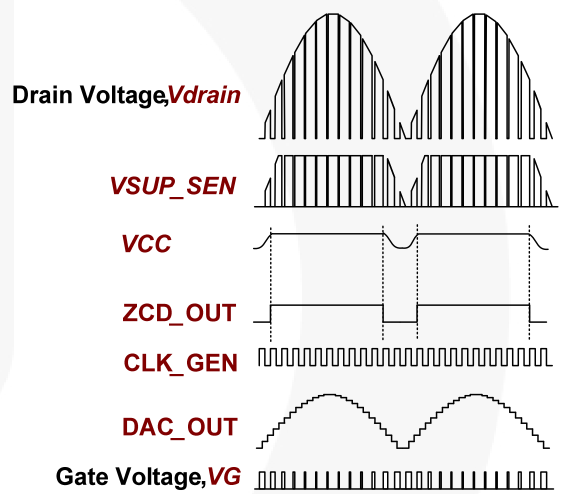


Figure 2. FL7701 Operation

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 settling down this transient period, the internal reference is fixed at a certain DC level. In this time, the IC continually tries to find input phase information from the VCC pin. If the IC succeeds in getting phase information from the VCC, the IC automatically follows a similar shape reference, which it made during the transient times, seven periods. If not, the IC has a DC reference level.

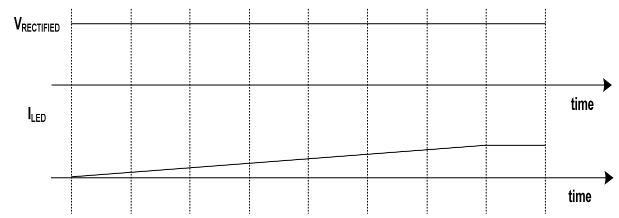


Figure 3. DC Input Condition

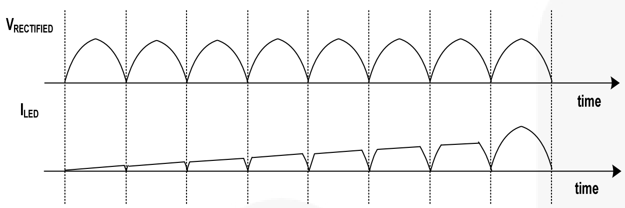


Figure 4. AC Input Condition

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.

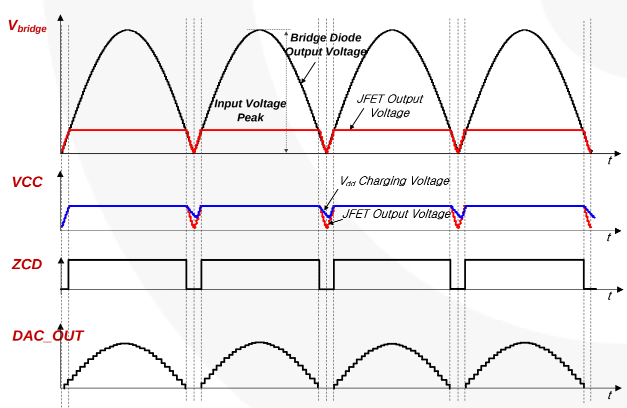


Figure 5. Internal PFC Function

The FL7701 detects the V_{CC} changing point for making the Zero Crossing Detection (ZCD) signal, which is an internal timing signal for making DAC_OUT. Normally, a capacitor connected to the VCC pin is used for voltage stabilization and acts as low-pass filter or noise-canceling filter. This increases the ability to get a stable timing signal at the VCC pin, even is 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.

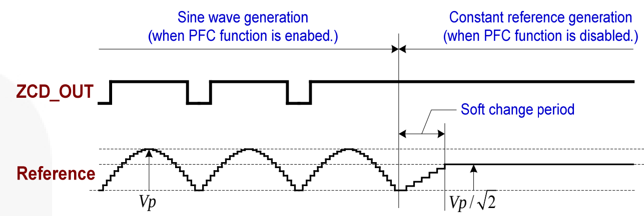


Figure 6. Internal Reference

This signal enters the final comparator and current information from the sensing resistor. Pin 1 is compared. As a result, the FL7701 has a high power factor and can operate as a normal peak current controller as shown in Figure 6, in the DC input condition. The relationship between AC Input Mode and DC Input Mode is $\sqrt{2}$.

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 45kHz when the RT pin is left open. For increasing system reliability, a small-value capacitor is recommended below 100nF in RT-open condition. The relationship between output frequency and the RT resistor is:

$$f_{OSC} = \frac{2.02\times 10^{9}}{RT}\ [\text{Hz}] \tag{1}$$

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 high-voltage process device. If the LED does not connect to the chip, the IC cannot start.

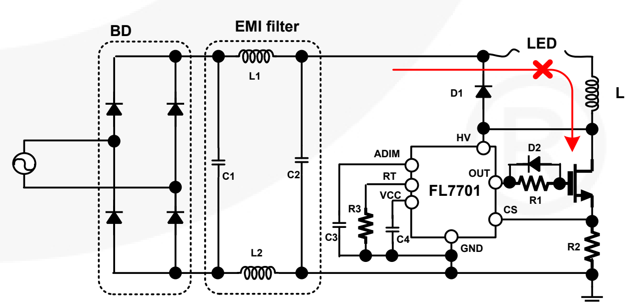


Figure 7. LED Open Condition

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 2.5V, even within Leading Edge-Blanking (LEB) time of 350ns; the IC stops operation.

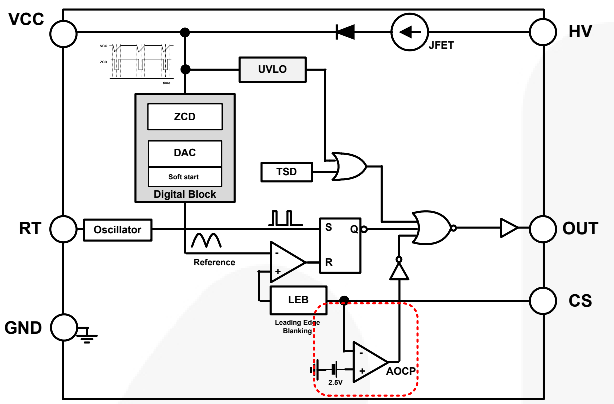


Figure 8. AOCP Function

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 305V_{AC} or 400V_{DC}.

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

Table 1. Target Design Specification

Item	Specification	Note
Frequency	45kHz	
Output Voltage	35	V_F=3.5V,
Output LED Current	0.3	rms
Output LED Current	0.5	Peak
Input Voltage (Max.)	220	$V_{AC(rms)}$

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.

$$D_{\min} = \frac{nV_F}{\eta \times V_{in(\max)}} \tag{2}$$

where η is efficiency of system; $V_{IN(max)}$ is maximum input voltage; V_F is forward-drop voltage of LED; and n is LED number in series connection.

For example, if $V_{IN(max)}$ = 220V and ten LEDs are in series connection, the minimum duty ratio is:

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

Step 2: Maximum Duty Ratio

Similar to Step 1, calculate maximum duty ratio as:

$$D_{\max} = \frac{nV_F}{\eta \times V_{in(\min)}} \tag{3}$$

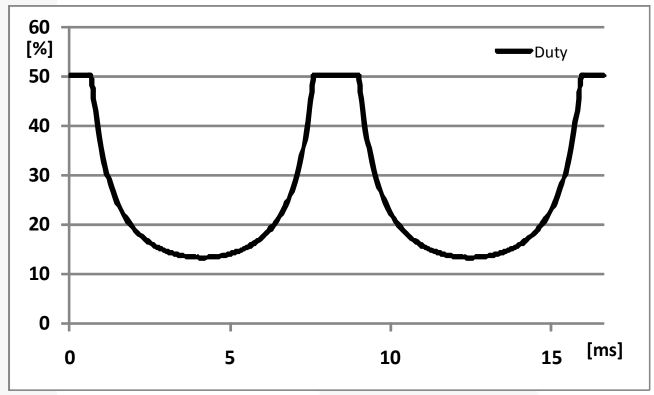


Figure 9. Duty Variation vs. Time

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:

$$V_{in(\min)} = \frac{nV_F}{\eta \times D} = \frac{35}{0.85 \times 0.5} = 82.35[V] \tag{4}$$

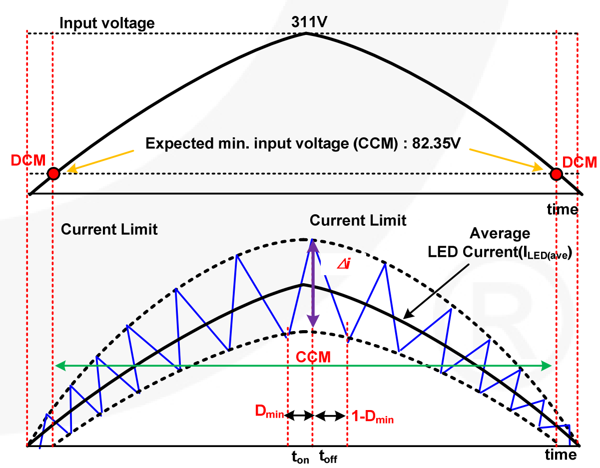


Figure 10. Estimated Waveforms

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. For example, the maximum on/off time at 45kHz operation condition is:

$$t_{on} = t_{off} = \frac{1}{2f_s} = \frac{1}{90000} = 11.11 \;[\mu s]$$

Step 4: Calculate the LED Current Ripple, ΔI

The Figure 11 shows the typical LED current waveforms of a FL7701 application. For more stable or linear LED current, operate in CCM.

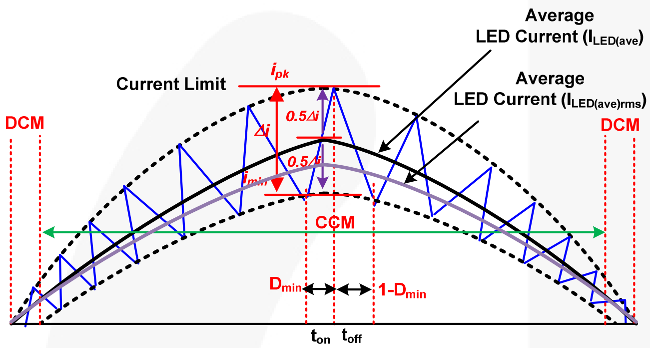


Figure 11. Target Waveforms of LED Current

Using the typical LED current waveform in Figure 11, derive the formula as:

$$I_{pk} = I_{LED(ave)} + \frac{\Delta I}{2} \quad \text{or} \quad I_{\min} = I_{LED(ave)} - \frac{\Delta I}{2} \tag{5}$$

The LED ripple current is defined as:

$$\Delta I = 2(I_{pk} - \sqrt{2} I_{LED(ave)}) \text{ or } \Delta I = 2(\sqrt{2} I_{LED(ave)} - I_{\min}) \tag{6}$$

where $I_{LED(AVE)}$ is equal to I_{LEDrms}.

From the Table 1, the target average LED current is defined as 0.3A and the LED peak current is set to 0.5A,. To calculate the LED current ripple:

$$\Delta I = 2(I_{pk} - \sqrt{2} I_{LED(ave)}) = 2(0.5 - 0.4242) = 0.1516 \,[\text{A}]$$

Step 5: Inductance

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

$$L = \frac{(V_{in(\max)} \times D_{\min})(1 - D_{\min})}{f_s \times \Delta I} \tag{7}$$

In Equation 10, the desired average LED current is always located between LED peak value, 500mA, 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:

$$L = \frac{(V_{IN(\max)} \times D_{\min})(1 - D_{\min})}{f_S \times \Delta I} = \frac{\sqrt{2} \times 220 \times 0.132 \times (1 - 0.132)}{45000 \times 0.1516} = 5.22 [mH]$$

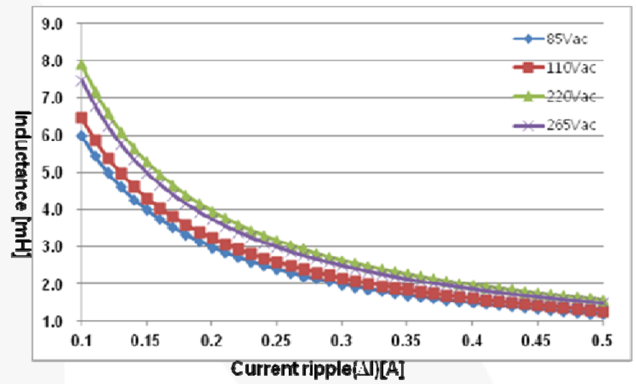


Figure 12. Current Ripple (ΔI) vs. Inductance

Therefore, the minimum current is 0.19A.

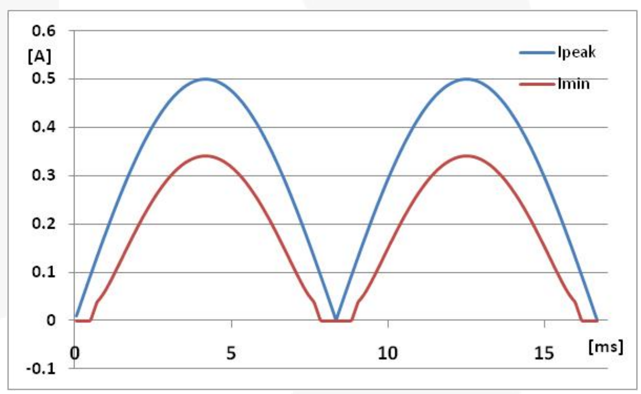


Figure 13. Expected Waveforms

As a result, assume the expected output and input power:

$$P_{LED} = V_{LED} \times I_{LED(ave)} = 10.15 \;[\text{W}]$$

$$P_{INPUT} = \frac{P_{LED}}{\eta} = 11.94 \,[\text{W}]$$

Step 6: Sensing Resistor

The FL7701 pulse-by-pulse current-limit of OSV protects the IC and the whole system. Calculate the sensing resistor value as:

$$R = \frac{0.5}{I_{pk}} = 1 \,[\Omega] \tag{8}$$

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

Step 7: Calculate Energy-Handing Capability (w-s):

$$Energy = \frac{LI_{pk}^2}{2} = \frac{(4.66\times10^{-3})(0.5^2)}{2} = 0.000583 \text{[w-s]} \tag{9}$$

Step 8: Calculate Electrical Conditions, K_e

For example, if 10eas, 1W LED for making 12.2W output power (V_F=3.5V, $I_{LED(rms)}$=0.35A), set up equation as:

$$K_e = 0.145 \times P_o \times B_m^2 \times 10^{-4}$$

$$= 0.145 \times 12.2 \times 0.4^2 \times 10^{-4} = 0.0000283$$

where P_o is target output power and B_m is operating flux density [T].

Step 9: Calculate Regulation Inductor α.

The regulation can be expressed as the power loss on the copper at inductor:

$$\alpha = \frac{P_{loss@copper}}{P_o} \times 100 \ [\%] \tag{10}$$

Assume the regulation, α, is assigned in Step 1 because system loss is strongly related to system efficiency.

$$P_{loss@copper} \le (1-\eta)P_{in} = \eta(1-\eta)P_o = 1.55 \ \text{[W]} \tag{11}$$

So, calculate the regulation as:

$$\alpha \le \frac{P_{loss@copper}}{P_O} \times 100 = \frac{1.55}{12.2} \times 100 = 12.7[\%] \tag{12}$$

In this design, 10% was used instead of 12.7% because there is another power consumption factor on this application, P_{FRD} or $P_{switching}$.

Step 10: Calculate Core Geometry, Kg

Calculate the core geometry:

$$K_g = \frac{(Energy)^2}{K_e\alpha} = \frac{0.000583^2}{0.0000283 \times 10} = 0.000012 \ [\text{cm}^5] \tag{13}$$

Step 11: Select a Core

Select a core comparable in core geometry Kg, using core information on the core maker's site *(see Table 2).*

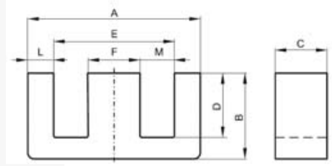
Table 2. Available Core Information

Part No.	MLT[cm]	Ac[cm²]	Wa[cm²]	Ap[cm⁴]	Kg[cm⁵]
EFD-10	1.82	0.0650	0.1163	0.007556	0.000108
EPC-40506	1.085	0.0410	0.0198	0.0008131	0.000123
EE-40904 (Mag)	1.664	0.036	0.064	0.002304	0.000020
EE0908S (Samhwa)		0.0253	0.0253	0.0027	
EE-41205 (Mag)		0.202	0.148	0.03	
EE1312S (Samhwa)		0.153	0.349	0.0253	

Notes:

1. Mag(magnetic): www.mag-inc.com
2. Samhwa: www.samwha.co.kr/electronics/

According to Table 2, select a core larger than EEFD-10 to overcome core saturation. Among core types, the EE core is the most popular because of its common shape and low cost. Select the EE core for this design.



(mm)	Nominal:	Tol. min.:	Tol. max.:
A	9.0	-0.4	+0.4
B	4.06	-0.25	+0.25
C	1.91	-0.13	+0.13
D	2.03 Min.		
E	4.85 Min.		
F	1.91	-0.13	+0.13
L	1.91	-0.25	+0.25
M	1.57	-0.25	+0.25
Eff. Parameters			
Ae mm²	Amin mm²	le mm	Ve mm³
5.0	3.6	15.6	78

Figure 14. Minimum Available Core Size (EE-40904(Mag))

Step 12: Calculate the Number of Turns, N

Select core turns if there is a well-known AL value estimated for certain turn conditions without gap condition:

$$N = \sqrt{\frac{L}{AL}} \ \text{[T] or } AL = \frac{L}{N^2} \tag{14}$$

To add a gap between cores to prevent core saturation, find a real AL-value using certain gap conditions. Select one of possible cores from Table 2; but it should have a larger Kg value than calculation results from Step 11. In this design step, EE1312S core was used because this part is available in the open market. Applying the EE1312S with gap made by three-layer insulation tape, 8.3μH measured when ten turns are winded the core. So, calculate a new AL-value with three-layer insulation tape as:

$$AL_{new} = \frac{L}{N^2} = 0.83 \times 10^{-6}$$

Using the new AL value, calculate the needed turns for the inductor:

$$N = \sqrt{\frac{L}{AL}} = \sqrt{\frac{4.66\times10^{-3}}{0.83\times10^{-6}}} = 74.92 \ \text{[T]}$$

In this design, 75T was used.

Step 13: Calculate the Current Density

Calculate the current density, J, using a window utilization k_U=0.4:

$$J = \frac{NI_{LED(AVE)rms}}{W_a K_u} = \frac{75 \times 0.29}{0.0253 \times 0.4} = 2149.20$$

Step 14: Calculate Required Bare Wire Area, $A_{W(B)}$:

$$A_{w(B)} = \frac{I_{LED(AVE)rms}}{J} = \frac{0.29}{2149.20} = 0.000134 \ [\text{cm}^2]$$

Step 15: Calculate Skin Depth, γ

The skin depth is the radius of the wire:

$$\gamma = \frac{6.62}{\sqrt{f_s}} = 0.031 \text{ [cm]}$$

Step 16: Calculate the Wire Area:

$$wire_A = \pi \times r^2 = 3.14 \times 0.031 = 0.0030 \text{ [cm2]}$$

Step 17: Select a Wire

Comparing Step 14 and Step 16 results. If the result of Step 17 is larger than the result of Step 14, need wire strands are not needed.

Step 18: Select Wire Size

Select the wire size with required area Table 3. AWG 35 with single wire in this case.

Table 3. Wire Table AWG

	Bare Wire Area [cm^2]	Heavy Insulation [cm^2]	Diameter [mm]
34	0.00002011	0.0002863	0.16
35	0.0001589	0.0002268	0.14
36	0.0001266	0.001813	0.127

Table 4. Design Results

Selected Core	EE1312S
Turns	75
Gap	3 Layers
Wire	AWG35/0.14mm

System Verification

Figure 15 shows the recommended circuit of a FL7701 system with just a few components.

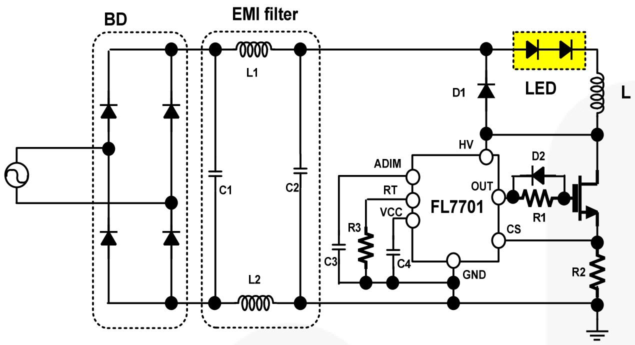


Figure 15. Test Circuit

Figure 16 and Figure 17 show the startup waveforms from a on FL7701 application in DC and AC input conditions at 220V with ten LEDs.

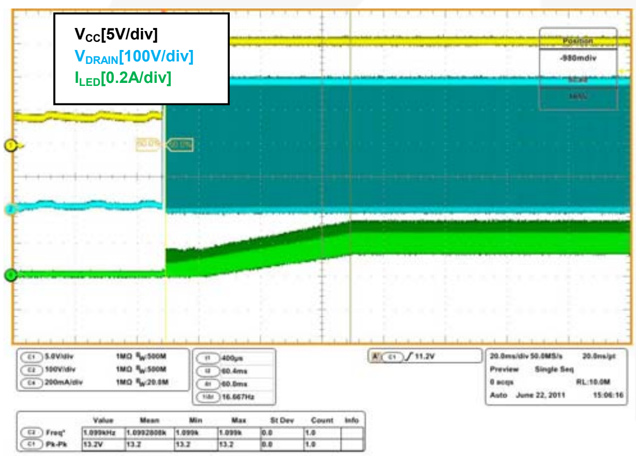


Figure 16. Soft-Start Performance in DC Input Condition

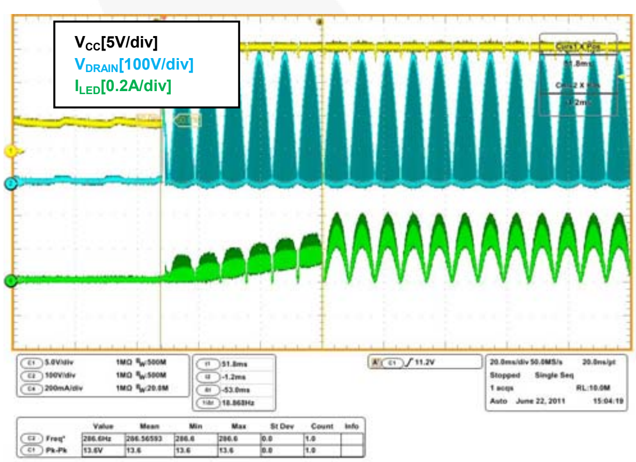


Figure 17. Soft-Start Performance in AC Input Condition

Figure 18 and Figure 19 show performance of FL7701 following the input source changes from high-line frequency, to lower frequency, then to higher frequency.

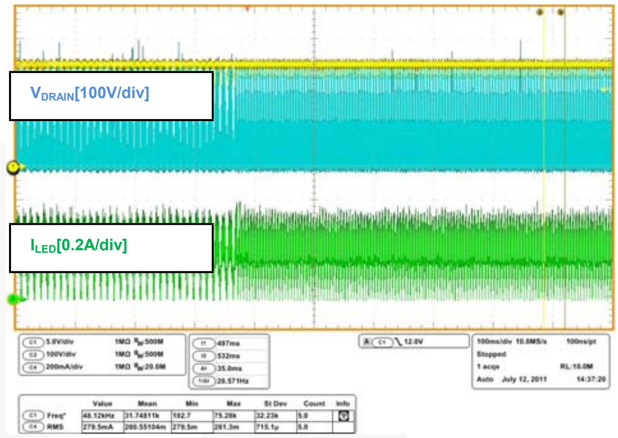


Figure 18. Input Source Changing: 45Hz to 100Hz

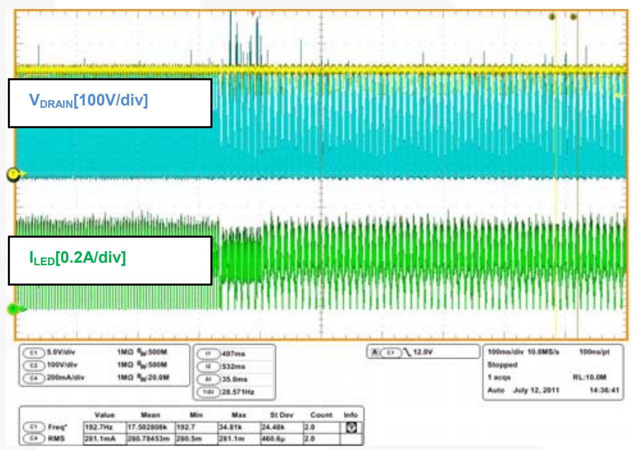


Figure 19. Input Source Changing: 100Hz to 45Hz

The Figure 20 shows the analog dimming performance with changing V_{ADIM}. The output LED current changes according to the control voltage.

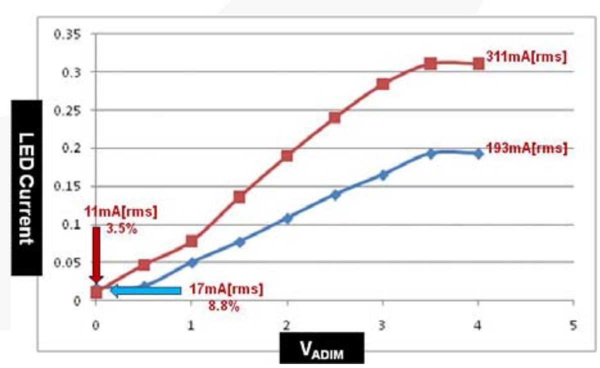


Figure 20. V_{ADMIN} vs. LED Current

Figure 21 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.

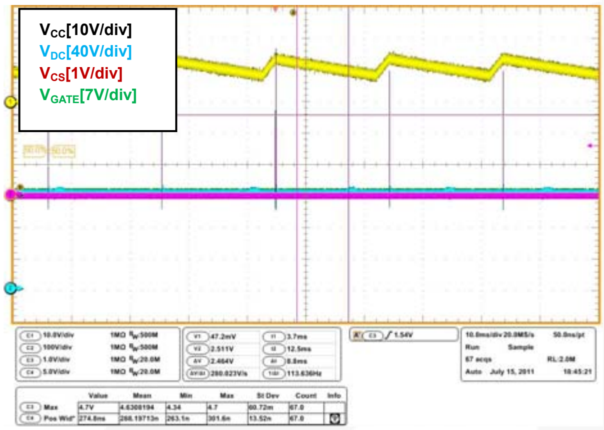


Figure 21. AOCP Function

Figure 22 shows the typical waveforms of FL7701 system. The LED current has the same phase as the input voltage source and rectified sinusoidal waveform.

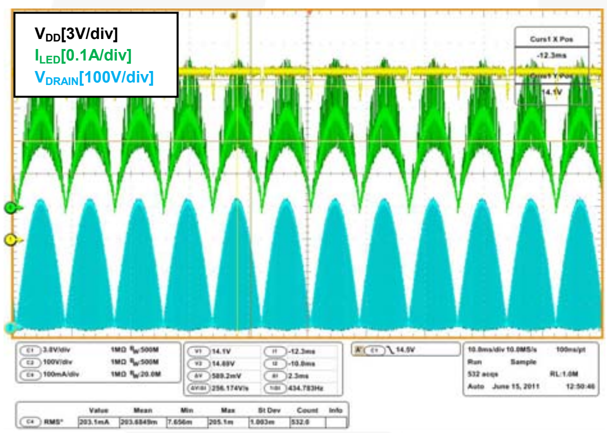


Figure 22. Typical Operating Waveforms

Design Tips

LED Current Changing

Figure 23 shows the recommended circuit for achieving high PF. In this condition, the LED current goes to 0 every half cycle period.

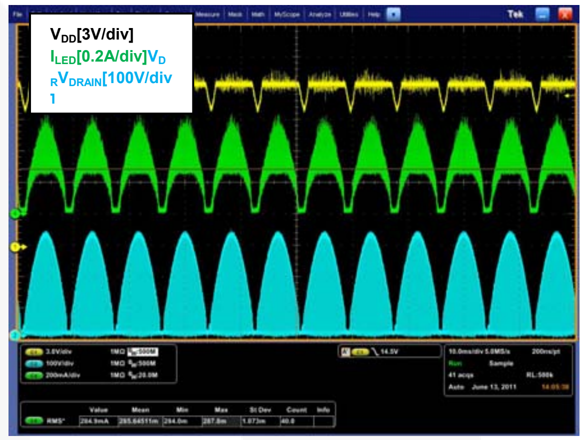


Figure 23. Typical Waveform

To design around this, add an electrolytic capacitor in parallel to the LED load, as shown in Figure 24. This added capacitor provides a truer DC LED current.

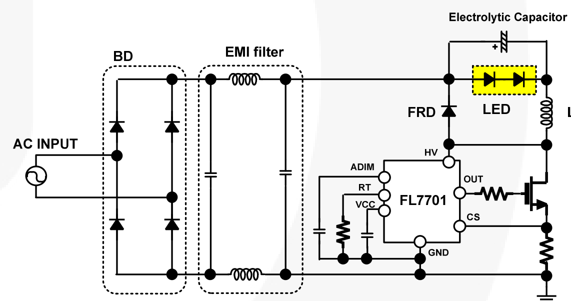


Figure 24. Circuit with Electrolytic Capacitor

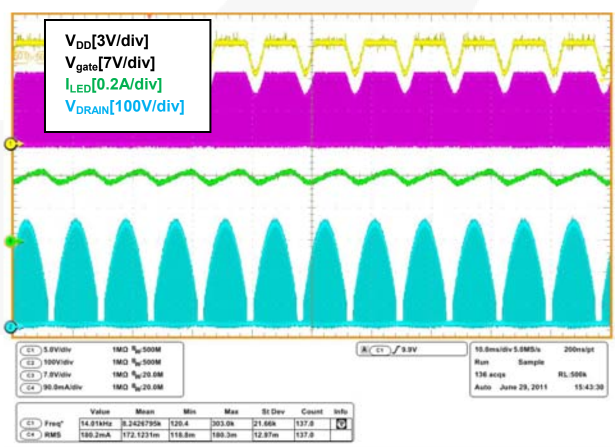


Figure 25. Typical with Bulk Capacitor

Increasing System Reliability

To increase system reliability in noisy conditions, add a small capacitor with below 100pF 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.
- V_{CC} capacitor should be located close to the VCC pin.

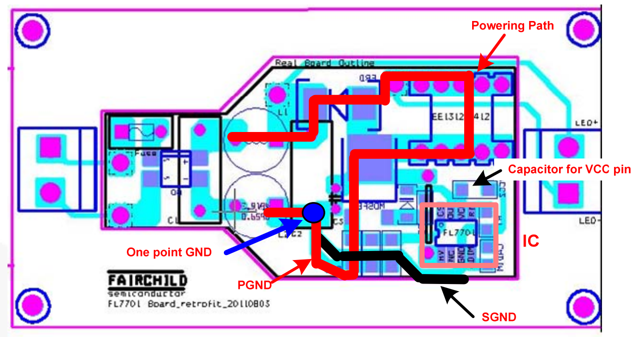


Figure 26. Example LED Layout

Related Datasheets

[*FL7701 — Smart LED Lamp Driver IC with PFC Function*]