AN-9737

Design Guideline for Single-Stage Flyback AC-DC Converter Using FL6961 for LED Lighting

Summary

This application note presents single-stage Power Factor Correction (PFC) and focuses on how to select and design the flyback transformer for 16.8W (24V/0.7A) solution for universal input for LED lighting applications using FL6961. The flyback converter using FL6961 operates in Critical Conduction Mode (CRM) and has functions such as CC/CV feedback circuit, soft-starting, and the cycle-by-cycle current limit for LED lighting applications.

Introduction

These days, engineers use various types of LEDs for general lighting systems because of their long life, excellent efficacy, price, environmental benefits, and requirements from end users. At the same time, high power factor (PF), isolation for safety, and constant current control (CC) for constant LED color are becoming requirements.

Conventional regulation is the minimum power factor correction for input power base above 25W, but many want to reduce power ratings and the new Energy-Star directive for solid-state lighting requires a power factor greater than 0.9 for commercial applications. Expect PF regulations to become more stringent.

Basic Operation: High Power Factor Flyback Converter

The basic idea of achieving high power factor (PF) flyback converter is to use a Critical Conduction Mode (CRM) PFC controller. The conventional PFC IC, such as FL6961, has constant on-time and variable off-time control method, which means the input average current always follows the input voltage shape.

Figure 1 shows the typical application schematic of single-stage PFC topology. The main difference of normal CRM boost converter is that single-stage PFC doesn't use a large electrolytic capacitor after the full rectification diode. Normally, the single-stage PFC method uses a small capacitor (C1 in Figure 1) to act as a noise filter to attenuate high-frequency components and doesn't use the INV pin for output voltage regulation.

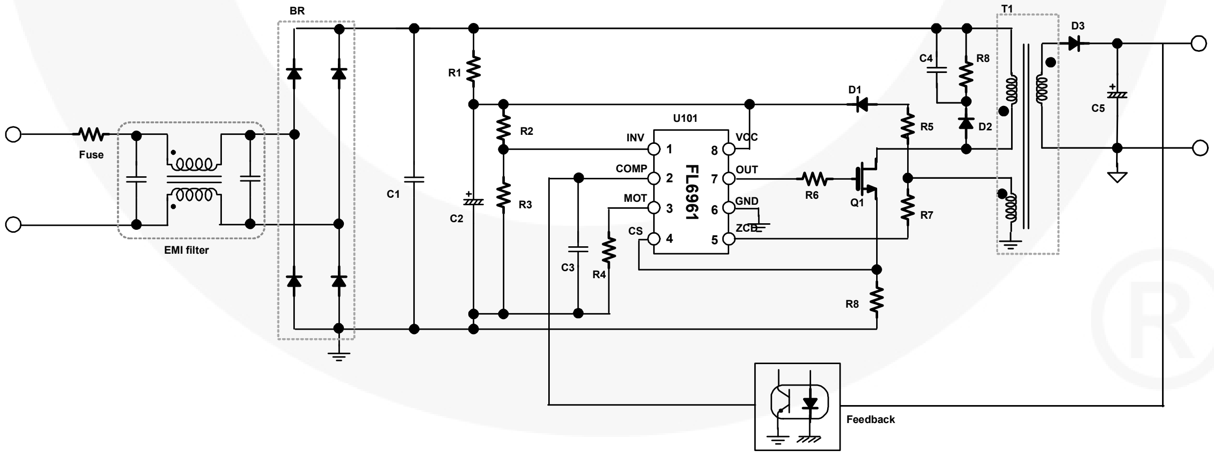


Figure 1. Simplified Schematic of High-Power Factor Flyback Converter with FLS6961

Figure 2 shows typical waveforms of the simplified circuit of a flyback converter with CRM. When the MOSFET (Q1) turns on, the primary current in primary side linearly increases and is clamped at a certain internal level because the FL6961 doesn't have cycle-by-cycle current limit like a conventional current mode control IC (such as FAN7527B). Its peak level is determined by the primary magnetizing inductance value and the fixed on-time. Instead of the cycle-by-cycle primary current limit, the FL6961 has an over-current protection (OCP) function. If the current sensing signal is larger than internal detection level, the FL6961 doesn't get output signal for operating the MOSFET (Q1).

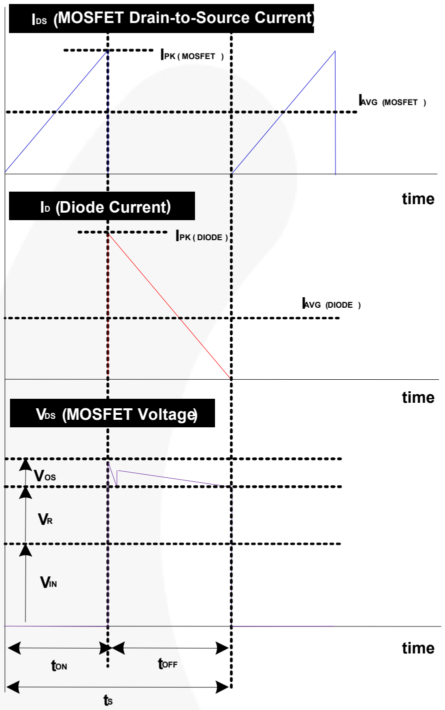


Figure 2. Key Waveforms of Flyback Converter on CRM

The FL6961 has a constant on-time across the whole range. The input average current always follows the peak input current, as shown in the equation:

$$I_{AVG(MOSFET)} = \frac{1}{2} I_{PK} t_{ON} \tag{1}$$

This is also proportional to the instantaneous input voltage. This means the input current shape is always the same as the input voltage shape. The reverse diode voltage is linearly increased and is equal to:

$$V_{PK(DIODE)} = V_O + V_{IN} \frac{N_S}{N_P} \tag{2}$$

During the MOSFET off-time, which is also the diode on-time; the input current instantly drops to zero, the diode in the secondary side conducts, and the diode current linearly decreases. The peak current of the secondary side is the same as the multiplication of the primary peak current and turns ratio between the primary side (N_P) and secondary side (N_S) and naturally decreases to zero. The average current of the secondary side is:

$$I_{AVG(DIODE)} = \frac{1}{2} \frac{N_P}{N_S} I_{PK} t_{off} \tag{3}$$

Since the diode forward-voltage drop decreases as current decreases, the output voltage reflects the primary winding and adds additional voltage due to overshoot made by resonance between the leakage inductance on primary-side winding and parasitic capacitance on the MOSFET (Q1). As a result, a superimposed voltage occurs on the MOSFET during off-time as:

$$V_{MOSFET(off)} = V_{IN} + V_R + V_{OS} \tag{4}$$

where V_R is the reflected voltage and V_{OS} is the voltage overshoot term.

The reflected voltage, V_R, is affected by the turns ratio between the primary and secondary side of the transformer and the output voltage, calculated as:

$$V_R = \frac{N_P}{N_S} V_O \tag{5}$$

Figure 3 shows the ideal waveforms of the primary-side current at MOSFET (Q1) and the secondary-side current at the diode. The input peak and average current on the primary side follows input voltage instantaneously. Normally, secondary-side current on the diode is larger than the primary side because of the turns ratio.

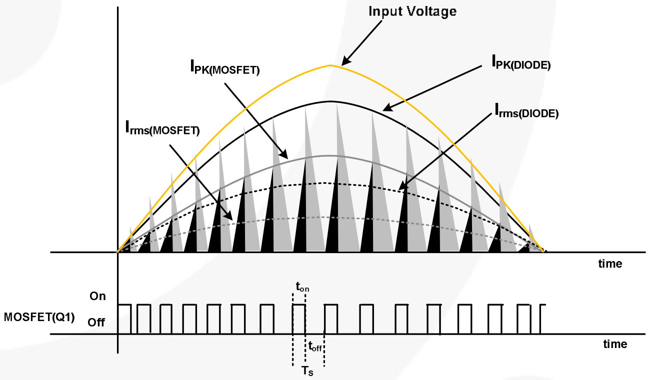


Figure 3. Ideal Waveforms

As a result, designers should consider two conditions before component selection: voltage and current capacity on primary-side MOSFET(Q1) and secondary-side diode (D3) to make a stable system with margin.

Figure 4 shows a guide to deciding two components on the boundary condition of flyback converter topology.

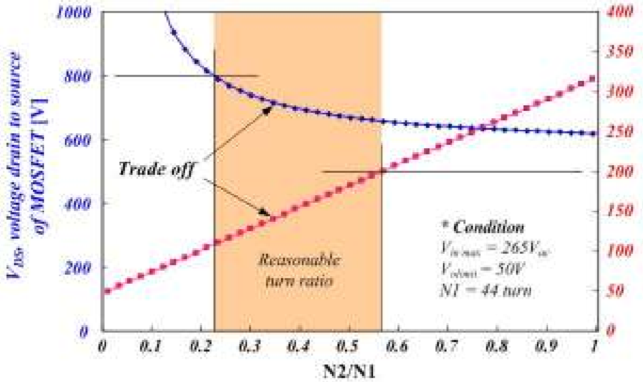


Figure 4. Boundary Conditions of Flyback Converter Topology (*Refer to AN-8025*)

Design Example

A. Transformer Design

A design guideline of 16.8W single-stage flyback AC-DC converter using FL6961 is presented. The applied system parameters are shown in Table 1.

Table 1. System Parameters

Parameter	Value
Main Input Voltage Range, $V_{AC(main)}$	90V~265V
Output Voltage, V_{OUT}	24V
Output Current, I_{OUT}	0.7A
Minimum Switching Frequency at $V_{AC(min)\_pk}$	50kHz
Diode Voltage Drop, V_d	1V
MOSFET On Resistance, R_{MOS}	1Ω
Window Utilization	0.4
Target System Efficiency	0.82
Maximum Duty at $V_{ac(min)\_pk}$	0.35
Operating Maximum Flux Density	0.35
Regulation, α	0.5%

Note:

1. Regulation is strongly related with the copper loss and 0.5% regulation means 0.084W loss on transformer.

There are many ways to decide core and coil size and turns, such as using AL value and following common practices. In this note, use the K_g value related with the core geometry to find optimum core and coil information.

Step 1. Calculate the total period, T:

$$T = \frac{1}{f} = 20 \ [\mu s]$$

Step 2. Calculate the maximum on-time at MOSFET in primary side.

$$t_{on} = TD_{\max} = (20 \times 10^{-6})(0.35) = 7 \ [\mu s]$$

Step 3. Calculate the output power:

$$P = I_o(V_o + V_d) = 0.7(24+1) = 17.5 \ [W]$$

Step 4. Calculate the maximum input current, I_{max}:

$$I_{in(\max)} = \frac{P_o}{V_{\min}\eta} = \frac{17.5}{(\sqrt{2} \times 90)(0.82)} = 0.168 \ [A]$$

Step 5. Calculate the MOSFET voltage drop, V_{vd}:

$$V_{vd} = I_{in(\max)} R_{MOS} = 0.168 \ [V]$$

Step 6. Calculate the primary voltage on transformer, V_p:

$$V_P = V_{\min} - V_{vd} = 127 - 0.168 \approx 127 \ [V]$$

V_p=126.83 use 127

Step 7. Calculate the primary peak current, I_{ppk}:

$$I_{ppk} = \frac{2TP}{\eta V_p t_{on(\max)}} = \frac{2(20 \times 10^{-6})(17.5)}{0.82(127)(7 \times 10^{-6})} = 0.96 \ [A]$$

Step 8. Calculate the primary rms current, I_{prms}:

$$I_{prms} = I_{ppk}\sqrt{\frac{t_{on}}{3T}} = 0.96\sqrt{\frac{(7 \times 10^{-6})}{3(20 \times 10^{-6})}} = 0.32 \ [A]$$

Step 9. Calculate the required minimum inductance, L:

$$L = \frac{V_p t_{on(\max)}}{I_{ppk}} = \frac{127(7 \times 10^{-6})}{0.96} = 0.926 \ [mH]$$

L=0.926[mH] use 1[mH]

Step 10. Calculate the energy-handing capability in watt-seconds, w-s:

$$ENG = \frac{LI_{ppk}^2}{2} = \frac{(1 \times 10^{-3})(0.96^2)}{2} = 0.0004608 \ [w\text{-}s]$$

Step11. Calculate the electrical conditions, K_e:

$$K_e = 0.145PB_m^2 \times 10^{-4} = 0.145(17.5)(0.35^2) \times 10^{-4} = 0.00003108$$

Step 12. Calculate the core geometry, K_g:

$$K_g = \frac{(ENG)^2}{K_e \alpha} = \frac{(0.0004608)^2}{0.00003108(0.5)} = 0.0136 \ [\text{cm}^5]$$

Step 13. *See Table 2 for core size.*

To prevent core saturation, select a little big core after comparing two K_g values: calculate value at Step 12 vs. the existing value in Table 2.

The PQ-42016 has a little bit big K_g value (0.01327) in Table 2 with 2500 permeability (μi).

Step 14. Calculate the current density, J.:

$$J = \frac{2(ENG)\times 10^4}{B_m A_P K_u} = \frac{2(0.0004608)\times 10^4}{0.35(0.2484)(0.4)} = 265 \ [\text{A/cm}^2]$$

Step 15. Calculate the required wire area. $A_{W(B)}$:

$$A_{W(B)} = \frac{I_{rms}}{J} = \frac{0.32}{265} = 0.001207 \quad [\text{cm}^2]$$

Step 16. Calculate the number of turns, N:

$$N = \frac{W_a K_u}{A_{w(B)}} = \frac{0.4283 \times 0.4}{0.001207} = 141.93 \ [\text{T}]$$

N=141.93; use 142 turns.

Step 17. Calculate the required gap, l_g:

$$l_g = \frac{0.4\pi(N)(\Delta I)\times 10^{-4}}{\Delta B_m} = \frac{0.4\pi(142)(0.96)\times 10^{-4}}{0.35} = 0.0489 \ [\text{cm}]$$

Step 18. Calculate the new turns using a gap from Step 15.

$$N = \sqrt{\frac{L(l_g + \frac{MPL}{\mu_i})}{0.4\pi(A_c)}} = \sqrt{\frac{1\times 10^{-3}(0.0489 + \frac{3.74}{2500})(10^8)}{0.4\pi(0.58)}} = 83.153 \ [\text{T}]$$

N=83.153; use 83[T].

where μ_i is permeability of selected core material and MPL is Magnetic Path Length of selected core.

Step 19. Calculate the fringing flux, F:

$$F = (1 + \frac{l_g}{\sqrt{A_c}} \ln \frac{2G}{l_g}) = (1 + \frac{0.0489}{\sqrt{0.58}} \ln \frac{2(1.001)}{0.0489}) = 1.238$$

where G is window height of selected core.

Step 20. Calculate the new turns, N_{new}:

$$N = \sqrt{\frac{l_g L}{(0.4\pi)(A_c)F(10^{-8})}} = \sqrt{\frac{0.0489 \times 1\times 10^5}{(0.4\pi)(0.58)(1.238)}} = 73.6 \ [\text{T}]$$

N_{new}=73.6; use 74.

Step 21. Calculate the AC flux density in Tesla, B_{AC}:

$$B_{ac} = \frac{(0.4\pi)N(\frac{I_{PK}}{2})F(10^{-4})}{l_g} = \frac{(0.4\pi)(74)(\frac{0.96}{2})(1.238)(10^{-4})}{0.0489} = 0.113 \ [\text{T}]$$

Step 22. Calculate the new wire size, $A_{W(B)}$:

$$A_{W(B)} = \frac{W_a K_u}{N_{new}} = \frac{0.4283 \times 0.4}{74} = 0.002315 \ [\text{A/cm}^2]$$

Step 23. Calculate the skin depth at expected operating frequency at low input voltage. The skin depth is the radius of the wire.

$$\gamma = \frac{6.62}{\sqrt{f}} = \frac{6.62}{\sqrt{50\times 10^3}} = 0.02960 \ [\text{cm}]$$

Step 24.Calculate the required wire area under considering skin depth :

$$Wire_A = \pi(r^2) = 0.0027535[\text{cm}^2]$$

Step 25. Select a wire size with the required area from Table 4. If the area is not within 10% of the required area, then go to the next smallest size.

AWG=#23

$A_{W(B)}$=0.00259[cm²]

μΩ/cm=666

Step 26. Calculate the required number of primary strands, S_{np}:

$$S_{np} = \frac{A_{w(B)}}{Wire_A} = \frac{0.002315}{0.00259} = 0.8938$$

This means that the selected wire from the Step 25, AWG23, is enough or has enough margins for supplying the primary-side current on the flyback converter.

Step 27. Calculate the secondary and auxiliary turns, N_s N_{aux}:

$$N_s = \frac{N_p(V_o + V_d)(1 - D_{\max})}{(V_p D_{\max})} = \frac{74(24+1)(1-0.35)}{(\sqrt{2}\times 90)(0.35)} = 27.05$$

N_s=27.05; use 27.

$$N_{aux} = \frac{N_p(V_o + V_d)(1 - D_{\max})}{(V_p D_{\max})} = \frac{74(15+1)(1-0.35)}{(\sqrt{2}\times 90)(0.35)} = 17.31$$

N_{aux}=17.31; use 17.

Step 28. Calculate the secondary peak current, I_{spk}:

$$I_{spk} = \frac{2I_o}{(1 - D_{\max})} = \frac{2(0.7)}{1 - 0.35} = 2.153 \ \textbf{[A]}$$

Step 29. Calculate the secondary rms current, I_{srms}:

$$I_{srms} = I_{spk}\sqrt{\frac{(1 - D_{\max})}{3}} = 2.153\sqrt{\frac{(1-0.35)}{3}} = 1.0021 \ [\text{A}]$$

Step 30. Calculate the secondary wire area, $A_{sw(B)}$:

$$A_{SW(B)} = \frac{I_{rms}}{J} = \frac{1.0021}{265} = 0.003781 \ [\text{cm}^2]$$

Step 31. Select a wire size with the required area from Table 4. If the area is not within 10% of the required area, go to the next smallest size.

AWG=#22

$A_{W(B)}$ =0.003243[cm2]

μΩ/cm=531.4

Step 32. Calculate the required number of primary strands, S_{np}:

$$S_{np} = \frac{A_{sw(B)}}{Wire_A} = \frac{0.003243}{0.00259} = 1.2521$$

This requires the AWG21 wire with two strands for secondary-side winding on the flyback converter.

Adapted Core Size		PQ-42614	AWG
Turns	Primary	74	23
	Secondary	27	22/ 2 Strands
	Auxiliary	17	
Estimated gap[mm]		0.489	

B. MOSFET and Diode Selection

Step 33. Calculate the maximum voltage of MOSFET drain voltage at primary side:

$$V_{MOSFET(off)} = V_{IN} + V_R + V_{OS} = V_{IN} + \frac{N_P}{N_S} V_O + V_{OS} = 490.54\,[\mathrm{V}]$$

where V_{OS} is assumed ~50V and its peak can degrade external snubber circuit performance. This means a 600V MOSFET can be used with some margin. Minimum requirements of the MOSFET are summarized below.

Current Rating [A]		Voltage Rating [V]	
Calculation	+20% Margin	Calculation	+20% Margin
0.96	1.152	490.54	588.65

Step 34. Calculate the maximum voltage of diode at secondary side:

$$V_{PK(DIODE)} = V_O + V_{IN}\frac{N_S}{N_P} = 24 + 265\sqrt{2}\,\frac{27}{74} = 160.74\,[\mathrm{V}]$$

This means a 200V diode can be used with some margin. The minimum requirement of the secondary diode as summarized below.

Current rating [A]		Voltage rating [V]	
Calculation	+20% Margin	Calculation	+20% Margin
2.153	2.584	160.74	192.88

C. Sensing Resistor

The CS pin of FL6961 has over-current protection (OCP) over the whole operating period and its internal clamping level, V_{LIMIT}, is 0.8V.

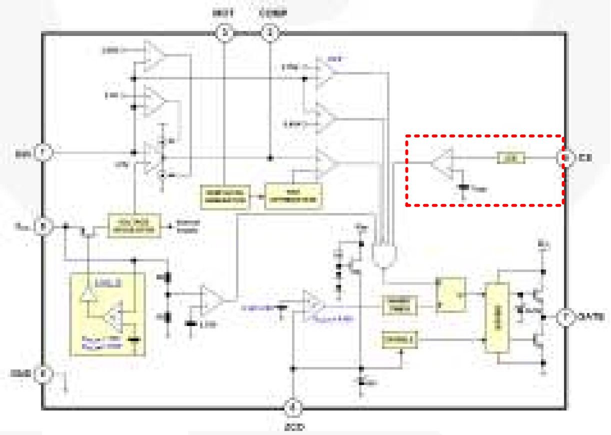


Figure 5. Switching Current Limit

Normally, it is reasonable to set the OCP level to 1.5 times higher than the peak current at primary side.

$$I_{LIMIT} = 1.5 I_{PPK} = \frac{3TP}{\eta V_p t_{on(\max)}} = 1.44$$

Calculate the sensing resistor as:

$$R_{sensing} \le \frac{0.8}{I_{LIMIT}} = 0.55\,[\Omega\,]$$

D. Voltage and Current Feedback for CC/CV Function

The constant voltage and current output is adapted by measuring the actual output voltage and current with external passive components and an op amp in the evaluation board. Because the output loads, the High Bright LED (HB LED) and passive components are effected by ambient temperature. Use the feedback path for stable operation.

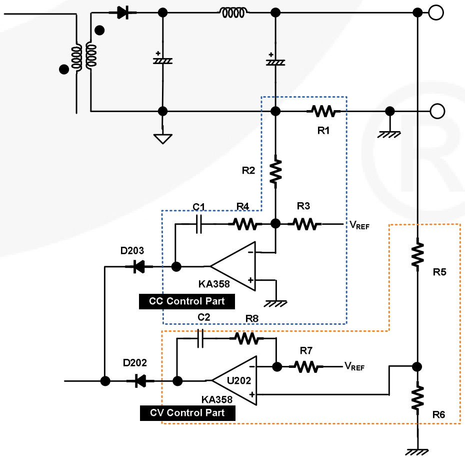


Figure 6. Feedback Circuit for CC/CV Operation

Normally, the CC block is dominate over the CV block in steady state and the CV block acts as the Over-Voltage Protection (OVP) at transient or abnormal mode, such as no-load condition.

The output signal of CC block is determined as:

$$V_{O\_cc} = R_4\left(\frac{V_{sensing\_CC}}{R_2} - \frac{V_{ref}}{R_3}\right) + \frac{1}{C_1}\int\left(\frac{V_{sensing\_CC}}{R_2} - \frac{V_{ref}}{R_3}\right)dt$$

where the $V_{sensing\_CC}$ means the sensing voltage from the sensing resistor (R1) and its values is as:

$$V_{sensing\_CC} = I_o \times R_1$$

The output signal of CV block is determined as:

$$V_{O\_CV} = \left(\frac{R_6}{R_5+R_6}\right)V_{sensing\_CV} + \frac{R_8}{R_7}\left[\left(\frac{R_6}{R_5+R_6}\right) V_{sensing\_CV} - V_{ref}\right] + \frac{1}{C_2}\frac{1}{R_7}\int\left(\frac{R_6}{R_5+R_6}V_{sensing\_CV} - V_{ref}\right)dt$$

where the $V_{sensing\_CV}$ means the output voltage on this circuit and this voltage is divided by two resistors, R5 and R6, and connected to non-inverted pin at the op amp.

Normally, set this divided voltage, $\left(\frac{R_6}{R_5+R_6}\right)V_{sensing\_CV}$, to V_{ref} or a little bit smaller value in steady state condition because the main role of this block is over-voltage protection. There are more high-voltage transfers to the output stage at transient or an abnormal case such as over-voltage output condition than in the steady state.

E. Soft-Start / Overshoot Prevention Function

Normally, the High Bright (HB) LED has a forward-current limitation to prevent the LED burn-out due to over-power dissipation. Thererfore, the output overshoot function is needed through the whole operating period. Though there are CC/CV blocks for output regulation, those blocks do not operate in transient modes, because they block have a long response time and cannot act instantly. Figure 7 shows the output voltage overshoot compression method using diode and resistor. The current flows through resistor, R9, and diode, D204, at startup, which is the period before activating the CC/CV block, and then decrease at steady state. The quantity of by-passing current goes into the feedback block on the control IC, FL6961, and controls the output power gradually.

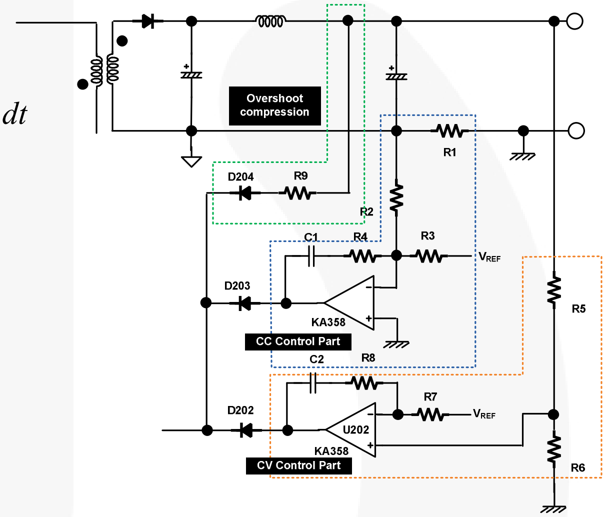


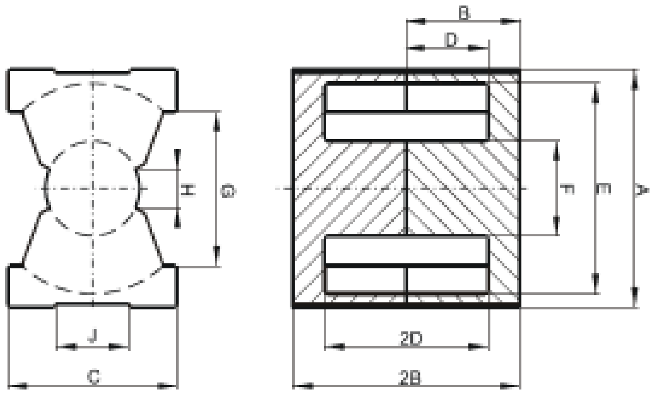
Figure 7. Soft-Start / Overshoot Prevention Method

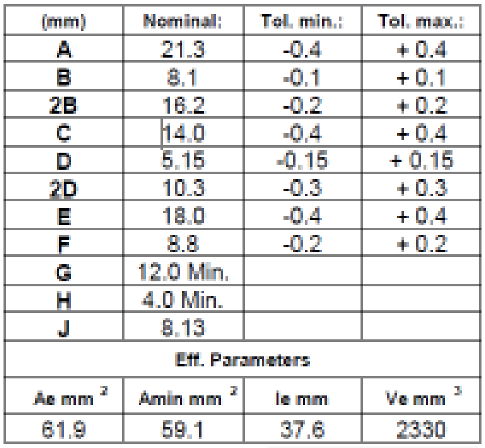
Table 2. Various Core Types and Size

Part #	MLT [cm]	MPL [cm]	G[cm]	A_C [cm]	W_a [cm^2]	A_p [cm^4]	K_g [cm^5]	Perm	AL	Manufacturer
RM-42316	4.17	3.80	1.074	0.640	0.454	0.2900	0.017820	2500	2200	Magnetics
PQ-42610	5.54	2.94	0.239	1.05	0.1177	0.1235	0.00937	2500	6310	Magnetics
PQ-42614	5.54	3.33	0.671	0.709	0.3304	0.2343	0.01200	2500	4585	Magnetics
PQ-42016	4.34	3.74	1.001	0.580	0.4283	0.2484	0.01327	2500	2930	Magnetics
EPC-25	4.930	5.92	1.800	0.4640	0.8235	0.3810	0.01438	2300	1560	Magnetics
EI-44008	7.77	5.19	0.356	0.9950	0.3613	0.3595	0.018416	2500	4103	Magnetics
EFD-25	4.78	5.69	1.86	0.5810	0.6789	0.3944	0.01917	1800	1800	Philips

Table 3. PQ-42016 Core Dimensions

(Magnetics: http://www.mag-inc.com/home/Advanced-Search-Results?pn=42016





(mm)	Nominal:	Tol. min.:	Tol. max.:
A	21.3	-0.4	+ 0.4
B	8.1	-0.1	+ 0.1
2B	16.2	-0.2	+ 0.2
C	14.0	-0.4	+ 0.4
D	5.15	-0.15	+ 0.15
2D	10.3	-0.3	+ 0.3
E	18.0	-0.4	+ 0.4
F	8.8	-0.2	+ 0.2
G	12.0 Min.		
H	4.0 Min.		
J	8.13		
Eff. Parameters			
Ae mm^2	Amin mm^2	le mm	Ve mm^3
61.9	59.1	37.6	2330

Table 4. Wire Table

AWG	Bare Wire Area		μΩ/cm	Heavy Insulation		
	Cm2	CIR-MIL		Cm2	Turns/cm	Turns/cm2
20	0.005188	1024.0	332.3	0.006065	11.37	98.93
21	0.004116	812.30	418.9	0.004837	12.75	124.0
22	0.003243	640.10	531.4	0.003857	14.25	155.5
23	0.002588	510.80	666.0	0.003135	15.82	191.3
24	0.002047	404.0	842.1	0.002514	17.63	238.6
25	0.001623	320.40	1062.0	0.002002	19.8	299.7
26	0.001280	252.80	1345.0	0.001603	22.12	374.2
27	0.001021	201.60	1687.6	0.001313	24.44	456.9
28	0.008048	158.80	2142.7	0.0010515	27.32	570.6
29	0.0006470	127.70	2664.3	0.0008548	30.27	701.9

Schematic

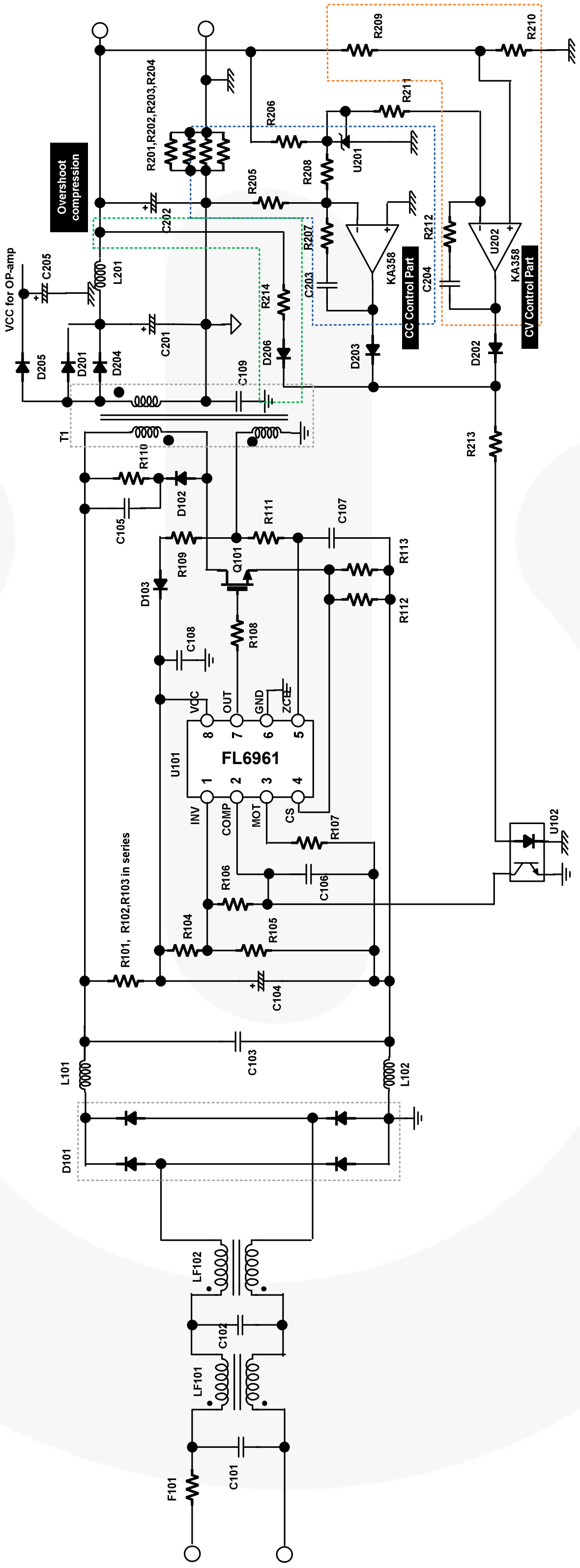


Figure 8. Schematic

Bill Of Materials

Item Number	Part Reference	Value	Quantity	Description (Manufacturer)
1	U101	FL6961	1	CRM PFC Controller (Fairchild Semiconductor)
2	U102	FOD817	1	Opto-Coupler (Fairchild Semiconductor)
3	U201	KA431	1	Shunt Regulator (Fairchild Semiconductor)
4	U202	KA358A(LM2904)	1	Dual Op Amp (Fairchild Semiconductor)
5	Q101	FQPF3N80C	1	800V/3A MOSFET (Fairchild Semiconductor)
6	D101	DF04	1	1.5A SMD Bridge-Diode (Fairchild Semiconductor)
7	D102	RS1M	1	1000V/1A Ultra-Fast Recovery Diode (Fairchild Semiconductor)
8	D103	RS1G	1	400V/1A Fast Recovery Diode (Fairchild Semiconductor)
9	D201,D204	EGP30D	2	200V/3A Ultra-Fast Recovery Diode (Fairchild Semiconductor)
10	D202,D203, D205,D206	LL4148	3	General-Purpose Diode (Fairchild Semiconductor)
11	R101,R102, R103	82KΩ	3	SMD Resistor1206
12	R104	120kΩ	1	SMD Resistor1206
13	R105	10KΩ	1	SMD Resistor1206
14	R106	20KΩ	1	SMD Resistor1206
15	R107	9.1kΩ	1	SMD Resistor1206
16	R108	47Ω	1	SMD Resistor 1206
17	R109	10Ω	1	SMD Resistor 1206
18	R110	220KΩ	1	2W
19	R111	30KΩ	1	SMD Resistor 1206
20	R112,R113	1Ω	2	SMD Resistor 1206
21	R201,R202, R203	1Ω	3	SMD Resistor 1206
22	R204	2.2Ω	1	SMD Resistor 0806
23	R205	4.3KΩ	1	SMD Resistor 0806
24	R206	1.5KΩ	1	SMD Resistor 0806
25	R207	30KΩ	1	SMD Resistor 0806
26	R208	51KΩ	1	SMD Resistor 0806
27	R209	33KΩ	1	SMD Resistor 0806
28	R210	3.9KΩ	1	SMD Resistor 0806
29	R211	120KΩ	1	SMD Resistor 0806
30	R212	47KΩ	1	SMD Resistor 0806
31	R213	4.7KΩ	1	SMD Resistor 0806
32	R214	47KΩ	1	SMD Resistor 0806

Bill Of Materials (Continued)

Item Number	Part Reference	Value	Quantity	Description (Manufacturer)
33	C101	100nF/250V	1	X – Capacitor
34	C102	47nF/250V	1	X – Capacitor
35	C103	100nF/630V	1	Film Capacitor
36	C104	33μF/35V	1	Electrolytic Capacitor
37	C105	2.2nF/1kV	1	Y-Capacitor
38	C106	2.2μF	1	SMD Capacitor 0805
39	C107	30pF	1	SMD Capacitor 0805
40	C108	100nF	1	SMD Capacitor 0805
41	C201,C202	470μF/35V	2	Electrolytic capacitor
42	C203	1μF	1	SMD Capacitor 0805
43	C204	470nF	1	SMD Capacitor 0805
44	C205	10μF/35V	1	Electrolytic Capacitor
45	LF101,LF102	80mH	2	Line Filter
46	L101	27μH	1	Line Filter
47	L102	6.8μH	1	Line Filter
48	L201	5μH	1	Output Inductor
49	F101	1A/250V	1	Fuse
50	T1	PQ-42016	1	1mH

Related Datasheets

FL6961 — Single-Stage Flyback and Boundary Mode PFC Controller for Lighting

AN-8025 — Design Guideline of Single-Stage Flyback AC-DC Converter Using FAN7530 for LED Lighting