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Boundary Mode Offline LED Driver Using MP4000

Application Note

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ABSTRACT

This application note explains the operation principle of a boundary mode offline LED driver and provides the detailed design procedure. The article is based on MP4000 which features true constant-current control, high efficiency and high reliability. The LED driver designed with MP4000 will be small magnetic size, low BOM cost and simple circuit design. Two design examples are presented: first one is lowest BOM cost design and the second one is the design with valley-fill PFC and the EMI filter.

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OPERATION PRINCIPLE OF BOUNDARY MODE OFFLINE LED DRIVER USING MP4000

Figure 1 shows a typical application circuit. The diode bridge rectifies the AC offline voltage to provide continues power. The Cin buffers the input energy and provide a bus voltage for the converter. A floating buck topology is used as the step down converter which is configured by MP4000, MOSFET S1, freewheeling diode D, inductor L and the output cap Cout. The MP4000 turns off the MOSFET S1 with a peak current control. The peak current is sensed by a resistor R_{sense} and feed back to CS pin. The peak current is regulated as:

$$I_{L\_PEAK} = \frac{V_{REF}}{R_{sense}} \cdot$$

In normal operation, MP4000 turns on S1 when the current in the freewheeling diode goes to zero. As a result, the average LED current is well regulated as:

$$I_{LED} = \frac{V_{REF}}{2 \cdot R_{sense}}$$

The zero-current detection is realized at the DRIVE pin by sensing the MOSFET drain dv/dt current through the S1's miller cap. When the freewheeling diode current goes to zero, S1 drain voltage (V_{SW}) drips from V_{supply} to to (V_{SUPPLY} -V_{OUT}) and starts oscillation, which is caused by the inductor and the parasitic caps. When V_{SW} reaches the minimum value, the dv/dt current through the miller cap changes from negative to zero. At this time, the MP4000 turns on S1. As a result, the MP4000 turns on S1 when the inductor current goes to zero and S1 drain voltage is at minimum. MP4000 controls the buck converter operating in current boundary conduction mode.

A cap Cout is normally used in parallel with the LED string to reduce the current ripple.

Such boundary operation mode can minimize the S1 turn-on loss and eliminate the freewheeling diode reverse recovery loss so that high switching frequency is possible to reduce passive components' size. Furthermore, the required inductance value is small, which can help further inductor size reduction.
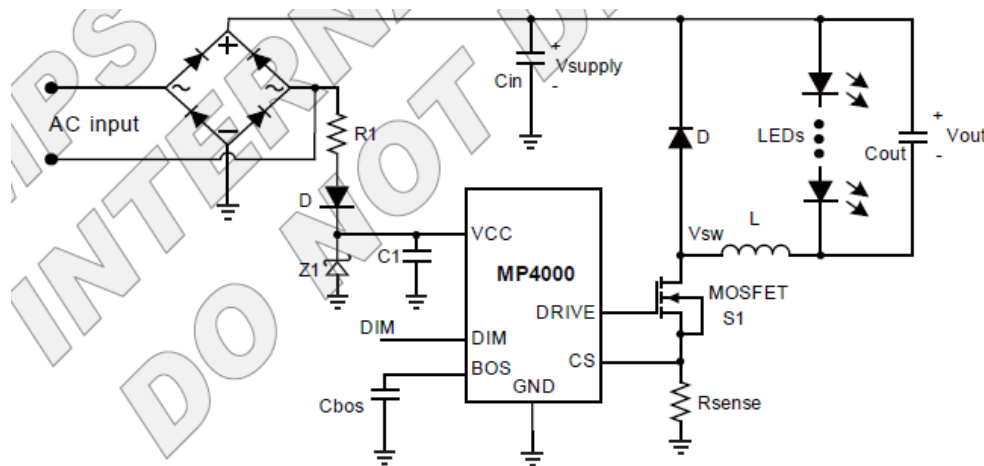

Figure 1—Boundary Mode Offline LED driver using MP4000

PIN FUNCTIONS OF MP4000:

MP4000 is a highly integrated driver IC design to minimize the external components counts and to simplify the external circuit design. It is available in SOIC8 package. The detailed pin functions are presented below.

1. Pin 1 (DRIVE)

This is the gate drive pin to drive the external MOSFET. Internally a totem pole output stage is used to provide 0.4A source current and 1.2A sink current. The high level voltage of this pin is 110mV below the VCC voltage tested with 10mA current. Since the VCC voltage is between 8V and 10.5V for normal operation, most high power MOSFET can be driven by MP4000. Directly connect this pin to the gate of the external MPSFET is recommended. Adding a driving resistor is also an option, which will slow down the driving speed and will provide better EMI performance.

2. Pin 2 (CS)

The CS pin is used to sense the rising edge of inductor current through the sensing resistor. The sensing resistor is in series with the external MOSFET. When the MOSFET is on, the inductor current generates the voltage potential on the resistor and is compared to an accurate reference which is 0.3V. When the sensed voltage is larger than the reference, MOSFET is turned off. Since the converter operates in boundary mode, the peak inductor current is two times of the LED current. By regulating the sensed voltage to 0.3V, the LED current is truly regulated.

A spike current is normally generated at the moment when the external MOSFET is turning on due to the parasitic capacitance discharging. In order to avoid the premature termination of the switching pulse by the current spike, a leading edge blanking (LEB) circuit is internally applied between the CS Pin and internal feedback. During the blanking time, the logic will not be reactive even a higher than reference signal is sensed. The blank time is set to be 110ns. Figure 2 shows the leading edge blanking concept.
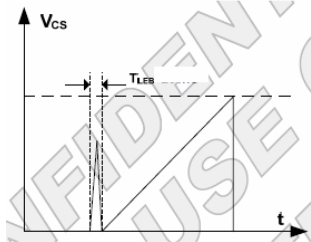

Figure 2— leading edge blanking concept used in MP4000

3. Pin 3 (BOS)

BOS is the pin to set the burst oscillator. For PWM input dimming control, the BOS pin is connected to GND through a 300kΩ resistor, setting about 1.2V reference voltage for the PWM input logic signal.

For the DC input dimming control, a cap is connected from BOS pin to the GND to program the burst frequency f_{DIM}:

$$C_{BOS} = \frac{i_{BOS}}{V_{BOSH} \cdot f_{DIM}}$$

For applications that do not need burst dimming control, open DIM pin and short BOS pin to GND.

4. Pin 4 (GND)

GND is the ground pin. All the voltage potential is reference to this pin.

5. Pin 5 (DIM)

In a typical DC-DC converter IC, the soft-start function is always needed to avoid inrush current during

6. Pin 6 (NC)

This pin is not internal connected.

7. Pin 7 (VCC)

The VCC pin provides the voltage bias to both internal logic circuit and the gate driver. The UVLO is 7.4V on the VCC and the ABS max is 11V. So an external circuit to provide 8V-10.5V VCC voltage is needed. The current needed for CVV depends on the switching frequency and the gate capacitance of the external MOSFET is used. 2mA is normally enough for most of cases.

8. Pin 8 (TST)

This pin is reversed for test. Connect this pin to GND in all applications.

DESIGN EXAMPLE 1:

This example is to provide a minimal BOM cost design for A-type LED bulbs.

Speciation:

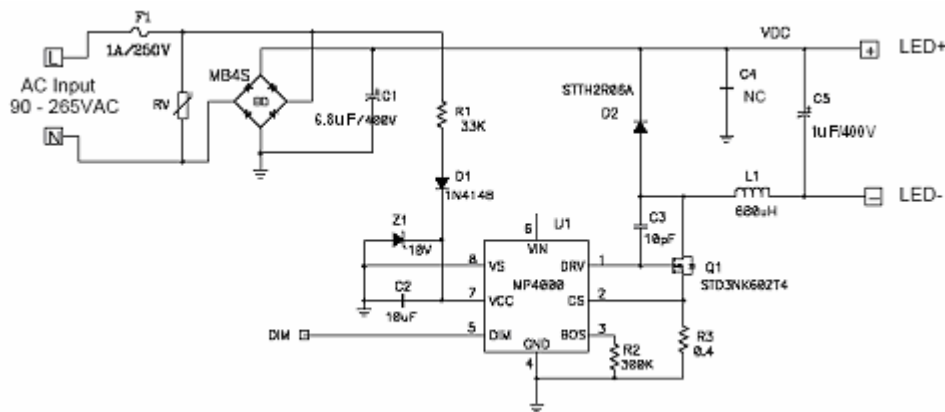| Parameter	Symbol	Value	Unit
Input voltage	VAC	90-265	V
Output voltage	V_O	10-25	V
Output current	I_O	350	mA

Schematic:

Figure 3—Schematic of design example 1

1. Choose the Input Diode Bridge (DB)

The voltage rating of the diode bridge depends on the maximum value of the input voltage. And a 50% safety margin is normally added. The current rating depends on the maximum average current drawn by the converter.

$$V_{DB} = 1.5 \cdot (\sqrt{2} \cdot V_{AC\max})$$

$$I_{DB} = \frac{V_O \cdot I_O}{V_{in\min} \cdot \eta}$$

In this design,

$$V_{DB} = 1.5 \cdot (\sqrt{2} \cdot 265) = 562$$

$$I_{DB} = \frac{25V \cdot 350mA}{90V \cdot 0.85} = 0.12$$

So a 600V/0.5A diode bridge is chosen for this design.

2. Choose the input capacitors

The design of the input capacitor is the trade off between the capacitor's size and the ripple voltage. Smaller capacitor is desired for lower BOM cost and to minimize the LED driver size. However, larger ripple will increase the loss on the capacitor and also decrease the capacitor's life time.

This design is for A-type bulb where the size and the cost are more important. So a smaller capacitance is used for the input filter.

$$C1 = \frac{V_O \cdot I_O}{(2 \cdot V_{in}^2 - V_{bus\_valley}^2) \cdot \eta \cdot f}$$

$$C1 = \frac{25V \cdot 350mA}{(2 \cdot 120^2 V - 50^2 V) \cdot 0.85 \cdot 60Hz} = 6.5uF$$

As the result, a 6.8u/400V capacitor is chosen for this design.

3. Frequency setting and Inductor design

The switching frequency determines the size of the inductor L1 therefore the size of the LED driver. A larger switching frequency will result in a smaller inductor, but will increase the switching losses in the converter. For off-line LED driver, the typical switching frequencies should be in the range of 20kHz to 100kHz. A maximum 110kHz switching frequency is set by the MP4000 to avoid the extreme losses in the circuit and ensure the better EMI performance. If the converter reaches the maximum frequency, it will operate in discontinuous current conduction mode. Such operation should be avoided since the LED current will be out of the regulation.

The inductance is calculated based on voltage-second balance:

$$L = \frac{1}{f_s \cdot 2 \cdot I_{LED}} \cdot \frac{(V_{bus} - V_O) \cdot V_O}{V_{bus}}$$

And the saturation current should be larger than:

$$I_{sat} = 2 \cdot I_{LED}$$

Choose 50kHz as the nominal switching frequency, and because the high line input is more like to exceed the max frequency limit, the inductance can be calculated as

$$L = \frac{1}{50kHz \cdot 2 \cdot 350mA} \cdot \frac{(220V - 25V) \cdot 25V}{220V} = 633uH$$

$$I_{sat} = 2 \cdot 350mA = 0.7A$$

As the result, a 680µH/1A inductor is chosen in this design.

Since this is a universal input design and also a small input capacitor is used as the input filer, the real frequency varies as the input voltage varies. To back test the inductor design, the inductance value can be filled into the equation and calculate the frequencies for different input voltages.

4. Choose the MOSFET and Diode

The peak voltage applied to the MOSFET is equal to maximum input voltage plus the voltage spikes. A 50% safety margin is added to determine the MOSFET's voltage rating.

$$V_{MOSFET} = 1.5 \cdot (\sqrt{2} \cdot V_{AC\max})$$

The peak current of the MOSFET is the peak current of the inductor, which can be calculated as

$$I_{MOSFET} = 2 \cdot I_{LED}$$

For this design:

$$V_{MOSFET} = 1.5 \cdot (\sqrt{2} \cdot 265) = 562V$$

$$I_{MOSFET} = 2 \cdot 350 \; mA = 0.7 \, A$$

The choice of R_{ON} is a trade off between the efficiency and the cost. Traditional offline floating buck has the reverse recovery issue, so the R_{ON} needs to be small enough to compensate the loss generated by the reverse recovery current. MP4000 based floating buck is running the boundary current mode where the reverse recovery is eliminated.

In this design a 600V, 3.6Ω MOSFET is chosen to achieve the 85% efficiency while to keep the cost of MOSFET to be low.

Since MP4000 solves the reverse recovery issue, normal fast recovery diode can be used to keep the cost low while not scarify the performance. The voltage and current rating should be similar as the MOSFET. In this design a 600V, 1A diode is used.

For some application that needs high dimming resolution, where the dimming off time would be smaller than the switching period, dimming ON signal will force the MOSFET to turn on even when the inductor currents not zero, ultra fast recovery diode is still recommended because the external dimming signal could force the converter running into the hard switching.

5. Choose the Sense Resistor

MP4000 is designed to simplify the LED driver design. So the LED current can be set very easy by sensing resistor.

$$R_{sense} = \frac{0.3}{2 \cdot I_{LED}}$$

In this design

$$R_{sense} = \frac{0.3}{2 \cdot 350mA} = 0.43\Omega$$

6. Design the bias circuit for VCC

The VCC needs to be biased between 8V and 10.5V and supply enough current to drive the external MOSFET. There are many circuits could be employed. Here we introduce a simple and efficiency circuit used in this design:
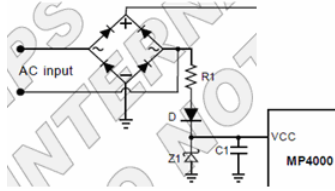
Figure 4—VCC bias circuit

R1 can be roughly calculated by

$$R1 \approx \frac{V_{AC\min}}{2 \cdot I_{cc}}$$

Icc is normally in the range of 1mA to 2mA depends on the MOSFET gate capacitance the switching frequency. In this design, Icc is around 1.35mA, so

$$R1 \approx \frac{90V}{2 \cdot 1.35mA} = 33k\Omega$$

7. Layout and final LED driver picture of the example 1

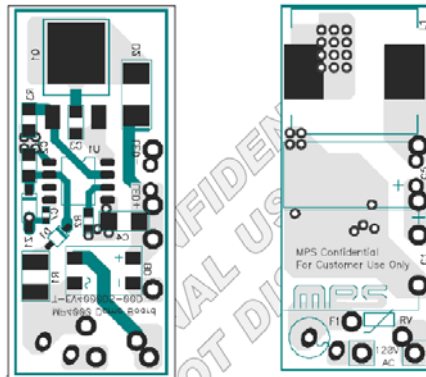Very compact LED driver can be made using MP4000. The example shows the final board has a dimension of 2.4"x1.2"x0.5" (L x W x H)
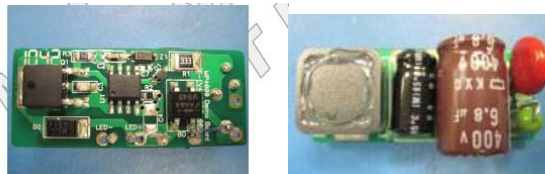

Figure 5—Layout of design example 1

Figure 6—board picture of design example 1

8. BOM of the example 1

With small inductor, 3.6Ω MOSFET, normal fast recovery diode and minimized external components, example 1 features low BOM cost.

Qty	RefDes	Value	Description	Package	Reference	Manufacturer P/N
1	C1	4.7uF	CAP., Alum., 4.7uF 400V	8.5x16	Panasonic	ECA-2EM220
1	C2	10uF	Ceramic Cap., 16V, X5R	0805	TDK	C2012X5R1C106M
1	C3	10pF	Ceramic Cap.,630V, X7R	0805	Johanson Dielectrics	C0805C100KBRACTU
1	C4	NC				
1	C5,	1uF	1uF Cap., 4000V, 10%	6.3x11.2	United Chemi-Con	EKMG401ELL1R0MF11D
1	D2	1A	400V 1A fast Diode	SMA	STMicroelectronics	STTH2R06A
1	D1	Diode	1N4148, 80V, 0.1A	SOD-523	Rohm Semi	1SS400TE61
1	BD	0.5A	Bridg Diode, SMD, 400V, 0.5A	SOIC-4	Fairchile Semi	MB4S
1	Z1	10V	Zener diode	SOD-123	Diode	DDZ9697-7
1	F1	1A	Fuse 1A/250V	Through Hold	LittlelFuse	0263002.MAT1L
1	L1	680uH	Inductor, 680uH/1.3A	12x12x10	WURTH Elektronik	744770968I
1	R1	33k	1/4W Res., 5%	Through Hold	Digikey	
1	R2,	300k	Film Res., 1%	0603	Digikey	
1	R3	0.4Ω	1/3W Film Res., 1%	0805	Cyntec	RLT1220-F-R400-FNH
1	R4	NS				
1	RV	ZNR	430V Transient Absorbers	Through Hold	Panasonic	P7257
1	Q1		N_C MOSFET 600V	D Pak	STMicroelectronics	STD3NK60ZT4
1	U1		DC-DC Converter	SOIC8	MPS	MP4000DS

Figure 7—BOM of design example 1

DESIGN EXAMPLE 2:

This example extends the design example 1 with valley-fill PFC and EMI filter for PAR38 LED bulbs. The design guidance for floating buck is same as the one discussed in example 1. This example will mainly focus on the valley-fill PFC design and EMI filter.

Speciation:

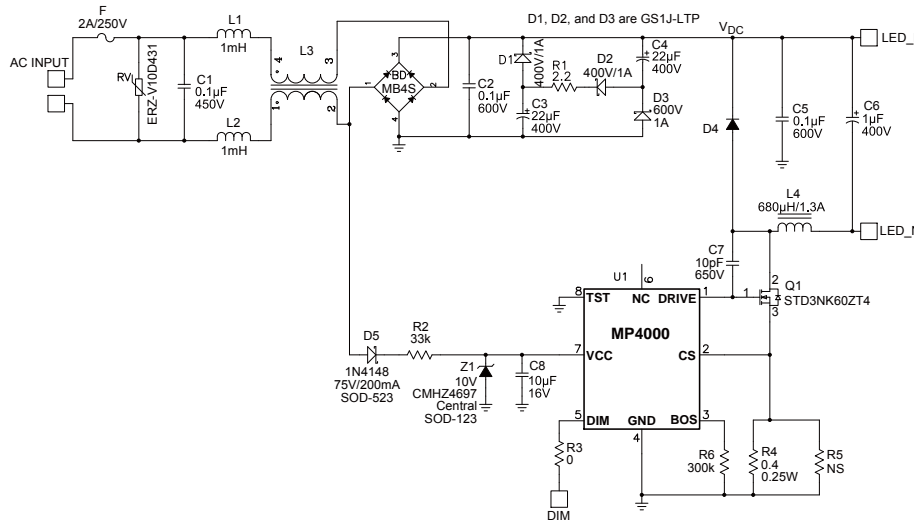| Parameter	Symbol	Value	Unit
Input voltage	VAC	90-265	V
Output voltage	V_O	10-40	V
Output current	I_O	350	mA
Power factor	PF	>0.7	
EMI		Meet EN55022	

Schematic:

Figure 8—Schematic of design example 2

1. Valley fill PFC principle and the design

If power factor >0.7 is required for the application. Valley-fill circuit is a simple choice to improve the power factor. The valley-fill circuit is shown in the Figure 9. When the input voltage is higher than the half of the peak voltage, power is delivered directly through the diode bridge. Meanwhile C4 and C3 is charged in series through D2 as shown in the equivalent circuit (Fig3).

The peak voltage of the valley-fill capacitor is:

$$V_{CAP} = 0.5 \cdot (\sqrt{2} \cdot V_{AC\,max})$$
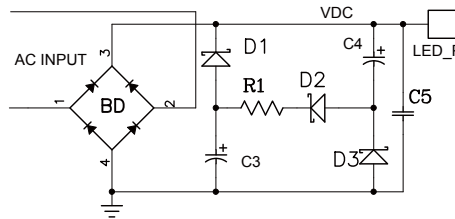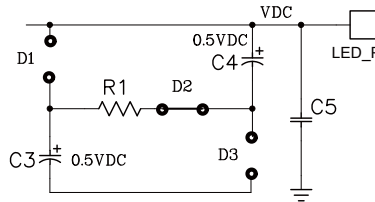

Figure 9—Valley fill PFC

Figure 10—equivalent circuit of valley fill- charging period

As the AC line decreases from its peak value every cycle, there will be a point where the voltage magnitude of the AC line is equal to the voltage that each capacitor is charged. At this point diode D5 becomes reversed biased, and the capacitors C4 and C3 are in parallel and are discharging by the load. The equivalent circuit is shown in figure 11.
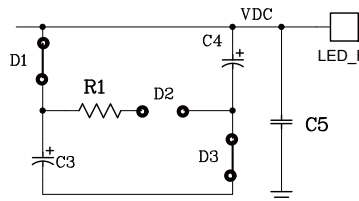

Figure 11—equivalent circuit of valley fill- discharging period

Through the valley-fill operation, the circuit extends the conduction angle thus improves the power factor. The resistor R1 is a current limit resistor. Figure 12 shows the result of the valley-fill PFC.
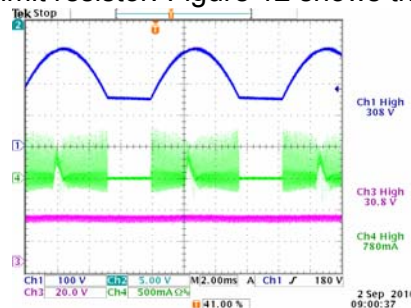

Figure 12— Valley fill waveforms

The design for the bulk cap is difference because the cap discharges only when the bus voltage drops to half of the peak bus voltage. C3 and C4 should be designed according to:

$$C3 = C4 > \frac{V_O \cdot I_O}{(\frac{1}{2} \cdot V_{in}^{\;2} - V_{bus\_valley}^{\;2}) \cdot \eta \cdot 6 \cdot f}$$

$$C3 = C4 = \frac{40V \cdot 350mA}{(\frac{1}{2} \cdot 120^2 V - 50^2 V) \cdot 0.85 \cdot 6 \cdot 60Hz} = 9.2uF$$

The capacitance decreases as the time goes. To extend the life of the system, redundant can be added. In this example the capacitance of the C3 and C4 is doubled as the calculation result. So 22uF/400V is chosen.

2. EMI filter design

Two EMI filter is recommended in this example:

In figure 13 C1, L1 and L2 composites the differential EMI filter and the L3 is common mode choke to reduce the common noise. The object of the design is to meet the EN55022 standard. The component values are chosen based on the bare noise that measured without the EMI filter. However, Step by step instruction will not be provide in this article.
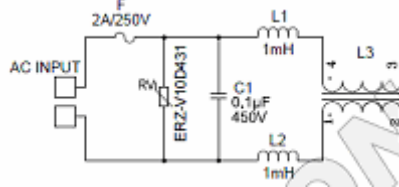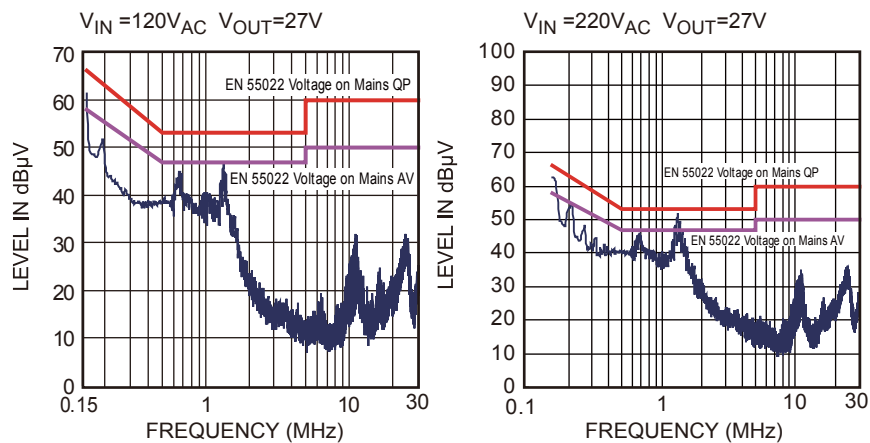

Figure 13— EMI filter design 1

Figure 13— EMI measurement with filter design 1

In figure 14 another EMI filter design is recommended. Two stage differential EMI filter is applied. The first stage is composed by C1, L1, R7, L2 and R8. The second stage is composed by C5 L3 and C2. Since the EN55022 standard regulates the total EMI noise, this design chose to knock down more differential noise as in the first design while leave the common mode EMI noise unfiltered. By doing this common choke which is a high cost component could be saved. Normally two stage EMI filter design needs to consider the impedance match between the filter output and the converter input. Otherwise, the converter may be unstable. The beauty of the MP4000 eliminated this consideration by use the boundary current mode control method. The design of the two stage EMI filter is much easier.
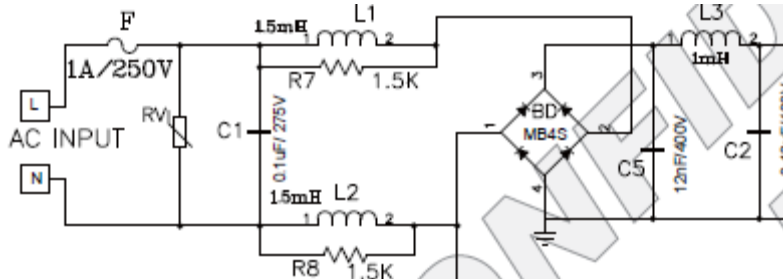

Figure 14— EMI filter design 2

3. Layout and final LED driver of the example 2

The design guide for the rest components is same as in the example 1. The layout shown in figure 15 is considered the size and shape that fits in the par38 lighting fixture.
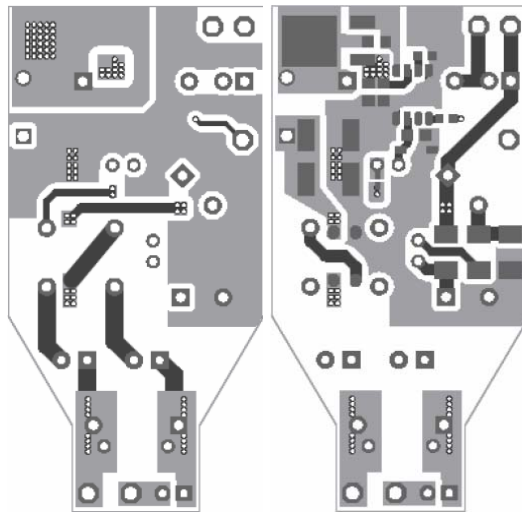

Figure 15— Layout of example 2

4. BOM of the example 2

Qty	RefDes	Value	Description	Package	Reference	Manufacturer P/N
1	C1	0.1µF	0.1µF 275VAC Cap	12.5x10x4	Mouser	BFC233912104
2	C2, C5	0.1µF	Ceramic Cap., 630V, 10%, X7R	1812	TDK	C4532X7R2J104K
2	C3, C4	22µF	CAP., Alum., 22µF 400V	12.5x20x5	Nichcon	UCA2G220MHD
1	C6,	1µF	1µF Cap., 400V, 10%	Through Hold	Digikey	ESMG401ELL1R0MF11D
1	C7	10pF	Ceramic Cap., 630V, X7R	0805	TDK	C0805C100KKBRACTU
1	C8	10µF	Ceramic Cap., 16V, X5R	0805	Vishay	0805YD106MAT
3	D1, D2, D3	1A	Diode, SMD, 400V, 1A	SMA	Digikey	S1G-FDICT-ND
1	D4	1A	600V 1A fast Diode	Through Hold	Digikey	STTH2R06
1	D5	Diode	1N4148, 75V, 0.2A	SOD-523	Central	CMZ5925B
1	BD	1A	Bridg Diode, SMD, 400V, 1A	SOIC-4	Digikey	MB4STR-ND
1	Z1	10V	Zener diode	SOD-123	Central	CMHZ4697
1	F1	2A	Fuse 2A/250V	Through Hold	Mouser	576-0263002
2	L1, L2	1mH	Inductor,	Through Hold	Mouser	580-22R105C
1	L3	10mH	Commen Chok,	Through Hold	Coilcraft	BU9H-103R25BL
1	L4	680µH	Inductor, 680uH/1.3A	7.2x8.2x10.5	Coilcraft	PCV2684-01L
1	R1	2.2Ω	1/2W Res., 1%	Through Hold	Digikey	
1	R2,	33k	1/4W Res., 5%	Through Hold	Digikey	
1	R3	0Ω	Film Res., 1%	0603	Digikey	
1	R6	300k	Film Res., 1%	0603	Digikey	
1	R4	0.4Ω	1/3W Film Res., 1%	0805	Cyntec	RLT1220-F-R400-FNH
1	RV	ZNR	430V Transient Absorbers	Through Hold	Digikey	ERZ-V10D431
1	R5		NS			
1	Q1		N_C MOSFET 600V	D Pak	Digikey	STD3NK60ZT4
1	U1		DC-DC Converter	SOIC8	MPS	MP4000DS

Figure 16— Layout of example 2