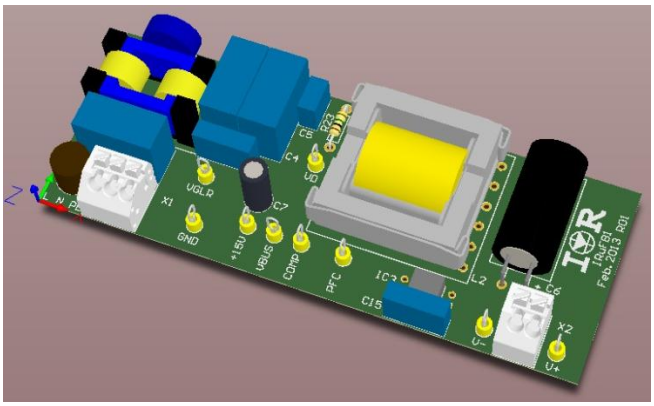
IRuFB1

40W Isolated Flyback PFC



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1. Introduction

The IRuFB1 40W Isolated Flyback PFC Reference Design is presented in this document. The circuit provides power factor correction (PFC), output voltage regulation and full protection against over-current/over-voltage conditions. Schematic, PCB drawings and BOM as well as a detailed design aid for dimensioning are included in this reference design. The circuit comprises a one-stage Flyback DC/DC converter operating in Critical Conduction Mode (CRM), controlled by the IRS2505 PFC control IC [1], ensuring high power efficiency, compact size, low cost and excellent power factor and THDI figures.

Safety Warning

The presented circuit operates from the AC line voltage. The maximum on-board DC voltage may be as high as 400V. However, the output provides galvanic isolation from the line voltage; an **electrical shock hazard** exists at any time when operating the circuit. The IRuFB1 demo circuit should be handled by qualified electrical engineers only! Note that the isolation of the flyback transformer has not been tested with high voltage, so it provides a functional isolation only.

Disclaimer

The IRuFB1 40W Isolated Flyback PFC reference design board is intended for evaluation purposes only and has not been submitted or approved by any external test house for conformance with UL or international safety or performance standards. International Rectifier does not guarantee that this design will conform to any such standards.

2. Specification

Parameter	*Description*	*Value*	*Units*
V_{OUT}	Nominal output voltage	50	[V]
$I_{OUT,MAX}$	Max. output current	800	[mA]
$P_{OUT,MAX}$	Max. output power	40	[W]
V_{IN}	Input voltage range	195 - 265	[VAC]
PF	Power factor	>0.97	[-]
THDI	Current THD	<10	[%]
η	Power efficiency	>90	[%]

Table 1: Specification

3. Circuit schematic

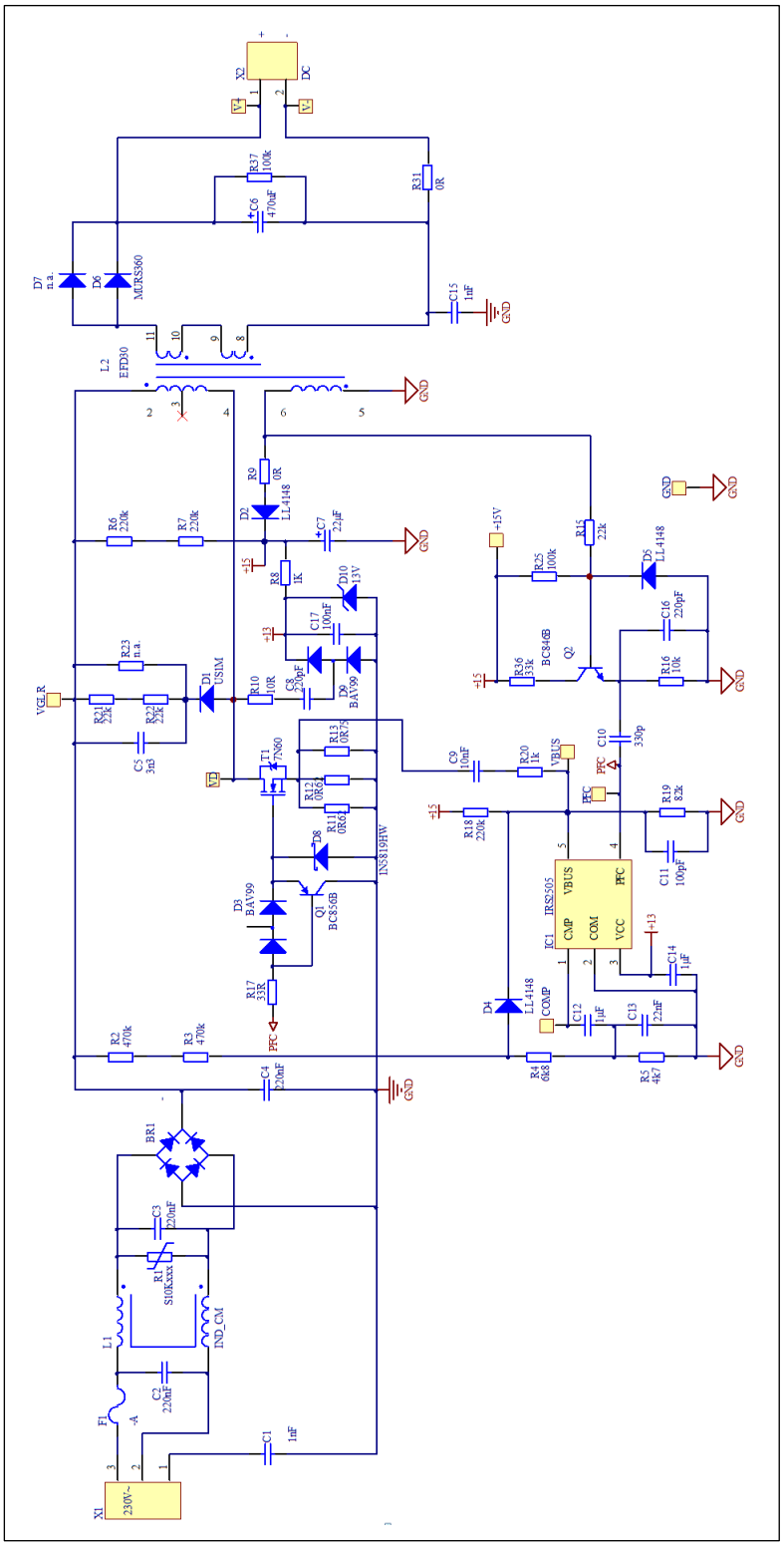


Figure 1: Circuit schematic

4. Dimensioning

4.1. Flyback inductor

Define the total output power for the Flyback:

$$P_{OUT,FLY} = P_{OUT} + P_{AUX} = 40W + 15V \cdot 0.1A \quad (1)$$

Where P_{AUX} belongs to the auxiliary supply. Now approximate the input power with the expected power efficiency:

$$P_{in} = \frac{P_{out}}{\eta} = \frac{40W}{0.9} = 46.1W \quad (2)$$

Define the desired duty cycle and the minimum switching frequency at the peak of the sinusoid line voltage ($\theta = 90°$):

$$D_{MAX} = 0.25 \quad (3)$$

$$f_{MIN} = 50kHz \quad (4)$$

The maximum on-time can be defined as:

$$T_{ON,MAX} = \frac{D_{MAX}}{f_{MIN}} = \frac{0.25}{50kHz} = 5\mu s \quad (5)$$

Calculate the maximum primary inductance:

$$L_{PRI} \le \frac{V_{IN,MIN}^2 T_{ON,MAX} D_{MAX}}{2P_{IN}} = \frac{195V^2 \cdot 5\mu s \cdot 0.25}{92.2W} = 516\mu H \quad (6)$$

Select a slightly smaller inductance:

$$L_{PRI} = 500\mu H \quad (7)$$

Determine the transformer turns ratio:

$$n = \frac{N_P}{N_S} = \frac{\sqrt{2} \cdot V_{IN,MIN}}{V_{OUT} + V_{FW}} \cdot \frac{D_{MAX}}{1 - D_{MAX}} = \frac{\sqrt{2} \cdot 195V}{50V + 1V} \cdot \frac{0.25}{1 - 0.25} = 1.8 \quad (8)$$

Where $V_{FW} = 1V$ is the forward voltage of the rectifier diode on the secondary.

Re-calculate the maximum on-time:

$$T_{ON,MAX} = \frac{2L_{PRI}P_{IN}}{V_{IN,MIN}^2 D_{MAX}} = \frac{2 \cdot 500\mu H \cdot 46.1W}{(195V)^2 \cdot 0.25} = 4.849\mu s \quad (9)$$

Check the maximum V_{DS} voltage of the flyback MOSFET. The maximum voltage reflected from the secondary (consider $V_{OUT,MAX} = 1.2 \cdot V_{OUT}$ in no-load condition):

$$V_{REFL,MAX} = n \cdot V_{OUT,MAX} = 1.8 \cdot 60V = 108V \quad (10)$$

The maximum drain-source voltage:

$$V_{DS,MAX} = \sqrt{2}V_{IN,MAX} + V_{REFL,MAX} + V_{PEAK} \quad (11)$$

Where: V_{PEAK} is the peak voltage of the ringing caused by the secondary leakage inductance and the parasitic capacitances, occurring at the beginning of the off-time. Note that V_{PEAK} has to be limited by the snubber circuit (C_5, R_{21}, R_{22}, R_{23}). By assuming $V_{PEAK} \approx 100V$ maximum peak voltage we get:

$$V_{DS,MAX} \approx \sqrt{2} \cdot 265V + 108V + 100V \approx 580V \quad (12)$$

So a MOSFET with 600V rating can be used at the given maximum line voltage, however, a MOSFET with higher breakdown voltage rating may improve the reliability of the circuit considering surge transients. The exact value of V_{PEAK} has to be verified by measurements and the snubber has to be optimized in order to limit that to an acceptable value.

Determine the primary peak current:

$$I_{PK,PRI} = \frac{\sqrt{2} \cdot V_{IN,MIN}}{L_{PRI}} T_{ON,MAX} = \frac{\sqrt{2} \cdot 195}{500\mu H} 4.849\mu s = 2.674A \quad (13)$$

Calculate the minimum number of turns for the primary:

$$N_{PRI} \geq \frac{L_{PRI} \cdot \Delta I_{MAX}}{A_e \cdot \Delta B_{MAX}} \quad (14)$$

Where: $\Delta I_{MAX} = I_{PK,PRI}$ is the peak magnetizing current, ΔB_{MAX} is the maximum flux density and A_e is the effective core area. Now select a core: EPCOS EFD 30/15/9

$$A_e = 69mm^2 \quad (15)$$

$$A_L = 2050nH \text{ (N87)} \quad (16)$$

So the minimum number of turns:

$$N_{PRI} \geq \frac{L_{PRI} \cdot \Delta I_{MAX}}{A_e \cdot \Delta B_{MAX}} = \frac{500\mu H \cdot 2.674A}{69mm^2 \cdot 0.35T} = 55.36 \quad (17)$$

Select a bit higher value (preferably, select a multiple of 2 in order to split the primary in two equal parts later):

$$N_{PRI} = 60 \quad (18)$$

For the secondary we get:

$$N_{SEC} = \frac{N_{PRI}}{n} = \frac{60}{1.8} \cong 33 \quad (19)$$

Determine the effective current through the primary (note: worst-case at D_{MAX}):

$$I_{RMS,PRI,MAX} = I_{PK,PRI}\sqrt{\frac{D_{MAX}}{3}} = 2.674A \cdot \sqrt{\frac{0.25}{3}} = 0.772A \quad (20)$$

Since this effective current is a worst-case value at D_{MAX} ($\theta = 90°$), we can give a rough estimation of the effective current over the line period with $0.5 \cdot I_{RMS,PRI,MAX}$. Calculate primary copper wire cross-section with $J_{MAX} = 6A/mm^2$ maximum current density:

$$A_{COPPER,PRI} \geq \frac{0.5 \cdot I_{RMS,PRI,MAX}}{J_{MAX}} = \frac{0.5 \cdot 0.772A}{6A/mm^2} = 0.064mm^2 \quad (21)$$

Use a multi-strand wire with $d = 0.1mm$ diameter. The copper cross section of 1 wire:

$$A_{WIRE} = \frac{d^2\pi}{4} = \frac{(0.1mm)^2\pi}{4} = 7.85 \cdot 10^{-3} mm^2 \quad (22)$$

Number of strands necessary:

$$S_{PRI} = \frac{A_{COPPER,PRI}}{A_{WIRE}} = \frac{0.064mm^2}{7.85 \cdot 10^{-3} mm^2} = 8.15 \approx 8 \quad (23)$$

Therefore, a $8x0.1mm$ multi-strand can be used for the primary winding.

The peak secondary current (note: worst-case at D_{MAX}):

$$I_{PK,SEC} = 2 \cdot \frac{2I_{OUT}}{1 - D_{MAX}} = 2 \cdot \frac{2 \cdot 0.8A}{1 - 0.25} = 4.267A \quad (24)$$

Determine the maximum effective current through the secondary (note: worst-case at D_{MAX}):

$$I_{RMS,SEC,MAX} = I_{PK,SEC} \sqrt{\frac{1 - D_{MAX}}{3}} = 4.267A \cdot \sqrt{\frac{1 - 0.25}{3}} = 2.134A \quad (25)$$

Calculate secondary copper wire cross-section with $J_{MAX} = 6A/mm^2$ maximum current density:

$$A_{COPPER,SEC} \geq \frac{0.5 \cdot I_{RMS,SEC,MAX}}{J_{MAX}} = \frac{0.5 \cdot 2.134A}{6A/mm^2} = 0.178mm^2 \quad (26)$$

Use a multi-strand wire with $d = 0.1mm$ diameter. The copper cross section of 1 wire as described in (22). Number of strands necessary for the secondary:

$$S_{SEC} = \frac{A_{COPPER,SEC}}{A_{WIRE}} = \frac{0.178mm^2}{7.85 \cdot 10^{-3} mm^2} = 22.67 \quad (27)$$

Therefore, a $25...30x0.1mm$ multi-strand wire can be used for the secondary winding.

The window area of the selected core is relatively small, so it may be necessary to reduce the number of wires in the primary and/or in the secondary multi-strands. A ~10% reduction of the strand number is in most cases still acceptable. Consider copper losses carefully.

Calculate the number of turns for the auxiliary winding so that it provides ~15V at the nominal output voltage:

$$N_{AUX} = N_{SEC}\frac{V_{AUX}+V_{FW}}{V_{OUT,MIN}+V_{FW}} = 33\cdot\frac{15+1}{50+1} = 10.3 \cong 10 \quad (28)$$

4.2. PFC over-current limit

Define a current limit margin as follows:

$$CLM = 10\% \quad (29)$$

The primary shunt resistor required for the overcurrent detection:

$$R_{SH,PRI} = \frac{V_{BUSOC+}}{(1+CLM)\cdot I_{EQ}}\frac{R_{14}\|R_{19}+R_1}{R_{14}\|R_{19}} \cong \frac{V_{BUSOC+}}{(1+CLM)\cdot I_{EQ}} \quad (30)$$

Where: $V_{BUSOC+} = 0.56V$ [1] and I_{EQ} is the equivalent sensed current (due to current sense DC decoupling):

$$I_{EQ} = I_{PK,PRI} - I_{SH,AV} = I_{PK,PRI}\left(1-\frac{D_{MAX}}{2}\right) = 2.674\cdot\left(1-\frac{0.25}{2}\right) = 2.34A \quad (31)$$

With the component values given in *Figure 1* we get:

$$R_{SH,PRI} = \frac{0.56V}{1.1\cdot 2.34A} = 0.22\Omega \quad (32)$$

Set shunt resistors so that $R_{SH,PRI} = R_{31}\|R_{32}\|R_{33}$:

$$R_{11} = R_{12} = 0.62\Omega \quad (33)$$

$$R_{13} = 0.75\Omega$$

4.3. Output voltage regulation

Now set the nominal output voltage by setting the R_{18}/R_{19} voltage divider fed from the auxiliary voltage. The resulting feedback voltage is:

$$V_{BUS} = V_{AUX} \frac{R_{19}}{R_{19} + R_{18}} \tag{34}$$

In steady-state, $V_{BUS} = V_{BUSREG} = 4.1V$ as per datasheet [1]. Now set the R_{18} resistor as follows:

$$R_{18} = R_{19}\left(\frac{V_{AUX} - V_{BUS}}{V_{BUS}}\right) = 82k\Omega \cdot \left(\frac{15V - 4.1V}{4.1V}\right) \cong 220k\Omega \tag{35}$$

5. Measurement Results

5.1. Switching waveforms

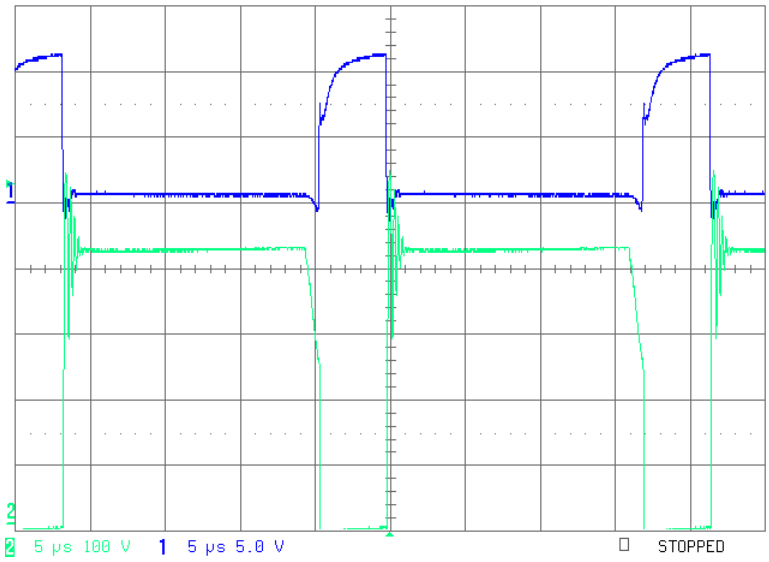


Figure 2: PFC gate drive and drain voltage (CH1: PFC, CH2: VD, steady-state, at line peak)

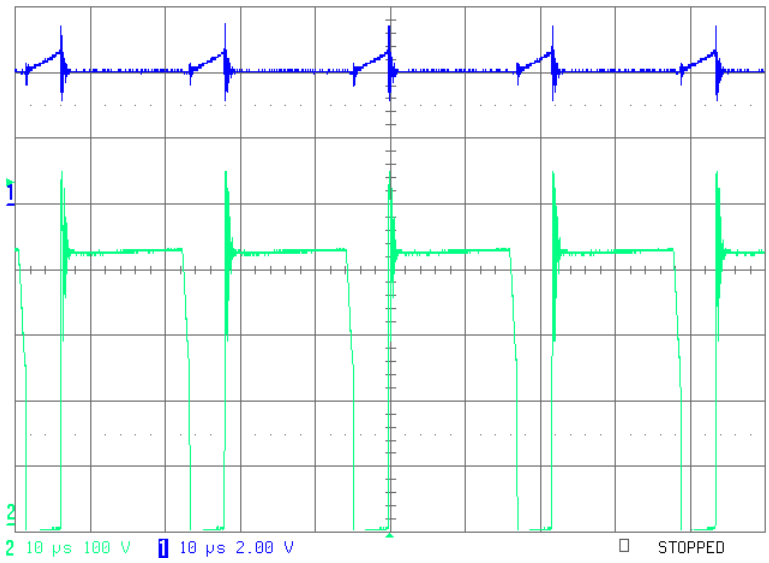


Figure 3: VBUS with current sense signal (CH1) and drain voltage (CH2) (steady-state, at line peak)

5.2. Start-up, load-step and output ripple waveforms

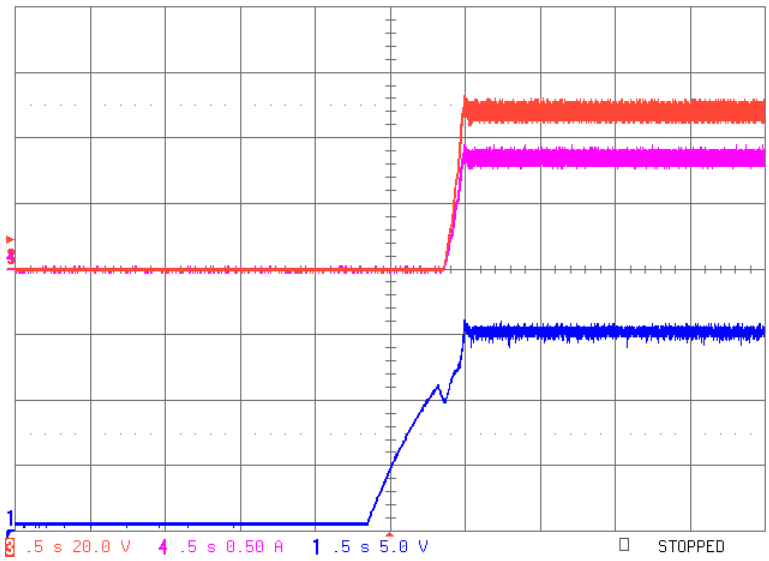


Figure 4: VCC (+15V) net voltage (CH1), output voltage (CH3) and output current (CH4) waveform at start-up with full load

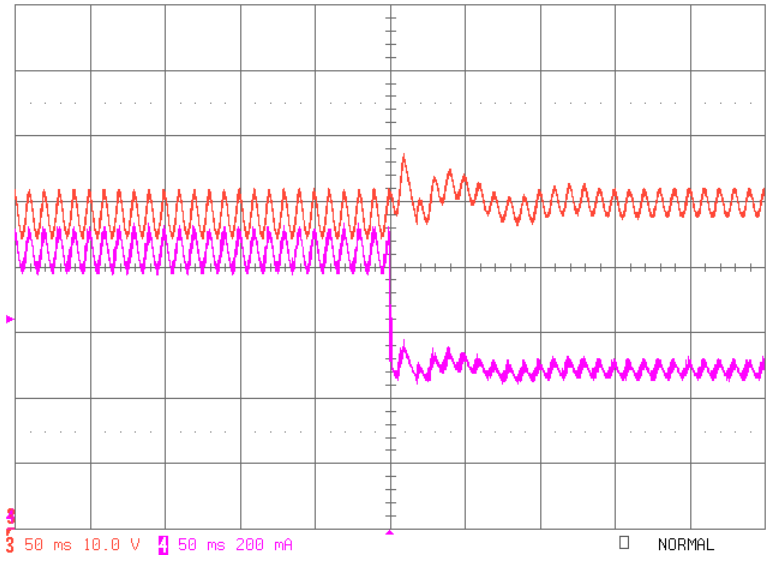


Figure 5: Output voltage (CH3) and output current (CH4) waveform at load step (100%→~60%)

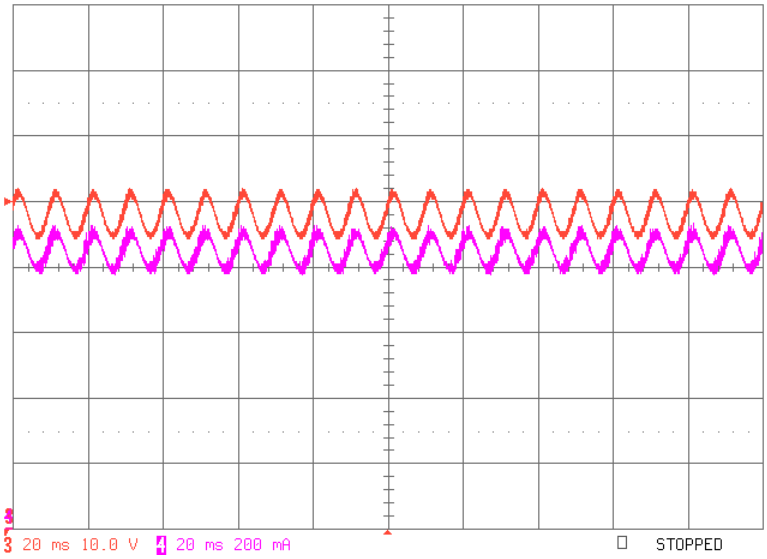


Figure 6: Output voltage (CH3) and output current (CH4) ripple at full load

5.3. Input waveforms

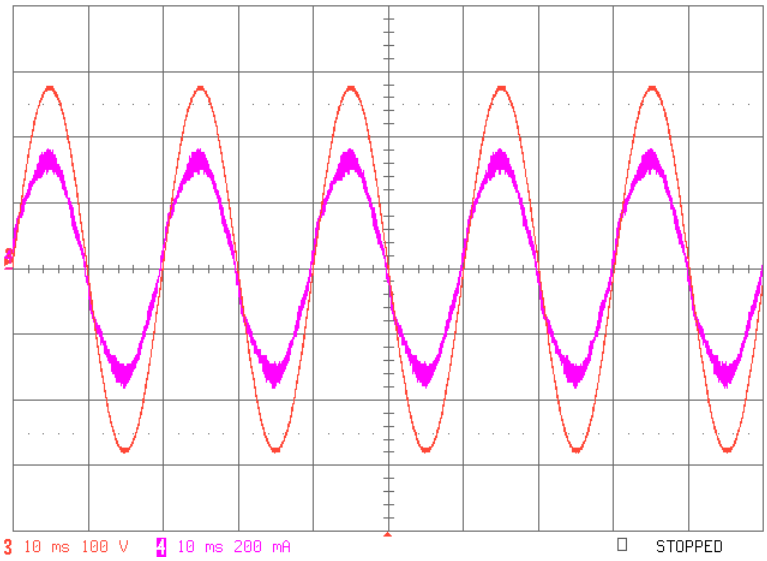


Figure 7: Input voltage (CH3) and current (CH4) waveform (V_{in}=195VAC)

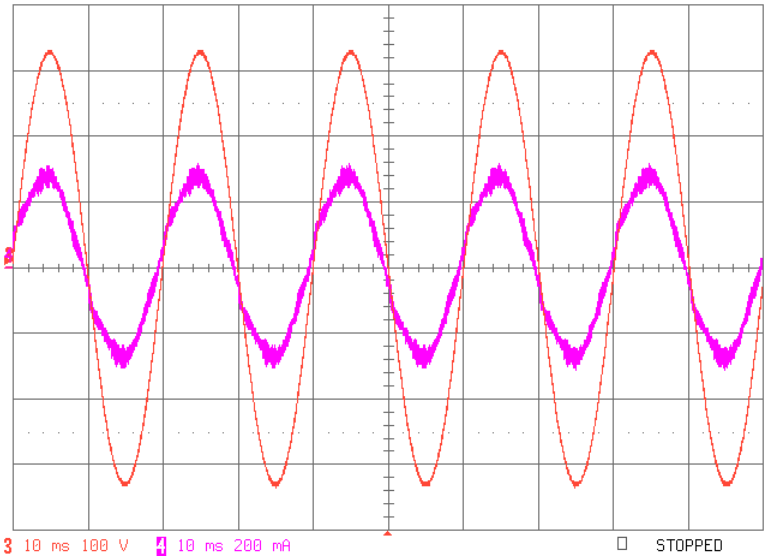


Figure 8: Input voltage (CH3) and current (CH4) waveform (V_{in}=230VAC)

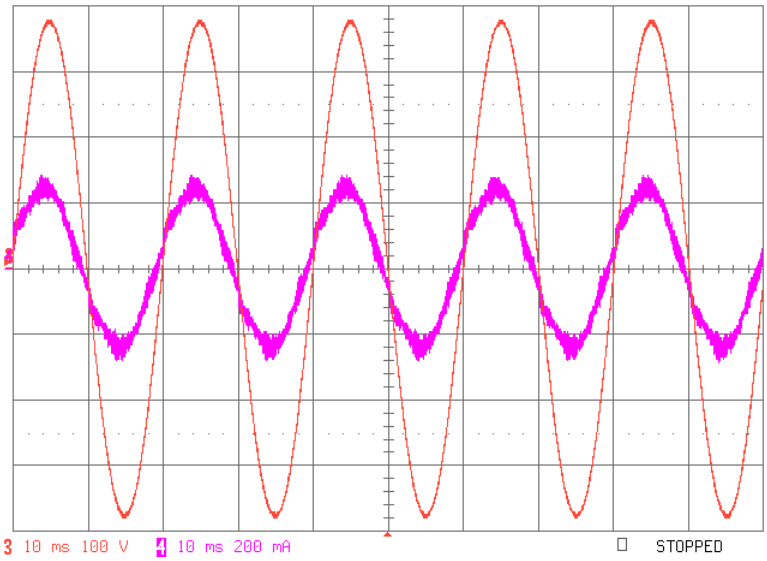


Figure 9: Input voltage (CH3) and current (CH4) waveform (V_{in}=265VAC)

5.4. Input parameters

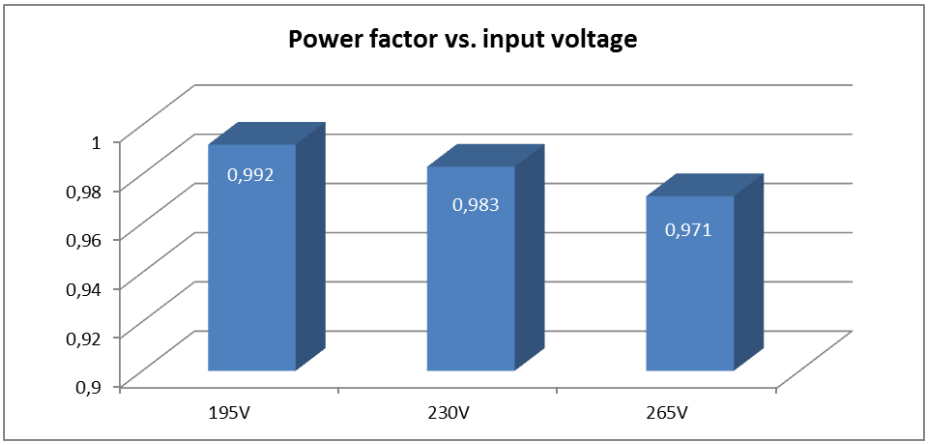


Figure 10: Measured power factor (P_{out}=40W)

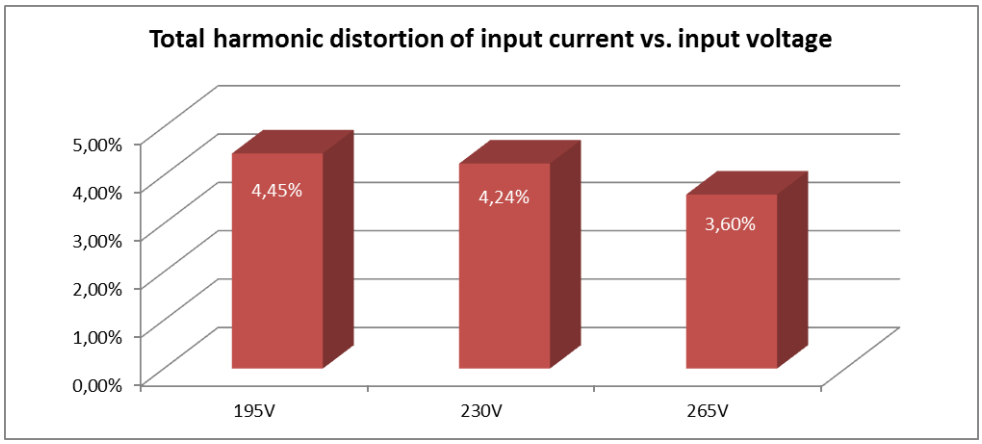


Figure 11: Measured THDI (P_{out}=40W)

5.5. Power losses and efficiency

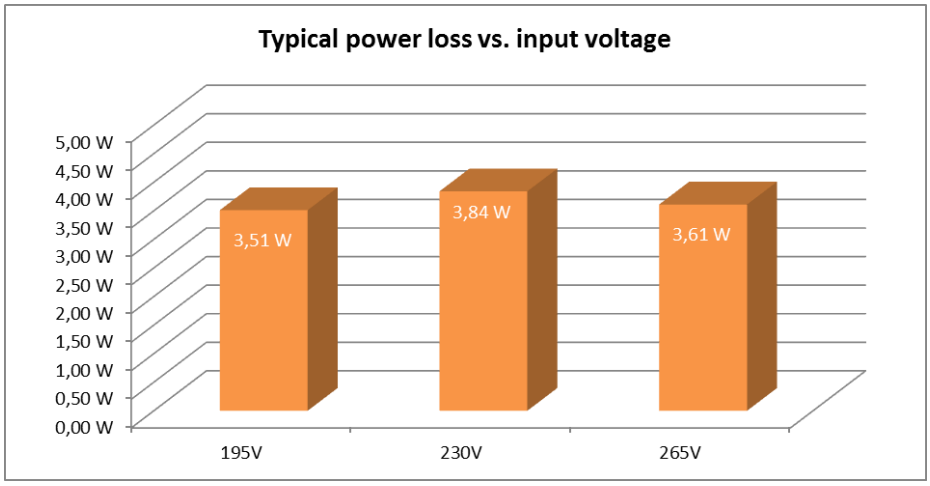


Figure 12: Measured power losses (P_{out}=40W)

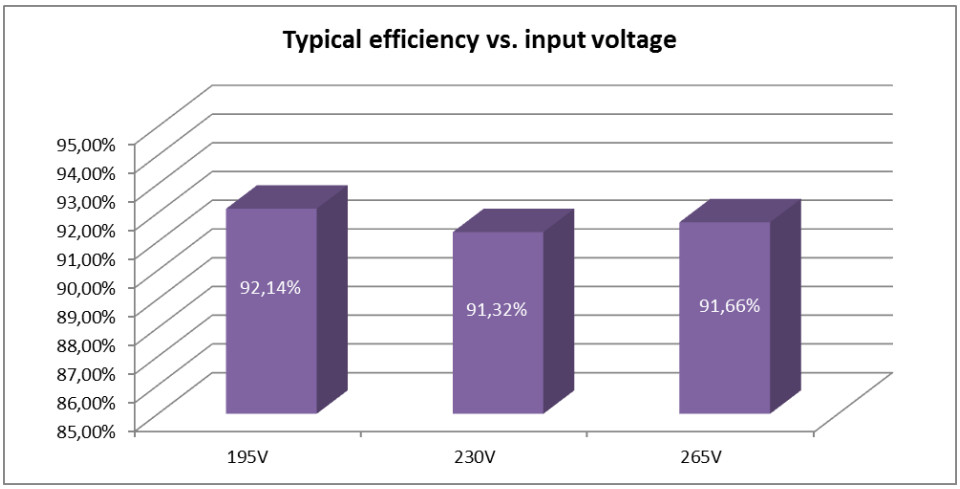


Figure 13: Measured power efficiency (P_{out}=40W)

6. PCB Layout

6.1. 3D PCB views

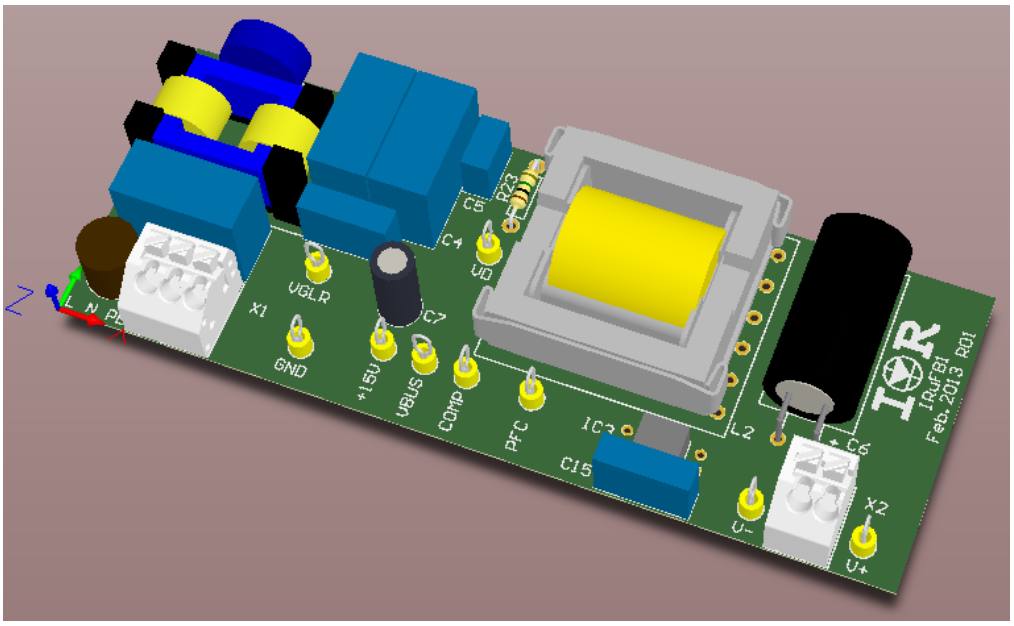


Figure 14: 3D PCB view – top side

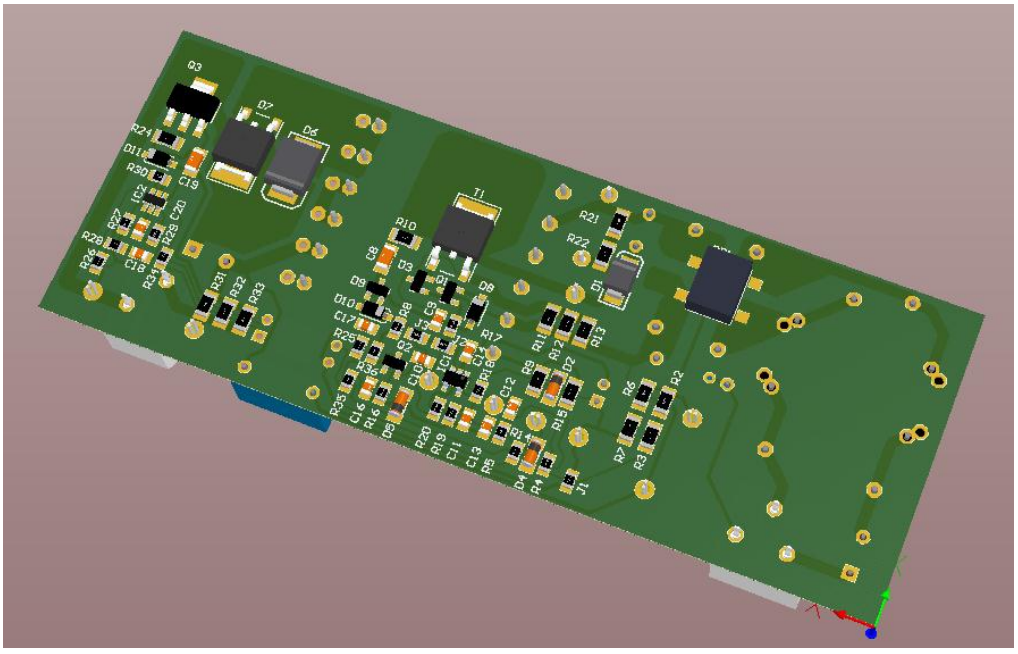


Figure 15: 3D PCB view – bottom side

6.2. PCB Top Assembly Drawing

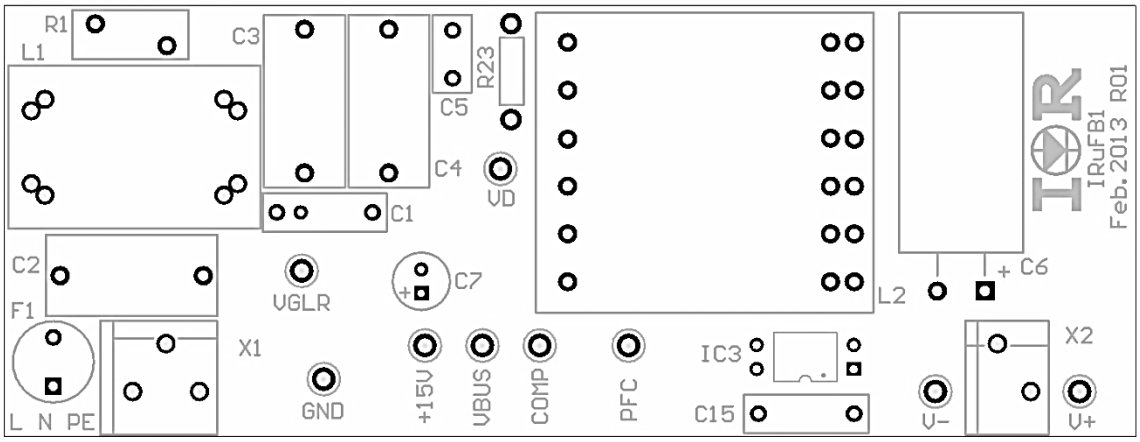
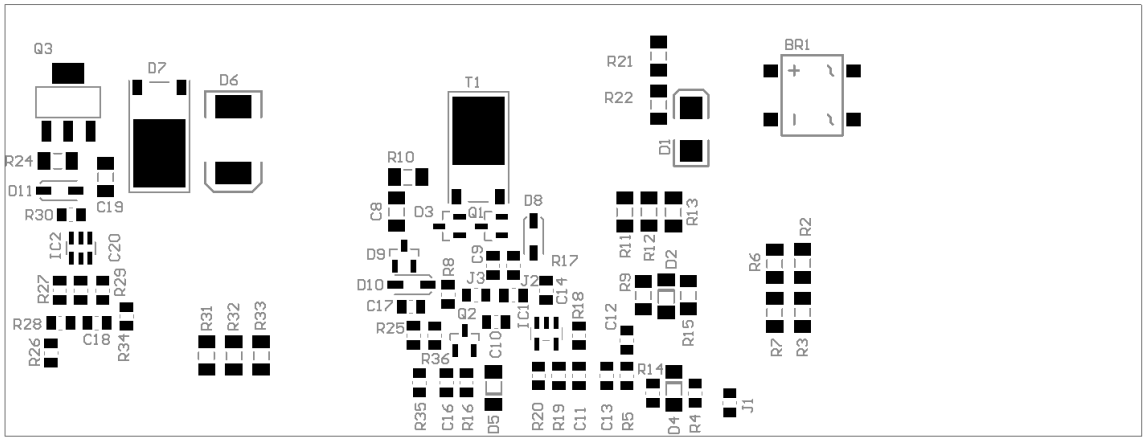


Figure 16: PCB Top assembly drawing

6.3. PCB Bottom Assembly Drawing



Note: do not populate components that are not shown in the BOM.

Figure 17: PCB Bottom assembly drawing

6.4. PCB Bottom Layer

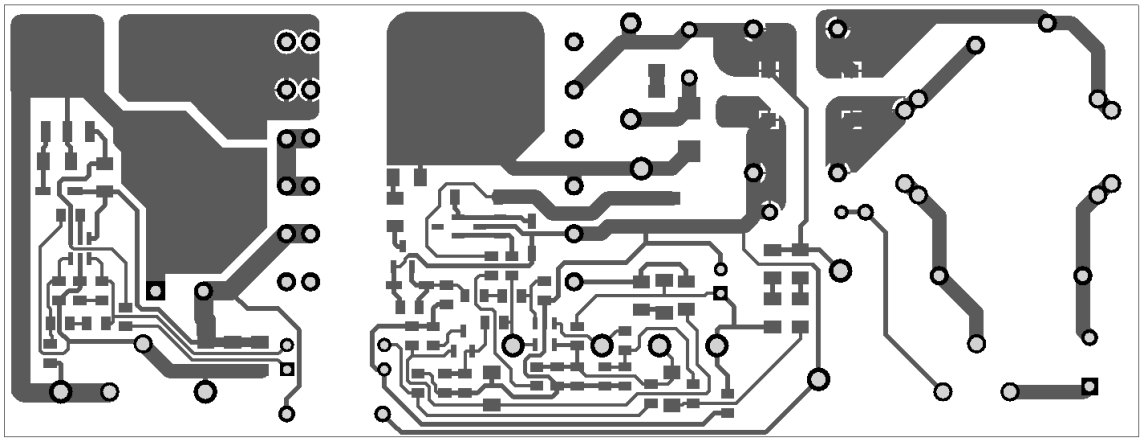


Figure 18: PCB Bottom layer

7. Bill of Materials

Index	Description	Part Number	Footprint	Manufacturer	Qty	Designator
1	PFC Control IC IRS2505L	IRS2505L	IR-SOT23-5L	International Rectifier	1	IC1
2	Bridge rectifier 1.5A/1000V	DF10S	IR-SDIP	Diodes Inc	1	BR1
3	Capacitor 1nF/300VAC/Y2	B32021A3102M	IR-MKP-RM10-4x13x9	Epcos	2	C1, C15
4	Capacitor 3.3nF/630V/MKP	MKP2J013301B00KSSD	IR-MKP-RM5-4x7.5x8	Epcos	1	C5
5	Capacitor 220nF/305VAC/MKP X2	B32922C3224M	IR-MKP-RM15-8.5x18x14.5	Epcos	3	C2, C3, C4
6	Capacitor 10nF/50V/X7R/0805	NA	IR-CC0805N	NA	1	C9
7	Capacitor 330pF/50V/C0G/0805	NA	IR-CC0805N	NA	1	C10
8	Capacitor 100pF/50V/C0G/0805	NA	IR-CC0805N	NA	1	C11
9	Capacitor 1uF/25V/X7R/0805	NA	IR-CC0805N	NA	2	C12, C14
10	Capacitor 220pF/50V/C0G/0805	NA	IR-CC0805N	NA	1	C16
11	Capacitor 22nF/50V/X7R/0805	NA	IR-CC0805N	NA	1	C13
12	Capacitor 100nF/50V/X7R/0805	NA	IR-CC0805N	NA	1	C17
13	Capacitor 220pF/630V/C0G/1206	C3216C0G2J221J	IR-CC1206N	TDK	1	C8
14	Capacitor (Radial) 22uF/50V	ECEA1HKA220	IR-EC6/13/2.5	Panasonic	1	C7
15	Capacitor (Radial) 470uF/100V	ECA2AHG471	IR-EC_12.5x25 RM5	Panasonic	1	C6
16	Diode Dual High-Speed Sw 200mA/100V/SOT-23	BAV99	IR-SOT23N	NXP	2	D3, D9
17	Diode Schottky Barrier 1A/40V/SOD-123	1N5819HW	IR-SOD-123	Diodes Inc	1	D8
18	Diode Small Signal 200mA/75V/SOD-80	LL4148	IR-MELF-D3516-1406	Vishay	3	D2, D4, D5
19	Diode Ultra-Fast Rectifier 1A/1000V/SMB	US1M	IR-SMB	Diodes Inc	1	D1
20	Diode Ultra-Fast Rectifier 3A/600V/SMC	MURS360	IR-SMC	Vishay	1	D6
21	Diode Zener 13V/500mW/SOD-123	BZT52C13	IR-SOD-123	Diodes Inc	1	D10
22	Fuse Radial 2.5A/250V	MCMET 2.5A 250V	IR-FUSE-RAD	Multicomp	1	F1
23	Ferrite core common-mode choke	NP7378	IR-CM-COMBO	ICT	1	L1

24	Flyback transformer EFD30	019-8510-00R	IR-EFD30/15/9	Precision Inc	1	L2
25	Transistor PNP General-purpose 65V/100mA	BC856B	IR-SOT23N	NXP	1	Q1
26	Transistor NPN General-purpose 65V/100mA	BC846B	IR-SOT23N	NXP	1	Q2
27	Varistor	S10K320	IR-S10K	Epcos	1	R1
28	Resistor 0R/0805	NA	IR-CR0805N	NA	3	J1, J2, J3
29	Resistor 33R/1%/0.125W/0805	NA	IR-CR0805N	NA	1	R17
30	Resistor 1k/1%/0.125W/0805	NA	IR-CR0805N	NA	2	R8, R20
31	Resistor 6k8/1%/0.125W/0805	NA	IR-CR0805N	NA	1	R4
32	Resistor 4k7/1%/0.125W/0805	NA	IR-CR0805N	NA	1	R5
33	Resistor 10k/1%/0.125W/0805	NA	IR-CR0805N	NA	1	R16
34	Resistor 33k/1%/0.125W/0805	NA	IR-CR0805N	NA	1	R36
35	Resistor 82k/1%/0.125W/0805	NA	IR-CR0805N	NA	1	R19
36	Resistor 100k/1%/0.125W/0805	NA	IR-CR0805N	NA	1	R25
37	Resistor 220k/1%/0.125W/0805	NA	IR-CR0805N	NA	1	R18
38	Resistor 0R/1206	NA	IR-CR1206N	NA	2	R9, R31
39	Resistor 0R62/1%/0.25W/1206	NA	IR-CR1206N	NA	2	R11, R12
40	Resistor 0R75/1%/0.25W/1206	NA	IR-CR1206N	NA	1	R13
41	Resistor 10R/1%/0.25W/1206	NA	IR-CR1206N	NA	1	R10
42	Resistor 22k/1%/0.25W/1206	NA	IR-CR1206N	NA	3	R15, R21, R22
43	Resistor 220k/1%/0.25W/1206	NA	IR-CR1206N	NA	2	R6, R7
44	Resistor 470k/1%/0.25W/1206	NA	IR-CR1206N	NA	2	R2, R3
45	Resistor 100k/5%/0.5W/MELF	NA	NA	NA	1	R37
46	MOSFET	SPD07N60C3	IR-DPAK	Infineon	1	T1
47	Connector 3-Pole Header	PTSA 1.5/3-3,5-Z	IR-PTSA_3pol	Phoenix Contact	1	X1
48	Connector 2-Pole Header	PTSA 1.5/2-3,5-Z	IR-PTSA 2pol	Phoenix Contact	1	X2
49	Testpoint	NA	IR-TP	NA	9	+15V, COMP, GND, PFC, V+, V-, VBUS, VD, VGLR

8. Inductor Specification

Core size	EFD 30/15/9
Core material	Epcos N87 or equivalent
Bobbin	Horizontal
Pins	12
Primary inductance	500µH ±10%
Primary peak voltage	550V max.
Maximum core temperature	100ºC
Electrical isolation (primary to secondary and auxiliary to secondary)	3000VAC / 1 min

Winding information:

Winding	*Start pin*	*Finish pin*	*Turns*	*Wire*
Primary 1.	2	3	30	8x0.1mm
Secondary 1.	8	9	17	30x0.1mm
Primary 2.	3	4	30	8x0.1mm
Secondary 2.	10	11	16	30x0.1mm
Auxiliary	5	6	10	1x0.2mm

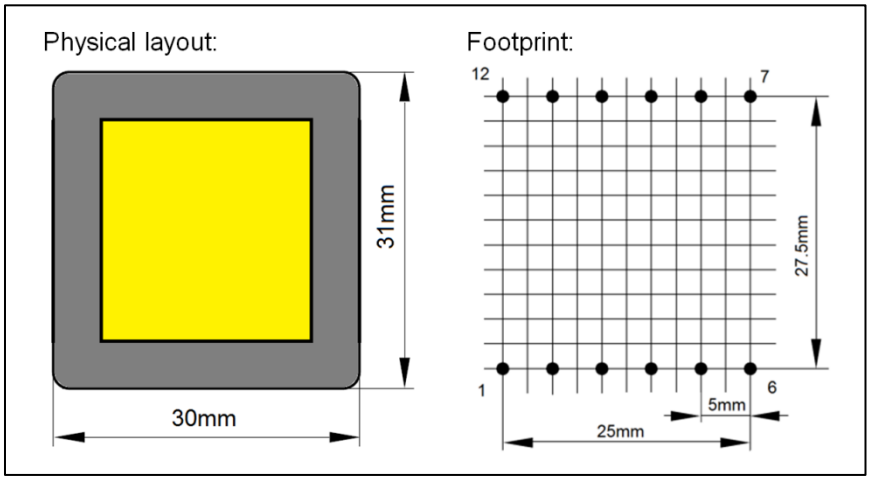


Figure 19: Inductor dimensions

9. List of Abbreviations

BOM	*Bill of Materials*
CRM	*Critical Conduction Mode*
PCB	*Printed Circuit Board*
PF	*Power Factor*
PFC	*Power Factor Correction*
THDI	*Total Harmonic Distortion of Current*

10. List of Figures

11. References

[1] IRS2505L PFC Control IC Datasheet

12. Revision History

Date	*Revision*	*Changes*	*Author*
18-Aug-2015	2	Minor updates	Akos Hodany