

IRuFB1

40W Isolated Flyback PFC

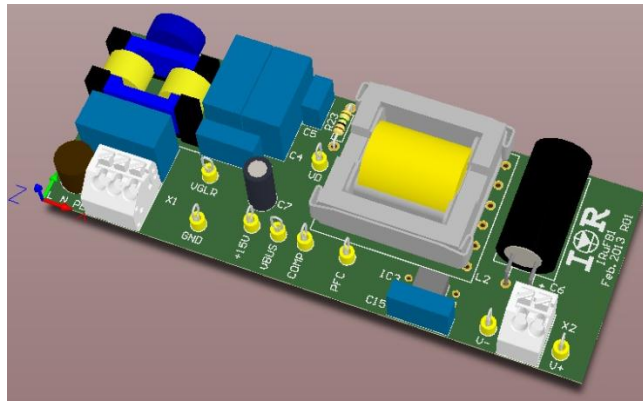


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1. Introduction

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

| <i>Parameter</i> | <i>Description</i> | <i>Value</i> | <i>Units</i> |
|------------------|------------------------|--------------|--------------|
| 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

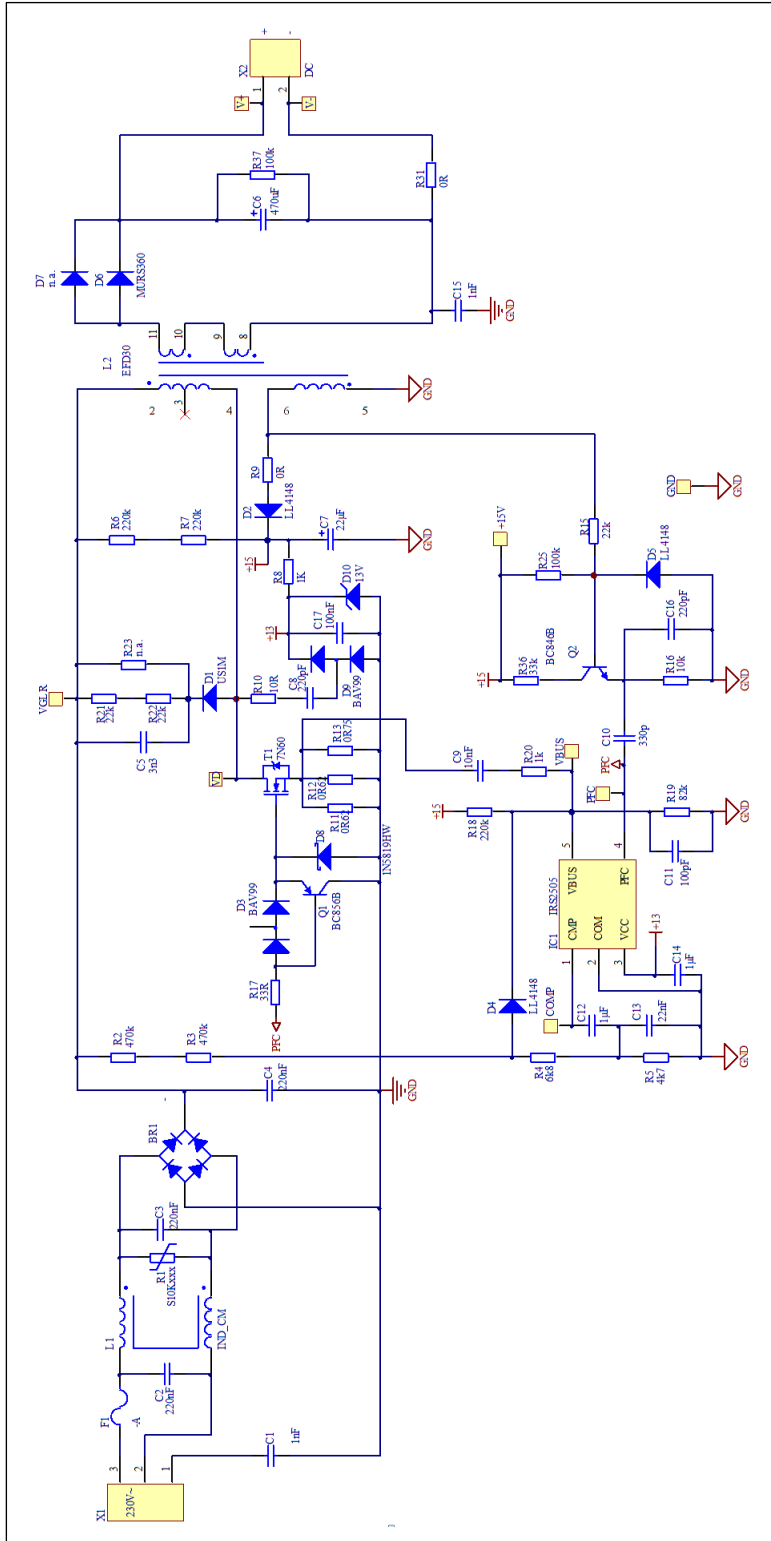


Figure 1: Circuit schematic

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 ($\theta = 90^\circ$):

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

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

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:

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

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} ($\theta = 90^\circ$), 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 $8 \times 0.1mm$ 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 $25...30 \times 0.1mm$ 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:

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

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 $R_{SH,PRI} = R_{31} \parallel R_{32} \parallel R_{33}$:

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

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

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:

$$V_{BUS} = V_{AUX} \frac{R_{19}}{R_{19} + R_{18}} \quad (34)$$

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

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

5. Measurement Results

5.1. Switching waveforms

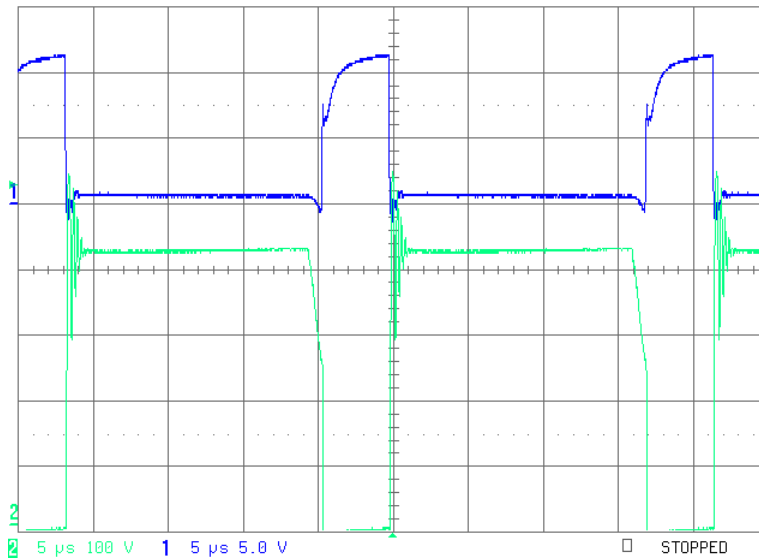


Figure 2: PFC gate drive and drain voltage (CH1: PFC, CH2: VD, steady-state, at line peak)

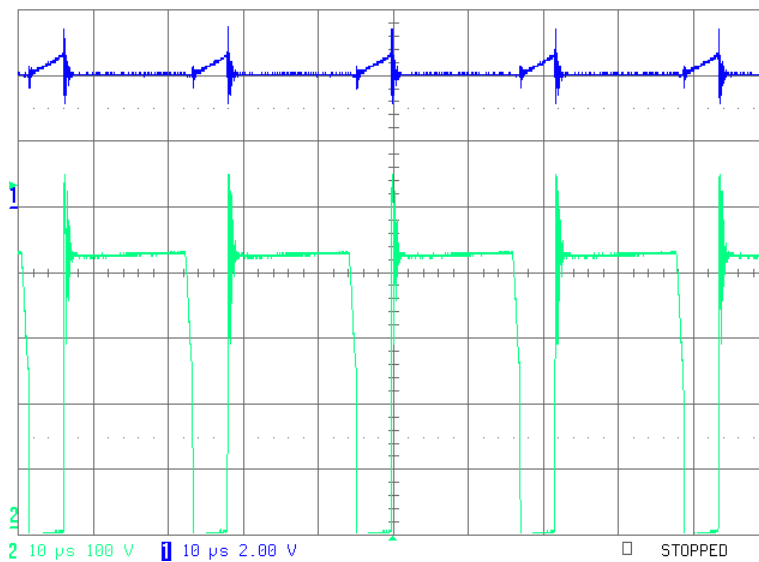


Figure 3: VBUS with current sense signal (CH1) and drain voltage (CH2) (steady-state, at line peak)

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

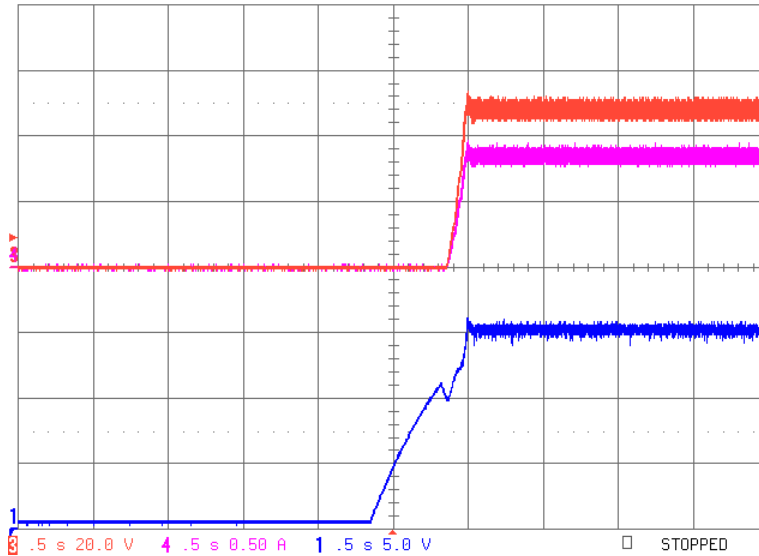


Figure 4: VCC (+15V) net voltage (CH1), output voltage (CH3) and output current (CH4) waveform at start-up with full load

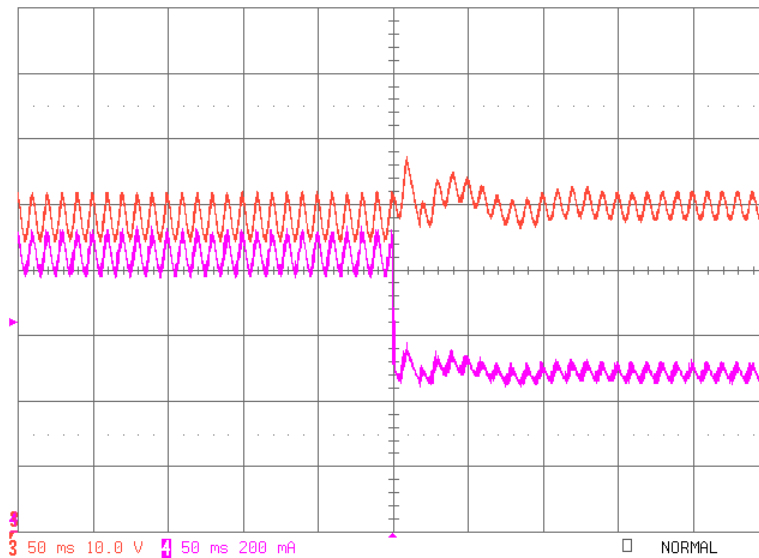


Figure 5: Output voltage (CH3) and output current (CH4) waveform at load step (100%→~60%)

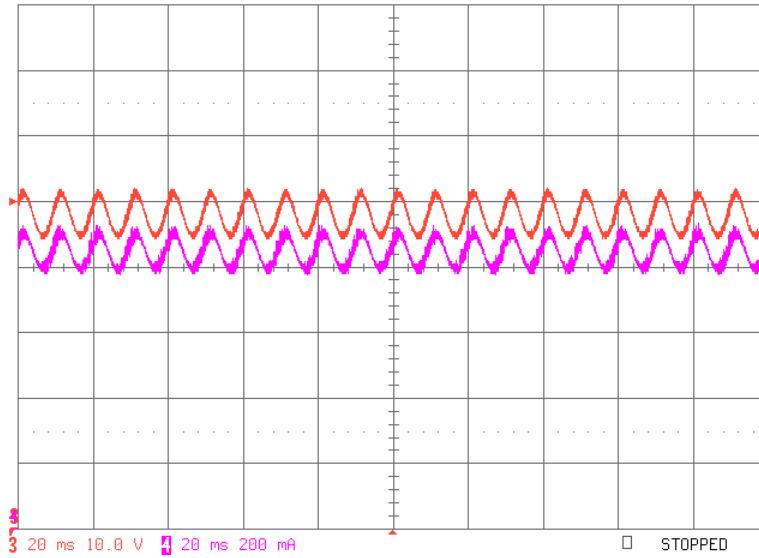


Figure 6: Output voltage (CH3) and output current (CH4) ripple at full load

5.3. Input waveforms

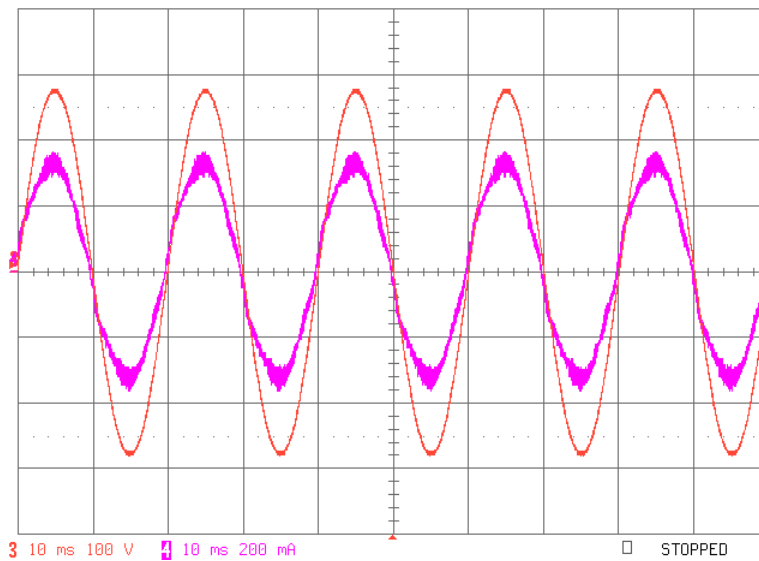


Figure 7: Input voltage (CH3) and current (CH4) waveform ($V_{in}=195VAC$)

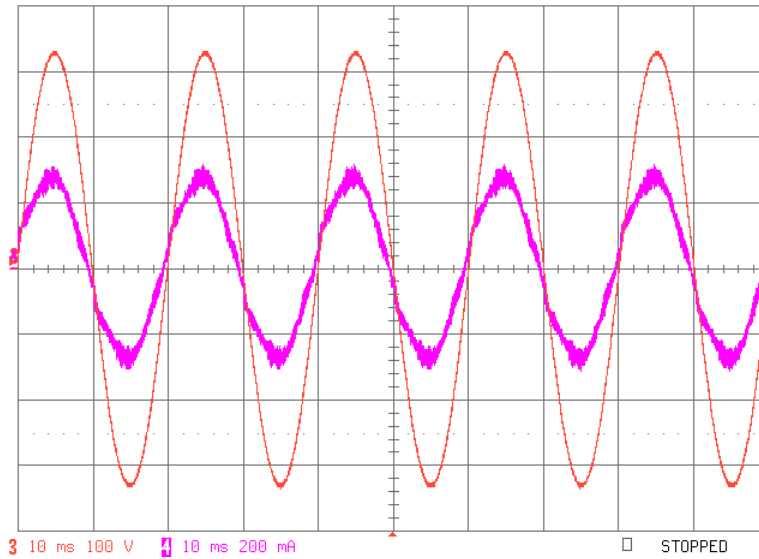


Figure 8: Input voltage (CH3) and current (CH4) waveform ($V_{in}=230VAC$)

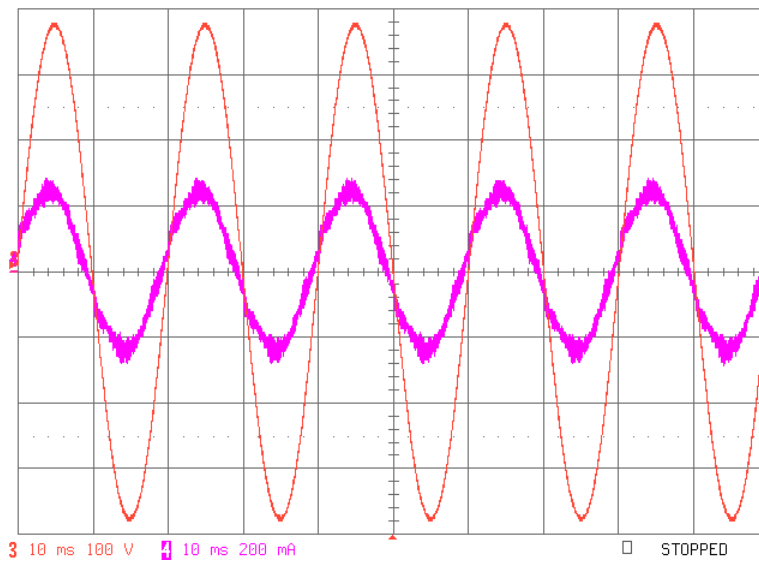


Figure 9: Input voltage (CH3) and current (CH4) waveform ($V_{in}=265VAC$)

5.4. Input parameters

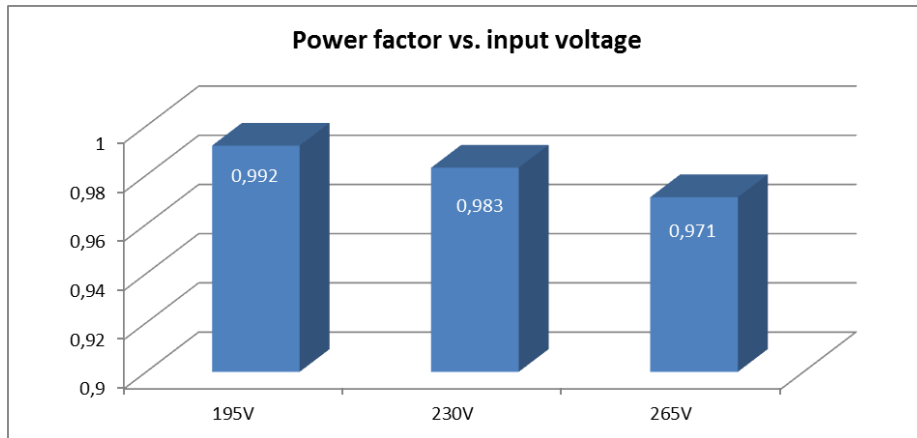


Figure 10: Measured power factor ($P_{out}=40W$)

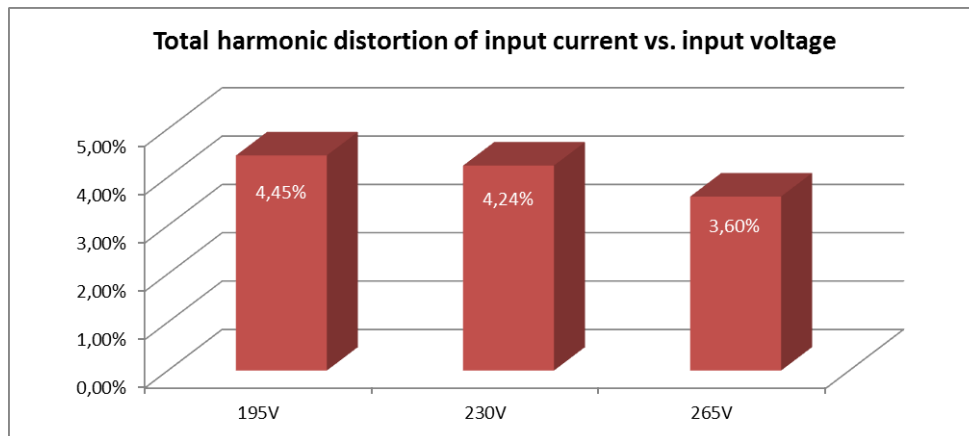


Figure 11: Measured THDI ($P_{out}=40W$)

5.5. Power losses and efficiency

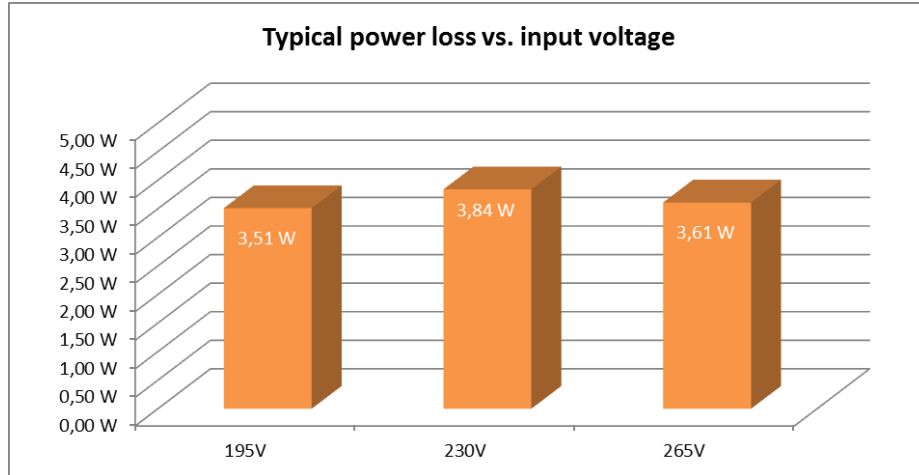


Figure 12: Measured power losses ($P_{out}=40W$)

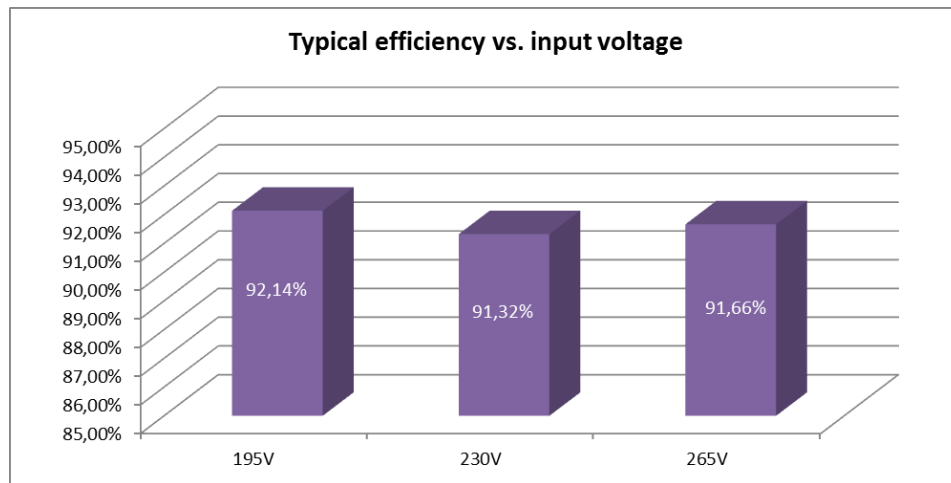


Figure 13: Measured power efficiency ($P_{out}=40W$)

6. PCB Layout

6.1. 3D PCB views

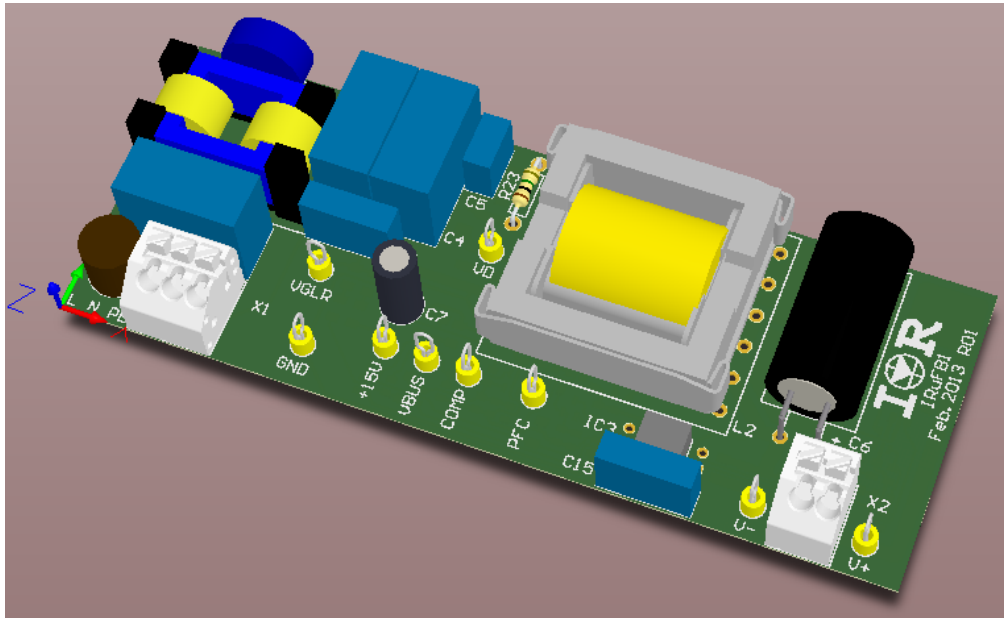


Figure 14: 3D PCB view – top side

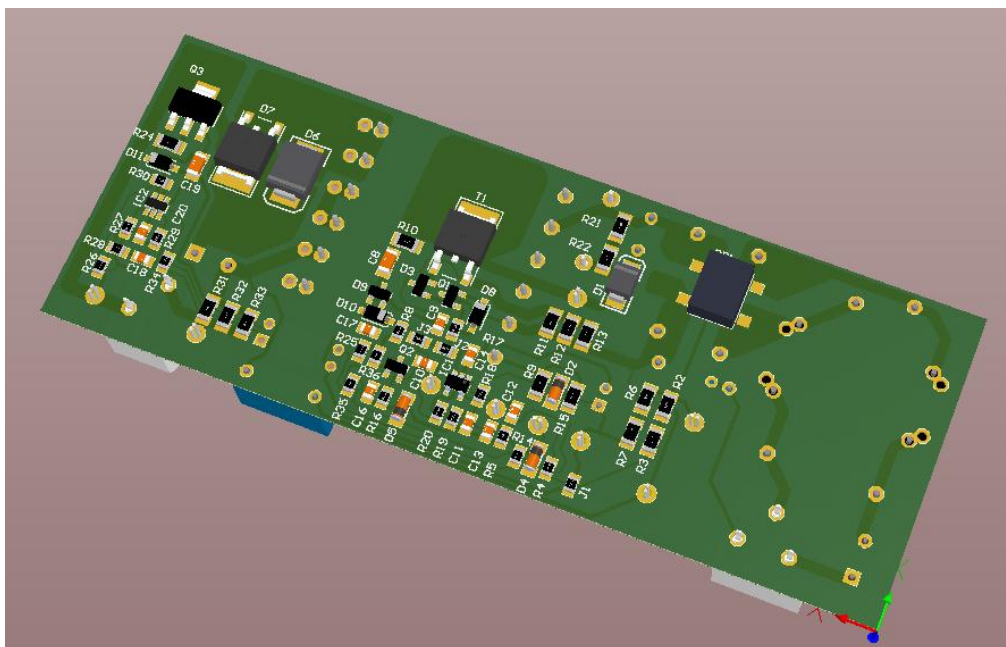


Figure 15: 3D PCB view – bottom side

6.2. PCB Top Assembly Drawing

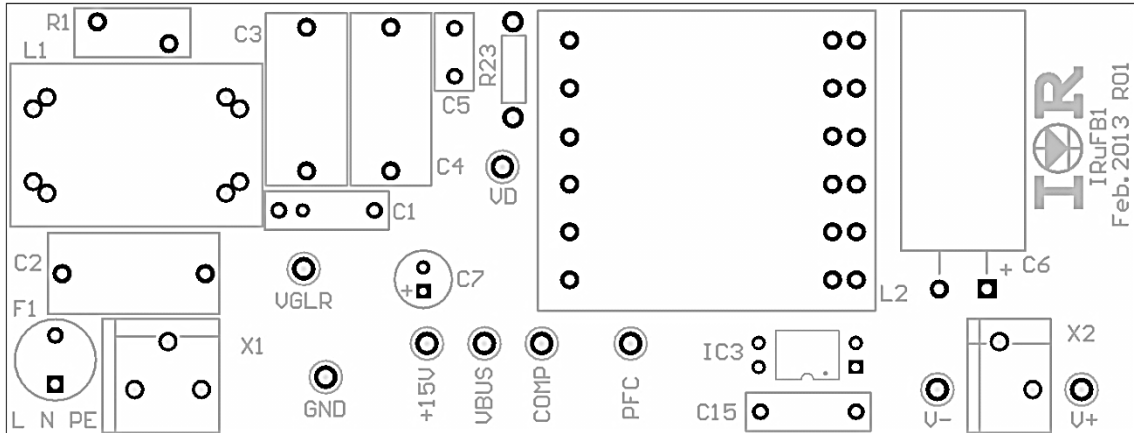
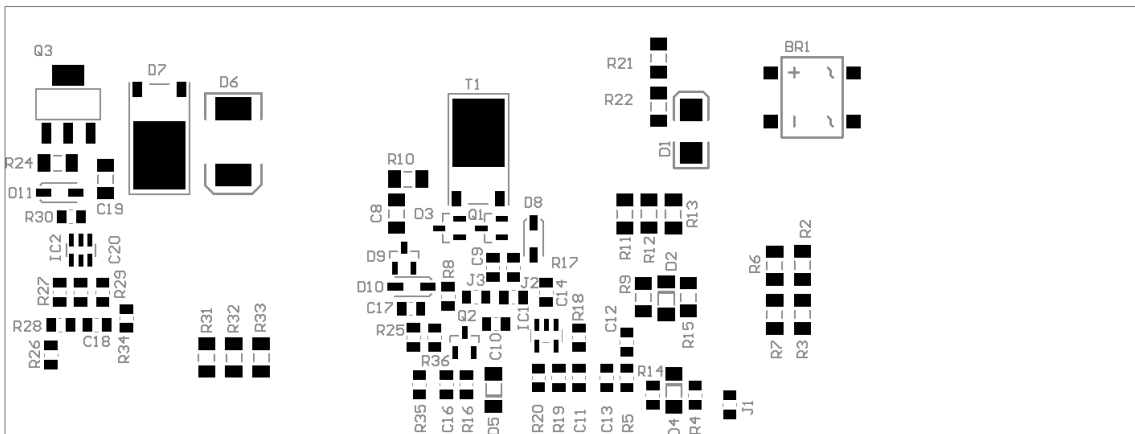


Figure 16: PCB Top assembly drawing

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

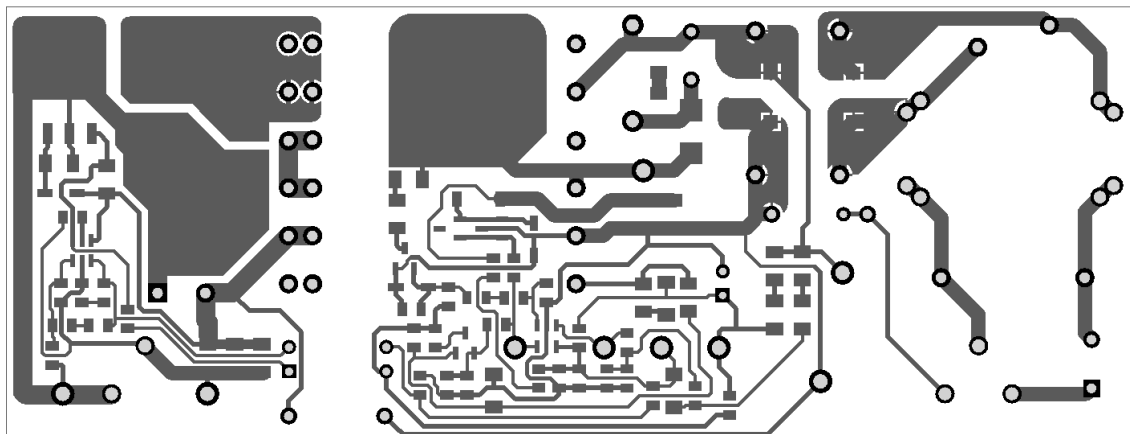


Figure 18: PCB Bottom layer

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 | 500 μ H \pm 10% |
| Primary peak voltage | 550V max. |
| Maximum core temperature | 100°C |
| 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 |

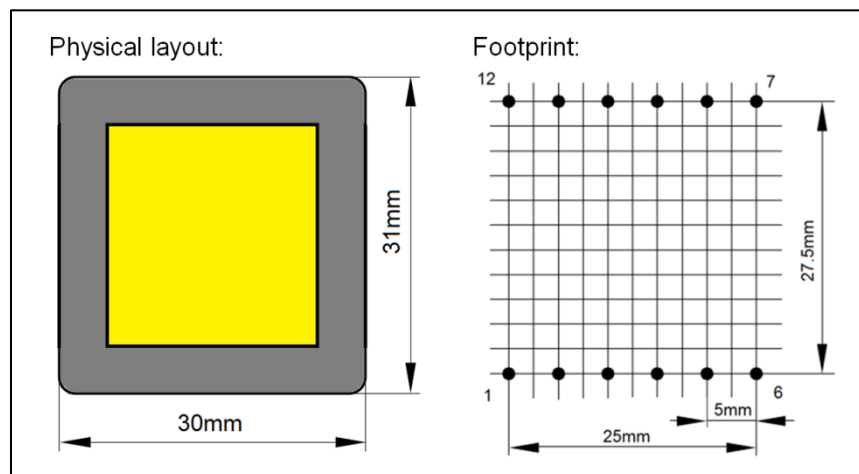


Figure 19: Inductor dimensions

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 |

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11. References

[1] IRS2505L PFC Control IC Datasheet

12. Revision History

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