PFC Demoboard - System Solution

High Power Density 800 W 130 kHz Platinum Server Design

Application Note

About this document

Scope and purpose

This document presents the design methodology and results of an 800 W 130 kHz Platinum Server Power Factor Correction (PFC) Continuous Conduction Mode (CCM) Boost Converter, based on:

- 600 V CoolMOS™ C7 Super Junction MOSFET and 650V thinQ!™ SiC Schottky Diode Generation 5
- 2EDN7524F Non Isolated Gate Driver (EiceDRIVER™)
- ICE3PCS01G PFC Controller
- XMC 1300 Microcontroller*
- ICE2QR4780Z Flyback Controller

Intended audience

This document is intended for design engineers who want to verify the performance of the latest 600 V CoolMOS™ C7 MOSFET Technology working at 130 kHz in a CCM PFC boost converter along with EiceDRIVER™ ICs and 650V thinQ!™ SiC Schottky Diode Generation 5 using analog and digital* control.

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1 Introduction

Power Factor Correction (PFC) shapes the input current of the power supply to be in synchronization with the mains voltage, in order to maximize the real power drawn from the mains. In a perfect PFC circuit, the input current follows the input voltage as a pure resistor, without any input current harmonics.

This document is to demonstrate the design and practical results of an 800 W 130 kHz Platinum Server PFC Demo Board based on Infineon Technologies devices in terms Power Semiconductors, non-isolated Gate Drivers, Analog and Digital controllers for the PFC converter as well as Flyback controller for the auxiliary supply.

1.1 Topology

Although active PFC can be achieved by several topologies, the boost converter (Figure 1) is the most popular topology used in Server PFC applications, for the following reasons:

- The line voltage varies from zero to some peak value typically 375 V; hence a step up converter is needed to output a DC bus voltage of 380 V or more. For that reason the buck converter is eliminated, and the buck-boost converter has high switch voltage stress (V_{in}+V_o), therefore it is also not the popular one.
- The boost converter has the filter inductor on the input side, which provides a smooth continuous input current waveform as opposed to the discontinuous input current of the buck or buck-boost topology. The continuous input current is much easier to filter, which is a major advantage of this design because any additional filtering needed on the converter input will increase the cost and reduces the power factor due to capacitive loading of the line.

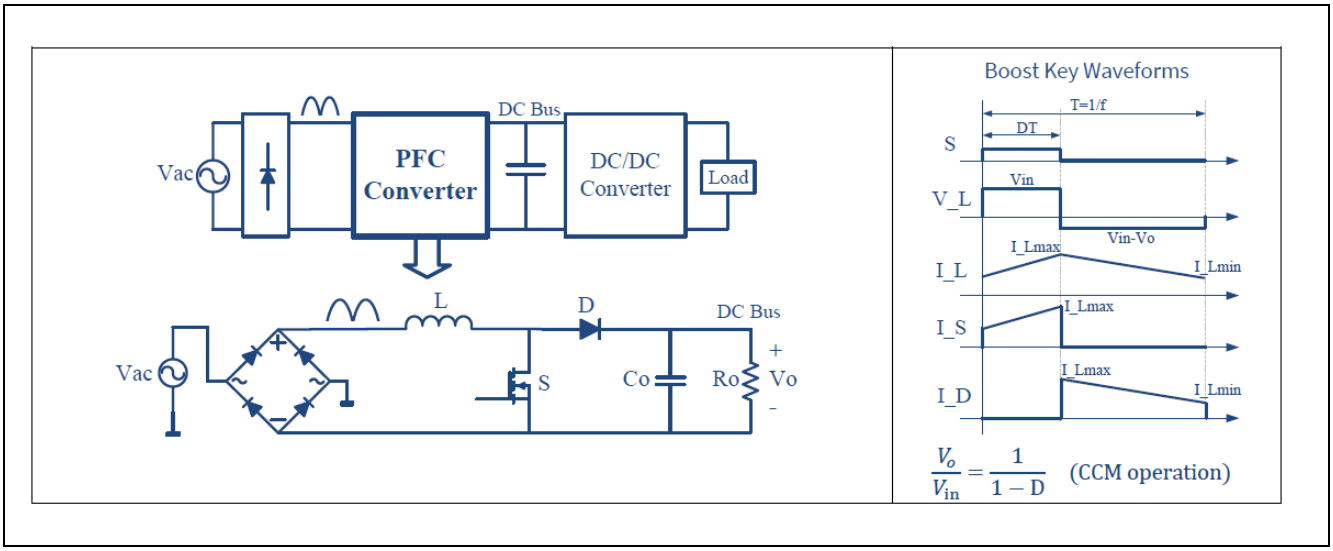


Figure 1 Structure and key waveforms of a boost converter

1.2 PFC Modes of operation

The boost converter can operate in three modes: continuous conduction mode (CCM), discontinuous conduction mode (DCM), and critical conduction mode (CrCM). Figure 2 shows modeled waveforms to illustrate the inductor and input currents in the three operating modes, for the same exact voltage and power conditions.

By comparing DCM among the others, DCM operation seems simpler than CrCM, since it may operate in constant frequency operation; however DCM has the disadvantage that it has the highest peak current compared to CrCM and also to CCM, without any performance advantage compared to CrCM. For that

reason, CrCM is a more common practice design than DCM, therefore, this document will exclude the DCM design.

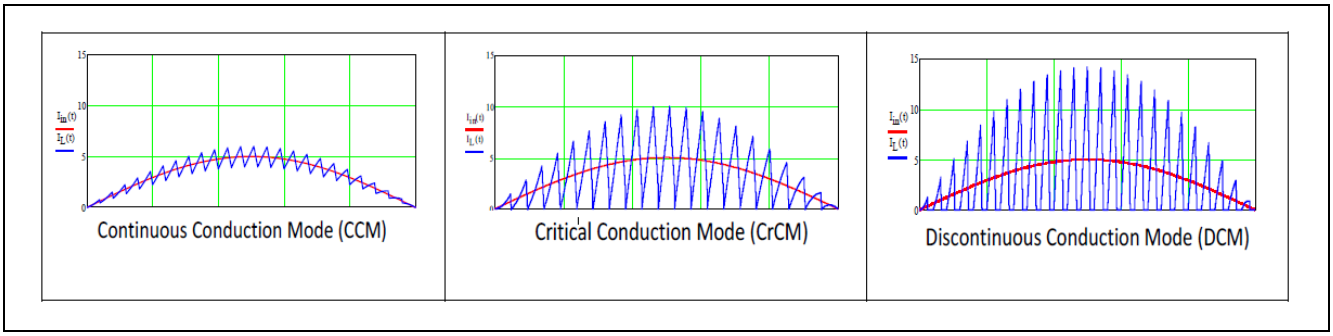


Figure 2 PFC Inductor and input line current waveforms in the three different operating modes

CrCM may be considered a special case of CCM, where the operation is controlled to stay at the boundary between CCM and DCM. CrCM usually uses constant on-time control; the line voltage is changing across the 60 Hz line cycle, the reset time for the boost inductor is varying, and the operating frequency will also change in order to maintain the boundary mode operation. CrCM dictates the controller to sense the inductor current zero crossing in order to trigger the start of the next switching cycle.
The inductor current ripple (or the peak current) in CrCM is twice of the average value, which greatly increases the MOSFET RMS currents and turn-off current. But since every switching cycle starts at zero current, and usually with ZVS operation, turn-on loss of MOSFET is usually eliminated. Also, since the boost rectifier diode turns off at zero current as well, reverse recovery losses and noise in the boost diode are eliminated too, another major advantage of CrCM mode. Still, on the balance, the high input ripple current and its impact on the input EMI filter tends to eliminate CrCM mode for high power designs unless inter-leaved stages are used to reduce the input HF current ripple. A high efficiency design can be realized that way, but at substantially higher cost. That discussion is beyond the scope of this application note.
The power stage equations and transfer functions for CrCM are the same as CCM. The main differences relate to the current ripple profile and switching frequency, which affects RMS current and switching power losses and filter design.
CCM operation requires a larger filter inductor compared to CrCM. While the main design concerns for a CrCM inductor are low HF core loss, low HF winding loss, and the stable value over the operating range (the inductor is essentially part of the timing circuit), the CCM mode inductor takes a different approach. For the CCM PFC, the full load inductor current ripple is typically designed to be 20-40% of the average input current. This has several advantages:

- Peak current is lower, and the RMS current factor with a trapezoidal waveform is reduced compared to a triangular waveform, reducing device conduction losses.
- Turn-off losses are lower due to switch off at much lower maximum current.
- The HF ripple current to be smoothed by the EMI filter is much lower in amplitude.

On the other side, CCM encounters the turn-on losses in the MOSFET, which can be exacerbated by the boost rectifier reverse recovery loss due to reverse recovery charge, Q_{rr}. For this reason, ultra-fast recovery diodes or silicon carbide Schottky diodes with extreme low Q_{rr} are needed for CCM mode.
In conclusion, we can say that for low power applications, the CrCM boost has the advantages in power saving and improving power density. This advantage may extend to medium power ranges, however at some medium power level the low filtering ability and the high peak current starts to become severe disadvantages. At this point the CCM boost starts being a better choice for high power applications.

Since this document is intended to support 800 W PFC applications, therefore a CCM PFC boost converter has been chosen in the application note with detailed design discussions and design examples for demonstration.

2 Power Stage Design

2.1 EMI Filter

The EMI filter implemented is as a two-stage filter, which provides sufficient attenuation for both differential mode (DM) and common mode (CM) noise.

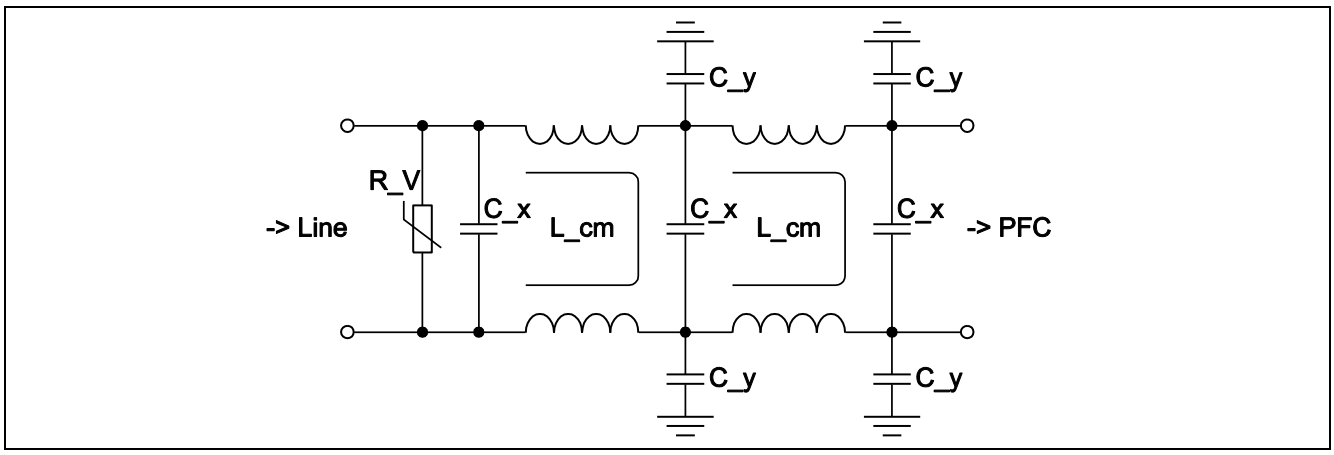


Figure 3 Two-stage filter structure

The two high current common mode chokes L_cm are based on high permeability toroid ferrite cores.

1. 2 x 26 Turns/ 2 x 4,76mH
2. 2 x 28 Turns/ 2 x 5,7mH

The relatively high number of turns causes a considerable amount of stray inductance, which ensures sufficient DM attenuation.

2.2 Rectifier Bridge

The bridge rectifier is designed for the worst case: maximum output power and minimum input voltage. To calculate the input current, an efficiency of 94% (at V_{in} = 90V) is applied.

Maximum rms value of the input current:

$$I_{INrms} = \frac{P_{OUTmax}}{\eta V_{INrms}} = \frac{800W}{0{,}94 \cdot 90V} = 9{,}46A \qquad \text{Equation 2-1}$$

Maximum rms value of the diode current:

$$I_{Drms} = \frac{I_{INrms}}{2} = 4{,}73A \qquad \text{Equation 2-2}$$

Maximum average value of the diode current:

$$I_{Davg} = \frac{\sqrt{2} I_{INrms}}{\pi} = 4{,}26A \qquad \text{Equation 2-3}$$

Due to the calculated mean and effective current values, the rectifier type LVB2560 with very low forward voltage drop was selected. This 800V device has sufficient voltage reserve with V_{in} = 265V.The smaller size types GBU and KBU are only available for currents up to 10A. For the following formula, r_d was extracted from the characteristic curve of the data sheet (T_A = 100 °C).

Conduction losses of a rectifier diode:

$$P_D = I_{Davg} \cdot V_D + (I_{Drms})^2 \cdot r_D = 4{,}26A \cdot 0{,}5V + (4{,}73A)^2 \cdot 0{,}016\Omega = 2{,}49W \quad \text{Equation 2-4}$$

Total losses of the rectifier:

$$P_{REC} = 4P_D = 4 \cdot 2{,}49W = 9{,}96W \quad \text{Equation 2-5}$$

2.3 PFC Choke

The PFC choke design is based on a toroid high performance powder core.

Toroid chokes allow well balanced and minimized core and winding losses, having a homogeneous heat distribution w/o hot spots and a large surface area. Hence they are predestined for systems which are targeting highest power density with forced air convection. Thereby very small choke sizes are feasible.

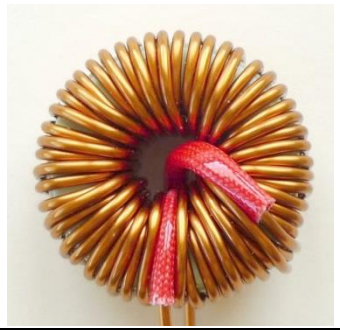


Figure 4 Photograph of PFC choke

The core material was chosen to be Chang Sung Corporation's (CSC) HIGH FLUX, which has an excellent DC bias and good core loss behavior. The part number is CH270060. The outer diameter of the core is 27mm.

The winding was implemented using enameled copper wire AWG 16 (1,25 mm diameter). The winding is roughly made in a 1,5 layer style, meaning there is one layer on the outer diameter, while inside there's a double layer structure. This arrangement allows a good copper fill factor, still having good AC characteristics.

The number of turns is 55, taking advantage of the high allowable DC bias. The resulting small signal bias inductance is 227 µH. The effective inductance with current bias is determined by the core material B-H characteristics and illustrated as following:

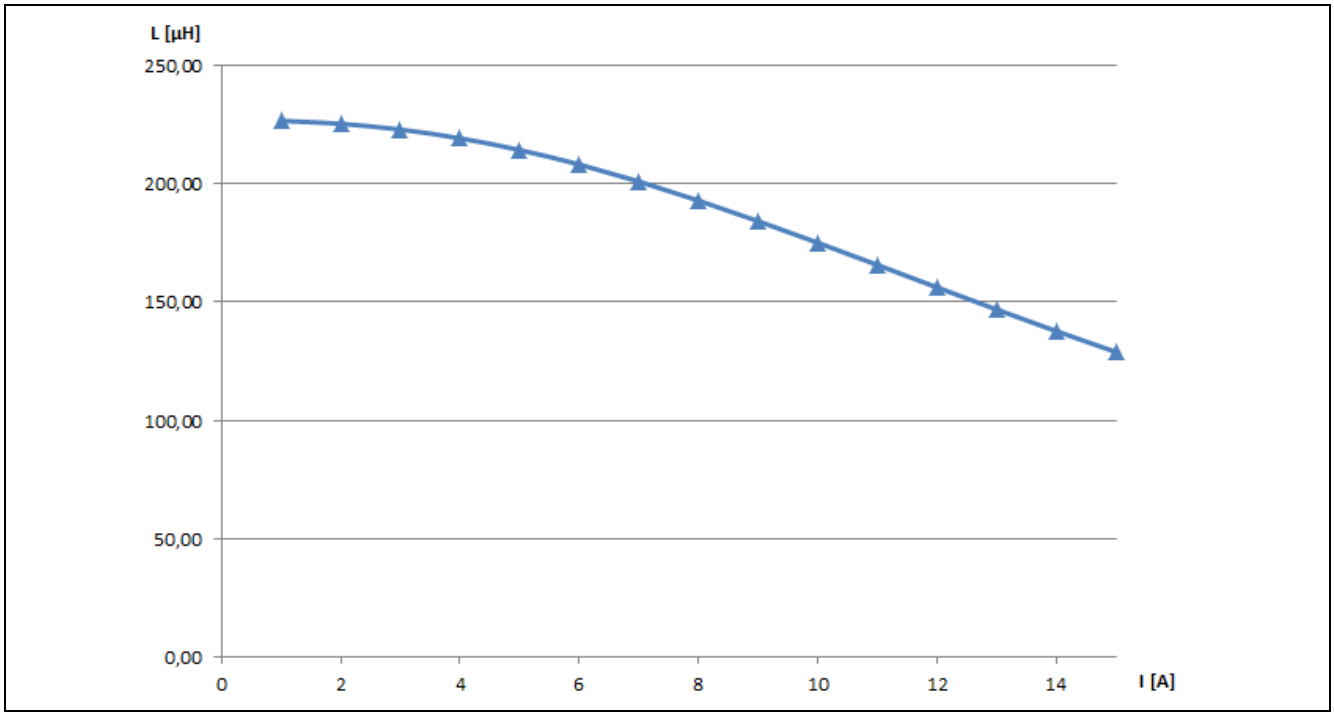


Figure 5 DC-Bias dependency of inductance

The effective inductance together with the switching frequency of 130 kHz, produce a relatively low current ripple, which supports the whole system performance. The peak and rms currents for the semiconductors and filter components are minimized. Besides, the low ripple design effects low core losses, which is important for system light load performance .

Table 1 Choke losses @800 W/130 kHz (calculation results of magnetic design software tool)

V_{in_ac} [V]	P_{core} [W]	P_{wi} [W]	P_{tot} [W]
90	1,2	4,5	5,7
115	1,5	2,9	4,4
230	1,5	0,9	2,4

2.4 Infineon Semiconductors

2.4.1 600 V CoolMOS™ C7

The 600 V CoolMOS™ C7 series of devices offers a ~50% reduction in turn-off losses compared to the CoolMOS™ CP, offering a GaN-like level of performance in PFC, TTF and other hard-switching topologies. The CoolMOS™ C7 delivers an area-specific on resistance ($R_{DS(ON)}$*A) of just 1Ω per mm^2, extending Infineon's portfolio of products with lowest $R_{DS(ON)}$ per package to support customer efforts to further increase power density.

The 600 V CoolMOS C7 series features ultra-low switching losses and targets high power SMPS applications such as server, telecom, solar and industrial applications requiring high efficiency and a reduced Bill of Materials (BoM) and total cost of ownership (TCO).

Efficiency and TCO driven applications such as hyper-scale data centers and telecom base stations benefit from the switching loss reduction offered by CoolMOS C7.
Efficiency gains of 0.3% to 0.7% in PFC and 0.1% in LLC topologies can be achieved, leading to significant total cost of ownership benefits. In the case of a 2.5kW server PSU, for example, using 600 V C7 MOSFETs can result in energy cost reductions of ~10% for PSU energy loss.

In BoM and cost driven designs such as enterprise servers, the 600 V CoolMOS™ C7 devices offer a cost reduction in magnetics. Due to the significantly lower gate charge and output capacitance, the C7 can be operated at 2x higher switching frequencies with only a marginal penalty in efficiency. This allows the size of magnetic components to be minimized, lowering the overall BoM cost. For example, doubling the switching frequency from 65 kHz to 130 kHz may reduce magnetic component cost by as much as 30%.

2.4.1.1 Design implementation

Based on several current server PSU analysis and customer feedback, it is a common practice to implement two MOSFETs in parallel in the classic PFC topology for improving thermal performance during both normal and critical operating conditions like AC Line Drop Out. As a result, in this demo board two 180 mΩ TO-220 MOSFETs working in parallel are designed and tested.

2.4.2 Fast Dual Channel 5 A Low Side Gate Driver

2.4.2.1 Introduction

The 2EDN7524 is a non-inverting fast dual-channel driver for low-side switches. Two true rail-to-rail output stages with very low output impedance and high current capability are chosen to ensure highest flexibility and cover a high variety of applications.

All inputs are compatible with LVTTL signal levels. The threshold voltages with a typical hysteresis of 1 V are kept constant over the supply voltage range.

Since the 2EDN7524 aims particularly at fast-switching applications, signal delays and rise/fall times have been minimized. Special effort has been made towards minimizing delay differences between the 2 channels to very low values of typically 1 ns.

The 2EDN7524 driver used in this demo board comes in a standard PG-DSO-8 package.

2.4.2.2 Driver Outputs

The two rail-to-rail output stages realized with complementary MOS transistors are able to provide a typical 5 A of sourcing and sinking current. The on-resistance is very low with a typical value below 0.7 Ω for the

sourcing p-MOS and 0.5 Ω for the sinking n-MOS transistor. The use of a p-channel sourcing transistor is crucial for achieving real rail-to-rail behavior and not suffering from a source follower's voltage drop.

Gate Drive Outputs held active low in case of floating inputs ENx, INx or during startup or power down once UVLO is not exceeded.

2.4.2.3 Under Voltage Lockout (UVLO)

The Under-Voltage Lockout (UVLO) function ensures that the output can be switched to its high level only if the supply voltage exceeds the UVLO threshold voltage. Therefore it can be guaranteed that the switch transistor is not operated if the driving voltage is too low to completely switch it on, so avoiding excessive power dissipation.

The default UVLO level is set to a typical value of 4.2 V / 8 V (with some hysteresis). A UVLO of 4.2 V is normally used for low voltage and TTL based MOSFETs. For higher level, like high voltage super junction MOSFETS, an active voltage of min. 8 V is used.

2.4.3 SiC G5 Diode

Selection of the boost diode is a major design decision in CCM boost converter. Since the diode is hard commutated at a high current, and the reverse recovery can cause significant power loss, noise and current spikes. Reverse recovery can be a bottle neck for high switching frequency and high power density power supplies. Additionally, at low line, the available diode conduction duty cycle is quite low, and the forward current quite high in proportion to the average current. For that reason, the first criteria for selecting a diode in CCM boost are fast recovery with low reverse recovery charge, followed by V_f operating at high forward current.

Since Silicon Carbide (SiC) Schottky diodes have capacitive charge, Qc, rather than reverse recovery charge, Q_{rr}. Their switching loss and recovery time are much lower compared to Silicon Ultrafast diode, and will show an enhanced performance. Moreover, SiC diodes allow higher switching frequency designs, hence, higher power density converters is achieved. The capacitive charge for SiC diodes are not only low, but also independent on di/dt, current level, and temperature; which is different from Si diodes that have strong dependency on these conditions.

The recommended diode for CCM boost applications is the 650 V thinQ!™ SiC Schottky Diode Generation 5, which include Infineon's leading edge technologies, such as diffusion soldering process and wafer thinning technology. The result is a new family of products showing improved efficiency over all load conditions, coming from both the improved thermal characteristics.

Note that even with high surge current capability of SiC diode Shottky Diode, it is still preferred to use a bulk pre-charge diode as shown earlier in section 6.1.1. This is a low frequency standard diode with high I^2t rating to support pre-charging the bulk capacitor to the peak of the AC line voltage; this is a high initial surge current stress (which should be limited by a series NTC) that is best avoided for the HF boost rectifier diode.

In this demo board, a 6 A IDH16G65C5 diode is selected.

2.5 Output Capacitor

Possible over-voltages require the selection of a 450 V (low impedance) type capacitor. The minimum capacitance is defined by the minimum hold up time and the minimum allowable DC-link voltage of the system:

- t_{hu} = 10ms
- V_{bmin} = 320V

$$C_b = \frac{2 * P_{out} * t_{hu}}{V_b^2 - V_{bmin}^2} = 381\ \mu F$$

Equation 2-6

The chosen type is a 470 µF RUBYCON 450 V XH470MEFCSN30X50 capacitor.

2.6 Heat sink design and cooling fan

Heatsinks for the rectifier and power semiconductors are made of a 1,5 mm copper plate.
Fan control depends on board/heatsink temperature. There are two speed levels. The fan starts with low speed at 57°C. Above 79°C the fan runs with high speed.

2.7 Specification: Input, Output, Efficiency, Power factor

2.7.1 Input Requirements

Table 2 Input Requirements

Parameter	Value
Input voltage range, V_{in_range}	90 V_{AC} – 265 V_{AC}
Nominal Input Voltage, V_{in}	230 V_{AC}
AC Line Frequency range, f_{AC}	47 – 64 Hz
Max peak Input current, I_{in_max}	10 ARMS @ V_{in} = 90 V_{AC} , P_{out_max} = 800 W , Max load
Turn on input voltage, V_{in_on}	80 V_{AC} – 87 V_{AC}, Ramping up
Turn off input voltage, V_{in_off}	75 V_{AC} – 85 V_{AC}, Ramping down
Power Factor Correction, PFC	Shall be greater than 0.95 from 20% rated load and above
Hold up time	10 ms after last AC zero point @ P_{out_max} = 800 W, V_{out_min} = 320 V_{DC}

2.7.2 Output Requirements

Table 3 Output Requirements

Parameter	Parameter
Nominal output Voltage, V_{out}	380 V_{DC}
Maximum Output Power, P_{out}	800 W
Peak Output Power, P_{out_max}	1 kW
Maximum Output Current, I_{out_max}	2,1 A
Output Voltage ripple	Max 20 $V_{pk\text{-}pk}$ @ V_{out} , I_{out}
Output OV threshold maximum	450 V_{DC}
Output OV threshold minimum	420V_{DC}

3 ICE3PCS01G PFC Controller

The ICE3PCS01G is a 14pin controller IC for power factor correction converters. It is suitable for wide range line input applications from 85 to 265 V_{AC} and with overall efficiency above 97%. The IC supports the converters in boost topology and operates in continuous conduction mode (CCM) with average current control.

The IC operates with a cascaded control; the inner current loop and the outer voltage loop. The inner current loop of the IC controls the sinusoidal profile for the average input current. It uses the dependency of the PWM duty cycle on the line input voltage to determine the corresponding input current. This means the average input current follows the input voltage as long as the device operates in CCM. Under light load condition, depending on the choke inductance, the system may enter into discontinuous conduction mode (DCM) resulting in a higher harmonics but still meeting the Class D requirement of IEC 1000-3-2.

The outer voltage loop of the IC controls the output bulk voltage and is integrated digitally within the IC. Depending on the load condition, internal PI compensation output is converted to an appropriate DC voltage which controls the amplitude of the average input current.

The IC is equipped with various protection features to ensure safe operating for the system and the device.

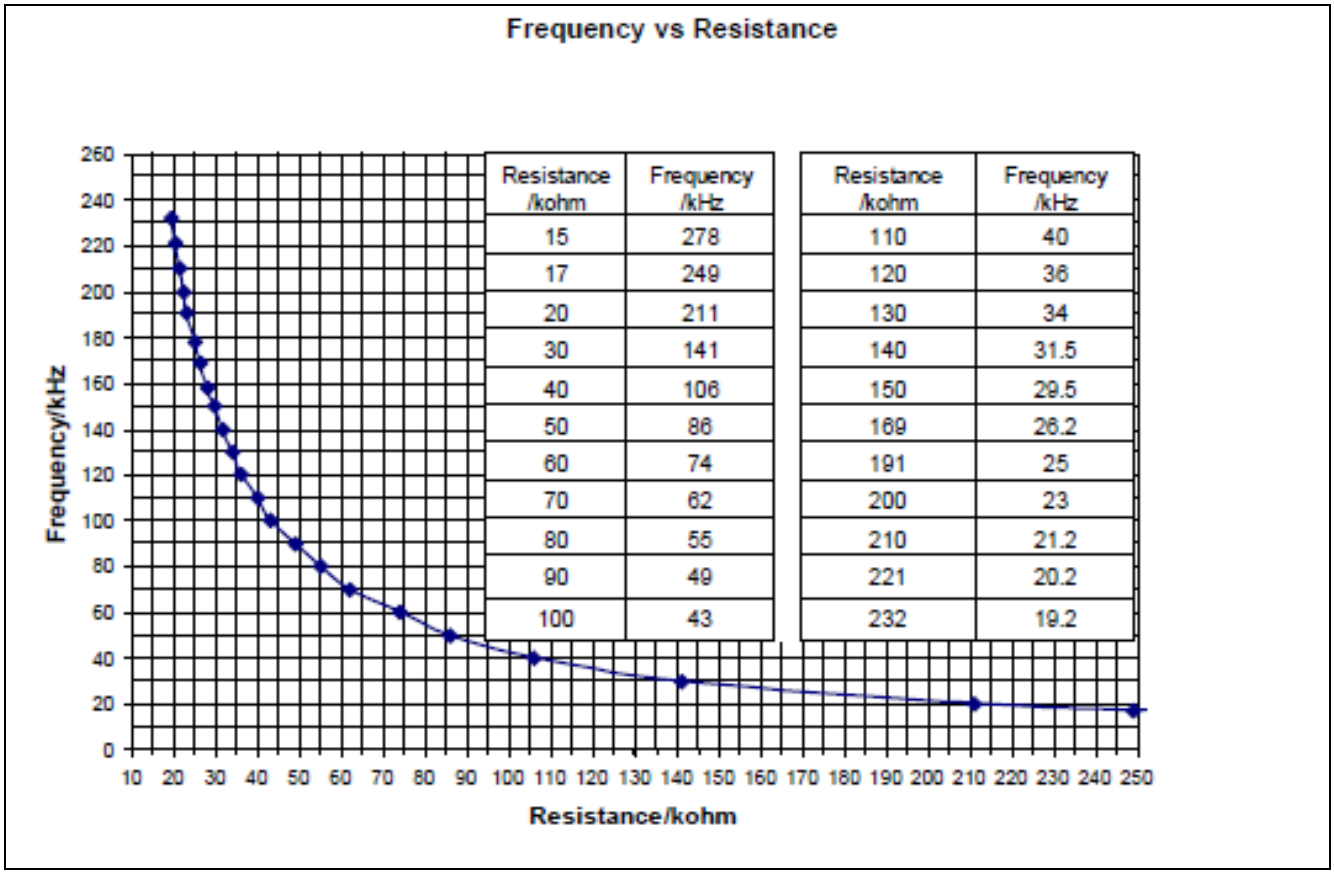
3.1 Soft Start

During power up when the V_{OUT} is less than 96% of the rated level, internal voltage loop output increases from initial voltage under the soft-start control. This results in a controlled linear increase of the input current from 0 A as can be seen in Figure 20. This helps to reduce the current stress in power components.

Once V_{OUT} has reached 96% of the rated level, the soft-start control is released to achieve good regulation and dynamic response and VB_OK pin outputs 5V indicating PFC output voltage in normal range.

3.2 Switching Frequency

The switching frequency of the PFC converter can be set with an external resistor R_{FREQ} at pin FREQ with reference to pin SGND. The voltage at pin FREQ is typical 1V. The corresponding capacitor for the oscillator is integrated in the device and the R_{FREQ}/frequency is given in Figure 7. The recommended operating frequency range is from 21 kHz to 250 kHz. In the case of this demo board, a R_{FREQ} of 33 kΩ at pin FREQ will set a switching frequency f_{SW} of aound 134 kHz typically.



Resistance /kohm	Frequency /kHz	Resistance /kohm	Frequency /kHz
15	278	110	40
17	249	120	36
20	211	130	34
30	141	140	31.5
40	106	150	29.5
50	86	169	26.2
60	74	191	25
70	62	200	23
80	55	210	21.2
90	49	221	20.2
100	43	232	19.2

Figure 6 Frequency setting in the ICE3PCS01G IC

3.3 Protection Features

3.3.1 Open Loop Protection

The open loop protection is available for this IC to safe-guard the output. Whenever voltage at pin VSENSE falls below 0.5 V, or equivalently V_{OUT} falls below 20% of its rated value, it indicates an open loop condition (i.e. VSENSE pin not connected). In this case, most of the blocks within the IC will be shutdown. It is implemented using a comparator with a threshold of 0.5 V.

3.3.2 Peak Current Limit

The IC provides a cycle by cycle peak current limitation (PCL). It is active when the voltage at pin ISENSE reaches -0.2 V. This voltage is amplified by a factor of -5 and connected to comparator with a reference voltage of 1.0 V. A de-glitcher with 200 ns after the comparator improves noise immunity to the activation of this protection. In other words, the current sense resistor should be designed lower than -0.2 V PCL for normal operation.

3.3.3 IC Supply Under Voltage Lock Out

When V_{CC} voltage is below the under voltage lockout threshold $V_{CC,UVLO}$, typical 11 V, IC is off and the gate drive is internally pulled low to maintain the off state. The current consumption is down to 1.4 mA only.

3.3.4 DC-link Voltage Monitor and Enable Function

The IC monitors the bulk voltage status through VSENSE pin and output a TTL signal to enable PWM IC or control inrush relay. During soft-start once the bulk voltage is higher than 95% rated value, pin VB_OK outputs a high level. The threshold to trigger the low level is decided by the pin VBTHL voltage adjustable externally.

When pin VBTHL is pulled down externally lower than 0.5V most function blocks are turned off and the IC enters into standby mode for low power consumption. When the disable signal is released the IC recovers by soft-start.

4 ICE2QR4780Z Controllers for Auxiliary Converter

4.1 Input and Output requirements

The auxiliary voltages needed to supply the control circuitry and the fans must be provided by the dedicated Flyback DC/DC converter ICE2QR4780Z, which is assembled on the power board. Auxiliary voltages are supplied by the DC-link voltage.

Table 4 Input / Output Requirements

Parameter	Value
Input voltage range, V_{in_range}	125 V_{DC} - 450V_{DC}
Nominal output Voltage, V_{aux_pri}	12 V_{DC} +/-10%
Nominal output Voltage, V_{aux_sec}	12 V_{DC} +/-10%
Maximum Output Power, P_{out}	6 W

4.2 Flyback Transformer

The transformer design is based on a gapped ferrite core EE 16/8/5 with a horizontal arranged bobbin. The total air gap is 0,2 mm. The selected core material is TDK N87 or equivalent.

The turns ratio was chosen to be 184:15:15, resulting in 150 V (approximately) reflected primary transformer voltage.

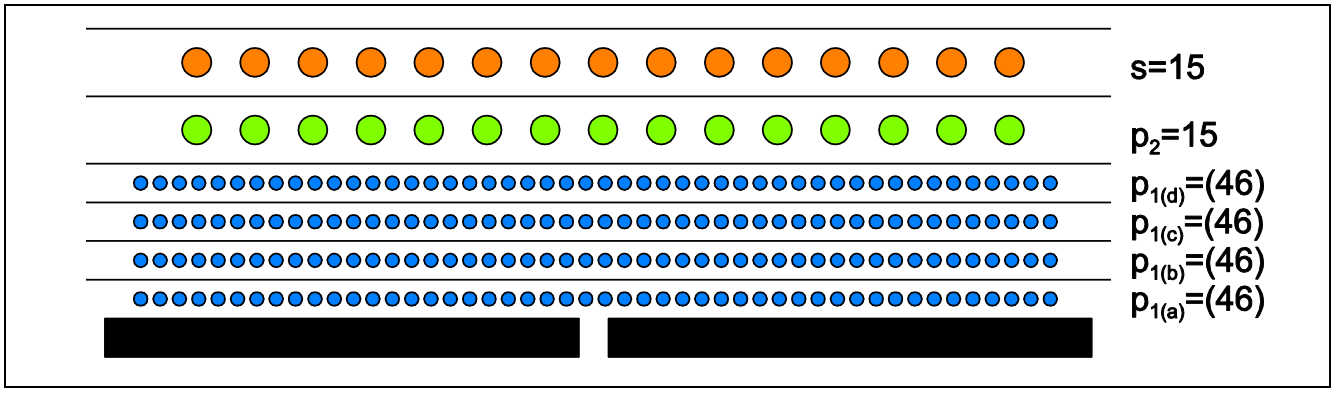


Figure 7 Winding arrangement

The secondary winding (S) has safety insulation from primary side, which is implemented using triple insulated wire. The other windings are made of standard enameled wire. The high voltage primary winding (P1) is split in to 4 layers.

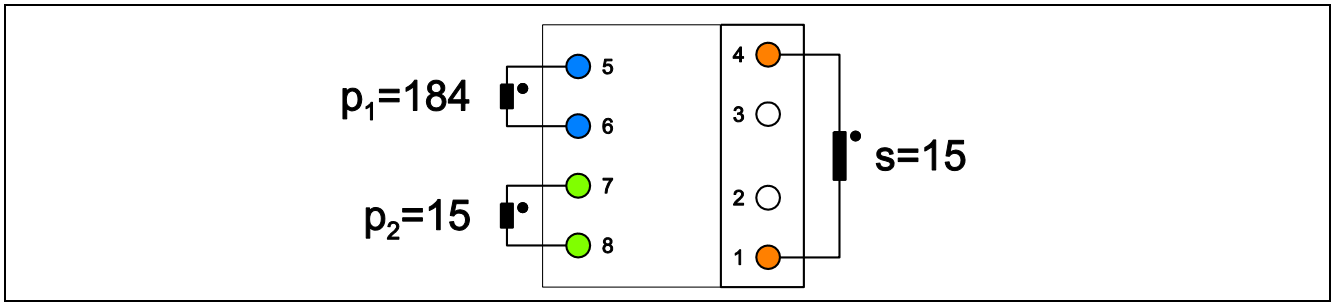
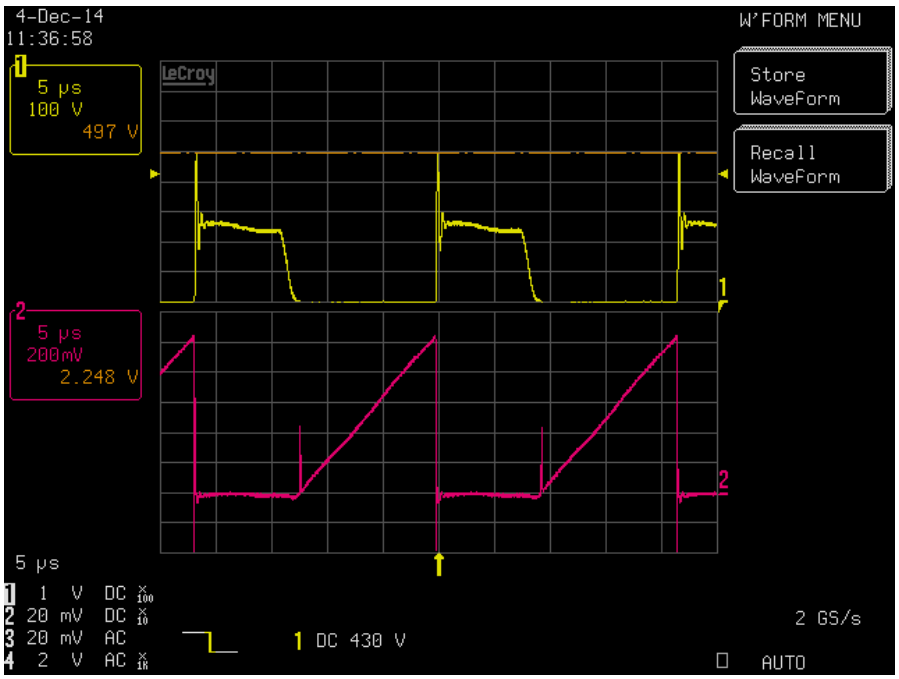


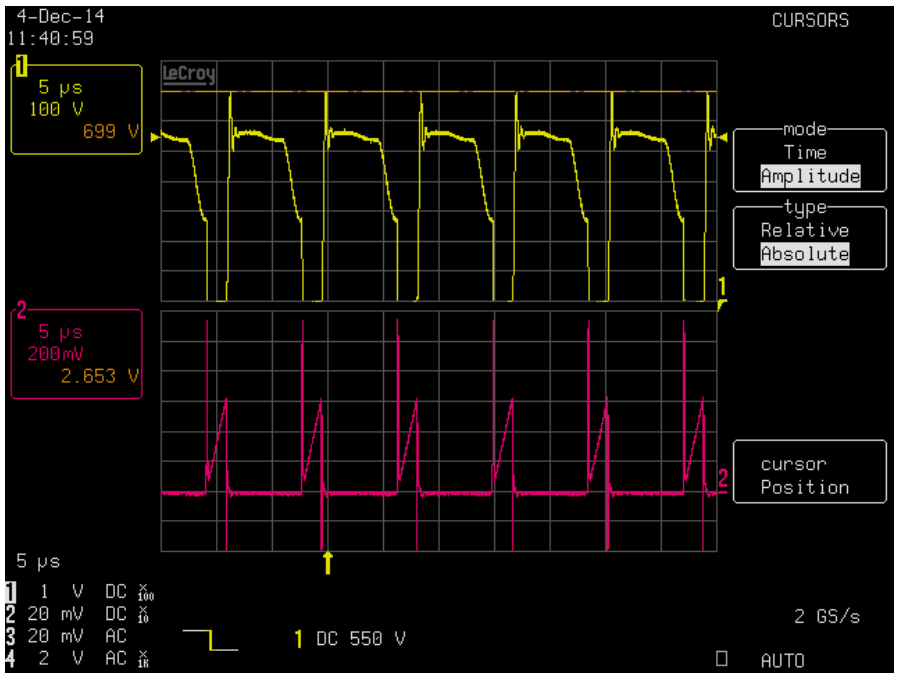
Figure 8 Pin arrangement, top view

4.3 Switching Frequency

The ICE2QR4780Z is a Quasi-Resonant PWM Controller with integrated 800V CoolMOS™. The switching frequency depends on load power and input voltage and is between 40 kHz and 130 kHz.



- V_{in}=100 V_{DC}
- C1-Drain-Source Voltage
- C2-Shuntvoltage (R3,9Ohm)



- V_{in}=400 V_{DC}
- C1-Drain-Source Voltage
- C2-Shuntvoltage (R3,9Ohm)

Figure 9 Characteristics of Auxiliary power supply

5 Experimental Results

5.1 Efficiency at Low and High Line

Efficiency measurements were carried out with a “WT3000” Yokogawa Power Meter. Losses of the EMI-Filter are included. The fan was supplied from an external voltage source.

Table 5 Efficiency Measurements

Input	V_{IN}	I_{IN}	P_{IN}	V_{OUT}	I_{OUT}	P_{OUT}	η	PF
230VAC	230,55	0,41	86,47	378,75	0,22	82,32	95,20	0,9131
	229,72	0,75	166,03	378,75	0,42	160,38	96,60	0,9666
	229,04	1,10	248,80	378,75	0,64	241,81	97,19	0,9838
	228,85	1,46	330,36	378,76	0,85	321,99	97,47	0,9905
	228,54	1,79	407,90	378,76	1,05	398,39	97,67	0,9945
	228,04	2,16	491,52	378,77	1,27	480,41	97,74	0,9961
	227,51	2,53	574,54	378,78	1,48	561,87	97,79	0,9967
	227,06	2,90	655,97	378,78	1,69	641,64	97,82	0,9966
	229,54	3,23	738,61	378,78	1,91	722,72	97,85	0,9970
	229,31	3,59	820,37	378,79	2,12	802,74	97,85	0,9971
90VAC	89,08	0,99	87,93	378,74	0,22	81,98	93,22	0,9946
	90,71	1,87	168,78	378,75	0,42	159,72	94,64	0,9969
	90,14	2,82	253,62	378,76	0,64	241,37	95,17	0,9979
	89,60	3,77	337,50	378,76	0,85	321,43	95,24	0,9982
	90,74	4,67	422,62	378,76	1,06	402,44	95,23	0,9982
	90,14	5,61	504,53	378,76	1,27	479,59	95,06	0,9984
	90,57	6,54	591,56	378,77	1,48	561,15	94,86	0,9984
	90,14	7,52	676,69	378,73	1,69	639,74	94,54	0,9986
	90,46	8,49	766,49	378,77	1,91	722,07	94,20	0,9985
	90,57	9,46	855,23	378,78	2,12	802,12	93,79	0,9986

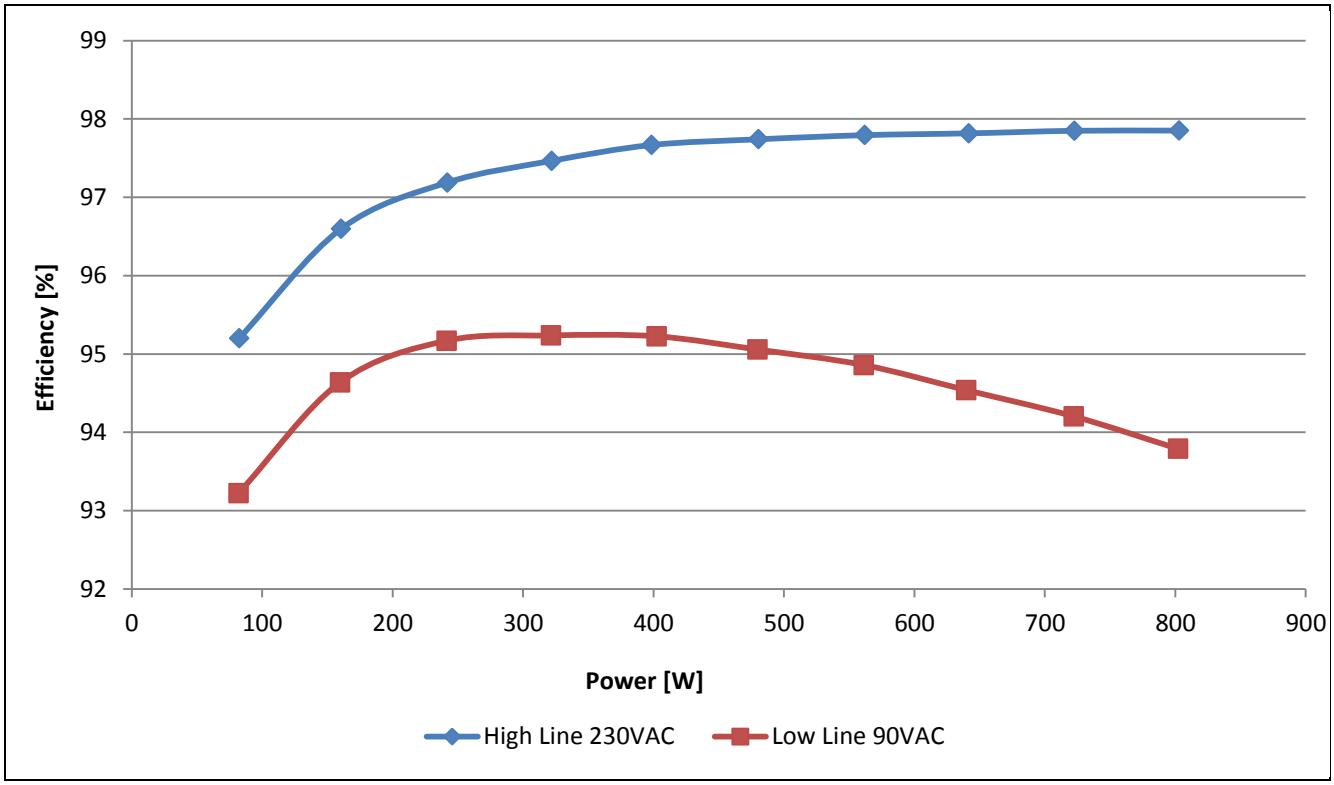


Figure 10 High line and low line efficiency with 2x IPP60R180C7 @ f_s = 130 kHz, R_{gate_on} = 39 Ω, R_{gate_off} = 14 Ω

5.2 Input current THD

The following results were measured with a“WT3000” Yokogawa Power Meter.

Regulation	:	IEC61000-3-2 Ed3.0 am2 IEC61000-4-7 Ed2.0 A1	PASS		
Class	:	CLASS A			
MeasureTime	:	300.06sec	Set Fundamental I	:	----------
Model	:	YOKOGAWA WT3000	Set Power Factor	:	----------
Rating Voltage	:	230.00 V	Set P	:	----------
Wiring	:	single-phase 2-wire	Sigma W Max	:	822.5498 W
Element	:	1	Sigma PF	:	0.9973
Range	:	300V/30A	Distortion factor(V)	:	1.80 %
Current(rms)	:	3.5893 A	V THDS	:	1.80 %
Voltage(rms)	:	229.20 V	V THDG	:	1.81 %
Frequency	:	49.990 Hz	Distortion factor(A)	:	4.93 %
Power Factor	:	0.9973	A THDS	:	4.97 %
POHC Limit	:	0.2514 A	A THDG	:	5.09 %
POHC Max	:	0.0327 A	P THD	:	0.06 %
THC	:	0.1823 A	Power Limit	:	----------

Figure 11 Operating conditions, norms and THD results

Order	Measure[A]	Limit[A]	Margin[%]	Order	Measure[A]	Limit[A]	Margin[%]
1	3.5847			2	0.0168	1.0800	98.4
3	0.0744	2.3000	96.8	4	0.0104	0.4300	97.6
5	0.1466	1.1400	87.1	6	0.0094	0.3000	96.9
7	0.0481	0.7700	93.7	8	0.0085	0.2300	96.3
9	0.0259	0.4000	93.5	10	0.0080	0.1840	95.6
11	0.0231	0.3300	93.0	12	0.0078	0.1533	94.9
13	0.0152	0.2100	92.7	14	0.0078	0.1314	94.1
15	0.0079	0.1500	94.7	16	0.0072	0.1150	93.7
17	0.0100	0.1324	92.5	18	0.0071	0.1022	93.0
19	0.0075	0.1184	93.7	20	0.0070	0.0920	92.4
21	0.0084	0.1071	92.2	22	0.0068	0.0836	91.9
23	0.0075	0.0978	92.4	24	0.0066	0.0767	91.4
25	0.0103	0.0900	88.6	26	0.0064	0.0708	91.0
27	0.0103	0.0833	87.6	28	0.0061	0.0657	90.7
29	0.0100	0.0776	87.1	30	0.0058	0.0613	90.6
31	0.0103	0.0726	85.9	32	0.0056	0.0575	90.2
33	0.0077	0.0682	88.6	34	0.0054	0.0541	89.9
35	0.0086	0.0643	86.7	36	0.0053	0.0511	89.7
37	0.0150	0.0608	75.4	38	0.0051	0.0484	89.4
39	0.0093	0.0577	83.9	40	0.0049	0.0460	89.3

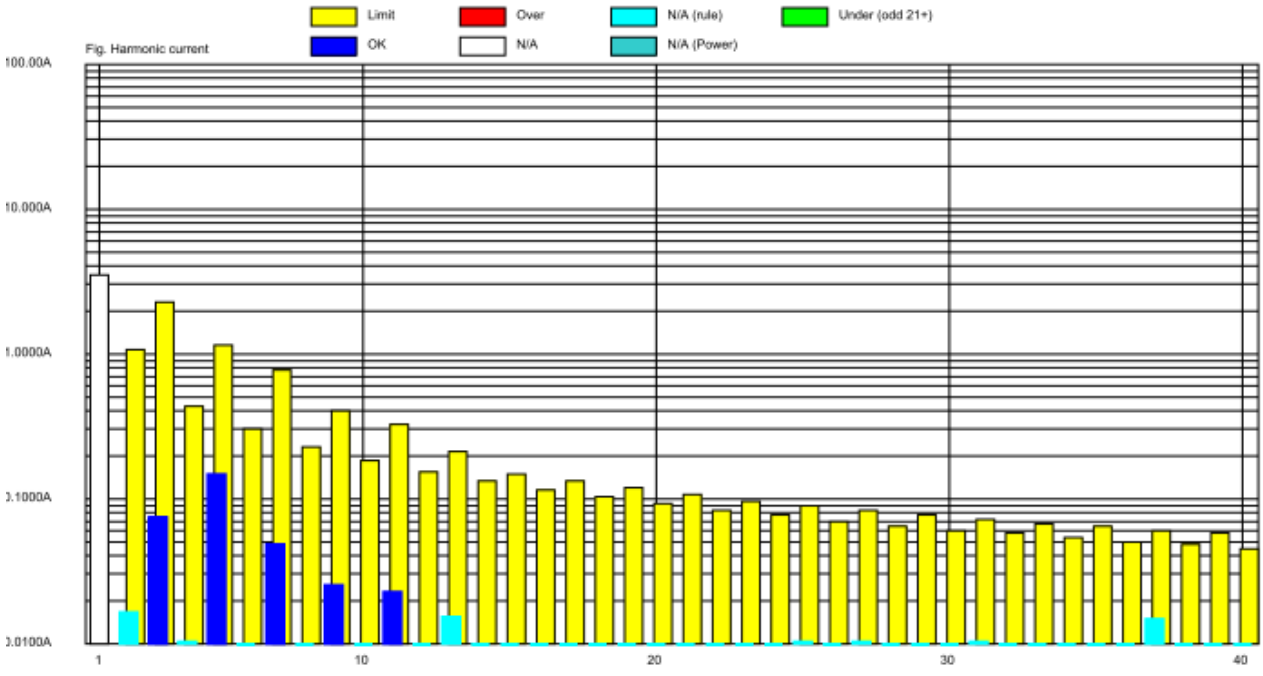


Figure 12 THD versus order of harmonics

5.3 Standby power consumption

Measurements show a standby power consumption below 1 W.

IEC 62301 Test Report

IEC62301 Second Edition compliance

Appliance(equipment) Details

<Product description>
Demoboard 800W

Item	Appliance	Equipment
Brand	IFX	YOKOGAWA
Model	5657_PWR_00	760304-04-MV
Type	Demo 800W	Firmware Ver.F5.13
Serial Number	002	0
Rated voltage / frequency	230 V / 50 Hz	-
Voltage Range	-	300V
Current Range	-	1A

Test Parameters

Item	Data
Name of mode	No Load
Mode category	Active mode
Cycle period	00:05:00
THD *(Upper Limit)	1.702 % (2.000 %)
Crest Factor *(Range)	1.386 - 1.399 (1.34 - 1.49)
Ambient temperature	25 degree
Test voltage / frequency	228.748 V / 50.022 Hz

Measured data, for each mode as applicable

Measured data

Item	Data
Measurement period	00:15:00 (Measure Period)
Power variation	29.290 %
Max Power Value	0.915 W
Last Power Value	0.824 W
Accumulated energy	0.207 Wh
Average Power	0.828 W

Test and laboratory details

<Test officer(s)>
Kurmis

Item	Data
Test report No./reference	N/A
Date of test	19 / 03 / 2015 09:10

Remarks column

N/A

Figure 13 Standby power consumption

5.4 Efficiency versus Semiconductor Stress

During the design process, there is always a trade-off between achieving high efficiency and semiconductor stress if the derating guidelines of the IPC 9592 standard are to be fulfilled. This stress depends on input current, output voltage, stray inductances and switching speed (di/dt).
Depending on the requirements of the application, the Designer can select the proper value of turn on and turn off gate resistors to achieve certain efficiency at a certain stress on MOSFET. The following table shows measurements of voltage characteristics and efficiency with different turn-off gate resistors.

Table 6 Scope

Channel	Remark
CH 1 (yellow)	Drain Source Voltage
CH 4 (green)	Gate Voltage
CH 2 (red)	Input Current

Table 7 Power Meter

Parameter	Remark
Urms1	Input Voltage
Irms1	Input Current
P1	Input Power
η1	Efficiency
λ1	Power Factor
Ithd1	Input Current Distortion
Urms2	Output Voltage
Irms2	Output Current
P2	Output Power
F5	Power Losses

5.4.1 Voltage characteristics and efficiency with different turn-off gate resistors

V_in=90VAC

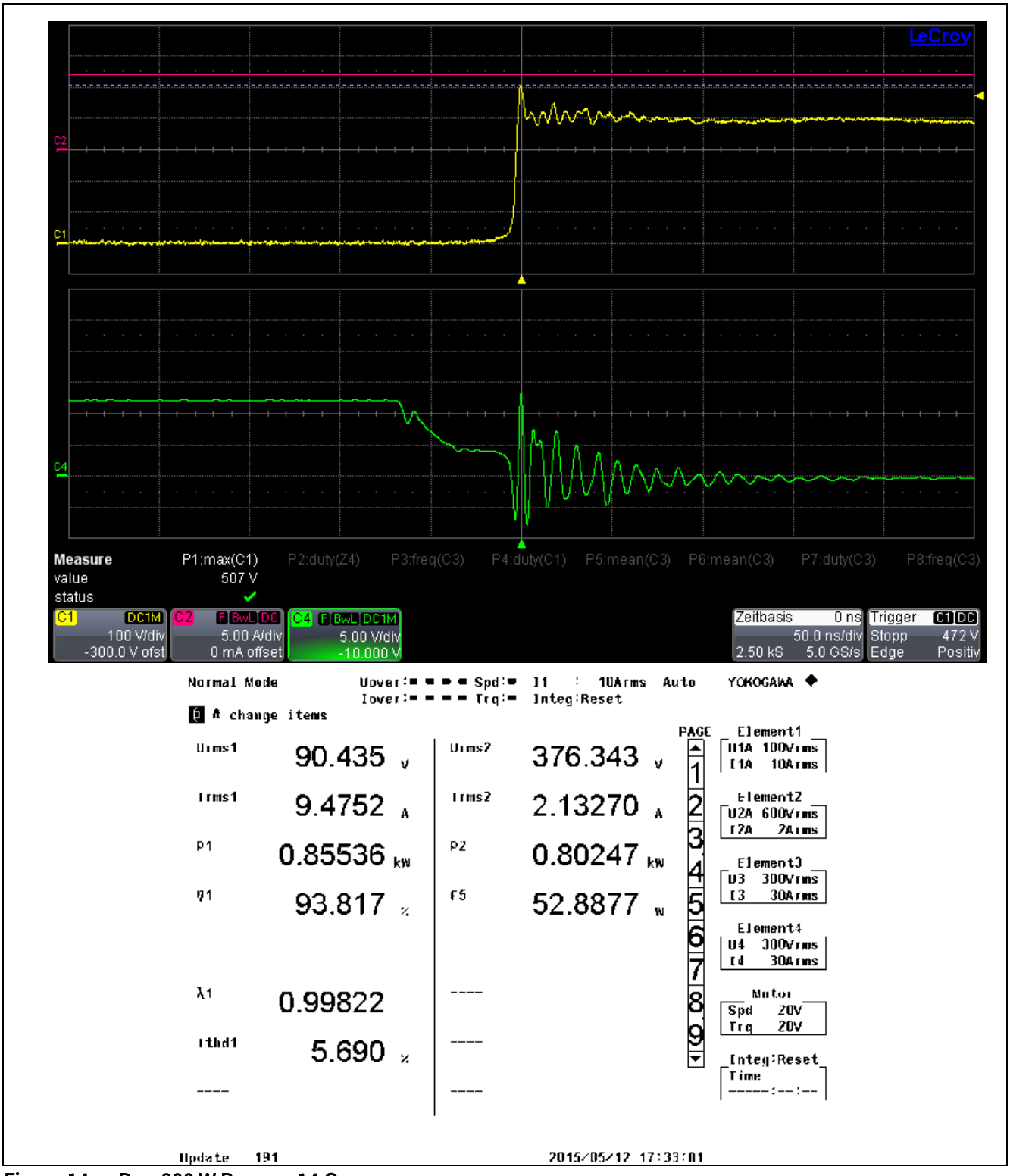


Figure 14 P_{out}=800 W R_{gate_OFF}=14 Ω

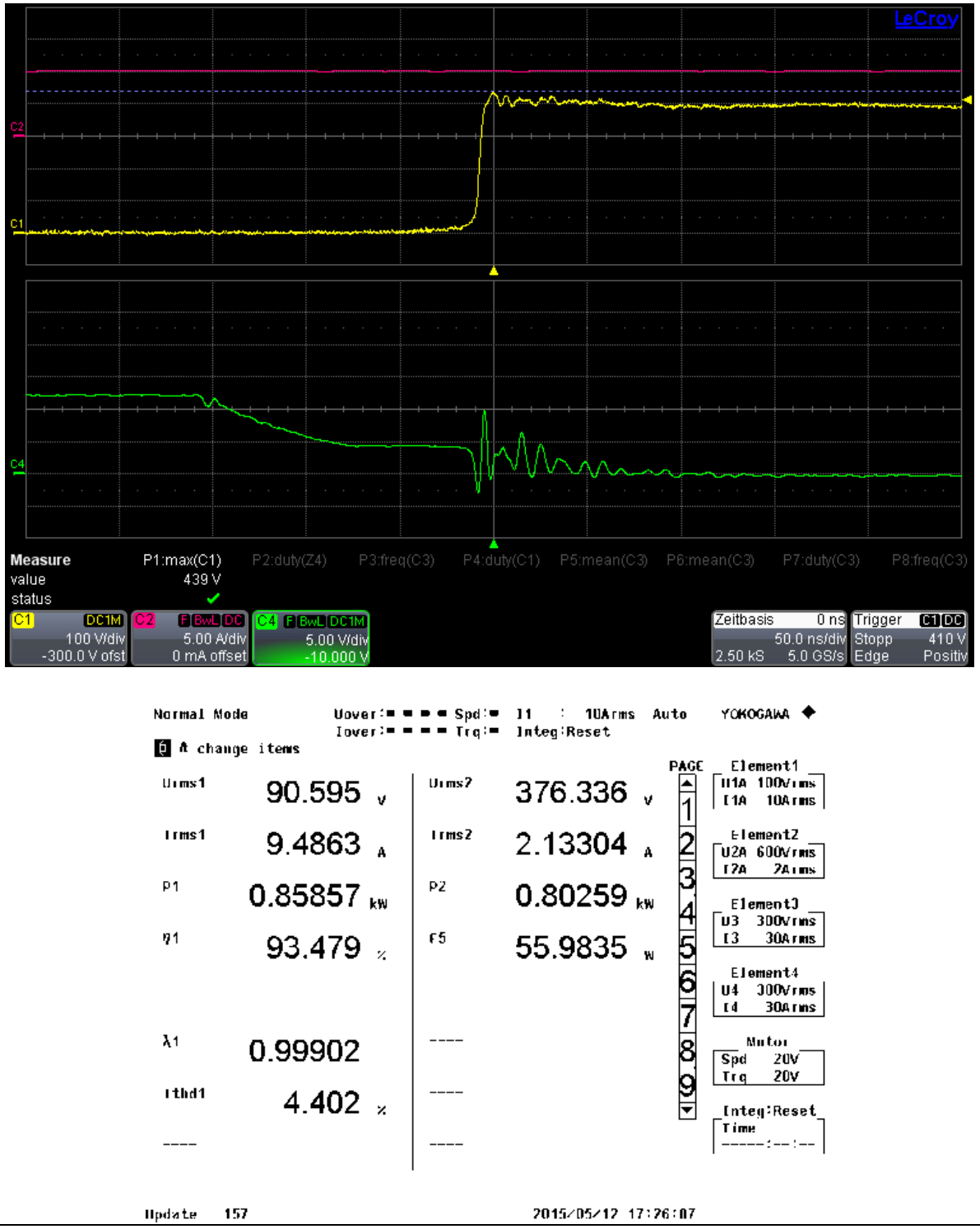


Figure 15 P_{out}=800 W, R_{gate_OFF}=39 Ω, V_in=230 V_{AC}

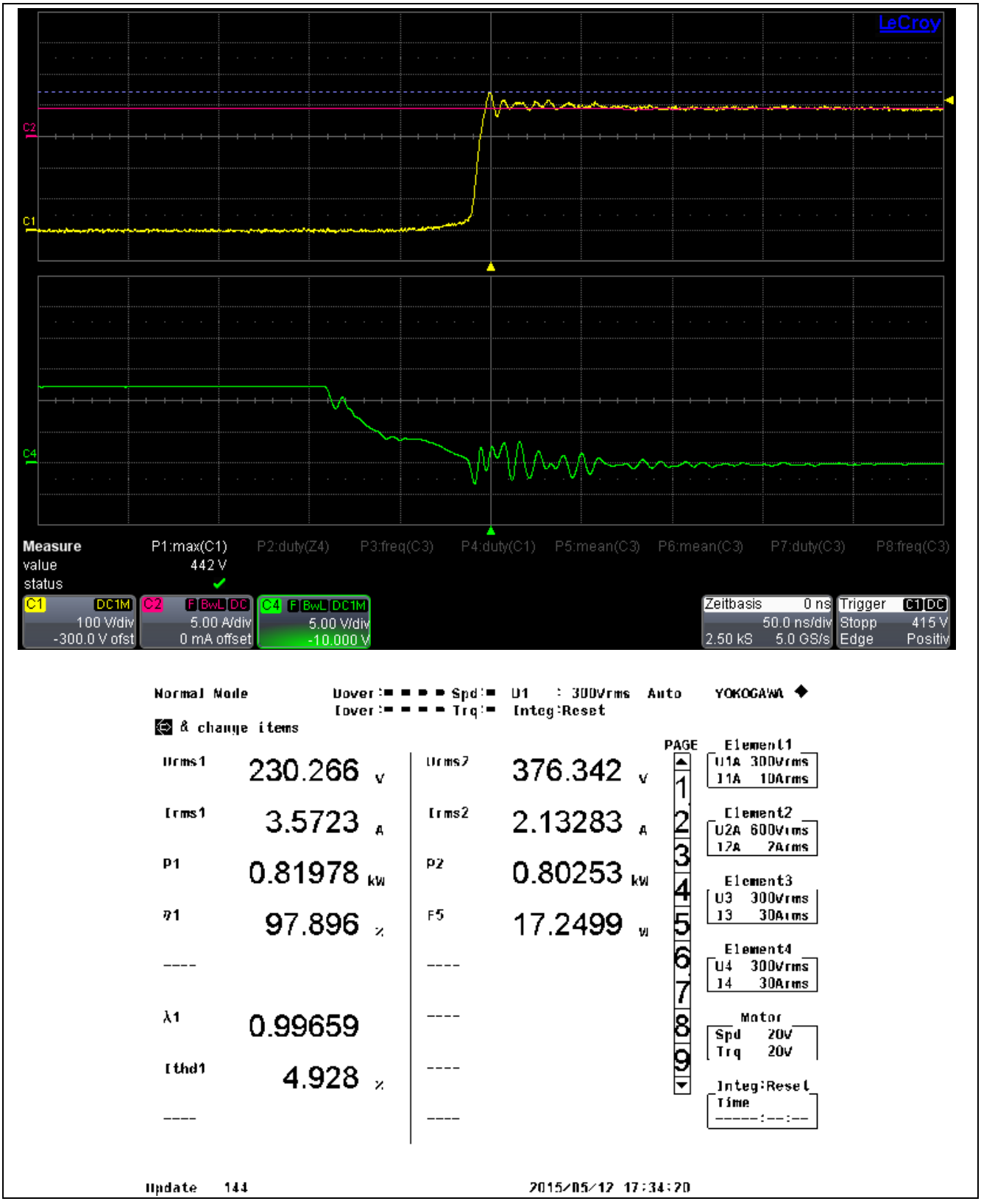


Figure 16 P_{out}=800 W, R_{gate_OFF}=14 Ω

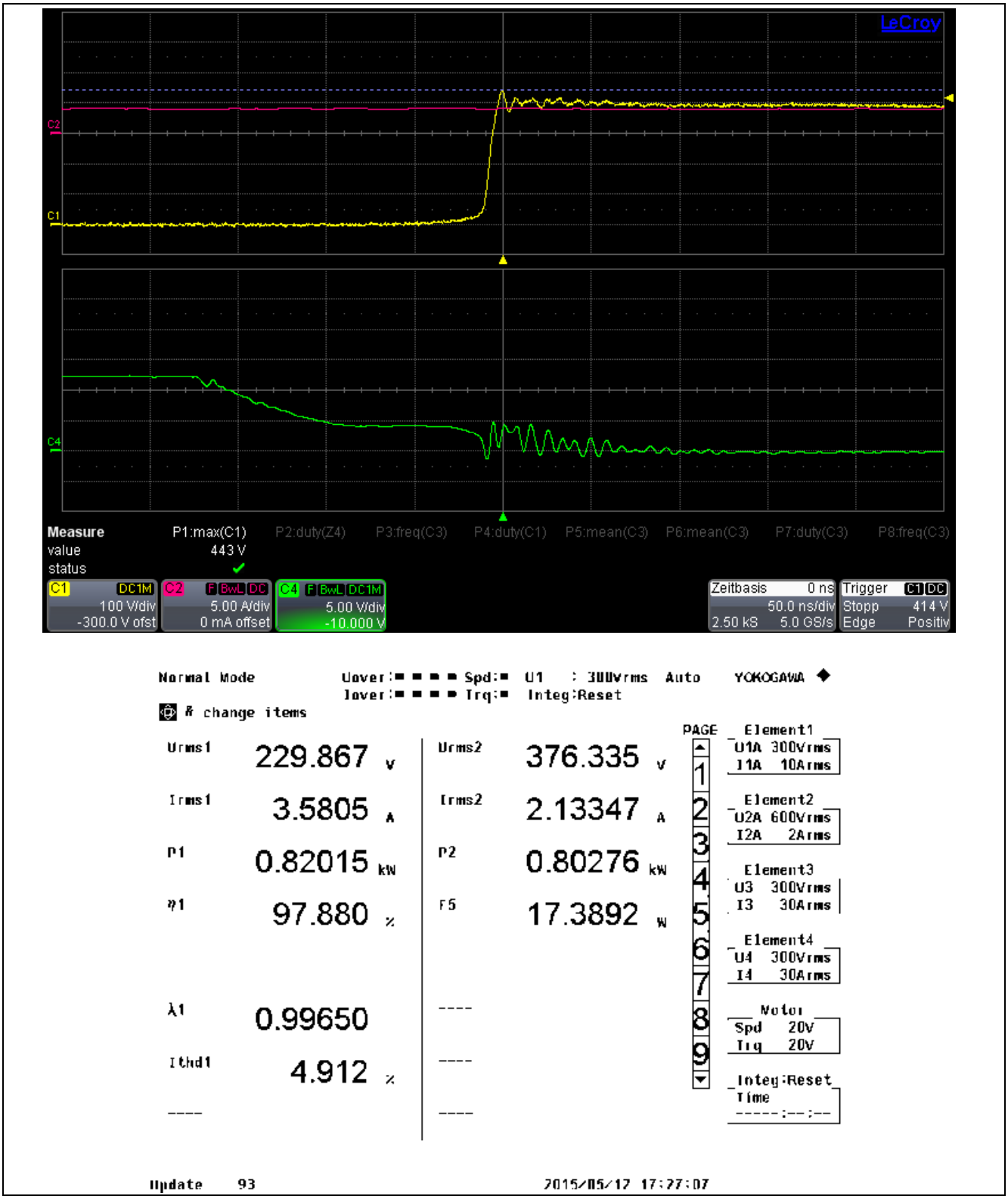


Figure 17 P_{out}=800 W, R_{gate_OFF}=39 Ω

5.5 Load Steps

- Channel 1 (yellow): DC-link Voltage
- Channel 4 (green): Load Current

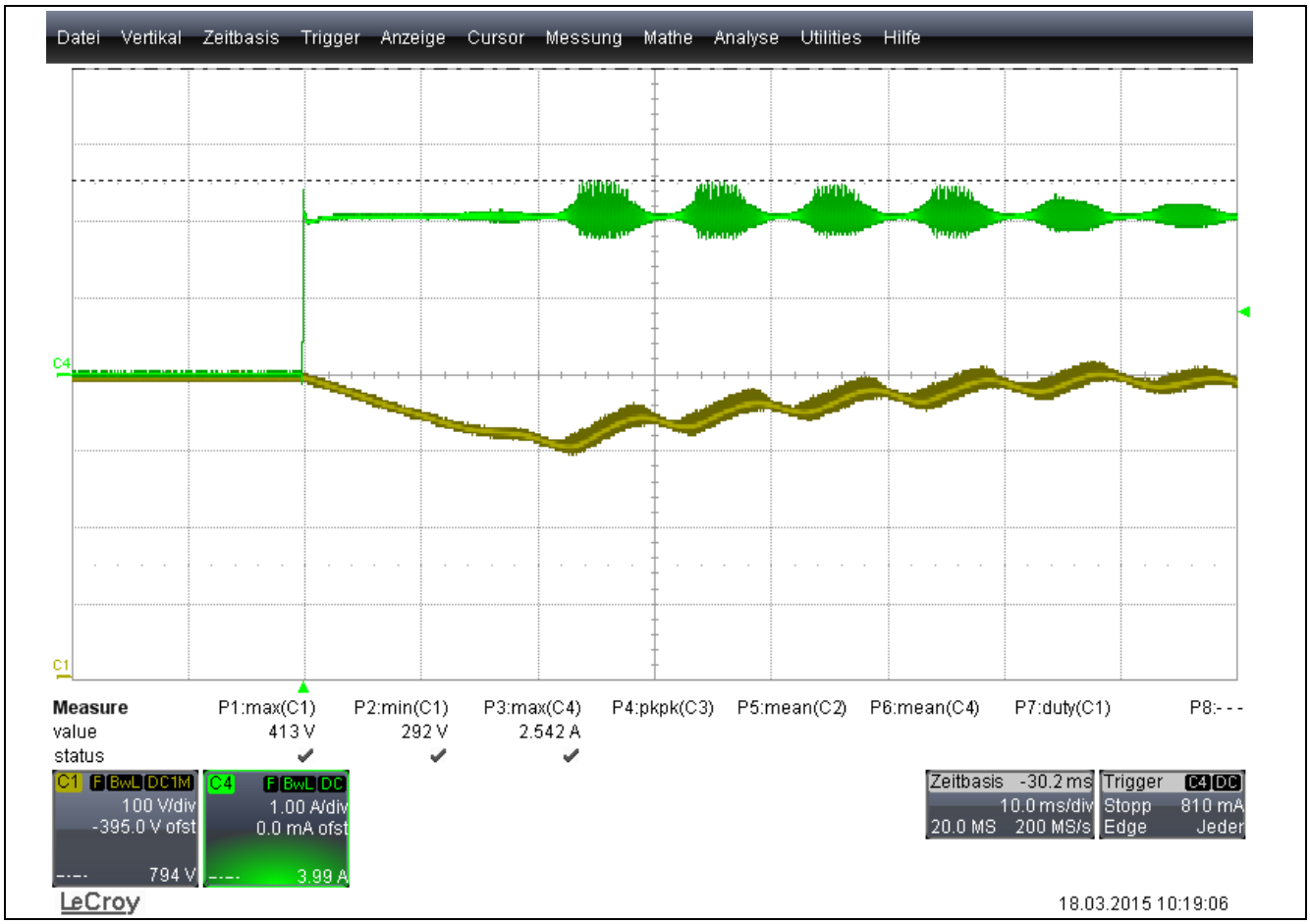


Figure 18 Load step 0% of load ➔ 100% of load V_{in}=90 V_{AC}

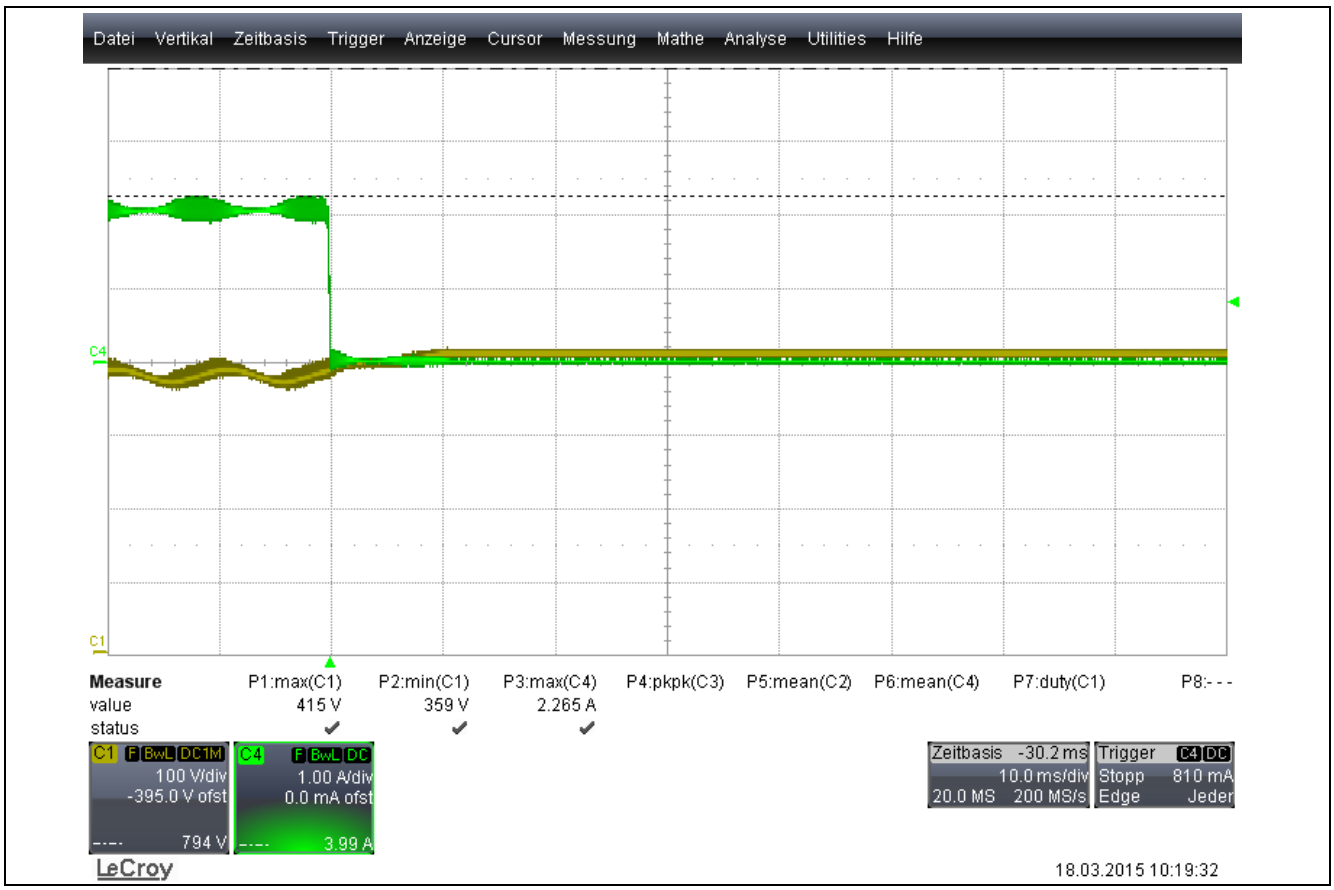


Figure 19 Load step 100% of load ➔ 0% of load V_{in}=90 V_{AC}

5.6 Signaling and Protection

5.6.1 Signaling

Three LEDs on the control board state operating conditions and errors:

- An orange LED indicates the presence of V_{in_range} at the input (LED turns on if V_{in}>90 V, LED turns off if V_{in}<83 V.
- A green LED indicates the presence of V_{out} at the output (LED turns on if V_{out}>359 V, LED turns off if V_{out}<351 V.
- A red LED indicates over-temperature protection.

5.6.2 Protection

Several protection functions are implemented on the demo-board.

- The converter is protected against over temperature conditions caused by loss of fan cooling or excessive ambient temperature which could cause failures of internal parts. The converter shuts down when the temperature monitored on the heatsink exceeds 90°C. This protection is latching type.
- The power factor correction has an Over-Voltage Protection (OVP) circuit for the DC-link voltage that is independent of the power factor correction control loop. This independent OVP circuit will latch the PFC section off when the DC-link voltage exceeds 436 V.
- The converter has a brown out protection. The turn on input voltage is 88 $V_{AC.}$ The turn off voltage is 72 V_{AC}.

- There is protection for the average input current, limiting the input current to 9,8 A_{rms}.
  The DC-link voltage will drop in case this protection is active.

Attention: ***The over current limit only works if the DC-link voltage is higher than the rectified input voltage!***

- To prevent the board from catastrophic failure, the input of the converter is protected by a solderable type 15 A/250 V_{AC} fuse

5.7 Conducted EMI measurements

EMI is a very important quality factor for a power supply. The EMI has to consider the whole SPMS and is split into radiated and conductive EMI considerations. For the described evaluation PFC board it is most important to investigate on the conducted EMI-behavior since it is the input stage of any SMPS below a certain power range.

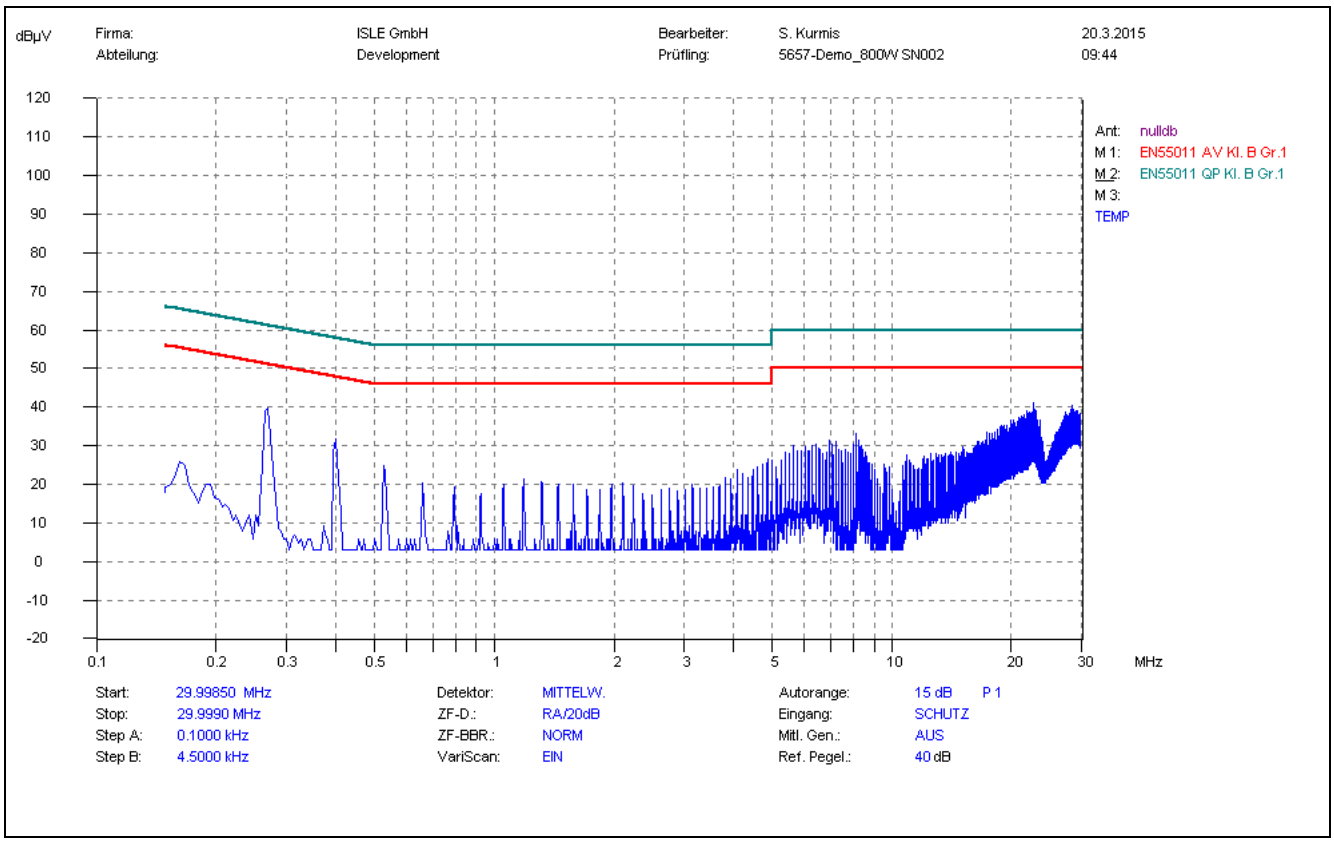


Figure 20 Conductive EMI Measurement (average measurement ➔ red limit) of the Board with resistive load (800 W) and input voltage of 230 V_{AC}

5.8 Start-up behavior

5.8.1 Inrush Current

The PFC converter provides a circuitry to limit the turn-on inrush current on the first half cycle to 35 A_{peak}. The NTC-Limiter is bypassed by relay when PFC is running and input current is greater than 0,2 A_{rms}. Turn off of this relay is delayed for 8 s.

Key to the following 2 figures

- Channel 1 (yellow): DC-link voltage
- Channel 2 (red): switching voltage at inrush relay
- Channel 4 (green): input current

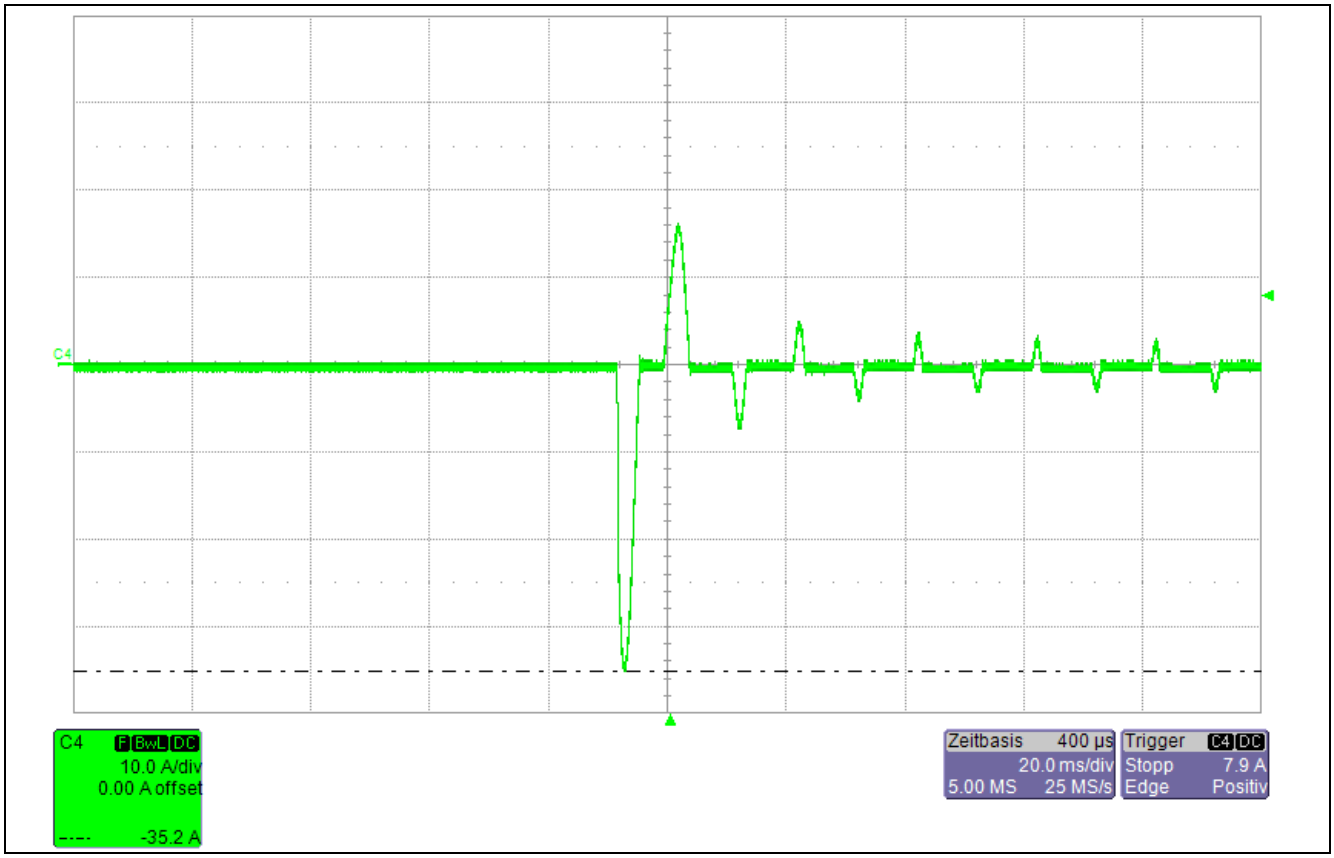


Figure 21 Limited inrush current at V_{in}=230 V_{AC}

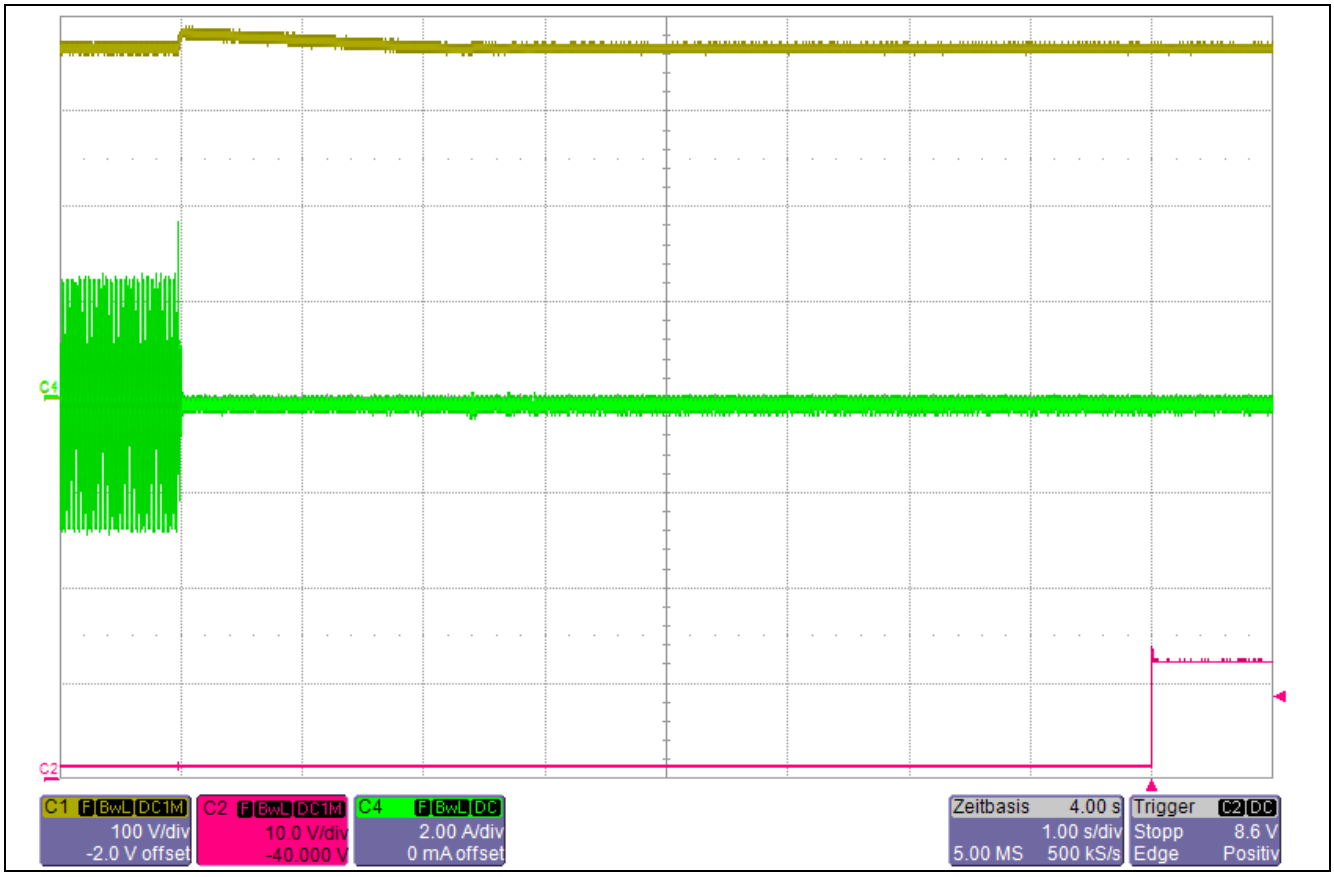


Figure 22 Delayed relay turn off

5.8.2 Start up

After turning-on the system, the auxiliary supply will provide a stable supply voltage of 12 V. If the components are supplied and the input voltage is higher than the brown out threshold the PFC begins to start operation.

Key to the following two figures

- Channel 1 (yellow): DC-link voltage
- Channel 2 (red): switching voltage at inrush relay
- Channel 3 (blue): 12V supply
- Channel 4 (green): input current

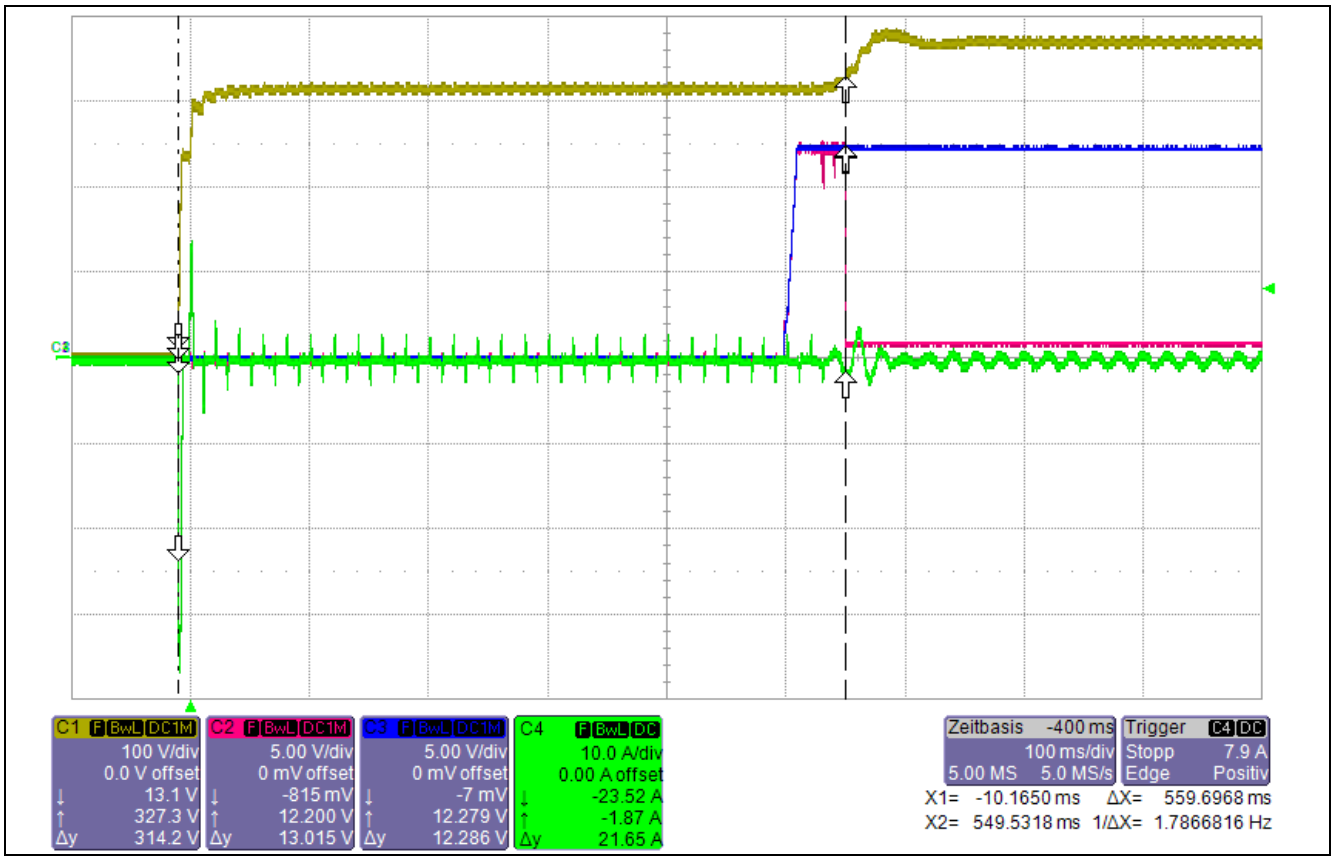


Figure 23 Start-up V_{in}=230 V_{AC}

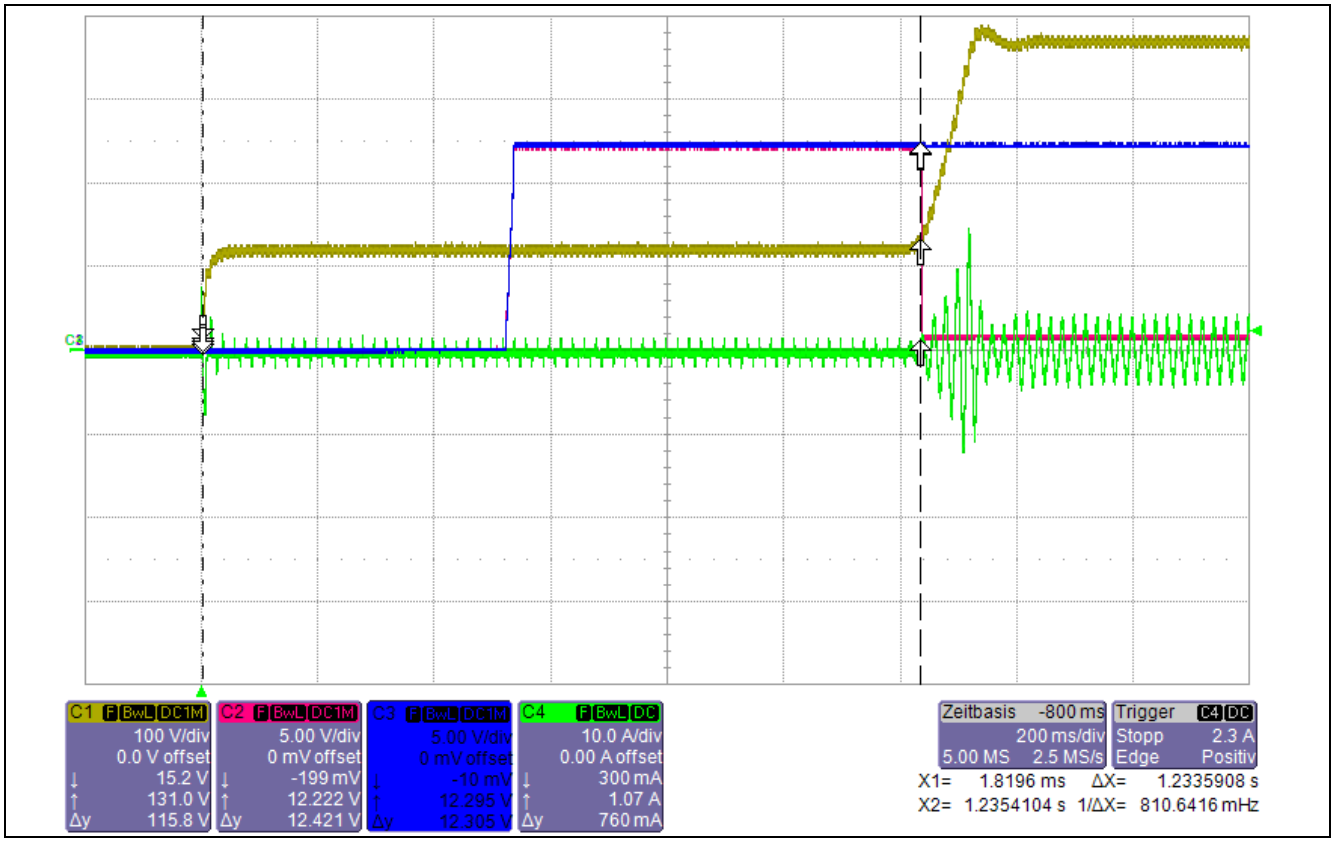


Figure 24 Start-up V_{in}=90 V_{AC}

6 Demo Board

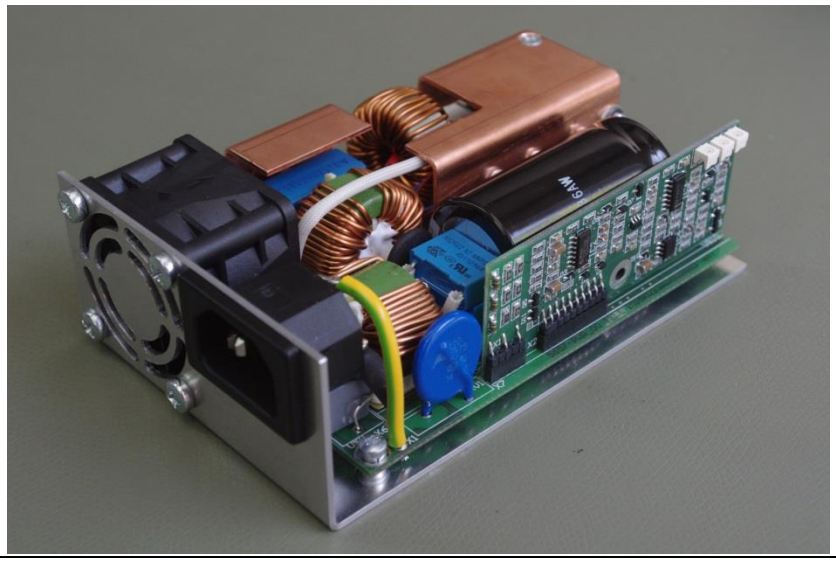


Figure 25 800 W PFC board

6.1 Power Board - Schematics

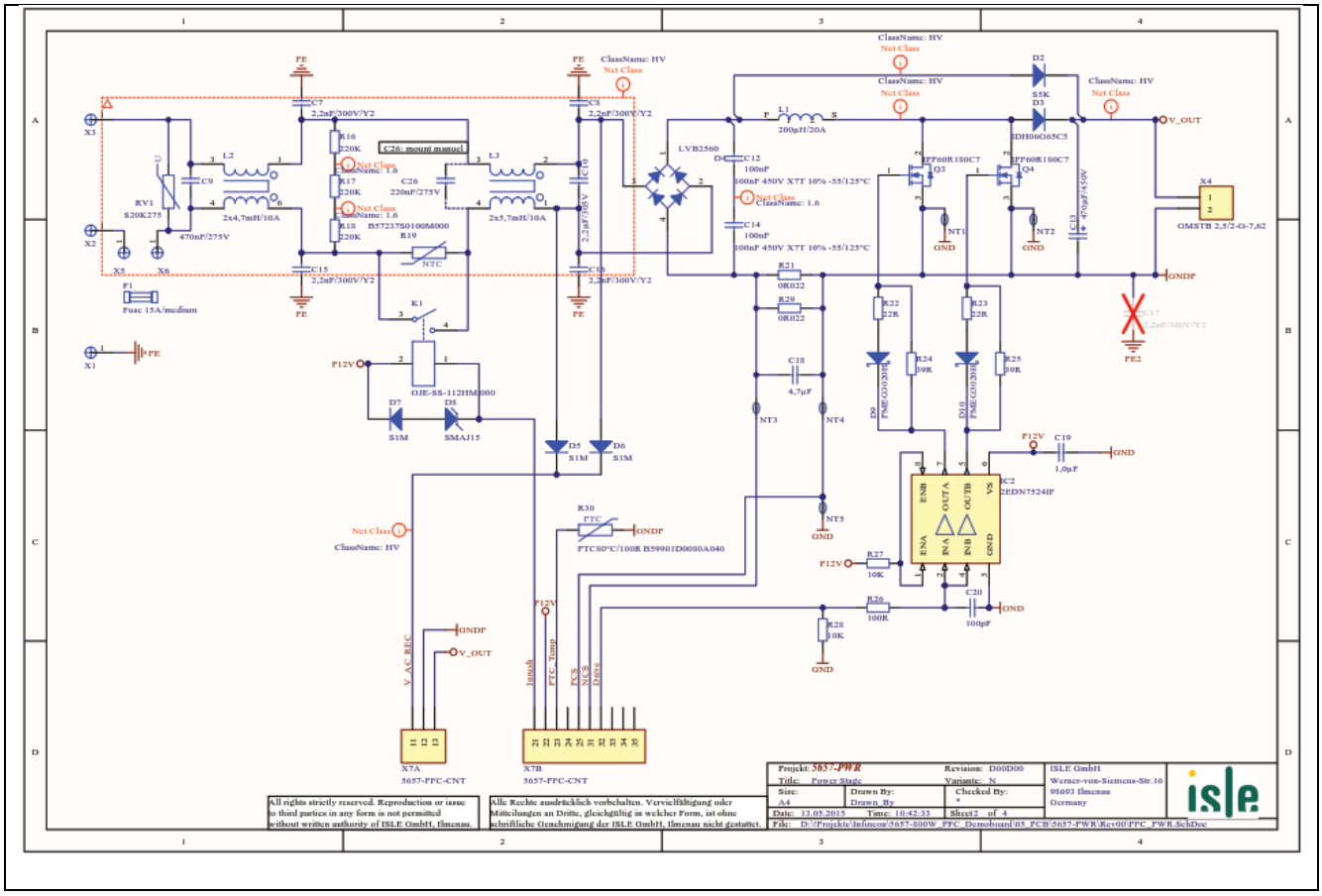


Figure 26 Schematic of power stage

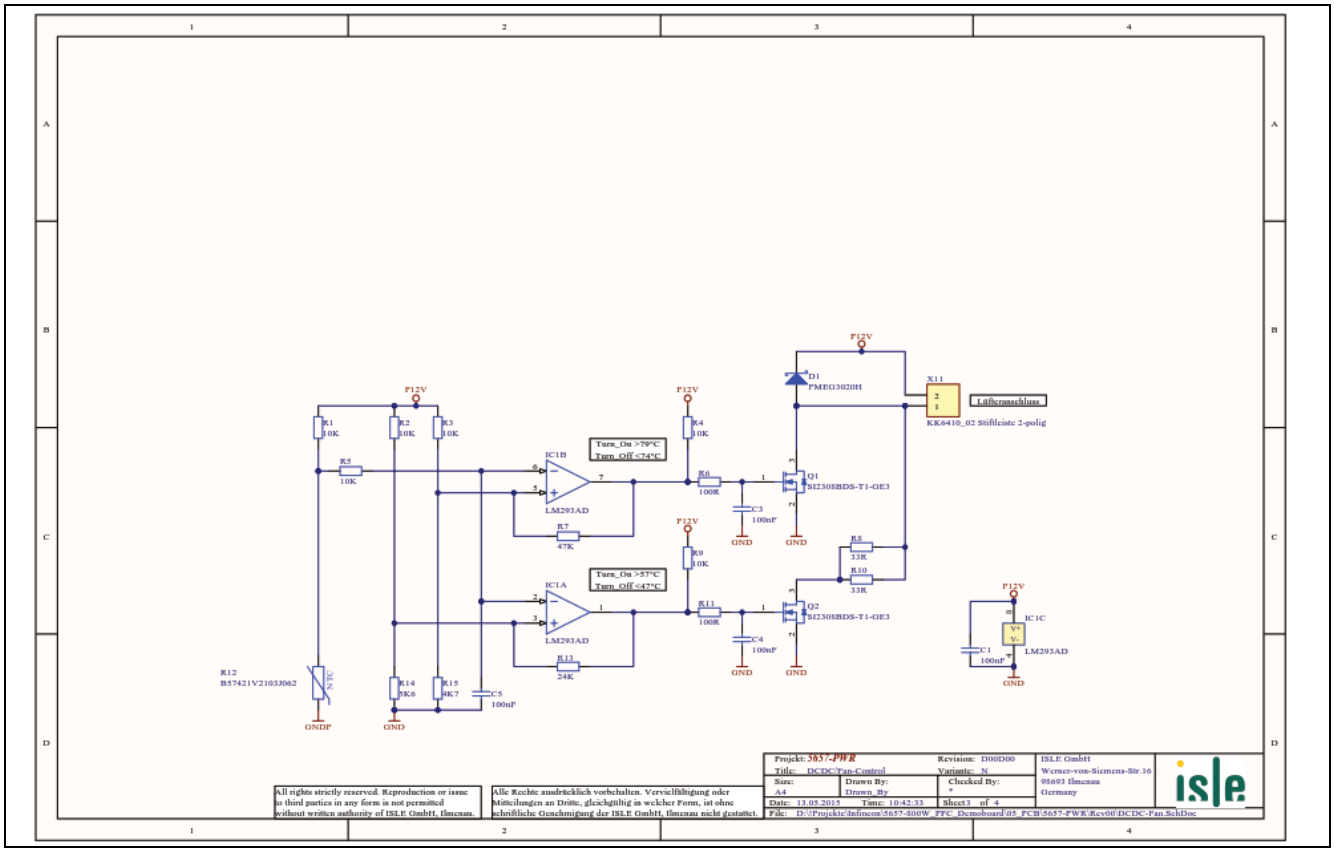


Figure 27 Schematic of fan control

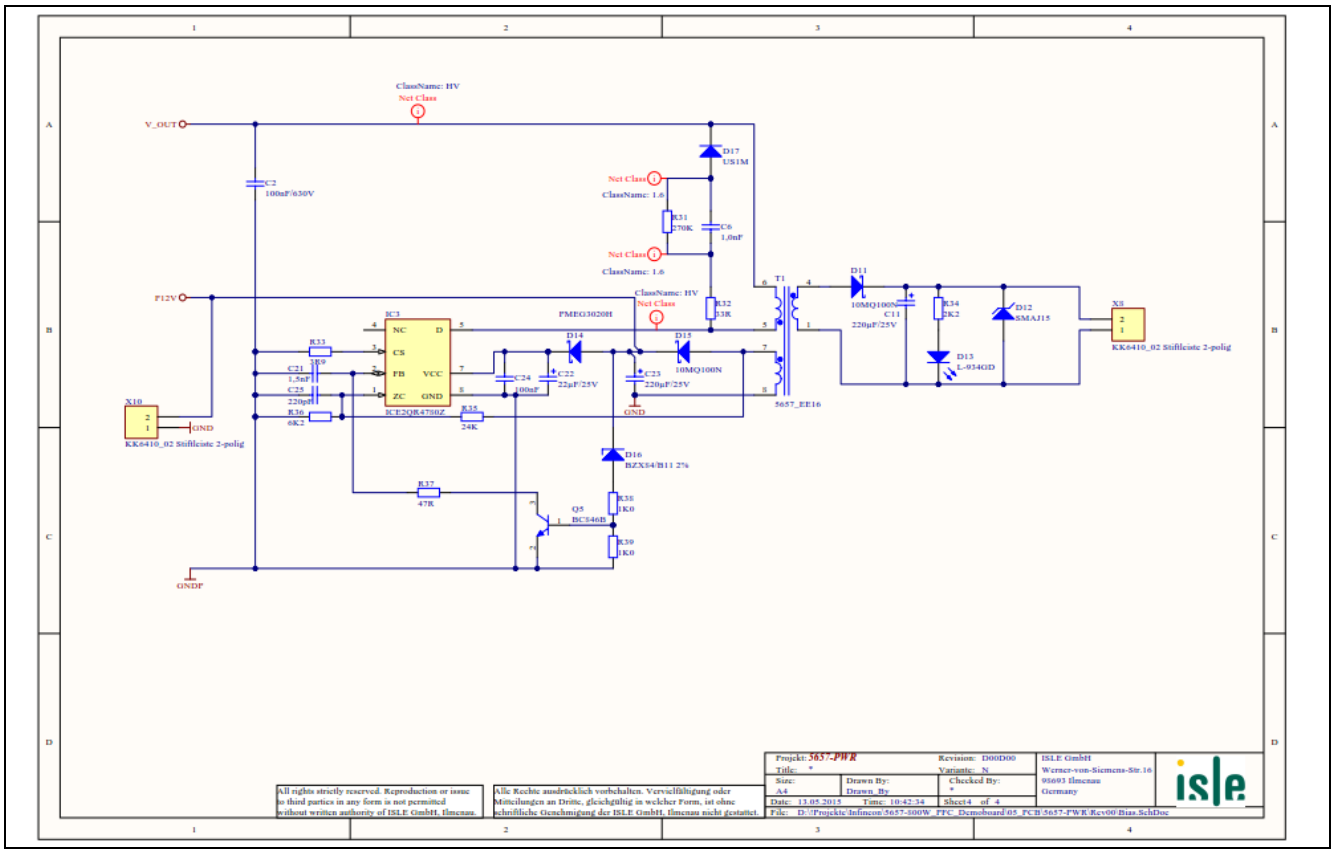


Figure 28 Schematic of auxiliary supply

6.1.1 PCB Layout

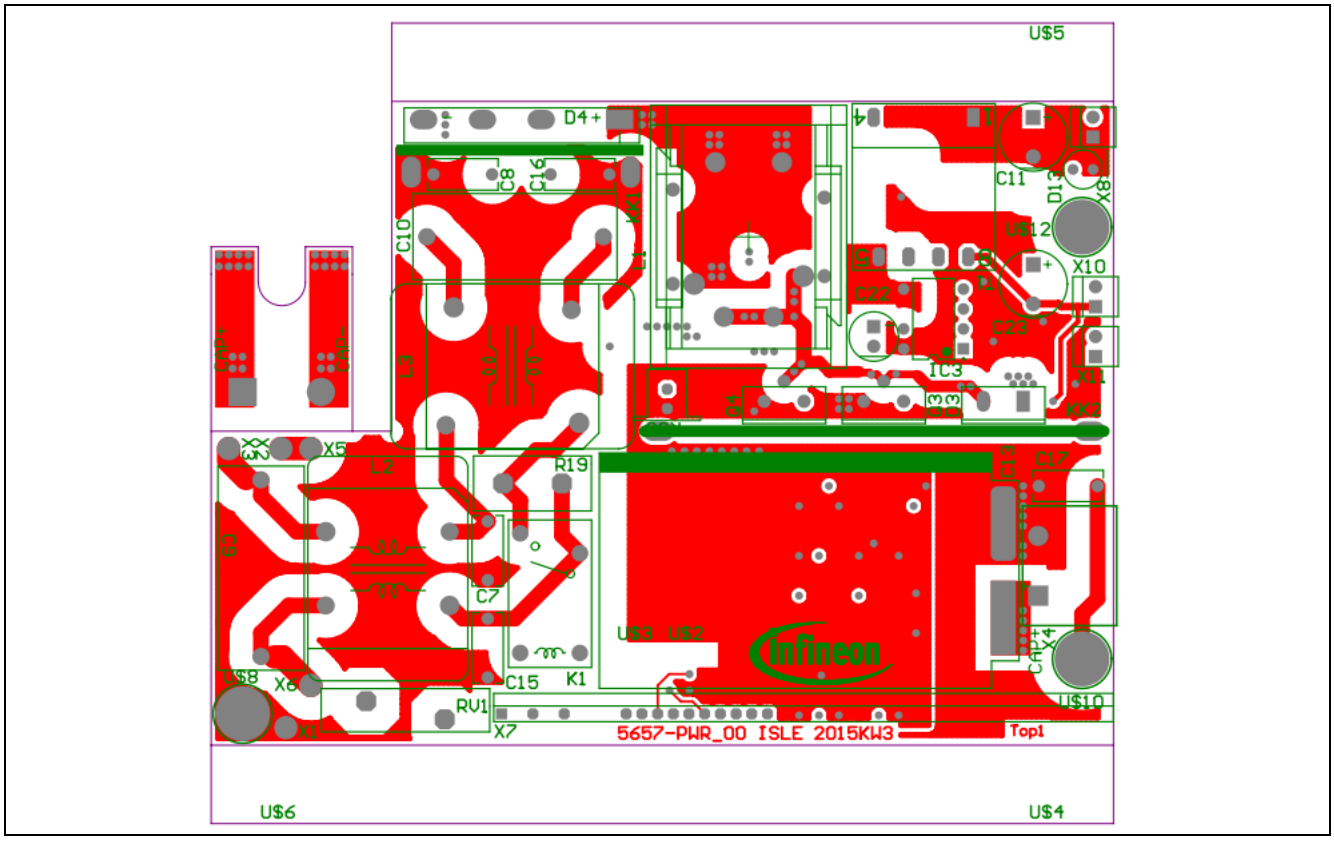


Figure 29 View of PCB top layer

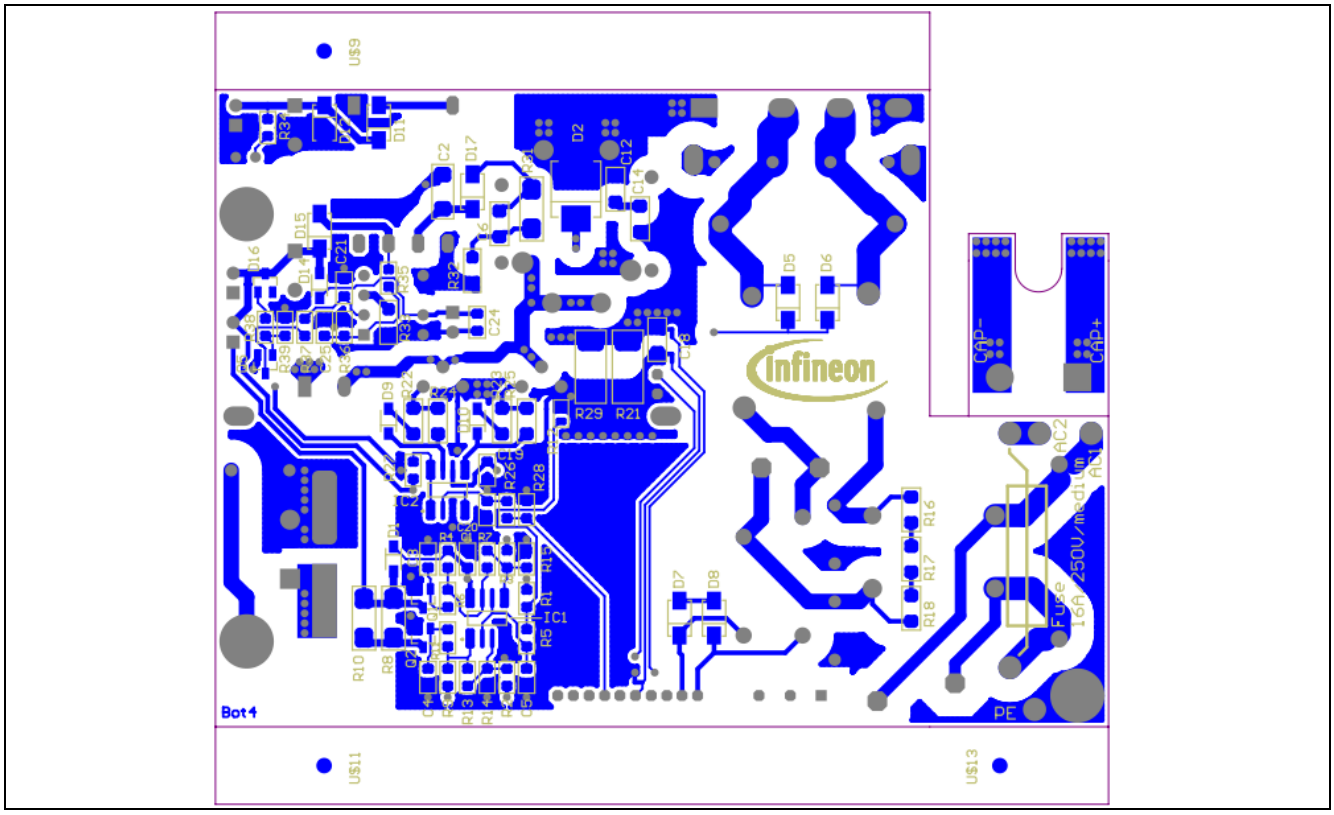


Figure 30 View of PCB bottom layer

6.1.2 Bill of Material

Table 8 BOM of Power Board

Quantity	Comment	Description	Footprint	Designator
1	220nF/275V	220nF 275V X2 manuell bestücken		C26
1	5657-PFC-CNT		5657-CNT_Con2	X7
1	Fuse 15A/medium	Sicherung 15A Mittelträge		F1
1	B57237S0100M000	NTC Inrush 10R 3300K 3,7 A 17mW/K	B57237-Sxxx	R19
1	PTC80°C/100R B59901D0080A040	PTC	B59901-Mxxx	R30
1	1,0µF	1,0µF 25V X7R 10% -55/125°C	CAPC2012M	C19
1	100pF	100pF 50V C0G 5% -55/125°C	CAPC2012M	C20
1	220pF	220pF 50V C0G 5% -55/125°C	CAPC2012M	C25
1	1,5nF	1,5nF 50V X7R 10% -55/125°C	CAPC2012M	C21
5	100nF	100nF 50V X7R 5% -55/125°C	CAPC2012M	C1, C3, C4, C5, C24
1	4,7µF	4,7µF 25V X7R 10%	CAPC3216m	C18
2	100nF	100nF 450V X7T 10% -55/125°C	CAPC3216M	C12, C14
1	1,0nF	1,0nF 630V C0G 5%	CAPC3216M	C6
1	100nF/630V	100nF 630V X7R 10% -55/85°C	CAPC4520M	C2
1	470µF/450V	120µF 450V 105°C	CAPPA10-30x50R	C13
1	22µF/25V	22µF 25V	CAPPR2.5-6.3x11	C22
2	220µF/25V	220µF 25V	CAPPR5-8.7x12	C11, C23
4	2,2nF/300V/Y2		CAPR7.5-9X4	C7, C8, C15, C16
1	2,2µF/305V	2,2µF 305V X2	CAPR22.5-11X26X20	C10
1	470nF/275V	470nF 275V X2	CAPR22.5-11X26X20	C9
1	ICE2QR4780Z	PWM Controller Current Mode QR	DIP-8_-6	IC3
1	GMSTB 2,5/2-G-7,62	Phoenix	GMSTBA2,5/2-G-7,62	X4
1	5657_EE16	EF16 Bias Supply	Hartu_E16-8-P2P3	T1
1	2x5,7mH/10A	5657 Common Mode	IFX_L-	L3

Quantity	Comment	Description	Footprint	Designator
		Choke	2875053801(L3)	
1	2x4,7mH/10A	5657 Common Mode Choke	IFX_L-2875070500(L2)	L2
3	KK6410_02 Stiftleiste 2-polig	Molex	KK6410_2	X8, X10, X11
1	5657-KK_GL	Kühlkörper	KK_GL	KK1
1	5657-KK_TO220	Kühlkörper	KK_TO220	KK2
1	L-934GD	LED Low Current green	LED_5MM	D13
1	200µH/20A	5657 PFC Choke	PFC_CHOKE-SK	L1
1	LVB2560	Brückengleichrichter 600V 25A	REC-GSIB-5S	D4
1	47R		RESC2012M	R37
3	100R		RESC2012M	R6, R11, R26
2	1K0		RESC2012M	R38, R39
1	2K2		RESC2012M	R34
1	4K7		RESC2012M	R15
1	5K6		RESC2012M	R14
1	6K2		RESC2012M	R36
8	10K		RESC2012M	R1, R2, R3, R4, R5, R9, R27, R28
2	24K		RESC2012M	R13, R35
1	47K		RESC2012M	R7
1	B57421V2103J062	NTC 10K 4000K	RESC2012N	R12
2	22R		RESC3216M	R22, R23
2	39R		RESC3216M	R24, R25
3	220K		RESC3216M	R16, R17, R18
2	0R022	0R022 2512 RESC6330 TK75	RESC6332M	R21, R29
1	3R9		RESMELF3614M	R33
1	33R		RESMELF3614M	R32
2	33R		RESMELF5822M	R8, R10
1	270K		RESMELF5822M	R31
1	OJE-SS-112HM,000	Relais SPST-NO	RLY_TE-OJE	K1
1	S20K275	Varistor 275V 1W	S20K275	RV1
2	SMAJ15	Diode Supressor	SMA_M	D8, D12
2	10MQ100N	Diode Schottky	SMA_M	D11, D15
3	S1M	Gleichrichter	SMA_M	D5, D6, D7
1	US1M	Diode Ultra Fast 1000V	SMA_M	D17

Quantity	Comment	Description	Footprint	Designator
1	S5K	Gleichrichter	SMC_M	D2
4	PMEG3020H	Diode Schottky 30V 2A	SOD123M	D1, D9, D10, D14
1	LM293AD	Komparator	SOIC127P600-8M	IC1
1	2EDN7524IF	Low Side Dual MOSFET Treiber, non-inverting	SOIC127P600-8M	IC2
1	BC846B	npn Transistor	SOT23-3M	Q5
1	BZX84/B11 2%	Diode Zener	SOT23-3M	D16
2	SI2308BDS-T1-GE3	MOSFET N-Kanal	SOT23-3M	Q1, Q2
2	IPP60R180C7	MOSFET N-Kanal	TO220-AB_HV	Q3, Q4
1	IDH06G65C5	Diode Schottky 650V	TO220-AC	D3

6.2 Daughter Board

6.2.1 Schematics

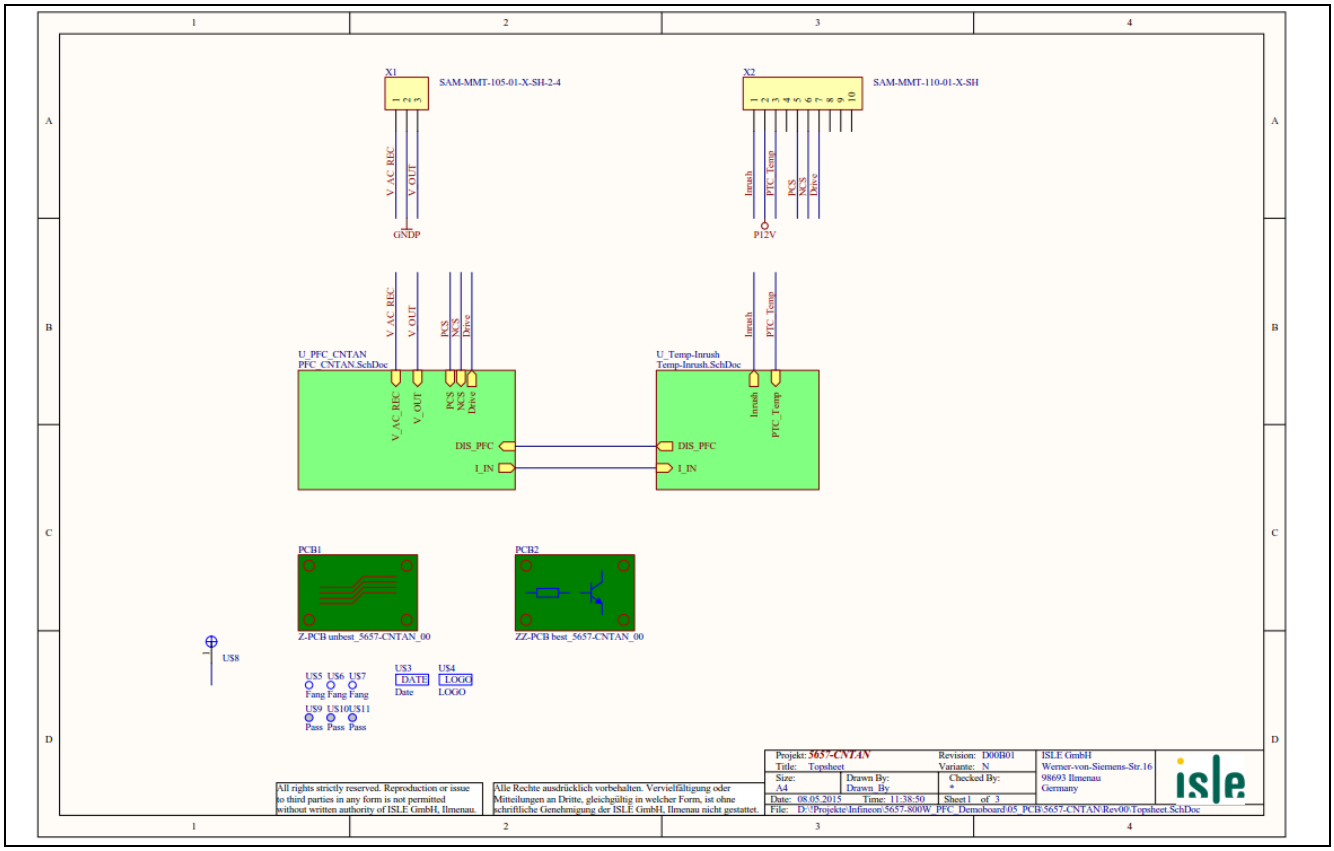


Figure 31 Schematic of connector

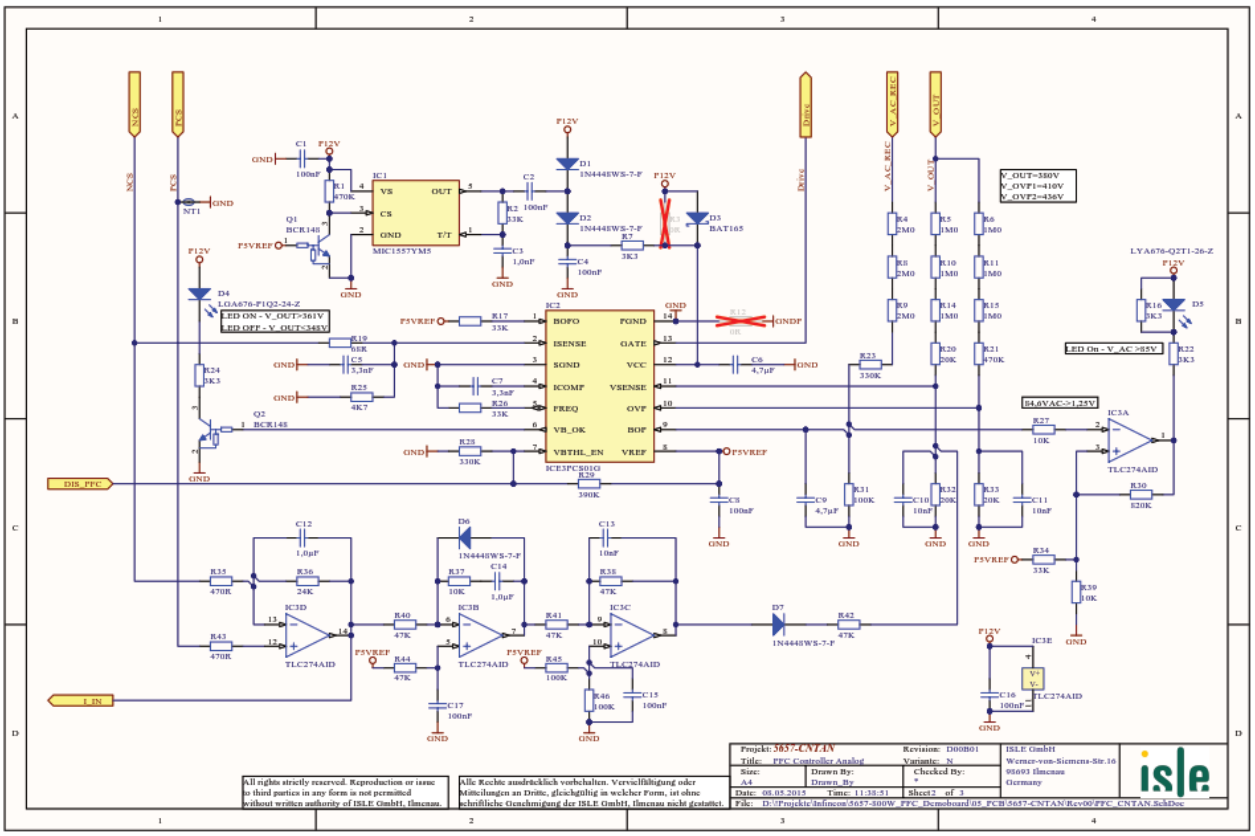


Figure 32 Schematic of PFC control

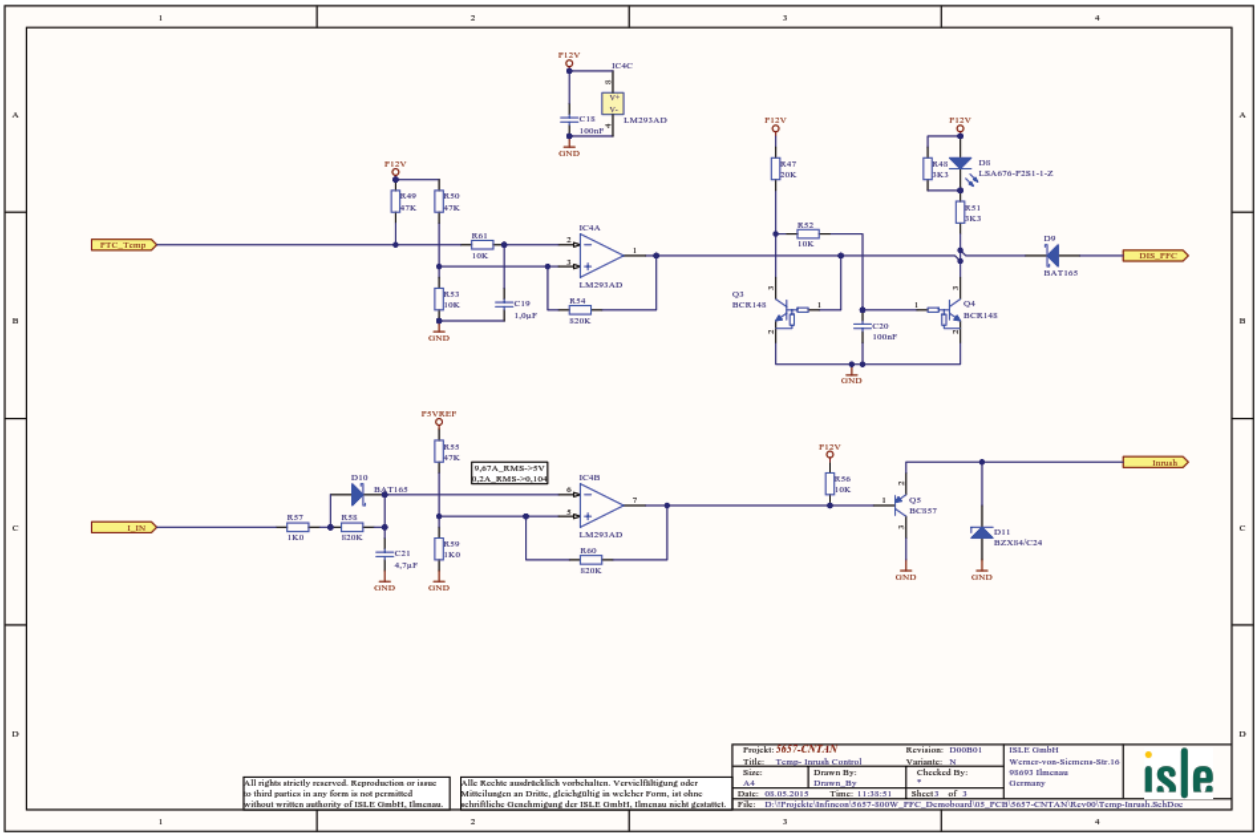


Figure 33 Schematic of temperature monitoring and inrush relay control

6.2.2 PCB-Layout

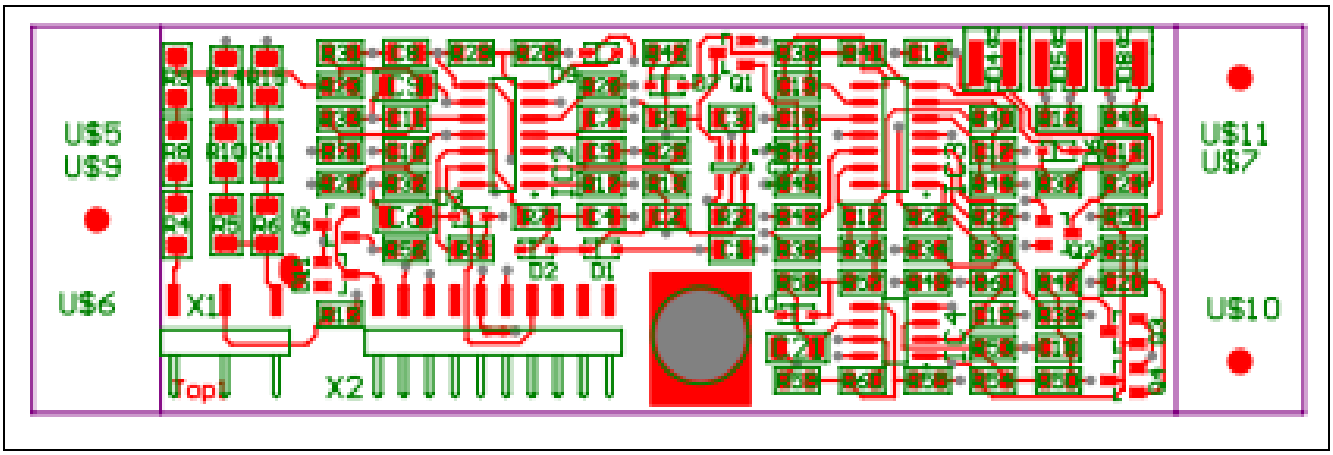


Figure 34 View of PCB top layer

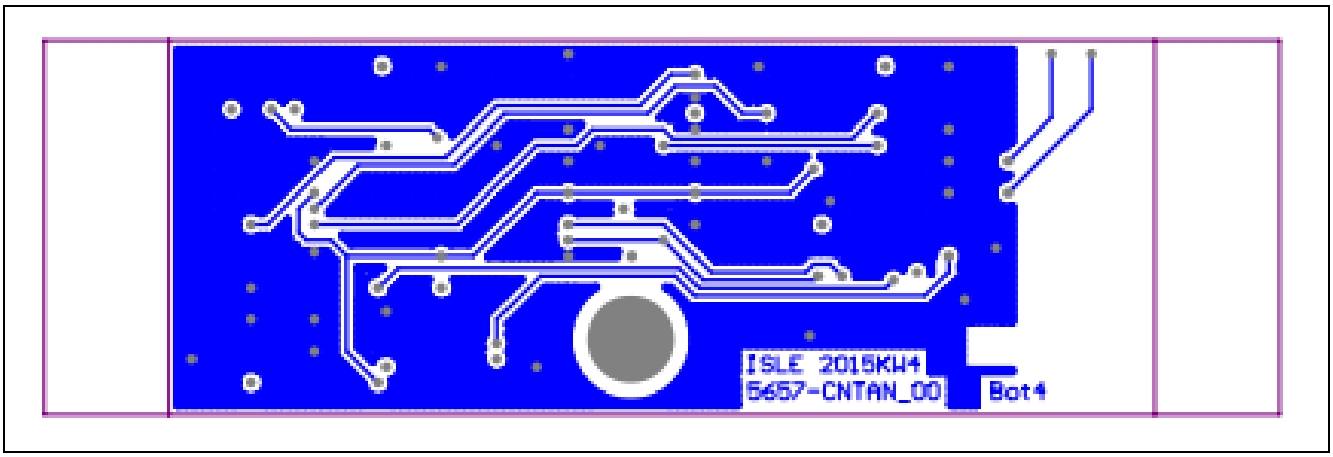


Figure 35 View of PCB bottom layer

6.2.3 Bill of Material

Table 9 BOM of control board

Quantity	Comment	Description	Footprint	Designator
3	1,0µF	1,0µF 25V X7R 10% -55/125°C	CAPC2012N	C12, C14, C19
1	1,0nF	1,0nF 50V C0G 5% -55/125°C	CAPC2012N	C3
2	3,3nF	3,3nF 50V X7R 10% -55/125°C	CAPC2012N	C5, C7
3	10nF	10nF 50V X7R 5% -55/125°C	CAPC2012N	C10, C11, C13
9	100nF	100nF 50V X7R 5% -55/125°C	CAPC2012N	C1, C2, C4, C8, C15, C16, C17, C18, C20
3	4,7µF	4,7µF 25V X7R 10%	CAPC3216N	C6, C9, C21
1	LSA676-P2S1-1-Z	LED Hyper Bright Super-Red	LED_LxA670	D8
1	LGA676-P1Q2-24-Z	LED Hyper Bright Grün	LED_LxA670	D4
1	LYA676-Q2T1-26-Z	LED Low Current yellow	LED_LxA670	D5
1	68R		RESC2012N	R19
2	470R		RESC2012N	R35, R43
2	1K0		RESC2012N	R57, R59
6	3K3		RESC2012N	R7, R16, R22, R24, R48, R51
1	4K7		RESC2012N	R25
7	10K		RESC2012N	R27, R37, R39, R52, R53, R56, R61
4	20K		RESC2012N	R20, R32, R33, R47
1	24K		RESC2012N	R36
4	33K		RESC2012N	R2, R17, R26, R34
8	47K		RESC2012N	R38, R40, R41, R42, R44, R49, R50, R55
3	100K		RESC2012N	R31, R45, R46
2	330K		RESC2012N	R23, R28
1	390K		RESC2012N	R29
2	470K		RESC2012N	R1, R21
4	820K		RESC2012N	R30, R54, R58, R60
6	1M0		RESC3216N	R5, R6, R10, R11, R14, R15
3	2M0		RESMELF3614N	R4, R8, R9

Quantity	Comment	Description	Footprint	Designator
1	SAM-MMT-105-01-X-SH-2-4		SAM-MMT-105-01-X-SH-2-3	X1
1	SAM-MMT-110-01-X-SH		SAM-MMT-110-01-X-SH	X2
3	BAT165	Diode Schottky	SOD323	D3, D9, D10
4	1N4448WS-7-F	Diode Fast Switching	SOD323	D1, D2, D6, D7
1	LM293AD	Komparator	SOIC127P600-8N	IC4
1	TLC274AID	Operationsverstärker	SOIC127P600-14N	IC3
1	ICE3PCS01G	PFC Controller Continuous Conduction Mode	SOIC127P600-14N	IC2
1	BC857	pnp Transistor	SOT23-3N	Q5
4	BCR148	npn Transistor	SOT23-3N	Q1, Q2, Q3, Q4
1	BZX84/C24	Diode Zener	SOT23-3N	D11
1	MIC1557YM5	Timer	SOT23-5N	IC1

7 Useful material and links

- 600 V CoolMOS™ C7 Webpage
  www.infineon.com/600V-C7

- Product Brief 600 V CoolMOS™ C7
  http://www.infineon.com/dgdl/Infineon-Product_Brief_600V_CoolMOS_C7-PB-v01_00-EN.pdf?fileId=5546d4624cb7f111014d664a241c4aa1

- 650 V thinQ!™ SiC Schottky Diode Generation 5 Webpage
  http://www.infineon.com/sic-gen5

- Product Brief 650 V thinQ!™ SiC Schottky Diode Generation 5
  http://www.infineon.com/dgdl/Infineon+-+Product+Brief+-+Silicon+Carbide+-+Schottky+Diodes+-+650V+thinQ%21+Generation+5.pdf?fileId=db3a3043399628450139b06e16a721d0

- 2EDN7524F Non Isolated Gate Driver (EiceDRIVER™)
  www.infineon.com/2EDN

- Product Brief 2EDN7524F Non Isolated Gate Driver (EiceDRIVER™)
  http://www.infineon.com/dgdl/Infineon-Product+Brief+2EDN+MOSFET+EiceDRIVER+Family-PB-v01_00-EN.pdf?fileId=5546d4624cb7f111014d668a5a004c12

- ICE3PCS01G PFC Controller Webpage
  http://www.infineon.com/cms/en/product/channel.html?channel=ff80808112ab681d0112ab6a716f0504

- XMC 1300 Microcontroller* Webpage
  http://www.infineon.com/cms/en/product/evaluation-boards/KIT_XMC13_BOOT_001/productType.html?productType=db3a30443ba77cfd013baec9c4b30ca8

- ICE2QR4780Z Flyback Controller Product Webpage
  http://www.infineon.com/cms/en/product/power/supply-voltage-regulator/ac-dc-integrated-power-stage-coolset-tm/quasi-resonant-coolset-tm/ICE2QR4780Z/productType.html?productType=db3a30432a7fedfc012ab2458b0c36ff

Revision History

Major changes since the last revision

Page or Reference	Description of change
--	First Release

www.infineon.com

Edition 2015-05-18

Published by

Infineon Technologies AG

81726 Munich, Germany

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Document reference

AN_201411_PL52_006

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