TN1424

Technical note

STDES-2KW5CH48V test report

Introduction

The STDES-2KW5CH48V reference design offers a charging solution mainly for industrial light electric vehicles (LEVs), such as e-bikes, e-rickshaws, forklifts, micro e-cars. It is also suitable for industrial logistics robots.

The charger implements two charging profiles: one for Li-ion batteries and the other one for lead-acid batteries, which are to the latest trends in battery charging.

The charger design is based on a boost power factor correction (PFC) circuit, controlled by the L4984D that provides high PF of greater than 0.9, followed by a DC-DC circuit based on a full-bridge LLC resonant power converter, controlled by the L6599A. For the output rectification, diodes have been chosen with an LLC transformer secondary winding using the center tapped configuration.

The design features a STM32F072CB microcontroller to control the power stages and the battery charging profiles and to manage protections and the user interface.

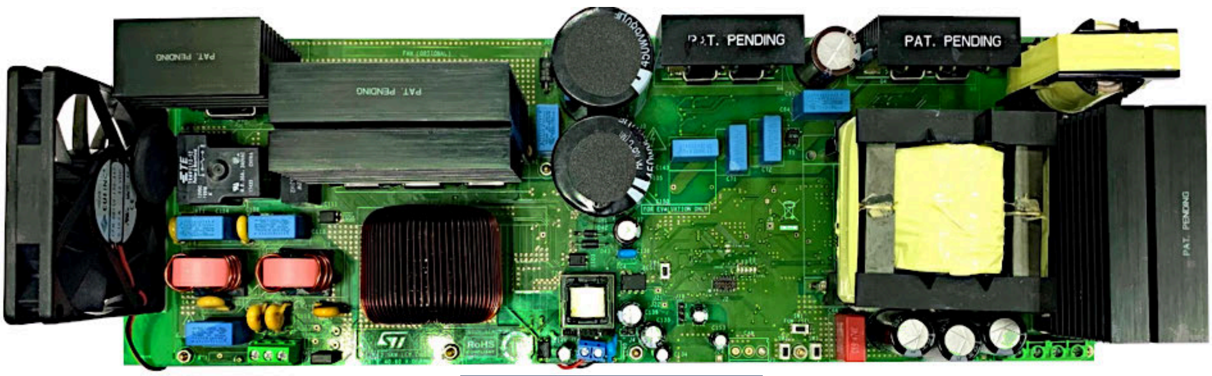
MDmesh M5 power MOSFETs and SiC diode are used in the PFC stage. MDmesh DM6 power MOSFETs are used for the LLC stage.

Both the primary and secondary sections, are supplied by an off-line flyback circuit based on the VIPER16. This circuit provides regulated voltages to the microcontroller, the gate driver ICs, and the signal conditioning circuitry.

Formal testing and measurement results confirm the ability of performance of ST power products combined with comprehensive digital control, to deliver high efficiency, power factor near unity, and low THD across wide input voltage and load conditions.

The STDES-2KW5CH48V is a fully assembled reference design developed for performance evaluation only, not available for sale.

Figure 1. STDES-2KW5CH48V reference design



Fully assembled board developed for performance evaluation only, not available for sale

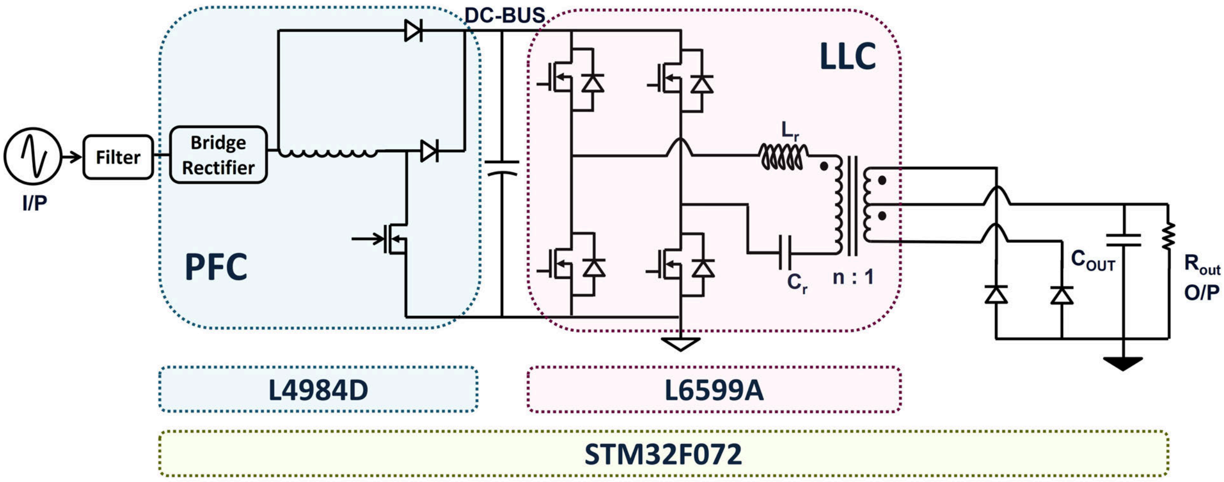
This test report describe the practical implementation of a 2.5 kW EV charger module, which is meant for charging various battery chemistries. It has a compact form-factor: 127 x 376 x 70 mm3. It is intended to deliver full power under forced convection cooling. It is also meant to be housed in a 2U height enclosure for a standard 19” rack mount fit. The electrical specifications are derived from common EV DC charger specifications.

Warning: *This reference design has potential lethal voltages across all stages. Only skilled personnel (minimum two persons) can operate the board. Technical know-how and specialistic skills are required for the reference design evaluation in live conditions.*

1 Overview

The system is built around a CCM PFC boost front end that runs two M5 MOSFETs in parallel and one x SiC rectifier. The input mains AC is converted to the DC bus of 415 V to feed the downstream LLC converter built in a center tap, full wave topology. Refer to the block diagram below to understand better the system features and operation.

Figure 2. **STDES-2KW5CH48V block diagram**



A holistic approach has been taken to make the unit compact, efficient, and easy to build. The output of the LLC converter is rectified with a full bridge. The operating frequency ranges from 140 kHz at 40 VDC output to 85 kHz at 60 VDC output.

There are two error amplifiers for CV and CC, to fall back and run in the standalone mode. This means that, while the system is capable of running under the MCU supervision, it is possible to preset non-supervised operating points. For example, even if the system can deliver from 40-60 V, with the suitable command set, if there is no command available, it can work by default at the factory preset setting (40 V and 5 A). This is useful for testing, debug, and to use it as a general-purpose power supply. One type 2 and one type 3 compensators, built around op-amps, are used for the CC and CV loop compensation. This is the inner analog loop.

The MCU sets the overall current and voltage to modulate the reference of the error amplifiers with two tertiary PWM signals. These PWM signals are low pass filtered and averaged to create the dynamic reference values for the set-point decided by the system controller.

The STDES-2KW5CH48V power stages are controlled through dedicated analog controllers and through a microcontroller, which manages the application according to your requirements.

The STDES-2KW5CH48V works with input mains voltage ranging from 85-265 V_{AC} and it can provide an output power of up to 2.5 kW when the input voltage is above 180 V_{AC}. Below this threshold, the output power capability derates down to 1.25 kW. The reference design adjusts the output power delivery parameters according to the EU or the US input voltage, sensed through the isolated amplifier.

The PFC and full-bridge LLC power stages are referred to the primary ground, while the LLC controller and the microcontroller are referred to the secondary ground. The auxiliary power supply powers the microcontroller, the gate driver ICs, and the signal conditioning circuitry.

For user information about the charger status and settings there are LEDs positioned on the PCB. If an error occurs or a protection is triggered, the on-board D5 LED blinks. The D5 LED blink count varies for the different errors/protections. To reprogram the microcontroller, apply +12 V DC on the J4 connector. Use the IAR Embedded Workbench for Arm (ver.9.10 or higher) or any other appropriate programming tool to program and debug.

Table 1. STDES-2KW5CH48V characteristics

Parameter	Value/range/comments
Input AC voltage	85 to 265 V AC
Peak efficiency	>93.5% at 1.75 kW load
Peak efficiency at full load	>93%
PFC output voltage	415 ± 2%
PFC operating mode	CCM
PFC controller	L4984D
Power factor over input voltage span 85 – 265 V AC	>0.97 for load > 20%
THD over input voltage span 85 – 265 V AC	<10% for load > 20%
Maximum output power	2.5 kW (Europe voltage range) 1.25 kW (US voltage range)
DC-DC converter topology	Full-bridge LLC
LLC power converter frequency range	90 – 160 kHz
Startup	Soft start
Rectification topology	Center tapped
Cooling	Forced air
Protections	Low and high input voltage, low and high output voltage, output overcurrent, and short-circuit protections

1.1 Startup and safety mechanism

During the startup phase, the microcontroller reads the input mains voltage. If the reading is within the limits, the microcontroller tunes different output power operational parameters as highlighted in Table 1. STDES-2KW5CH48V characteristics. After two seconds (voltage settling time), the system has a soft start to avoid high current spikes. During the operation, the microcontroller senses various parameters, continuously. In case of any error or a triggered protection, the evaluation boards stops and the D5 LED starts blinking. The details of the errors are highlighted in Table 3. STDES-2KW5CH48V error codes. To clear the error, disconnect the reference design from the input mains voltage and wait until the LED D5 stops blinking.

Table 2. STDES-2KW5CH48V LED indications

LED no.	Color	Indication
D5	Red	Error/protection
D6	Blue	Battery mode
D7, D8, D9, D48, D49	Red (D7), Yellow (D8), Yellow (D9), Green (D48), Green (D49)	Output battery voltage

Table 3. STDES-2KW5CH48V error codes

Error name	Condition	LED D5 no. of blinks	Recoverable
Input mains voltage	V_{IN} < 85 V AC or V_{IN} > 265 V AC	2	No
Output voltage	V_{OUT} < 38 V DC or V_{OUT} > 60 V	4	No
Output current	I_{OUT} > 45 A	6	No
Temperature	80°C	8	No

1.2 CC-CV implementation

The CC-CV implementation is a blend of analog and digital controls. The L6599AD RF_{min} pin provides an accurate 2 V reference with about a 2 mA source capability. The higher the current sourced by the pin, the higher the oscillator frequency.

By default, the L6599AD LLC controller is configured to give a 41 V ± 2% DC. This is achieved by using R25 as 24 k and setting 1.25 V voltage reference at the noninverting end of the operational amplifier (U4A).

At power-up, the STDES-2KW5CH48V initially starts with 41 V ± 2% DC. In parallel, the microcontroller starts sensing the output voltage and current. As the output of the reference design is connected to the battery, the microcontroller reads the battery terminal voltage and the charging current.

To charge the battery, the reference design should generate a higher voltage. To charge the battery in the CC configuration as per the battery charging profile, a PWM with a slow duty cycle ramp-up is given at the noninverting end of the operational amplifier (U4B). Beyond a particular value of the duty cycle, the voltage reference at the noninverting end of the operational amplifier (U4A) starts increasing. Thus, the output voltage increases as the switching frequency decreases. The switching frequency decreases as the current through the RF_{min} pin decreases. The increase in the converter output voltage causes the battery charging current to increase. According to the charging current required as per the battery charging profile, the duty cycle changes continuously along with the monitoring of the output voltage and current.

1.3 Operating modes

1.3.1 Battery mode selection

By default, the STDES-2KW5CH48V firmware enters the testing mode, to test the reference design on an electronic load.

There is also a battery mode, which allows you to select between a Li-ion and a lead-acid battery.

In the testing mode, there are nine current levels, which can be adjusted using the SW2 (to increase) and SW3 (to decrease) switches.

In the battery mode, before powering up the reference design, use the three-pin jumper (J19) to select the battery chemistry as per requirement. Place J19 at (2:3) position to select the lead-acid battery configuration. Place it at (2:1) position, instead, for the li-ion battery configuration. At board power-up, press the SW1 switch to make the firmware enter the battery mode. After that, the D6 LED glows. The firmware tunes the parameters as per the J19 jumper setting.

Table 4. STDES-2KW5CH48V firmware modes

Level	Output current rating (A)	Comment
1	5	Default level
2	10	Switch SW2 and switch SW3 can be used to increase and decrease the output current level when the output voltage ranges are between 40 and 60 V DC.
3	15	
4	20	
5	25	
6	30	
7	35	
8	40	
9	42	

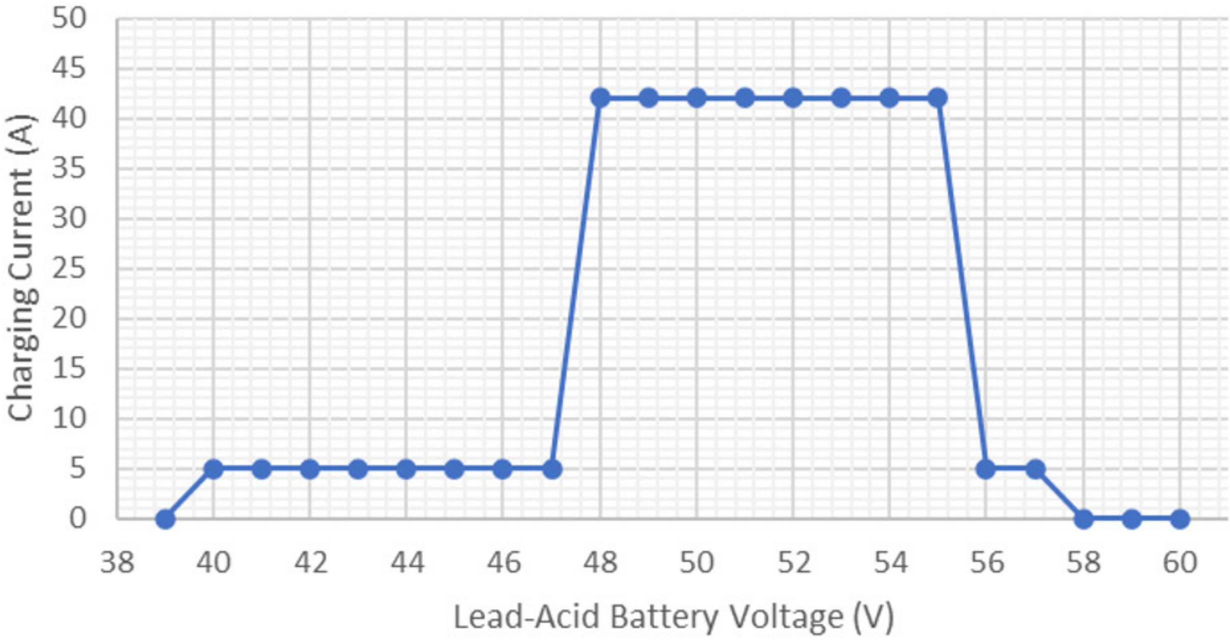
1.3.2 Battery charging profiles

The STDES-2KW5CH48V firmware include two battery charging profiles: lead-acid and Li-ion. If the battery is deeply discharged, the charging profile starts with a precharge.

Once the battery voltage reaches the nominal range, the charging current ramps up as shown in the figures below.

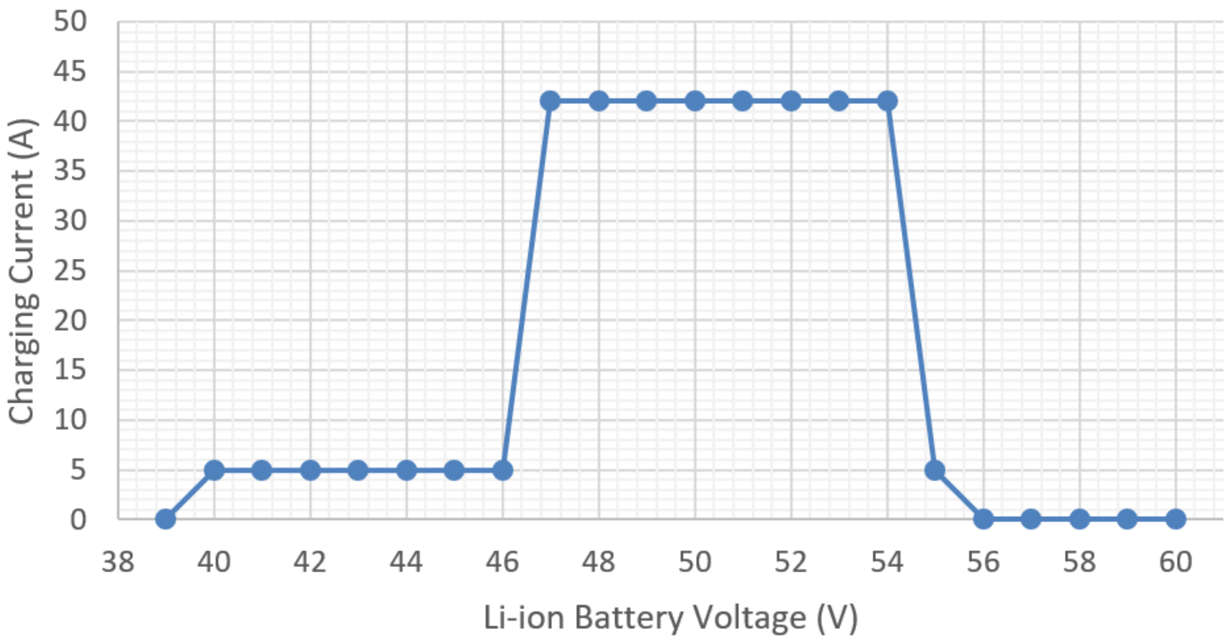
When reaching a certain threshold, the charging current goes down and stops when reaching the maximum limit. For the lead-acid battery, the bulk charging is given by 0.1 x C_{nom}.

Figure 3. Lead-acid battery charging profile



For the Li-ion battery, the bulk charging is given by 0.5 x C_{nom}.

Figure 4. Li-ion battery charging profile

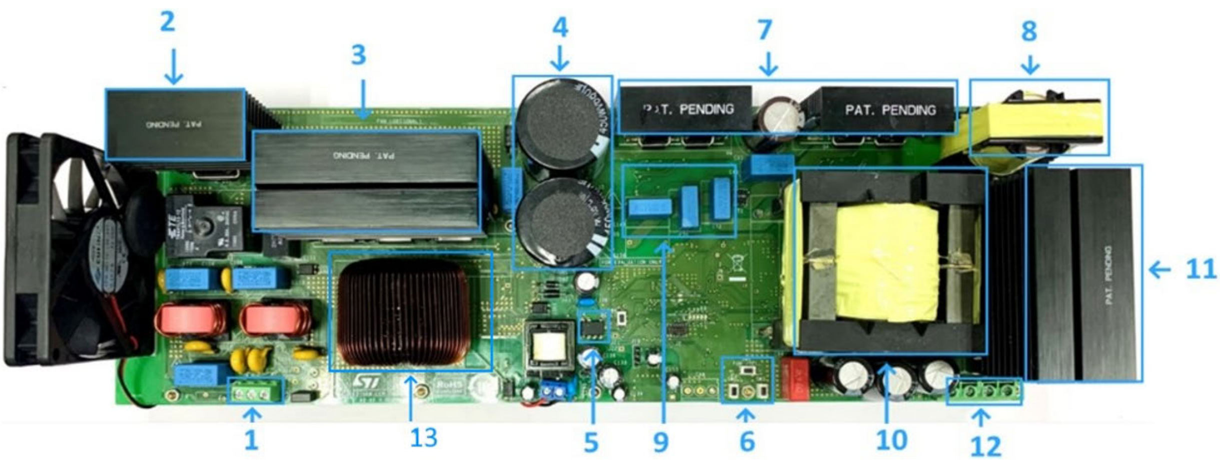


2 STDES-2KW5CH48V key components

The STDES-2KW5CH48V power supply consists of the following key components:

1. AC input mains AC power terminal
2. Bridge rectifier mounted on the heat-sink
3. PFC MOSFETs and SiC diode mounted on the heat-sink
4. PFC output bulk capacitors
5. Auxiliary power supply
6. User interface – switches
7. LLC MOSFETs mounted on a dedicated daughter board and the daughter card mounted on the heat-sink
8. LLC resonant inductor
9. LLC resonant capacitors
10. LLC transformer
11. Output rectifier diodes mounted on the heat-sink
12. DC output terminal
13. PFC swinging choke

Figure 5. **STDES-2KW5CH48V key components**



2.1 Power factor correction (PFC) circuit

For the power range of 1-3.3 kW, the CCM boost PFC is the most popular topology for its low current ripple, simplistic implementation and sensing, and reasonably good performance, with efficiencies reaching 98%, using the M5 series super junction MOSFETs. A suitable MOSFET must fulfill these requirements:

- a key FOM as low as possible ($R_{DS(on)}$, Q_g, E_{oss})
- low output capacitance (C_{oss}) for a higher light load efficiency
- a sufficient drain-source breakdown voltage to handle overshoots
- a high dV/dt rating
- a low thermal resistance from the junction to the case for an effective heat sinking

For this function, we have used two STW57N65M5. Each of them is driven by its own totem pole driver.

The boost converter has the inductor on the input side, which provides a smooth continuous input current waveform opposed to the discontinuous input current of a buck or buck-boost topology. The continuous input current is easier to filter. This is a major advantage of this topology as any additional filtering needed on the converter input increases the cost and reduces the power factor, thanks to the capacitive component across the line in the form of large X capacitors. For the CCM PFC, the full load inductor current ripple is taken to be 40% of the average input current. This is a tradeoff in terms of size, cost, acceptable losses, and overall performance, that is, summarizing:

- the peak current is lower and the RMS current factor with a trapezoidal waveform is reduced in comparison to a triangular waveform, reducing the device conduction losses

- turn-off losses are lower thanks to the switch-off at a lower maximum current
- the HF ripple current to be smoothed by the EMI filter is much lower in amplitude

On the other hand, the CCM encounters the turn-on losses in the MOSFET, which can be worsened by the boost rectifier reverse recovery loss, due to the reverse recovery charge, Qrr. For this reason, ultra-fast recovery diodes or silicon carbide Schottky diodes with extreme low Qrr are needed for the CCM mode. The available diode conduction time is low and the forward current is high in comparison to the average current. For that reason, a diode in the CCM boost should feature a fast recovery with a low reverse recovery charge, followed by the forward drop, operating at a high forward current. We have chosen a high performance, high surge 20 A SiC diode from ST. Silicon Carbide (SiC) Schottky diodes only have capacitive charge, Qc, but no reverse recovery charge, Q_{rr}. The capacitive charge for SiC diodes is not only low, but also independent of the di/dt, current level, and temperature, unlike traditional Si diodes. Their switching loss and recovery time are much lower compared to the traditional silicon ultrafast diodes and clearly enhance the efficiency. SiC diodes allow higher switching frequency designs and can reach higher junction temperatures, also reducing the heatsink size.

The STDES-2KW5CH48V power factor correction circuitry is based on the L4984D controller, which works in the CCM mode.

The swinging choke is used as a PFC boost inductor so that it has a high inductance at lighter loads and a low inductance at heavier loads.

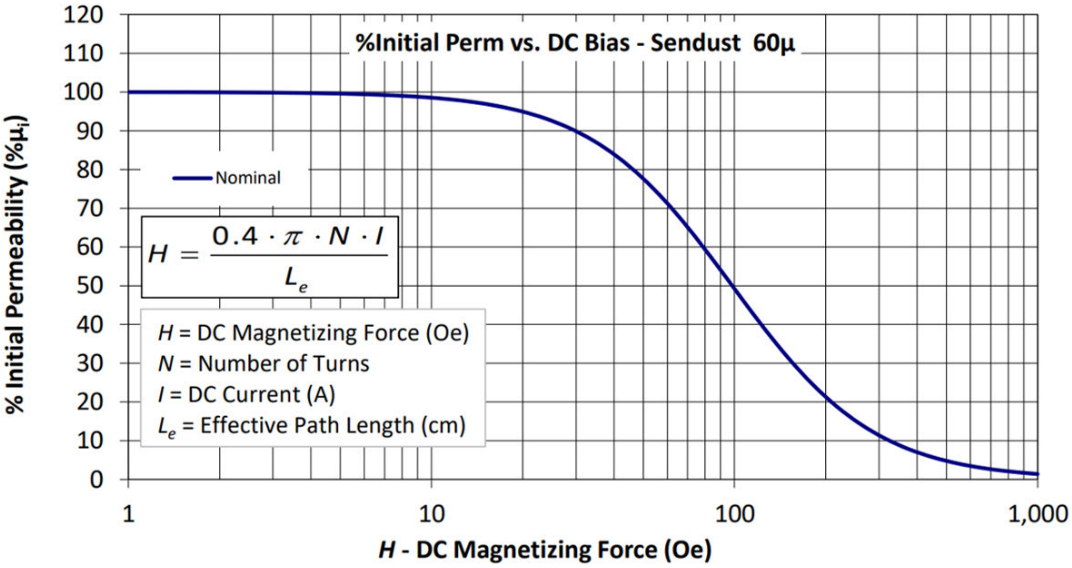
Due to its saturation current limits, the reference design delivers 2.5 kW for the European input voltage range and 1.25 kW for the US input voltage range.

2.1.1 Key devices used in the PFC circuit

- **L4984D: PFC controller**
  The L4984D is a current-mode PFC controller that operates with a line-modulated fixed-off-time (LM-FOT) control. A proprietary LM-FOT modulator allows the fixed-frequency operation for boost PFC converters as long as they are operated in continuous conduction mode (CCM). The chip comes in a 10-pin SO package and offers a low-cost solution for CCM-operated boost PFC pre-regulators in EN61000-3-2 and JEIDA-MITI-compliant applications, in a power range that spans from few hundred W to 1 KW and above. The highly linear multiplier includes a special circuit, able to reduce the crossover distortion of the AC input current, which allows wide-range-mains operation with a reasonably low THD, even over a large load range. The output voltage is controlled through a voltage-mode error amplifier and an accurate (1% at Tj = 25°C) internal voltage reference. The loop stability is optimized through the voltage feedforward function (1/V2 correction), which uses a proprietary technique in this IC that also significantly improves the line transient response in the case of mains drops and surges (“bidirectional”).The device features low consumption and includes a disable function suitable for IC remote on/off. These features allow use in applications, which also comply with the latest energy saving requirements (Blue Angel, ENERGY STAR, Energy 2000, etc.). In addition to the overvoltage protection able to keep the output voltage under control during transient conditions, the IC is also provided with protection against feedback loop failures or erroneous settings. Other onboard protection functions allow handling safely the brownout conditions and boost inductor saturation. The soft-start limits the peak current and extends the off-time to prevent the flux runaway in the initial cycles.
- **STW57N65M5: PFC MOSFET**
  The STW57N65M5 is an N-channel 650 V power MOSFET available in the TO-247 package. It features an extremely low $R_{DS(on)}$ of 0.056 Ω, making it suitable for applications that require a high power density and efficiency. In the STDES-2KW5CH48V, two STW57N65M5 and STPSC20H065C have been mounted on a single heat-sink.
- **STPSC20H065CW: PFC diode**
  The STPSC20H065CW SiC diode is a ultrahigh performance power Schottky diode. It is manufactured using a silicon carbide substrate. The wide band gap material allows the design of a Schottky diode structure with a 650 V rating. Due to the Schottky construction, no recovery is shown at turn-off and ringing patterns are negligible. The minimal capacitive turn-off behavior is independent of the temperature. This ST SiC diode boosts the performance in hard switching conditions. Its high-forward surge capability ensures a good robustness during transient phases.

- **PFC choke**
  Commercial inductors are available and usable for a first pass design, typically with single layer windings and a permeability drop of 30% or less. They may be ferrite or powdered iron and may exhibit a stable inductance over currents and line cycle. It is actually desirable to optimize the inductor configuration in order to meet the requirements for high power factor over a wide input line range. The PFC controller use cycle by cycle current loop control, which ensures good THD performance provided that the inductor remains in CCM operation. At low-line this is not an issue, but for operation at high-line band (175 VAC to 265 VAC), the operating current will be much lower. If the inductor used retains the full current value of inductance, it works well at low-line and higher peaks, but results in DCM operation for a significant part of the load range at high-line or lighter loads, with bad power factor, THD or EMI. A swinging choke made of Sendust is like a line variable inductor. With a suitable permeability (60) and size, we can see that at full load permeability drops by 75-80%, so that at lighter load the inductance swings up. This is actually beneficial for a dynamic THD control over the line cycle as well as load range. We have worked with WURTH, and they have prepared such an inductor for us, such that the minimum to maximum swing of inductance of x5. From 150uH to over 800uH in light load/low current/high line condition.

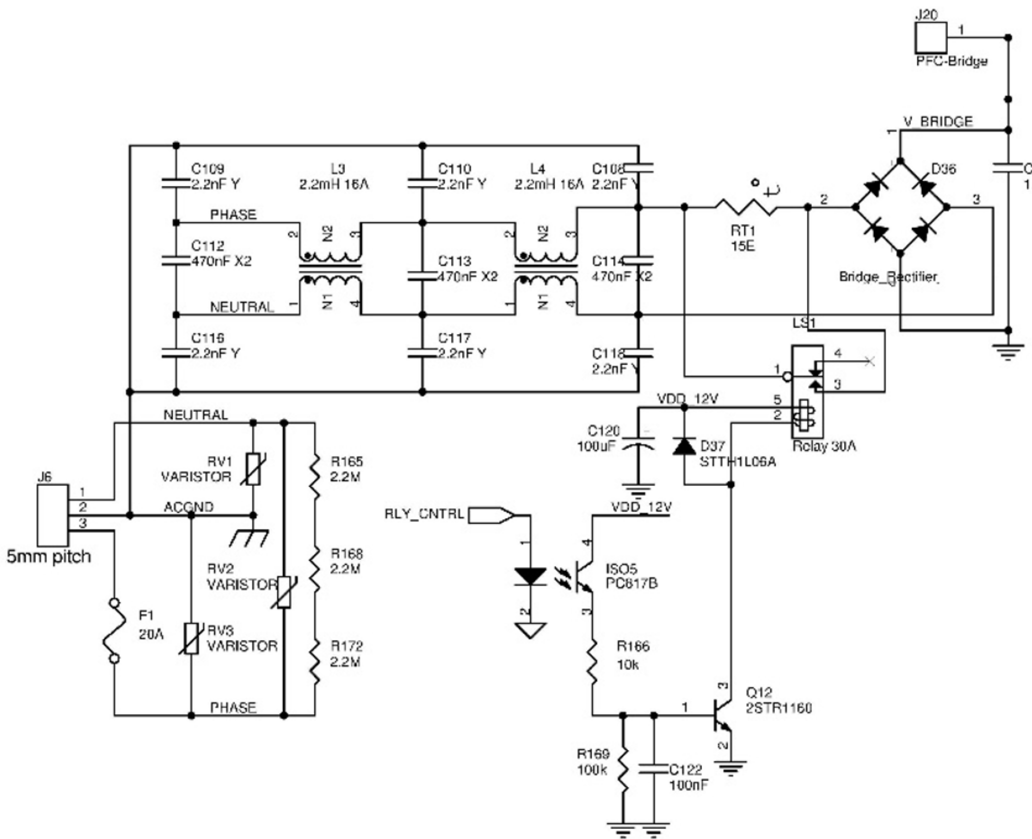
Figure 6. **Sendust 60µ Toroid – permeability vs DC bias (from Micrometals)**



- **Inrush current limiter**
  This is a very critical aspect that contributes to board robustness and transients in the grid. Its creation is a combination of an NTC thermistor with a very high I2T rating and a relay. In the cold state, the thermistor offers a resistance of approximately 15 Ohms at 25°C. It drops at around 3 Ohms at 90°C. Initially, the PFC bulk capacitor is discharged, causing a virtual short-circuit. To prevent a heavy inrush, in the range of several hundred amperes from the mains, the thermistor is put in series to limit the current to acceptable values. In the meanwhile, the capacitor charges up. After two seconds, the relay is used to bypass the NTC. Thus, there are no further losses across the NTC, which is now out of circuit. The entire current is now handled by the relay. This scheme also protects the SiC PFC diode from the high surge current at startup, which is detrimental to it.

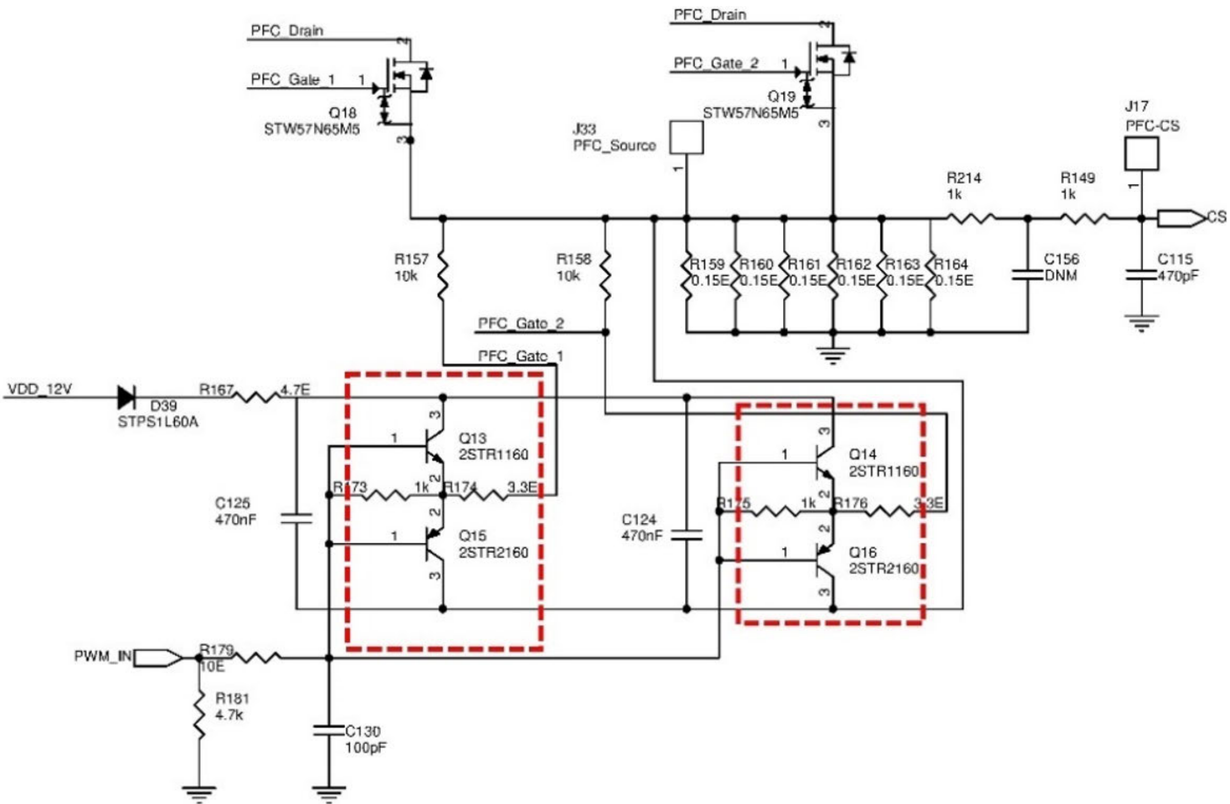
- **EMI filter**
  This is the input filter and protection section. The input section is a dual pi section common mode filter that attenuates the conducted emissions out of this board and avoids polluting the mains and vice versa. In this stage, losses are minimized by the careful selection of the magnetics. Nano-crystalline cores with an extremely high permeability have been used to minimize the physical size and the DC resistance of the windings. Nanocrystalline common mode chokes (CMCs) are designed to filter out common mode electromagnetic interference (EMI) noise in AC-DC, DC-DC, and DC-AC circuits. The amorphous core enables a very high impedance per volume, which minimizes the board space while aiding the common-mode noise rejection. The CMCs block high-frequency alternating currents and allow the low-frequency direct currents to pass through. They also feature a high impedance per unit volume and stable impedance over a wide temperature range as is expected in harsh commercial heavy-duty applications. The DCR of each winding is now only 4 mΩ as the total inductance of 2.2 mH is achieved by only seven turns instead of a large winding with a much higher DCR in the range of 20 mOhms. A direct saving of about 60% in losses, arising from the filter stage, has been achieved. It is also important to highlight other aspects of this stage. As the design specification limits the maximum input AC current to about 16-A RMS, the components must support this maximum current. The chokes (L3 and L4) reduce the common-mode noise as well as 2.2 nF Y capacitors; their values are heavily dependent on the instantaneous dV/dT switch nodes and the associated stray capacitance to ground, through heatsink coupling and traces coupling, which are not easy to predict. L3 and L4 also provide some differential-mode filtering and should take care of the high-frequency range. The leakage inductance of the common mode chokes definitely helps. After initial calculations and bench tests, we found L4 = L3 = 2 mH to be a good fit. In the final product, it is imperative to check using various values until the expected results are met. The switching frequency is close to 65 kHz, which is way less than 150 kHz, the initial frequency limit of CISPR 22 quasi-peak measurement.
- **Bridge rectifier**
  A 35 A glass passivated bridge of 600 V rating has been used to lower losses in the rectifier stage. The forward drop in a larger rated diode is lower at the intended maximum operating current of 16 A. Since the choice was to have 25 A, 35 A, and 50 A in the same package, the 50 A part (PB5006) by Vishay was chosen for the lowest losses as the cost difference is marginal.

Figure 7. EMI filter and bridge



- **Gate drive totem-pole**
  The ease of charging and discharging the gate might seem a relatively "simple gate drive" scheme. However, this simplicity is not without problems and pitfalls. Often, supplying the gate with enough current is not the problem, but the parasitic and layout often play a detrimental role. Problems most often encountered with the gate drive circuit are voltage spikes damaging the gate oxide, oscillation, ringing, or false turn-on due to the miller capacitance. Mostly, these problems are due to the layout and not the actual design of the driver stage. To minimize these problems, we have used a totem pole, especially because two devices have been used in parallel and the symmetrical operation is the key to a reliable performance, high efficiency and repeatability over production lines. The source lead inductance acts as a negative feedback to the gate drive, essentially detrimental for the switching speed. The source inductance device cannot be reduced by the designer, but the inductance drive layout can be made tight and small to mitigate the degradation. The problem is where the gate drive and the load current share the same conduction paths: source to shunt to ground connection. Here, the load current path should be separate from the gate drive return path on the PCB layout track placement. The closer to the source terminal of the device the better. A ground loop is also overlooked in the gate driver circuitry layout. A ground loop is created when the return of the gate driver stage is terminated at the power ground multiple times inadvertently. This results in a high slew rate voltages and the load current polluting the gate drive stage net ground. This results in a slower switching and causes an excessive ringing on the gate with a false triggering of the power device and eventual destruction. Hence, we have used a totem pole, with the source as a floating reference. Since they are bipolar devices, this method of operation provides no challenges if the emitter is floating and also clamps the gate source properly at a very short distance from the MOSFET. The figure below shows the component placement on the totem-pole.

Figure 8. Totem-pole configuration



2.2 DC-DC LLC full-bridge resonant converter

The LLC stage is a full bridge converter based on the DM6 series of super junction MOSFETS. For a power handling of 2500 W, four of these devices have been used in a full-bridge configuration. By slightly changing the magnetics, a total power throughput of up to 3000 W is also possible, with similar efficiency figures. In this particular application, the power section runs between 85 and 140 kHz depending on the exact load conditions and battery voltage. All three operating modes (below, above, and at resonance) have been used. The full-bridge topology handles load variations well but requires some effort to implement a design to handle the 1.5 span of the output voltage. This must be considered in the tank design. A wide output range design has some performance trade-offs. In any case, the LLC is running from a regulated PFC front end. Keeping a judicious L_m to L_r ratio, a 40-60 V output voltage range is achieved. The system is tested at full load with good efficiency.

The LLC operates at a slightly less than 50% duty ratio and a fixed 180° phase shift. The regulation is obtained via the frequency modulation. Primary MOSFETs turn on at “resonance” or zero voltage switching, resulting in recirculation of the energy stored in the MOSFETs parasitic output capacitance C_{oss}. Secondary diodes operate at ZCS to minimize switching losses associated with the hard switching. The resonant operation of all switching and commutation components in the LLC converter ensures an increased overall efficiency.

The fundamental aspect to keep in mind is the total gain = MOSFET switch gain * Tank gain * Turns ratio.

Some key parameters to consider during the design are:

- Q factor
- L_m/L_r ratio
- f_r the resonance frequency
- reflected load resistance
- Nnormalized frequency

The switch gain is 1 for the full-bridge and 0.5 for the half-bridge configuration. Arriving at the optimal Q and M values is not a trivial task and requires a couple of iterations even for experienced professionals. So, physical experiments are required, preferably run-in an open loop, for an easier conclusion. For the complex calculations and derivations, and further elaborate analysis, refer to AN2450. The practical implementation tips are provided henceforth. To start, we suggest a value of maximum Q less than 0.7. Q reaches its minimum value at light loads, where the gain curve starts to flatten as the frequency is increased. The converter must be able to regulate at these high frequencies encountered, especially when the battery is deep discharged, for example. A ratio of L_m/L_r = 4 and a Q_{max} of 0.35 has been chosen for this application for a limited operating span and good regulation.

There are three modes of operation:

1. At a resonant frequency operation, f_s=f_r. The resonant tank is close to the unity gain and is best fit for a high efficiency. So, the transformer turns ratio is chosen so that the converter operates at this point at the nominal input and output voltages.
2. Above the resonant frequency operation f_s>f_r. Over resonant mode results in buck operation, or reduction of the output voltage, to an extent, dependent on the resonant tank components, the M ratio, and the degree of output loading. Turn off commutation is no longer ZCS, and losses increase somewhat, depending upon the operating point of the primary resonant tank. Use of extremely fast diodes or better still Schottky or SiC Schottky diodes is mandatory for a peak efficiency.
3. Below Resonant frequency operation, f_s<f_r. Below resonant frequency, it results in boost operation until the resonant frequency is reached, based on the tank components C_r, (L_r + L_m), and R_{ac}, the effective loading reflected to the primary side. Boost gain comes into picture, but the primary to secondary current transfer is discontinuous. Furthermore, operating at a lower frequency increases the magnetizing current value, but, since this current is not transferred to the output during energy transfer cycle, it only contributes to increased conduction losses in the primary switch side. You can move the left of the resonance by 12-15% of the resonance frequency (provided it is not entering the capacitive zone ever). With a relatively low value of M, the system can have a very tight regulation due to the steep nature of the gain curve at this region.

In fact, the LLC resonant converter can be operated in all three modes and each mode operates at somewhat different efficiency levels. Above resonance, ZVS achieved, CCM on secondary, rectifiers not soft switched. Lower RMS currents for a given power, primary switches operate at higher frequencies. At resonance, ZVS achieved, CCM on secondary, rectifiers are soft switched (ZCS), optimum efficiency. Below resonance, ZVS achieved, DCM on sec, rectifiers are soft switched (ZCS), RMS currents higher for given power.

MOSFET selection: in an off-line application with a pre-regulated bus, the primary side MOSFETs see a maximum voltage equal to the bus voltage. Due to resonant operation, over- and under-shoot is negligible, so a breakdown voltage rating of 650 V is a very comfortable figure. Since this topology is expected to operate fully in ZVS mode (given appropriate MOSFET Q_g, Q_{oss}, selected Q_{max} and M-values and an ample pre-programmed deadtime), switching loss caused by E_{oss} can be considered negligible. To this extent, E_{oss} is not a critical MOSFET parameter for LLC. Different families of MOSFETs are available in this voltage rating range. STO67N60DM6 MOSFET has been used for this application.

Ideally, the MOSFET for the LLC should operate with a zero dead time (maximum power transfer/no duty cycle loss) and no conduction loss. R_{dsON} is obviously important for the latter consideration, but as the dead time must be sufficient to cover all three phases of MOSFET turn on/off characteristics: turn off delay time (gate drive low until the MOSFET channel starts restricting electron flow), turn off time (actual time it takes for the MOSFET channel to go totally high impedance/open circuit) and resonance time (node voltage transition due to L_r/C_r, until the V_{bus}).

The STDES-2KW5CH48V DC-DC stage is based on a full-bridge LLC resonant converter while the output rectification stage is used in a center-tapped configuration.

Table 5. DC-DC LLC resonant tank parameters

LLC resonant tank parameters	Value
Resonant inductor (Lr)	45 µH
Magnetizing inductance (Lm)	180 µH
Resonant capacitor (Cr)	45 nF
Turns ratio (Np: Ns1: Ns2)	8.66: 1: 1

2.2.1 Key devices used in the DC-DC LLC resonant converter

- **L6599AD: full-bridge LLC controller**
  The L6599AD is a double-ended controller specific to the series-resonant half bridge topology. It provides a 50% complementary duty cycle: the high-side switch and the low-side switch are driven on/off 180° out-of-phase for exactly the same time. The output voltage regulation is obtained by modulating the operating frequency. A fixed deadtime, between the turn-off of one switch and the turn-on of the other, guarantees the soft-switching and enables the high-frequency operation. To drive the high-side switch with the bootstrap approach, the IC incorporates a high-voltage floating structure able to withstand more than 600 V with a synchronous-driven high-voltage DMOS that replaces the external fast-recovery bootstrap diode. At startup, to prevent an uncontrolled inrush current, the switching frequency starts from a programmable maximum value and progressively decays until it reaches the steady-state value determined by the control loop. This frequency shift is non-linear to minimize the output voltage overshoots; its duration is programmable as well. At light loads, the IC might enter a controlled burst mode operation that keeps the converter input consumption to the minimum. IC functions include a non-latched active-low disable input with a current hysteresis useful for power sequencing or for brownout protection, a current sense input for the OCP with frequency shift and delayed shutdown with automatic restart. A higher level OCP latches off the IC if the first-level protection is not sufficient to control the primary current. Their combination offers a complete protection against overload and short-circuits. An additional latched disable input (DIS) allows an easy implementation of OTP and/or OVP. An interface with the PFC controller is provided that enables the pre-regulator to be switched off during fault conditions, such as the OCP shutdown and DIS high, or during the burst mode operation.

- **STO67N60DM6: LLC MOSFET**
  The STO67N60DM6 is an N-channel 600 V power MOSFET, available in a TO-LL SMD package. It features a low $R_{DS(on)}$ of 0.059 Ω, low recovery charge (Q_{rr}) and low recovery time (t_{rr}) making it suitable for high-efficiency bridge topologies and ZVS phase-shift converters. In the STDES-2KW5CH48V, four STO67N60DM6 have been used. The MOSFETs have been mounted on a dedicated daughter card, which can be mounted on a heat-sink. Each daughter card have two MOSFETs as shown below.

Figure 9. TO-LL package MOSFET mounted on a daughter card

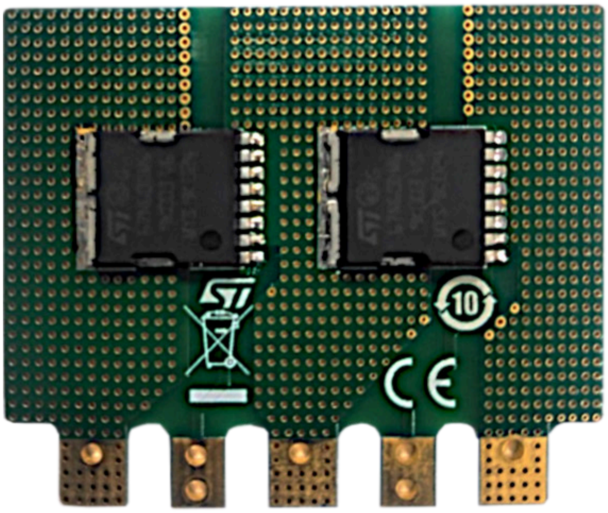
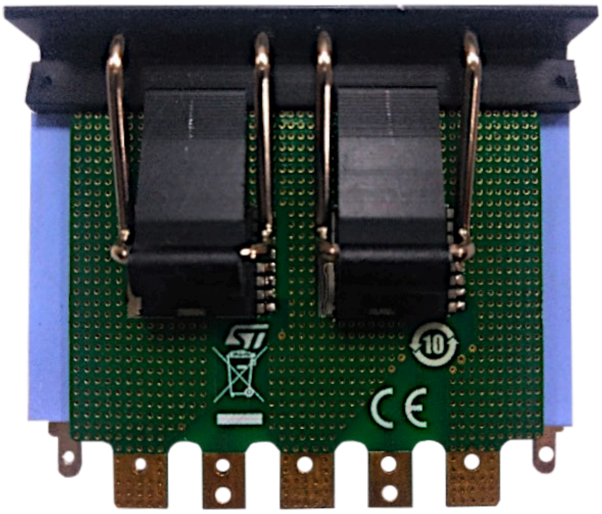


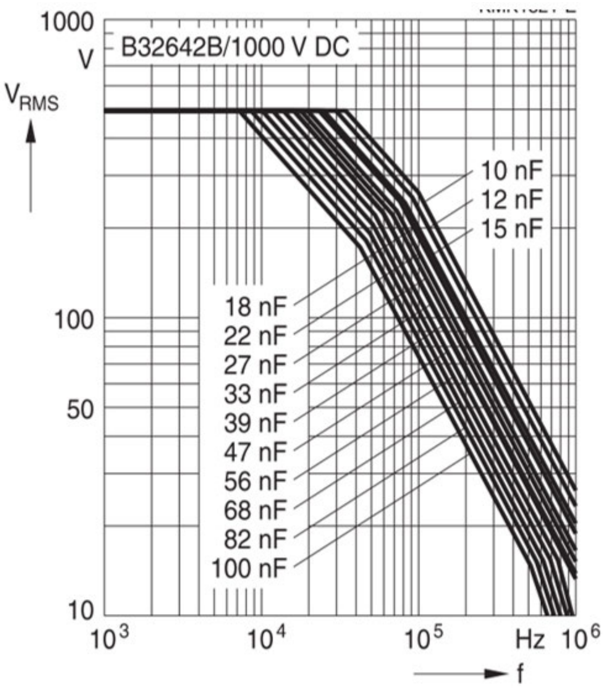
Figure 10. TO-LL package MOSFET daughter card with heat-sink



- **STPS60SM200CW: output rectification diode**
  The most stringent operating condition for the rectifier diodes is under full load (since RMS current is the highest). The user must select diodes with a reverse voltage rating high enough to allow an appropriate derating (20%). The rectifying diodes reverse recover, so low reverse recovery charge is important. For this application, Schottky diodes can be used with negligible reverse recovery characteristics. For Schottky diodes that have virtually no reverse recovery, the capacitance determines the switching loss.
  The STPS60SM200CW is a 200 V dual Schottky rectifier suited for high frequency switched-mode power supplies. Housed in a TO-247 package, this device is designed for telecom base station SMPS, providing these applications with a good efficiency at both low and high loads.

- **Resonant capacitor**
  The resonant capacitor must have a very low dissipation factor (DF), due to its high-frequency operation and a very high sinusoid and non-sinusoid current. Electrolytic or ceramic capacitors are unsuitable and polyester capacitors need a careful look. NP0 capacitors could be used for their low loss, but their maximum capacitance has limitations. Their high cost is a limitatio, too. Capacitors for LLC converters are popularly metalized polypropylene film. These capacitors have a low DF and are capable of a high-frequency current. However, before a capacitor is selected, its voltage rating has to be derated from the datasheet curve, depending on the extremities of the switching frequency in use. Often, it is better to use many smaller capacitors in parallel than one single large capacitor.

Figure 11. Capacitor derating with frequency (by TDK)



- **Output filter**
  In an LLC converter, the output filter usually consists of capacitors only, instead of the LC PI filter seen in PSFB or PWM topologies. However, a small second-stage LC filter may be seen for EMI issues. So, they should be chosen to allow the passage of the large ripple currents in the high current charger applications. The ripple voltage is a function of the AC current component, which flows in and out of the capacitors in each switching cycle, and the capacitors ESR. It is better to choose capacitors with a higher temperature grade like 125°C and with a maximum possible ripple current rating. Rubycon ZLH series, for example, is a suitable part. Usually, a single capacitor does not allow such a high RMS ripple current. So, several capacitors connected in parallel are often used to avoid overheating and a lesser height.

2.3 Auxiliary power supply

The auxiliary power supply is based on a flyback topology using VIPER16HN HV converter, which operates at a fixed frequency of 115 kHz. The auxiliary generates two 15 V outputs. The first 15 V output is w.r.t. primary ground and it supplies the PFC controller, PFC gate drive, fan, relay for NTC bypass, and LLC stage gate drive, while the second 15 V output is w.r.t. secondary ground and it supplies the LLC controller, microcontroller, and the secondary side sensing and control circuitry. High speed opto-couplers are used between the gate drive signal generated from the LLC controller and the gate drive input to the LLC gate driver.

3 Experimental results

The STDES-2KW5CH48V has been tested for the European and American input voltage ranges.

3.1 Test setup

The overall efficiency, power factor, and total harmonic distortion (THD) of the STDES-2KW5CH48V have been tested at different loads The converter maximum efficiency at the maximum load is greater than 93%.

Figure 12. STDES-2KW5CH48V test setup

The figures below shows the results of the reference design at 230 V input with 25°C ambient temperature in terms of efficiency, power factor, and THD.

Figure 13. Efficiency (%) vs output current (A) @ 230V AC

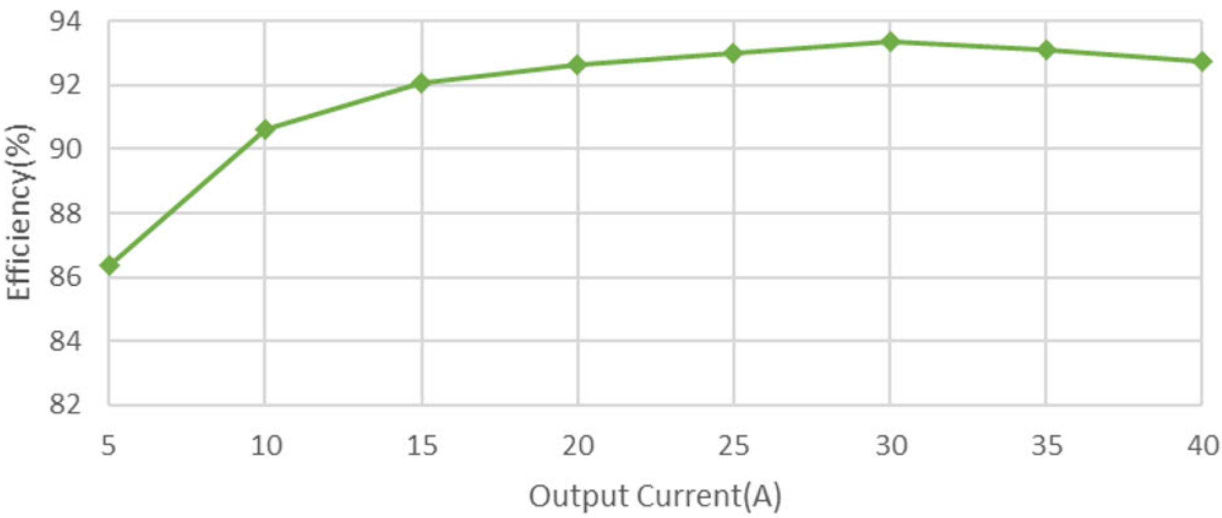


Figure 14. **Power factor (PF) vs output current (A) @ 230V AC**

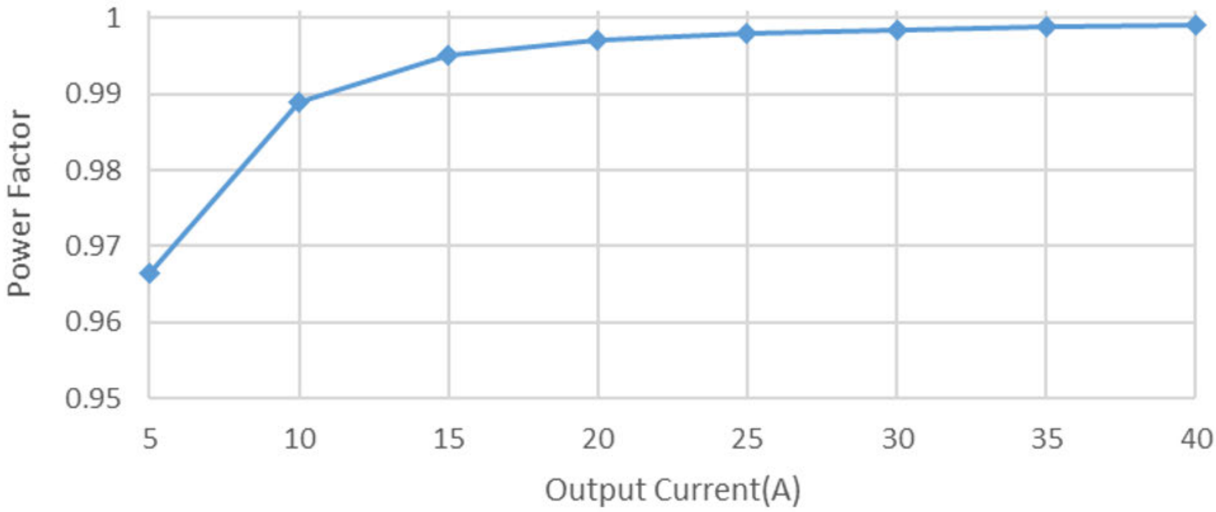
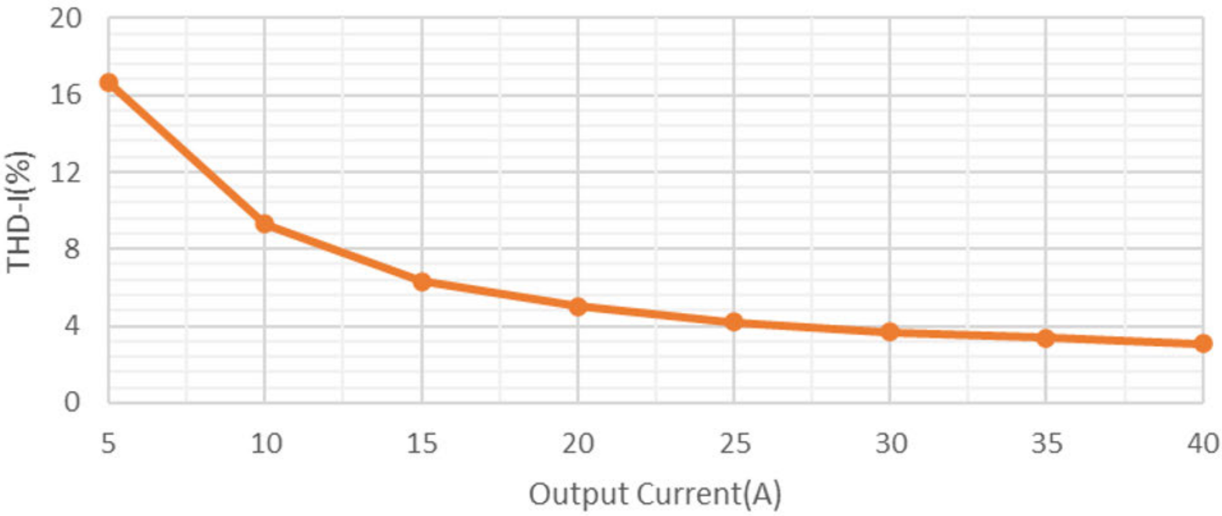


Figure 15. **THD (%) vs output current (A) @ 230V AC**



The figures below show the results of the reference design at 110 V input with 25°C ambient temperature in terms of efficiency, power factor, and THD.

Figure 16. **Efficiency (%) vs output current (A) @ 110V AC**

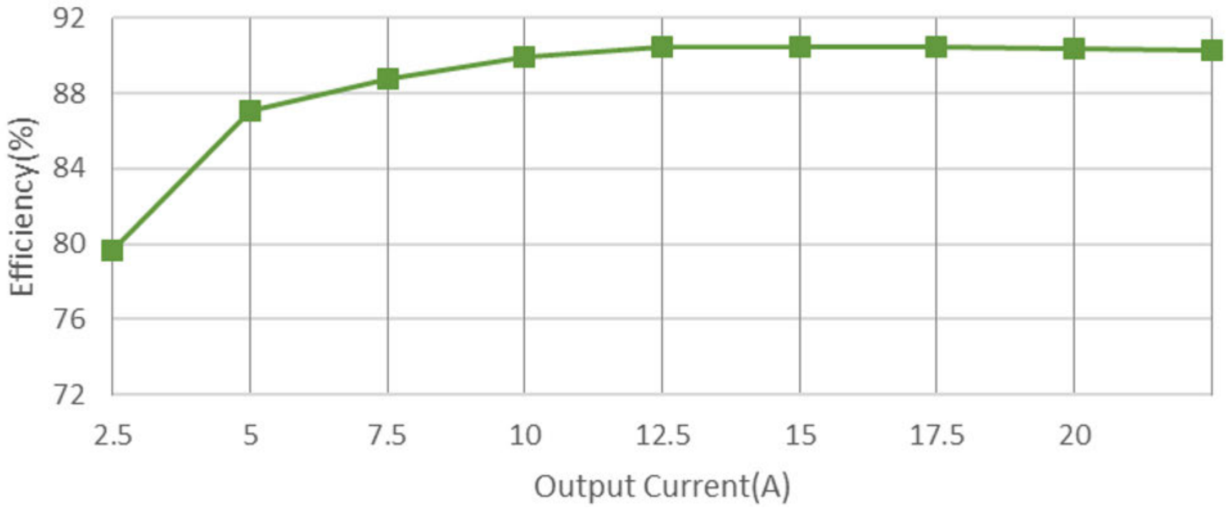


Figure 17. **Power factor (PF) vs output current (A) @ 110V AC**

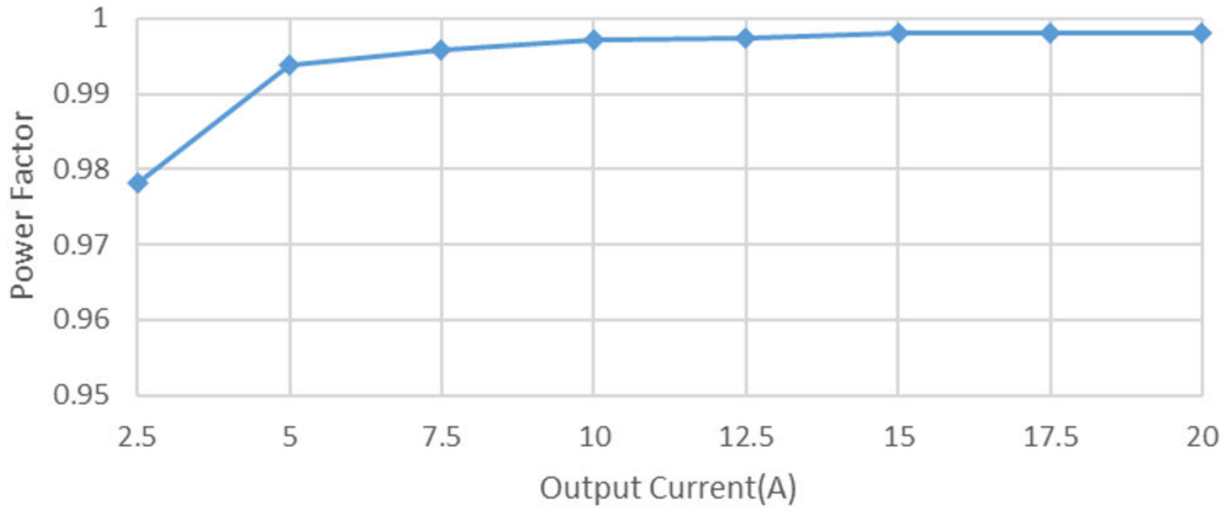
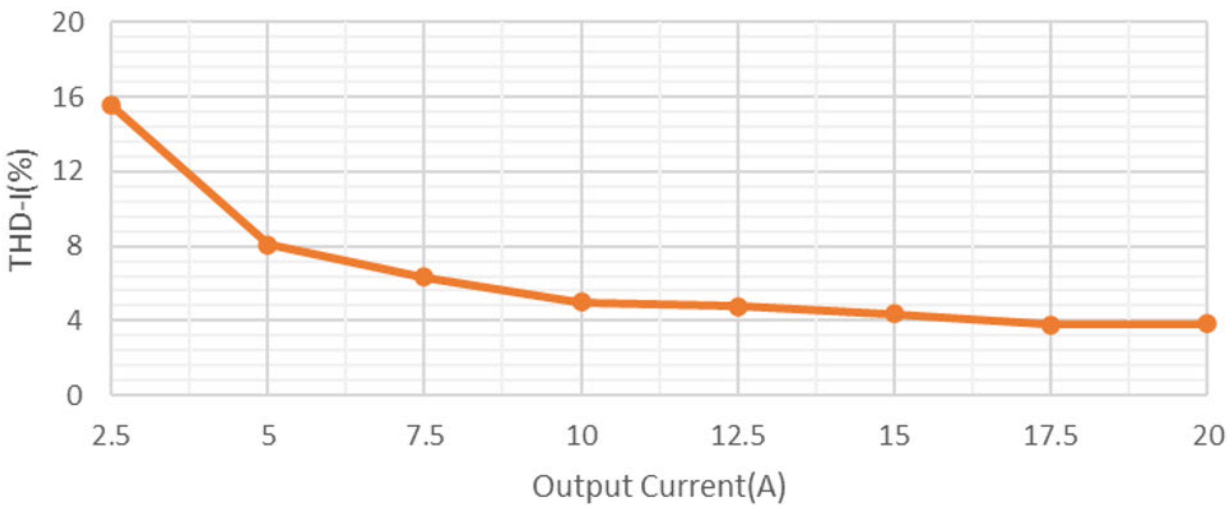


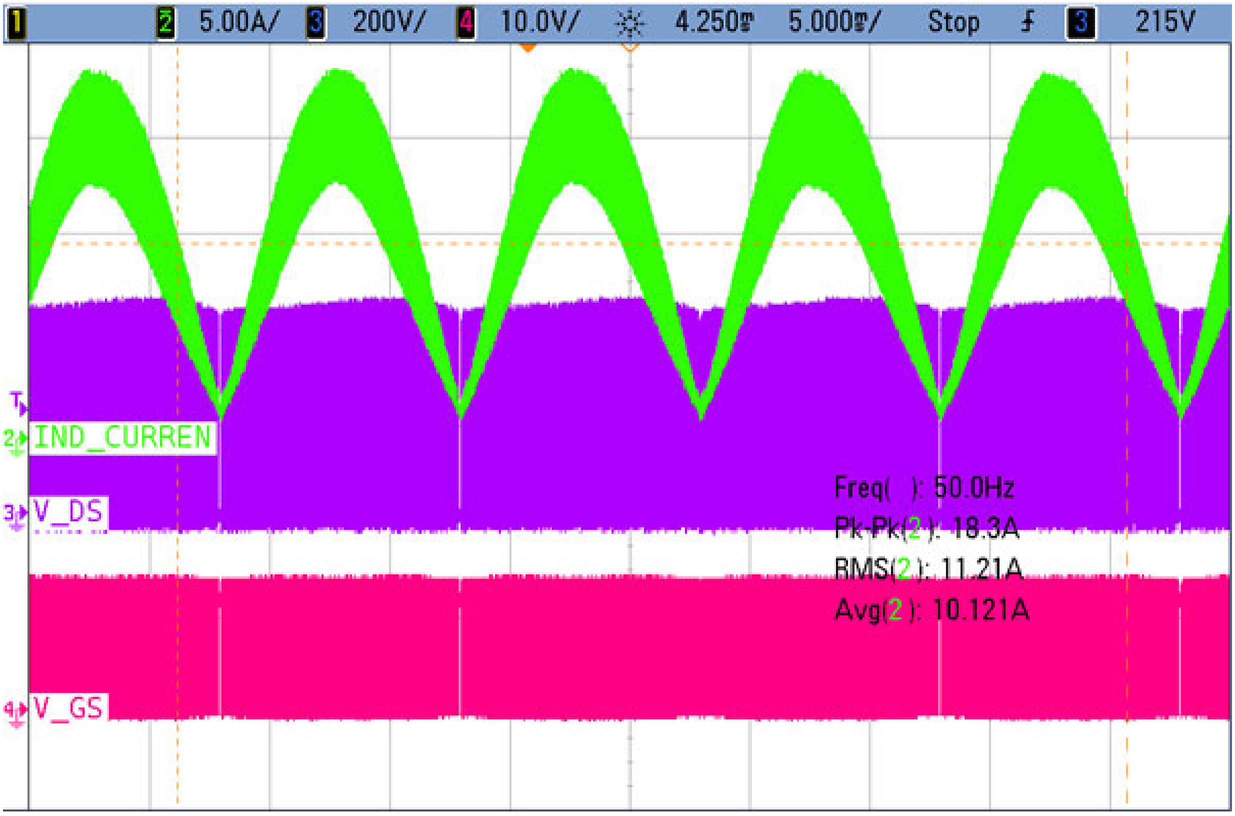
Figure 18. **THD (%) vs output current (A) @ 110V AC**



3.2 Key waveforms

3.2.1 Power factor correction (PFC) circuit

Figure 19. PFC with 100 % load @ 230V AC (1 of 4)



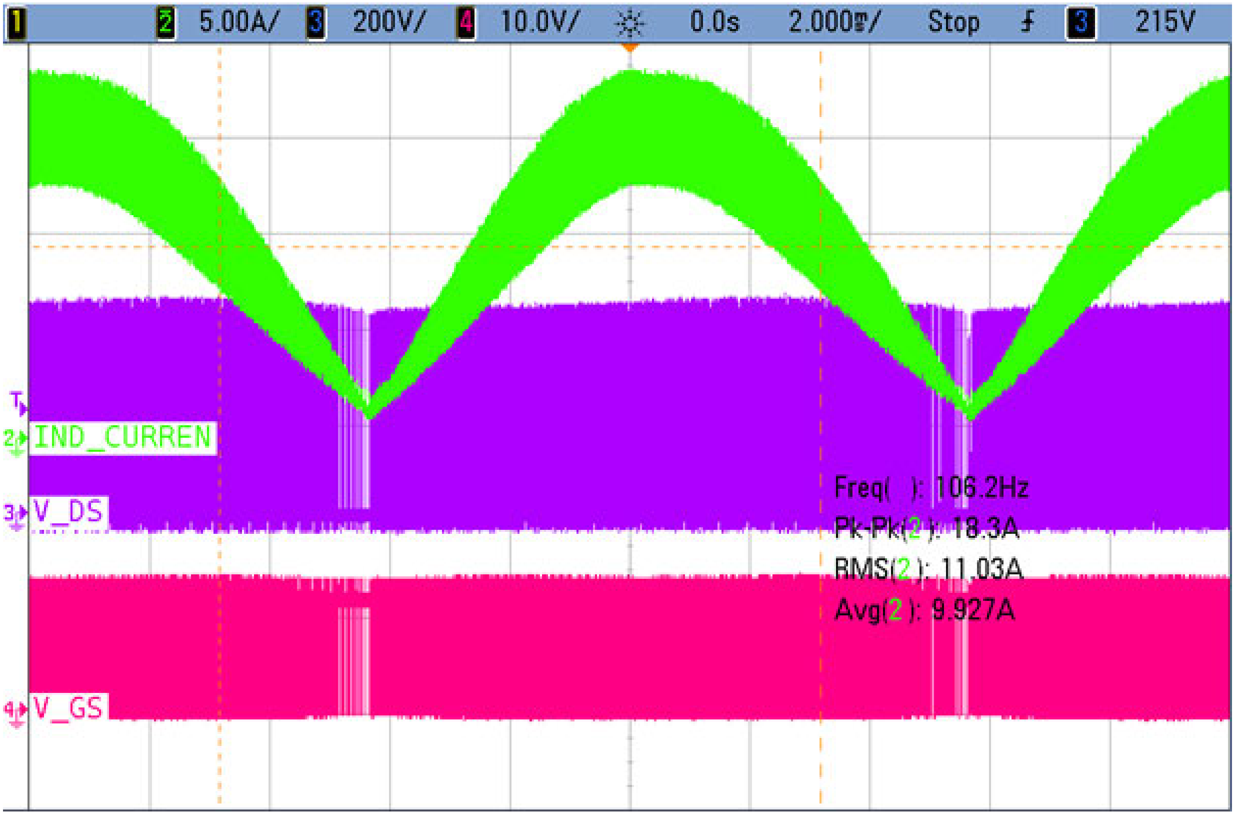


Figure 20. **PFC with 100 % load @ 230V AC (2 of 4)**

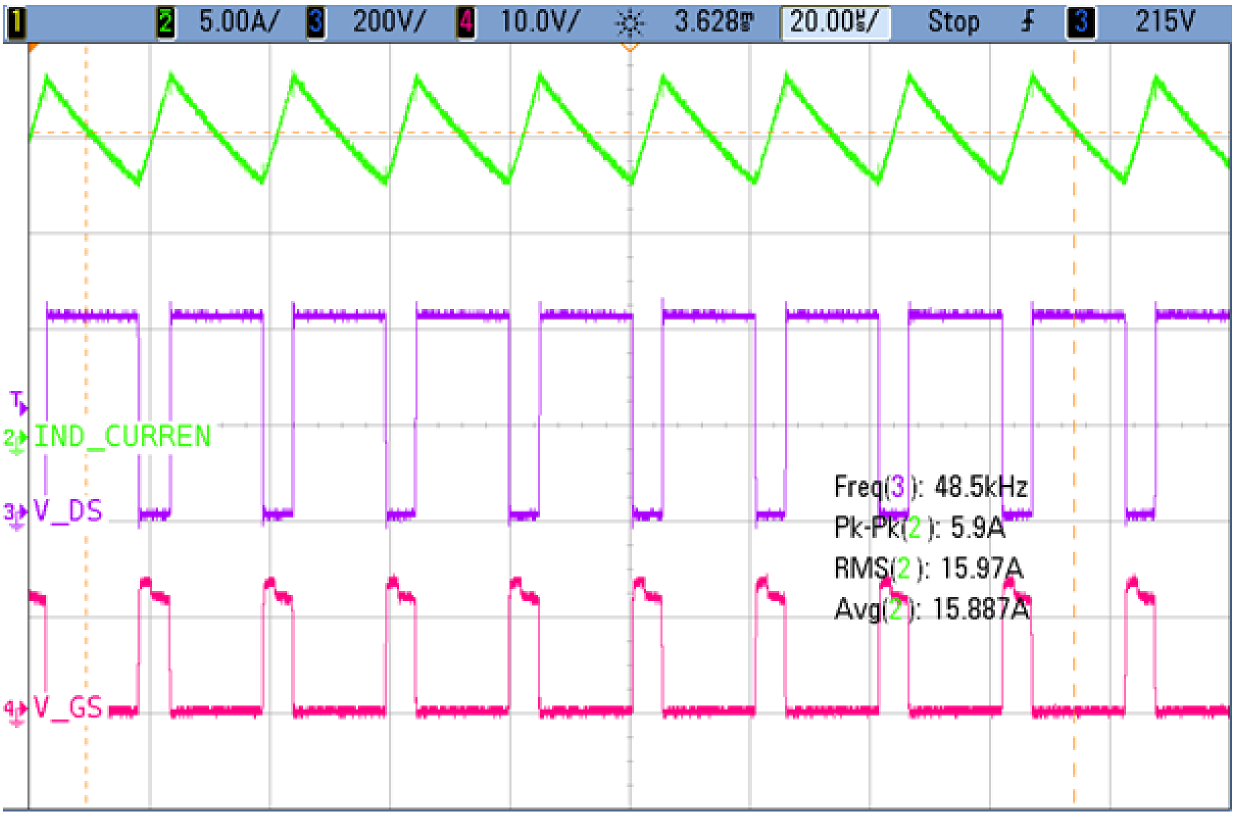


Figure 21. **PFC with 100 % load @ 230V AC (3 of 4)**

Figure 22. PFC with 100 % load @ 230V AC (4 of 4)

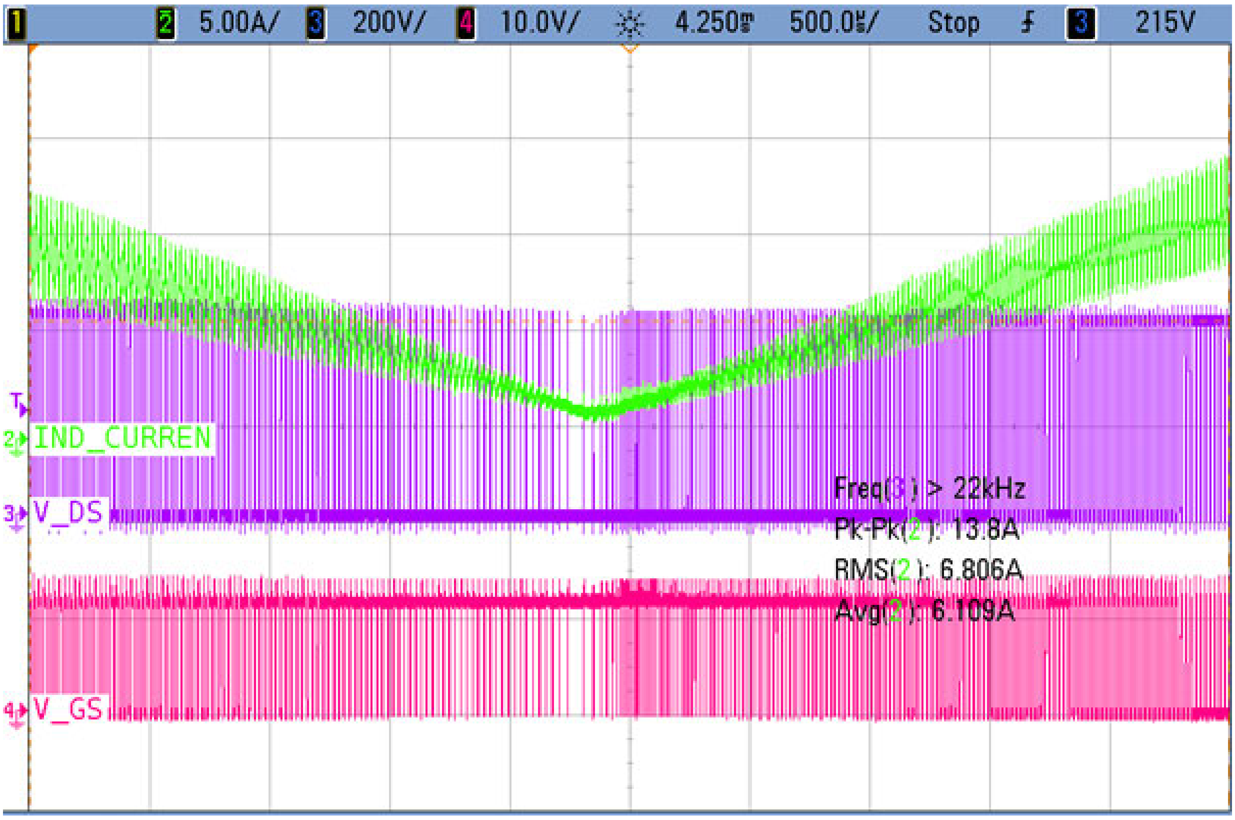


Figure 23. PFC with 50 % load @ 230V AC (1 of 4)

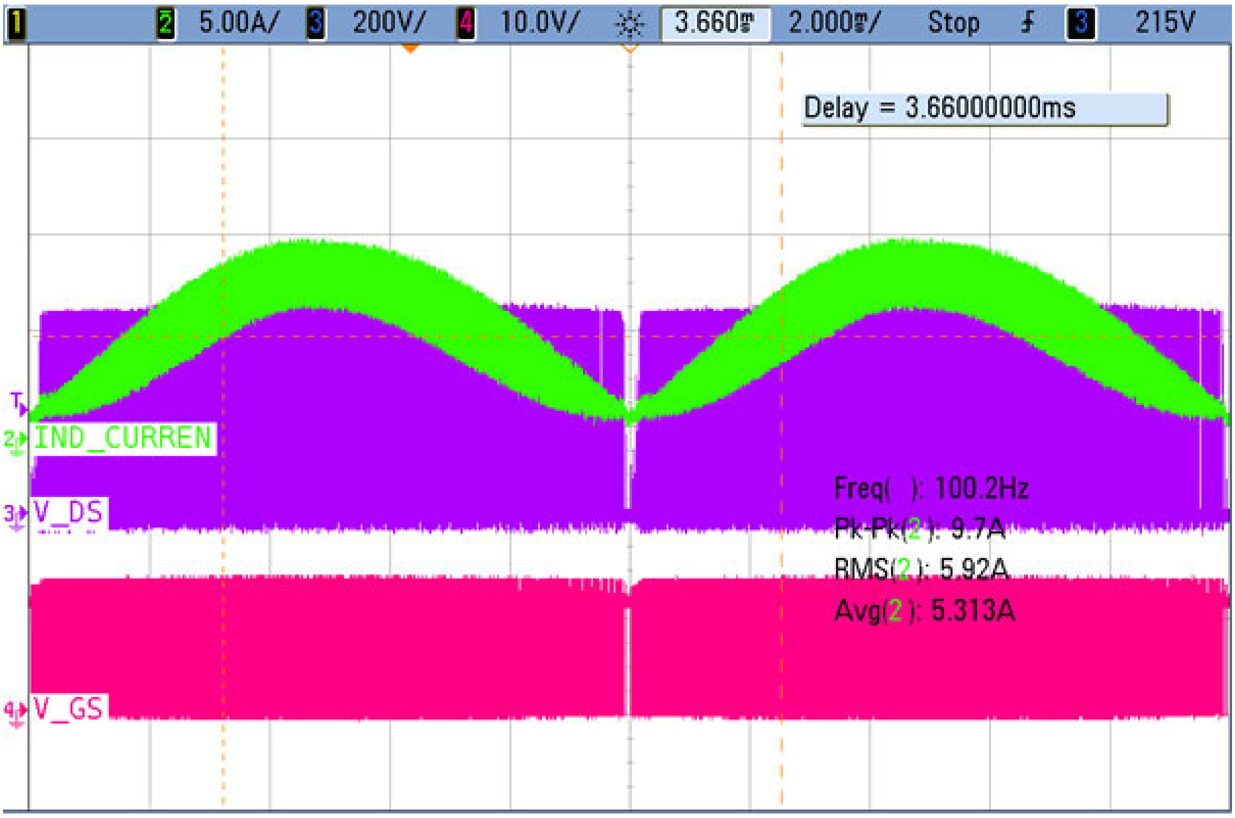


Figure 24. **PFC with 50 % load @ 230V AC (2 of 4)**

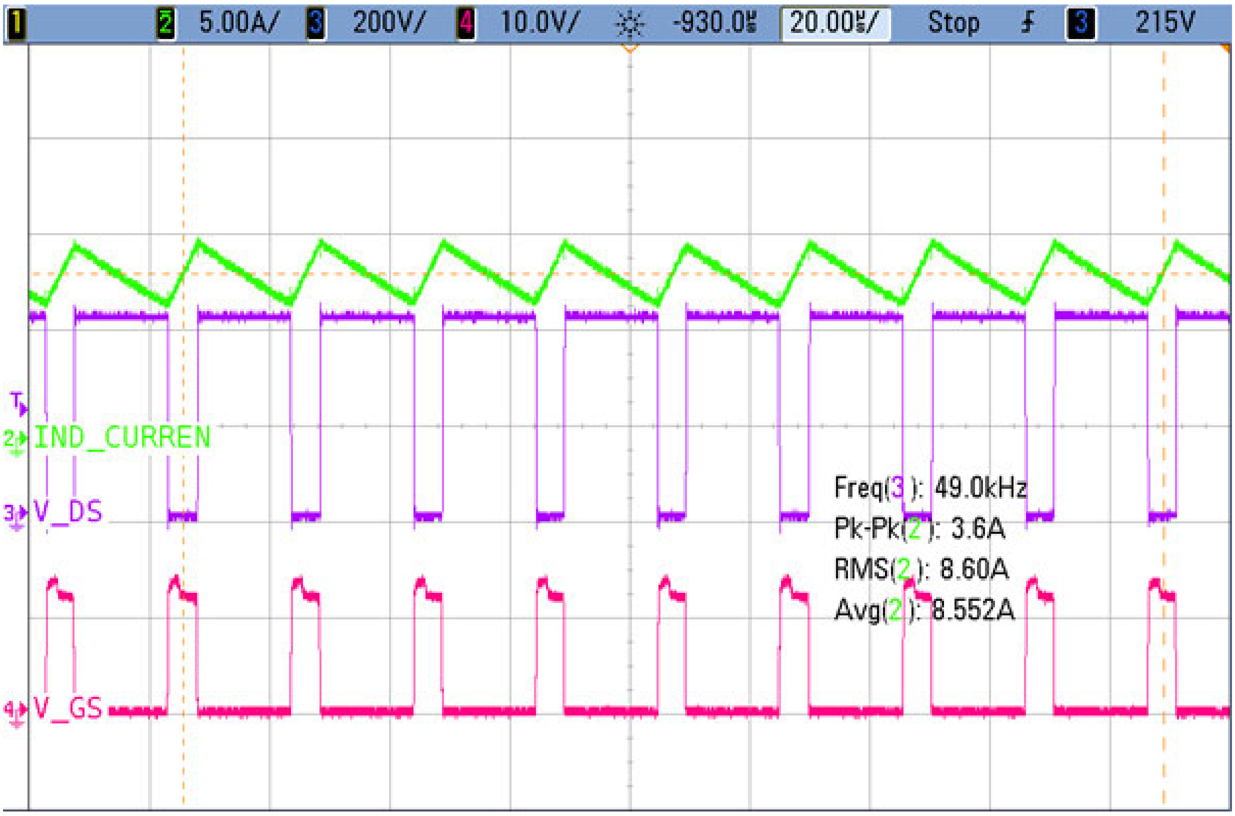


Figure 25. **PFC with 50 % load @ 230V AC (3 of 4)**

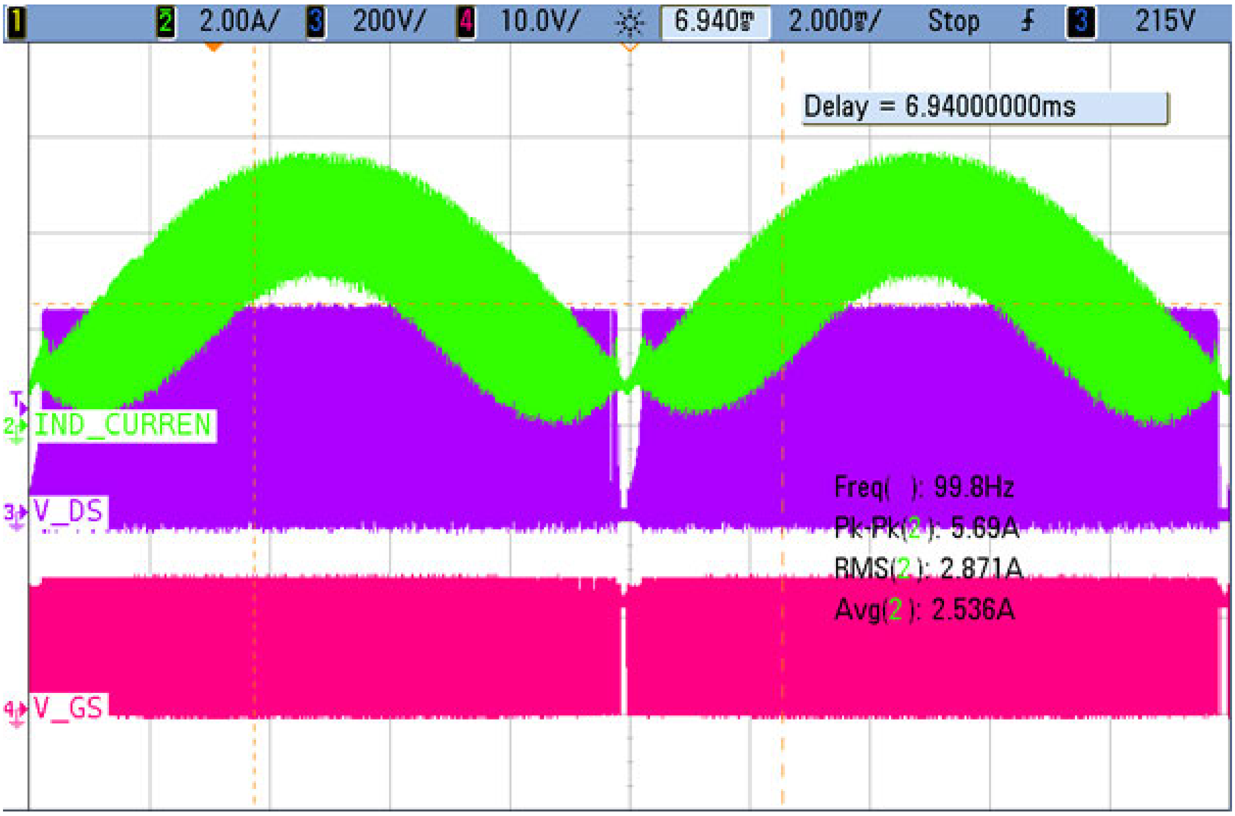
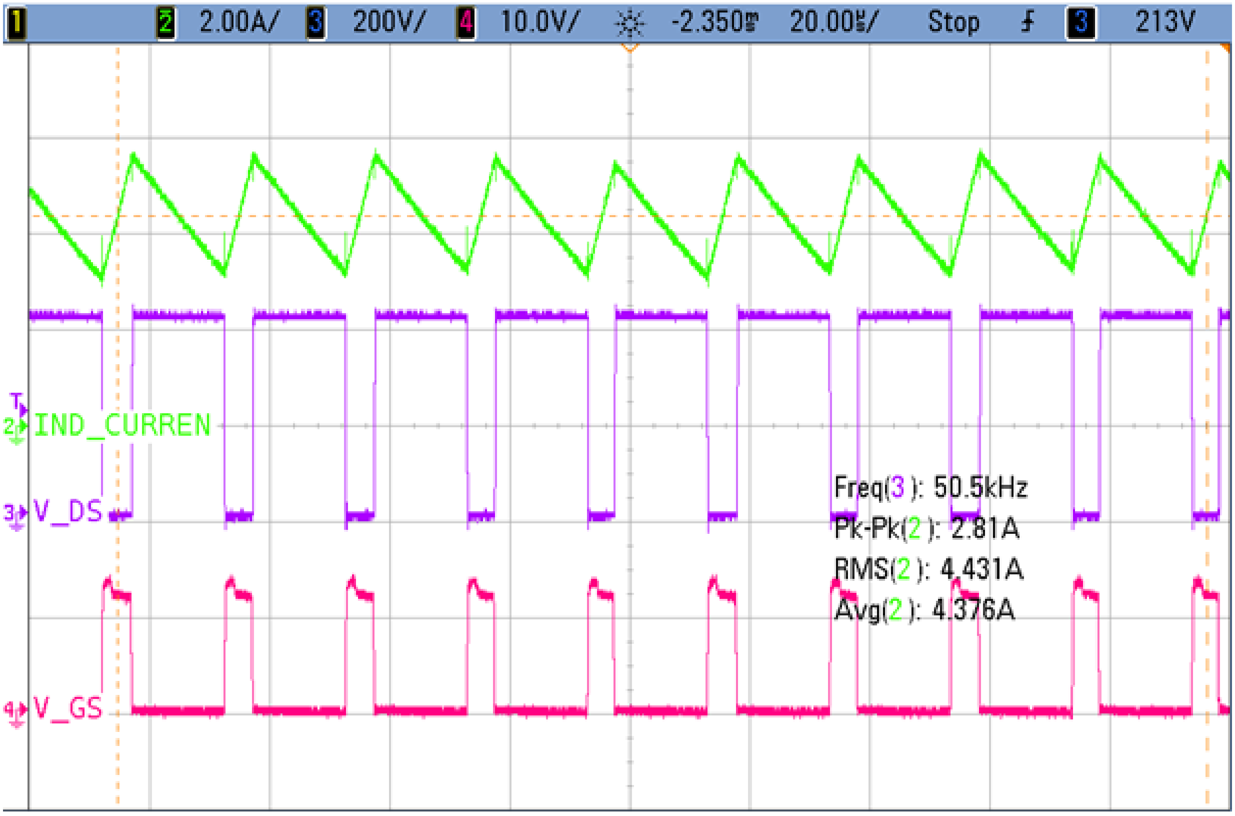


Figure 26. PFC with 50 % load @ 230V AC (4 of 4)



3.2.2 DC-DC converter based on the full-bridge LLC resonant topology

Figure 27. Full-bridge LLC with 100% load @230V AC

- Gate_HS1 (green)
- Gate_LS1 (purple)
- Tank current (magenta)
- Node1 (yellow)

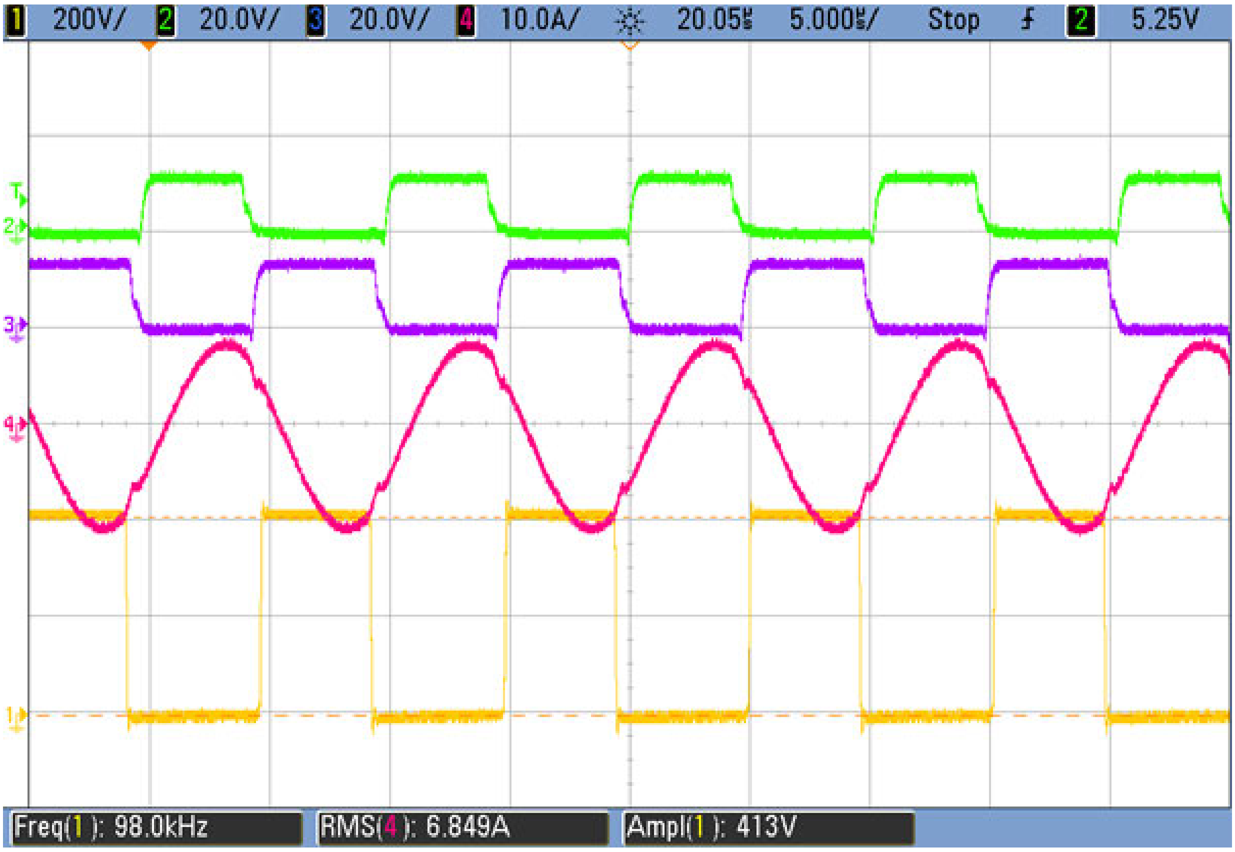


Figure 28. Full-bridge LLC with 50% load @230V AC

- Gate_HS1 (green)
- Gate_LS1 (purple)
- Tank current (magenta)
- Node1 (yellow)

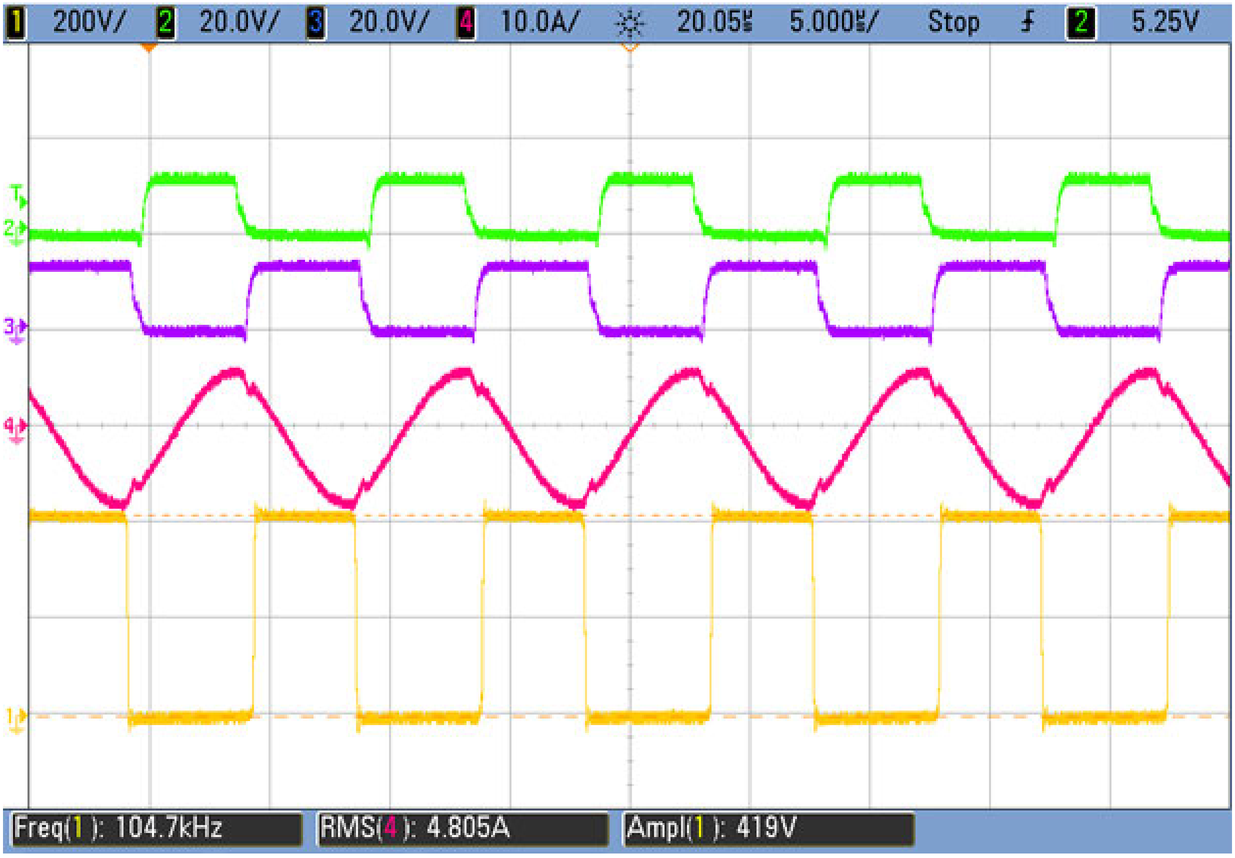


Figure 29. **Full-bridge LLC with 10% load @230V AC**

- Gate_HS1 (green)
- Gate_LS1 (purple)
- Tank current (magenta)
- Node1 (yellow)

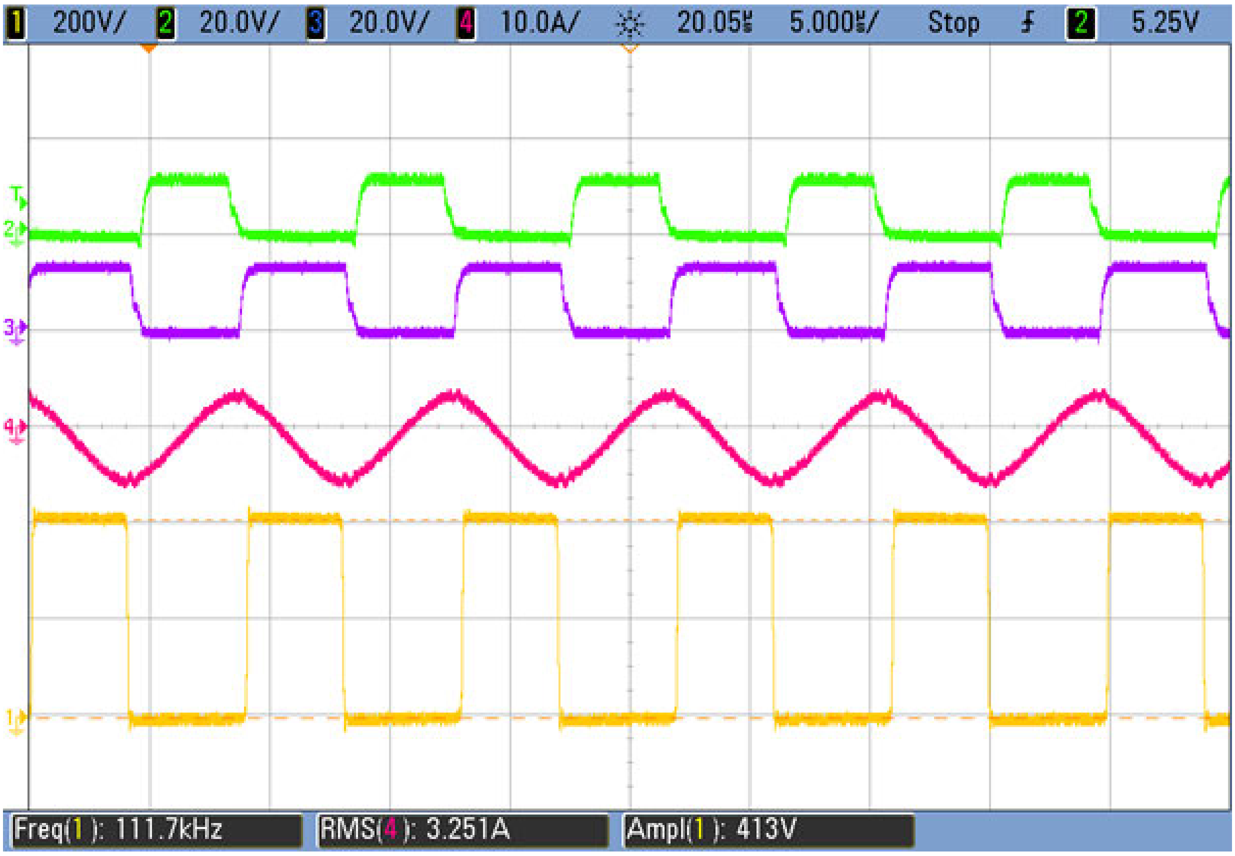


Figure 30. Full-bridge LLC with 100% load @110V AC

- Gate_HS1 (green)
- Gate_LS1 (purple)
- Tank current (magenta)
- Node1 (yellow)

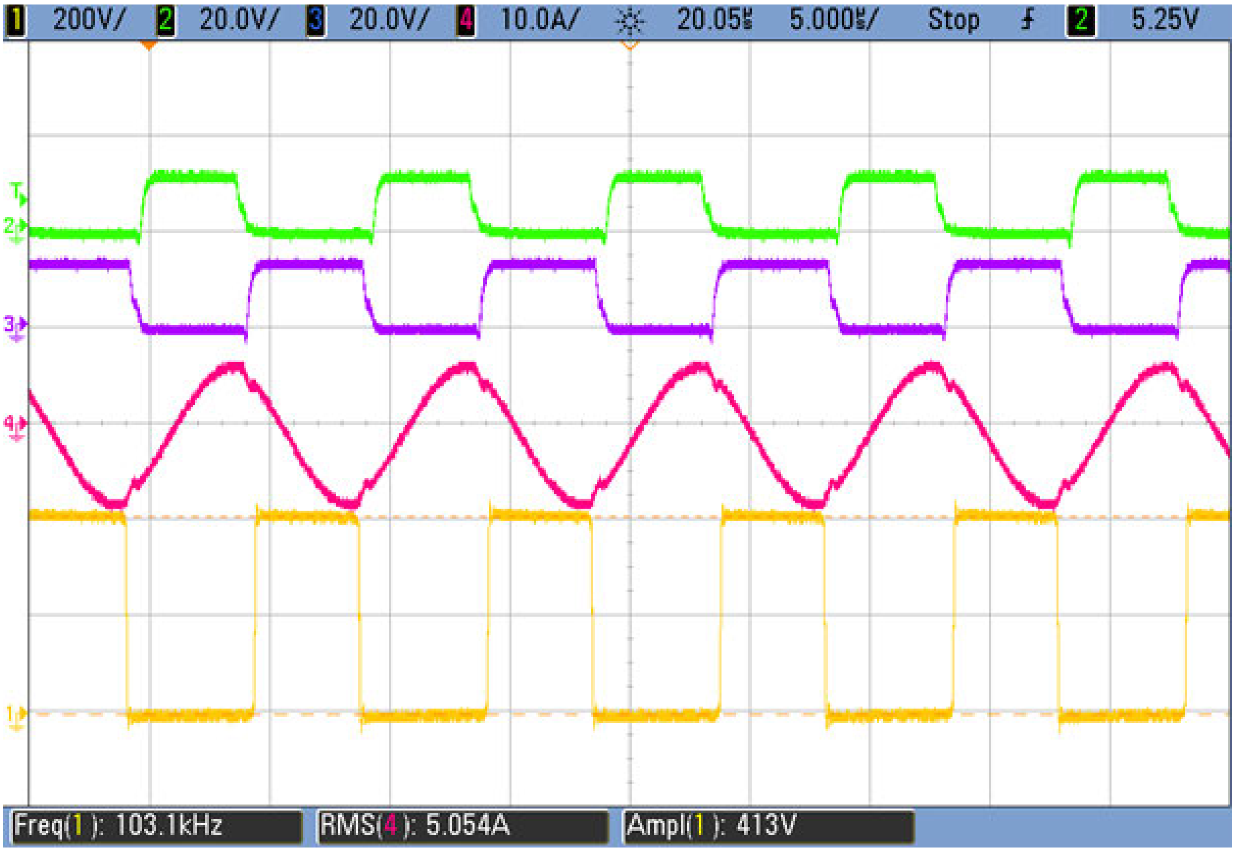


Figure 31. **Full-bridge LLC with 50% load @110V AC**

- Gate_HS1 (green)
- Gate_LS1 (purple)
- Tank current (magenta)
- Node1 (yellow)

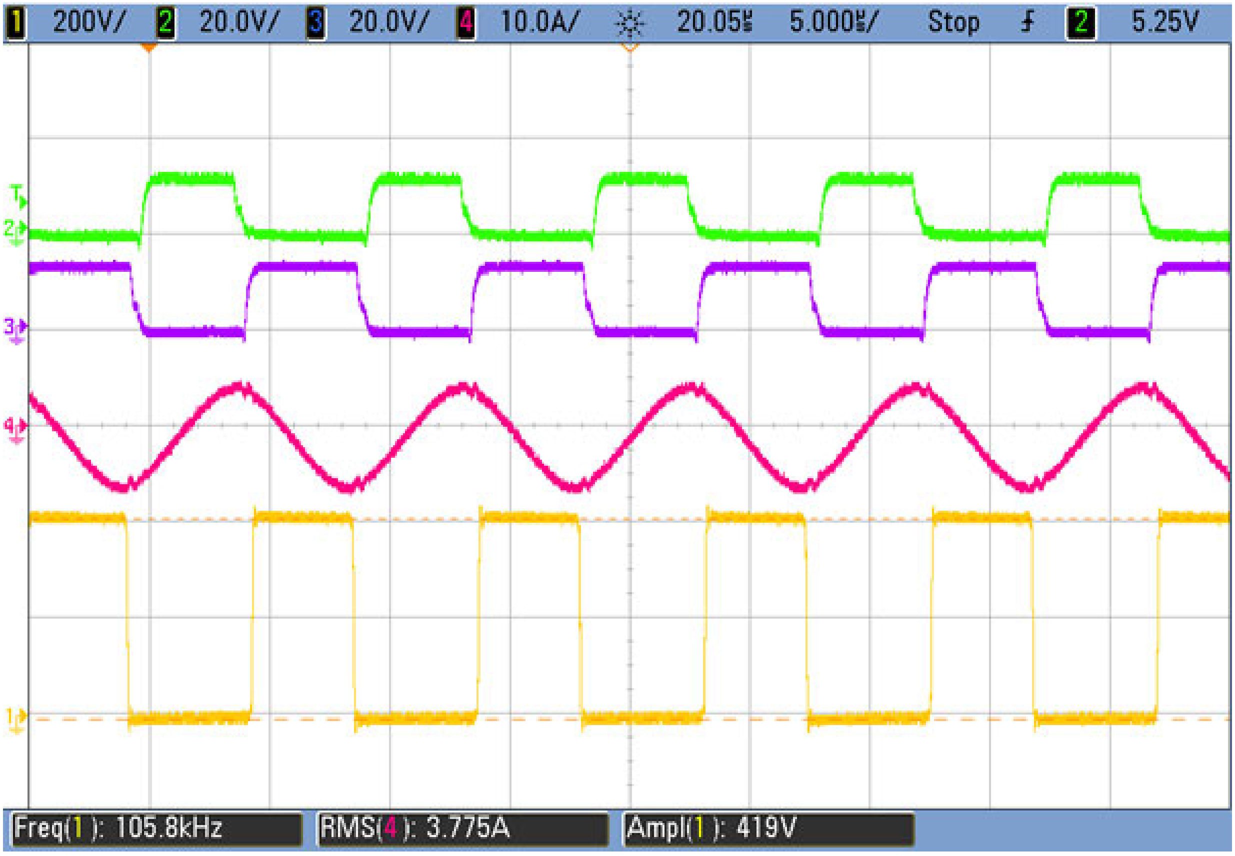
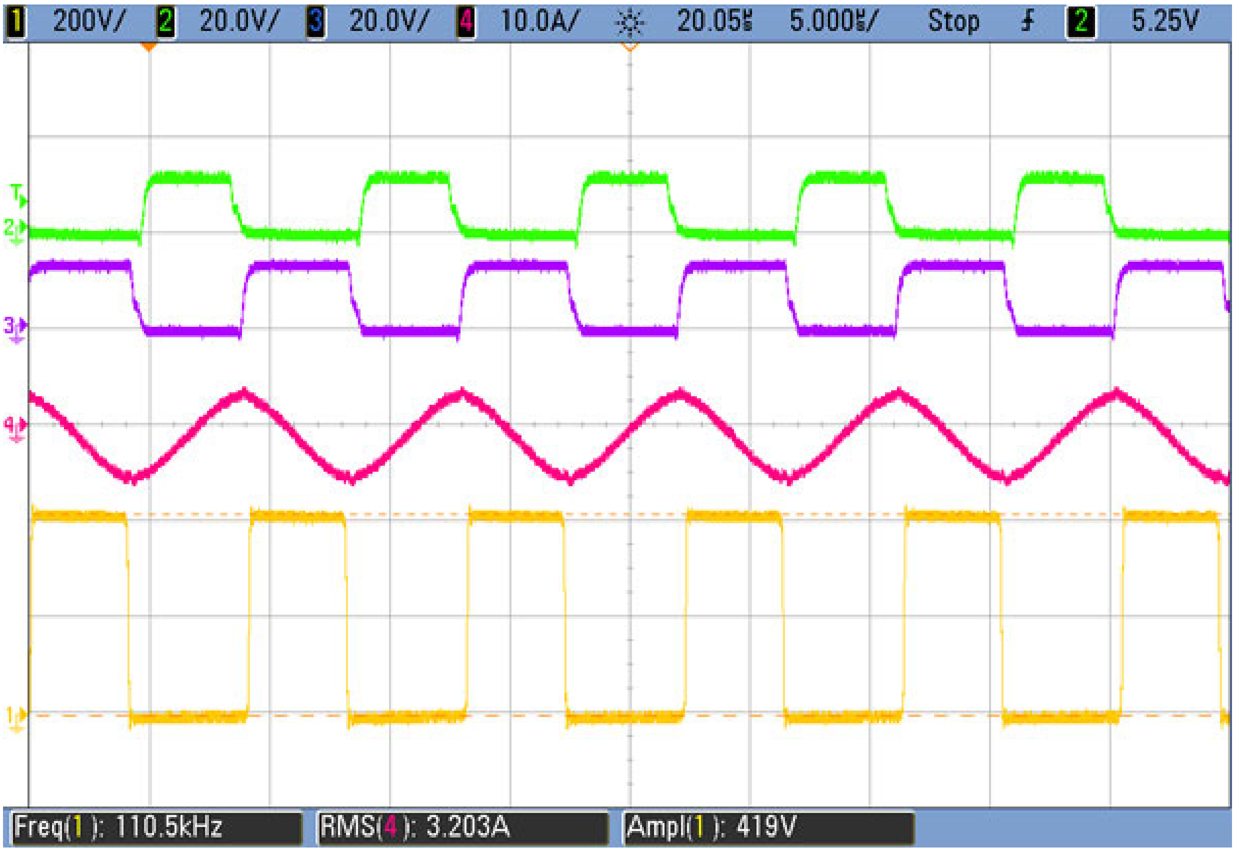


Figure 32. Full-bridge LLC with 10% load @110V AC

- Gate_HS1 (green)
- Gate_LS1 (purple)
- Tank current (magenta)
- Node1 (yellow)



4 STDES-2KW5CH48V magnetics

The STDES-2KW5CH48V involves several customized transformers and inductors. The magnetics design specifications are detailed in the next sections.

4.1 PFC inductor (swinging choke)

For the power factor correction (PFC) circuit, we used a swinging choke, which consists of two stacked cores (CS400060) with 72 turns.

Figure 33. PFC swinging choke

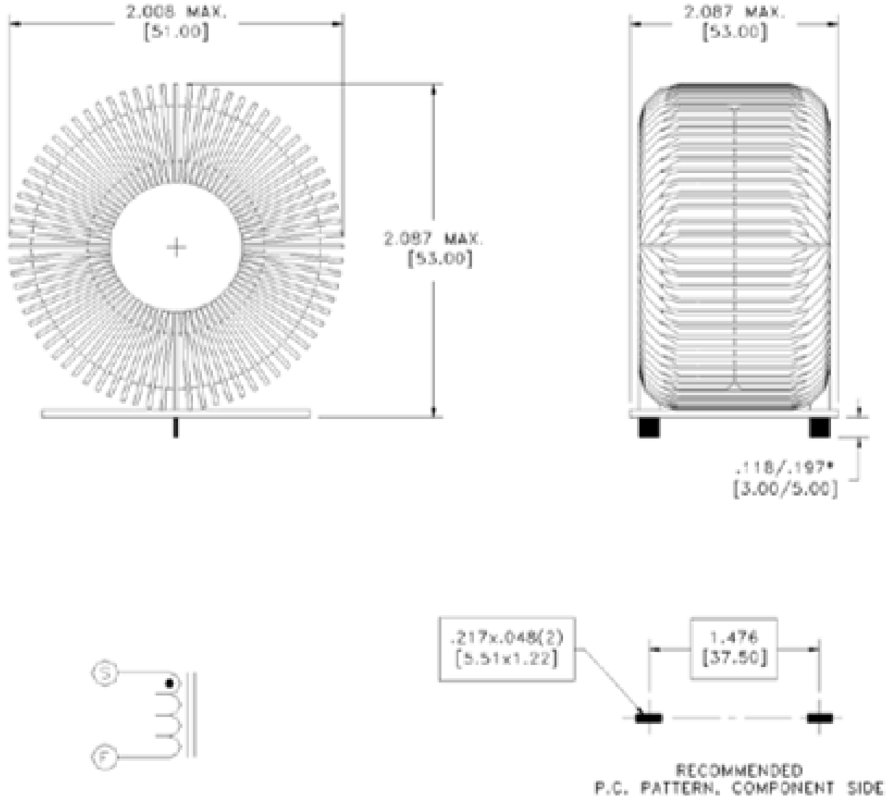


Table 6. PFC swinging choke details

Parameter	Test conditions	Value/name
D.C. resistance	@20°C	0.09 ohms max.
Inductance	10 kHz, 100 mV	800 µH ±20%
Saturation current	30% roll-off from initial	5.5A
Manufacturer	-	Wurth Elektronik
Manufacturer order code	-	750344954

4.2 LLC choke/inductor

For the DC-DC stage, based on the full-bridge LLC topology, the LLC choke is made using the ETD39 bobbin and the Litz wire.

Figure 34. **LLC inductor electrical pin diagram**

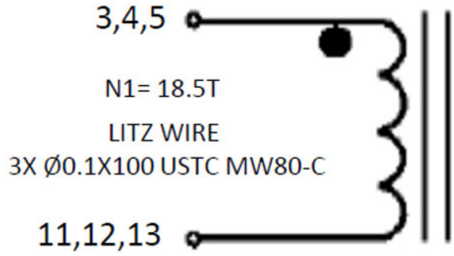


Figure 35. **LLC inductor**

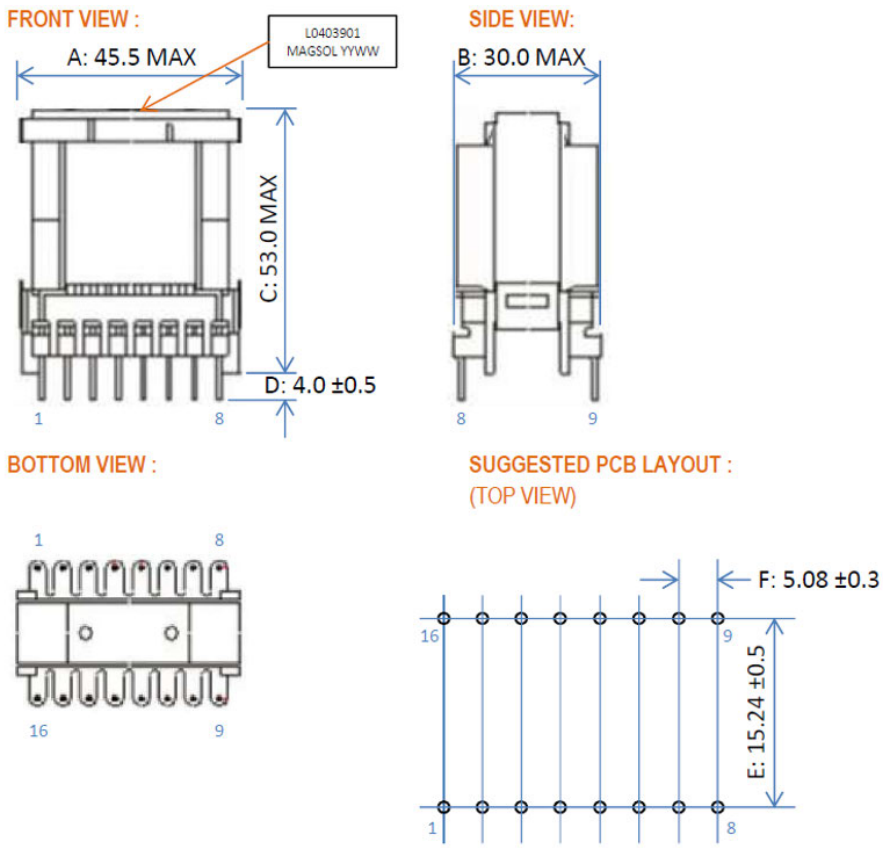


Table 7. **LLC inductor details**

Parameter	Test conditions	Value/name
D.C. resistance	@25ºC	13 mohms max.
Inductance	10 kHz, 1 V	36 µH ±10%
Saturation current	-	18.5
Manufacturer	-	Magsol Technologies
Manufacturer order code	-	L0403901

4.3 LLC transformer

For the DC-DC stage, based on the full-bridge LLC topology, the LLC transformer is used in a center-tapped configuration. It is made using the ETD59 bobbin and the Litz wire.

Figure 36. **LLC transformer electrical pin diagram**

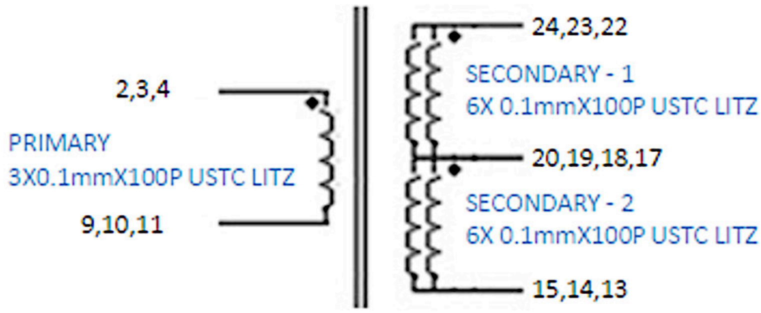


Figure 37. **LLC transformer**

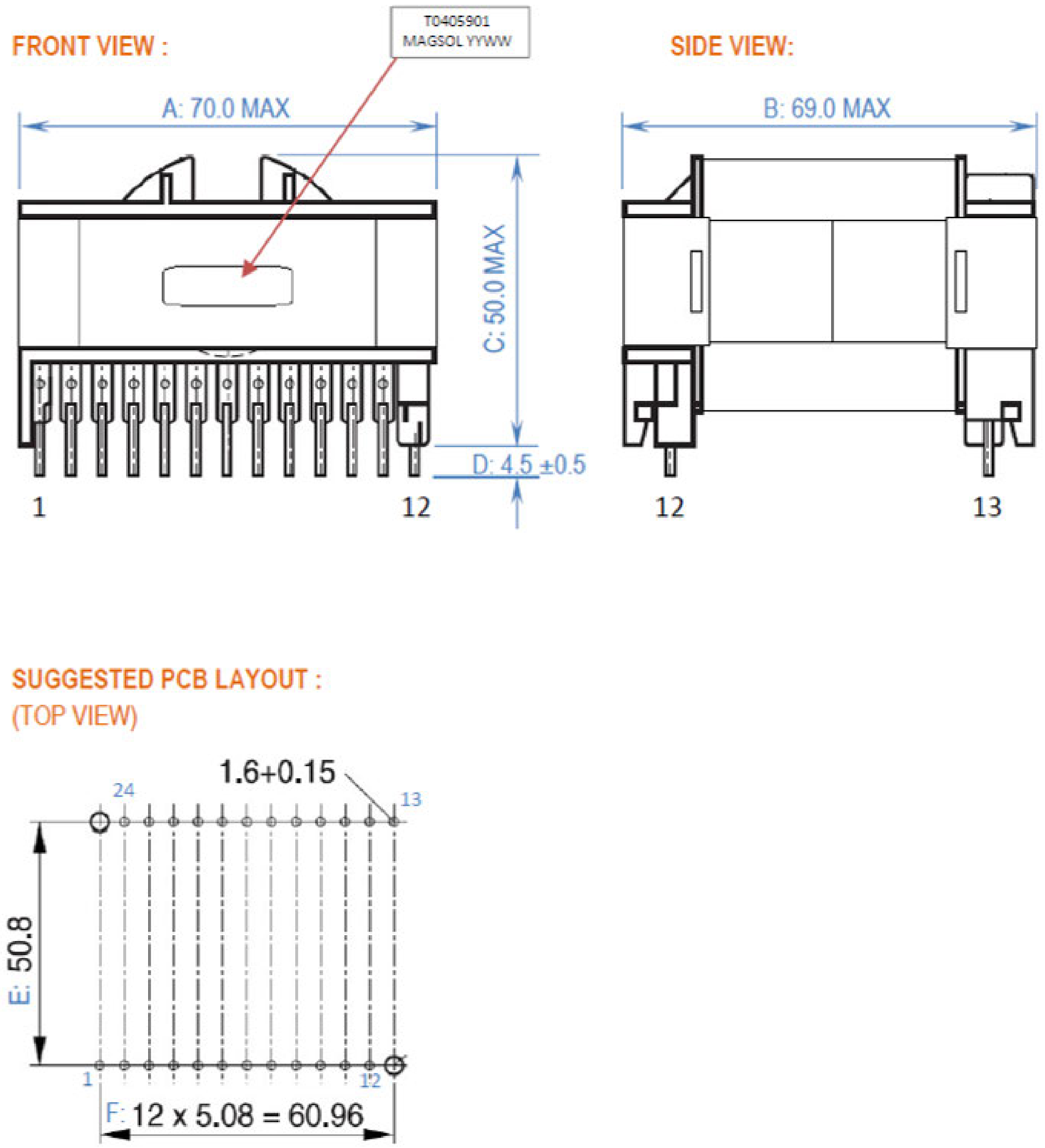


Table 8. **LLC transformer details**

Parameter	Test conditions	Value/name
D.C. resistance	@25°C	24 mohms max.

Parameter	Test conditions	Value/name
Inductance	10 kHz, 1 V	180 µH ±10%
Leakage inductance	100 kHz, 1 V	10 µH ±20%
Turns ratio	-	(Np: Ns1: Ns2) 26: 3: 3
Manufacturer	-	Magsol Technologies
Manufacturer order code	-	T0405901

4.4 Flyback transformer for the auxiliary power supply

The auxiliary power supply based on flyback topology, generates two voltages, both 14.5 V DC but primary and secondary ground.

Figure 38. Flyback transformer

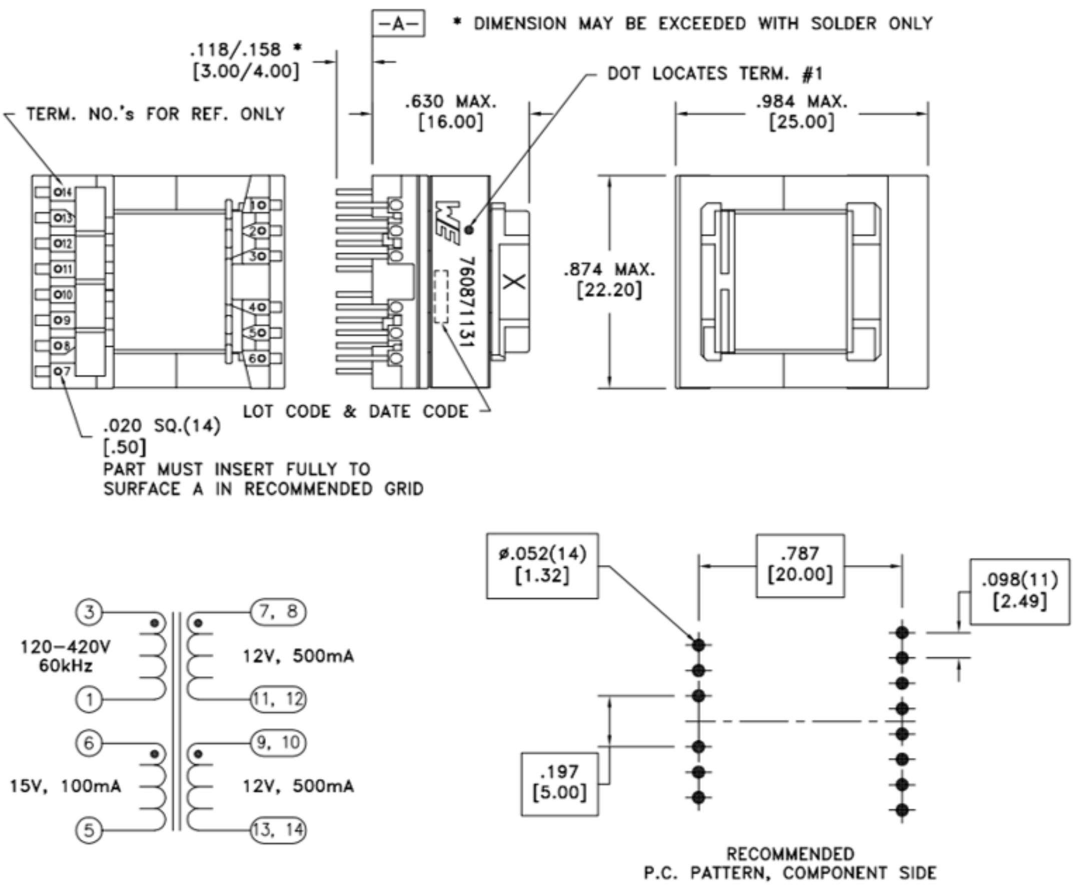


Table 9. Flyback transformer details

Parameter	Test conditions	Value/name
D.C. resistance	@25ºC	1.6 mohms max.
Inductance	10 kHz, 100 mV	11.396mH ±10%
Turns ratio	3-1: 7-11	(Np: Ns1) 9.6: 1
Turns ratio	3-1: 9-13	(Np: Ns2) 9.6: 1
Manufacturer	-	Wurth Elektronik
Manufacturer order code	-	760871131

5 Firmware flowchart

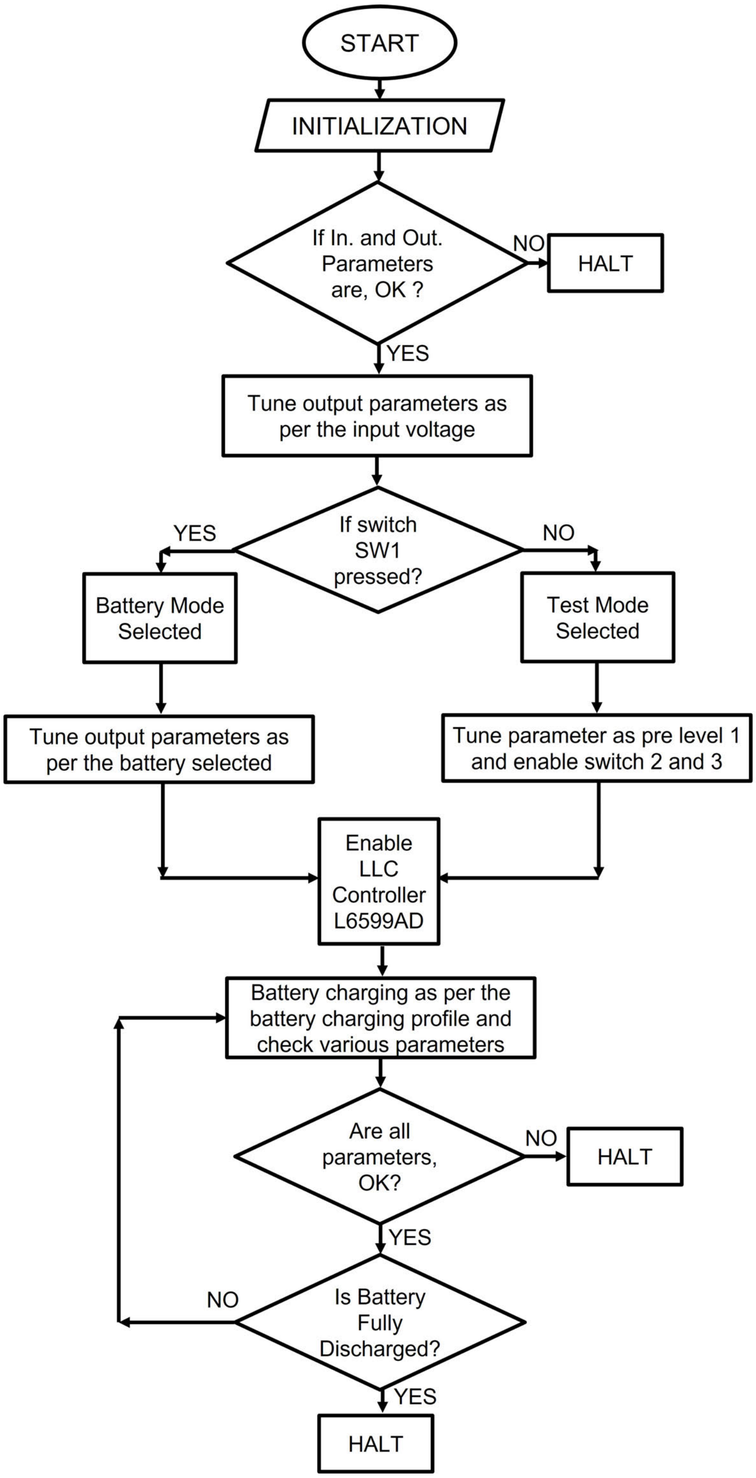


Figure 39. **STDES-2KW5CH48V firmware flowchart**

6 STDES-2KW5CH48V hardware modifications

If higher battery voltages are required, few hardware modifications are required. The whole primary side (PFC stage, DC-DC full-bridge LLC) remains unchanged. Instead, on the secondary side, the output voltage sense resistor needs to be modified. Most common LEV batteries target 48, 72, or 144 V systems.

- A 72 V nominal voltage system is expected to work from a lower end of 65 V to an upper end of 88 V. The current is limited to a 32 A or 2500 W power output. The constant power is beyond 75 V and the constant current is below 75 V maximum 32 A. The rectifier stage (center-tap secondary) remains unchanged. Due to the higher output voltage, 250-300 V Schottky or ultra-fast diodes are recommended. The transformer turns ratio should be 6:1:1. Correspondingly, a thinner Litz should be used. The wire strand diameter must not exceed 0.1 mm. The original transformer is 8.67:1:1 ratio. The primary should not be modified. With a very careful layout and transformer design, we suggest to start with a 250-300 V device diode, and check for overshoot under all conditions. Then, replace it with a 200 V Schottky as it is already used and verify the performance. Thus, the same diode could be reused. Change also the output filter capacitors: the same value must be used, but the voltage rating must be 100 V at least. The ESR is also very important as the ones used are special types for the lowest losses. The Rubycon ZLH series is a suitable examples. Similarly, the reverse protection MOSFETs can be reused as there are only DC switches. However, you should follow the proper startup sequencing procedure. The shunt can be the same, changing only the firmware to set the maximum current. No change in the current amplifier gain is needed. The output voltage sense resistor can be modified accordingly. R114,123, and 134 need to be suitably scaled to start at 64 V.
- A 144 V nominal voltage system is expected to work from a lower end of 135 V to an upper end of 175 V. The current is limited to a 20 A or 2500 W power output. The constant power is beyond 160 V and the constant current is below 160 V maximum 16 A. The rectifier stage (center-tap secondary) remains unchanged. Due to the higher output voltage, 400 V ultra-fast diodes are recommended. The transformer turns ratio should be 3:1:1. Correspondingly, a thinner Litz should be used. The wire strand diameter must not exceed 0.1 mm. The original transformer is 8.67:1:1 ratio and the primary should not be modified. Changes must also be made to the output filter capacitors: half the value must be used, but the voltage rating must be 200 V at least. The ESR is also very important as the ones used are special types for the lowest losses. The Rubycon ZLH series is a suitable example. Similarly, the reverse protection MOSFETs can be rated for 200 V at least.However, you should follow the proper startup sequencing procedure. The shunt can be the same, changing only the firmware to set the maximum current. No change in the current amplifier gain is needed. The output voltage sense resistor can be modified accordingly. R114,123, and 134 need to be suitably scaled to start at 134 V.

7 PCB layout

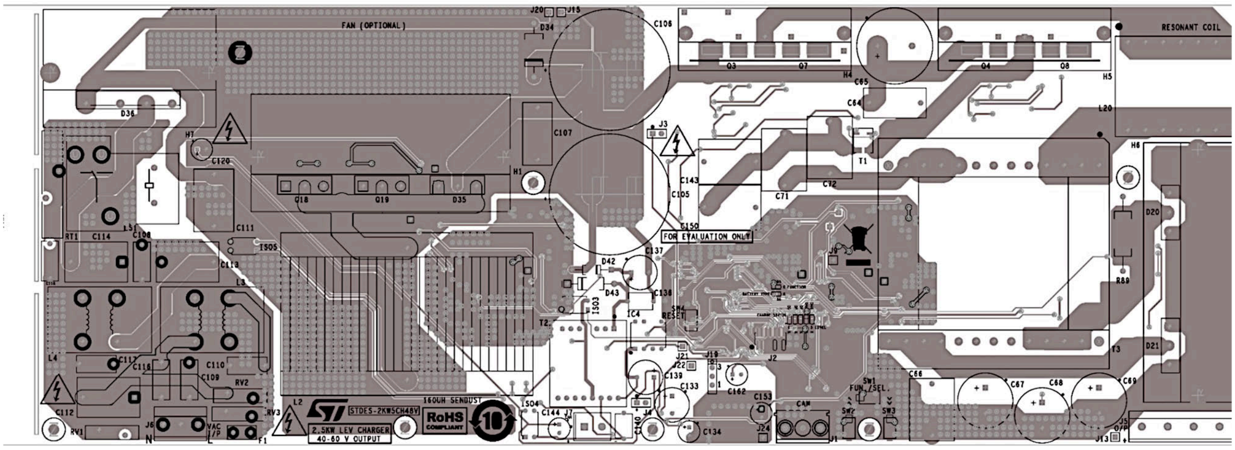


Figure 40. STDES-2KW5CH48V layout (top view)

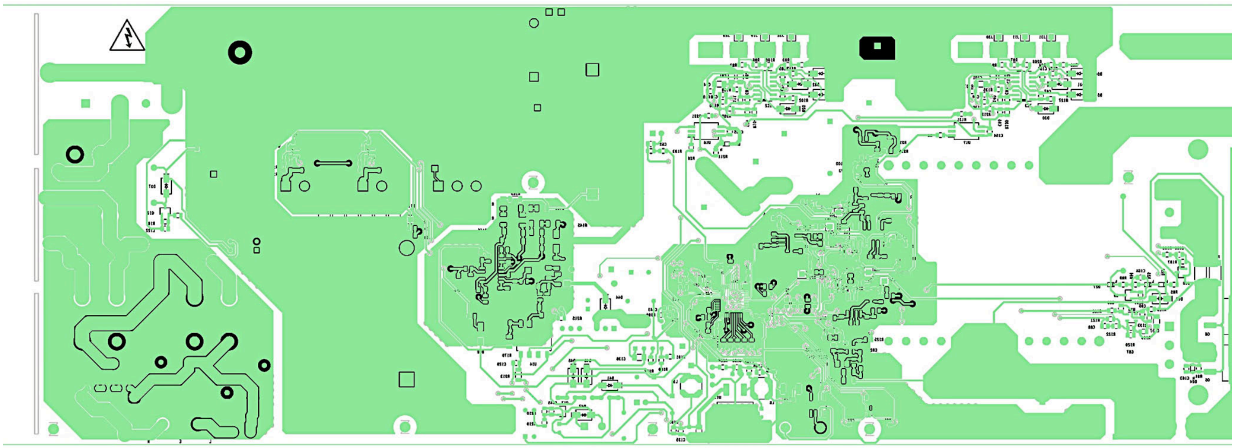


Figure 41. STDES-2KW5CH48V layout (bottom view)

8 Thermal performance

Figure 42. STDES-2KW5CH48V PFC thermal performance

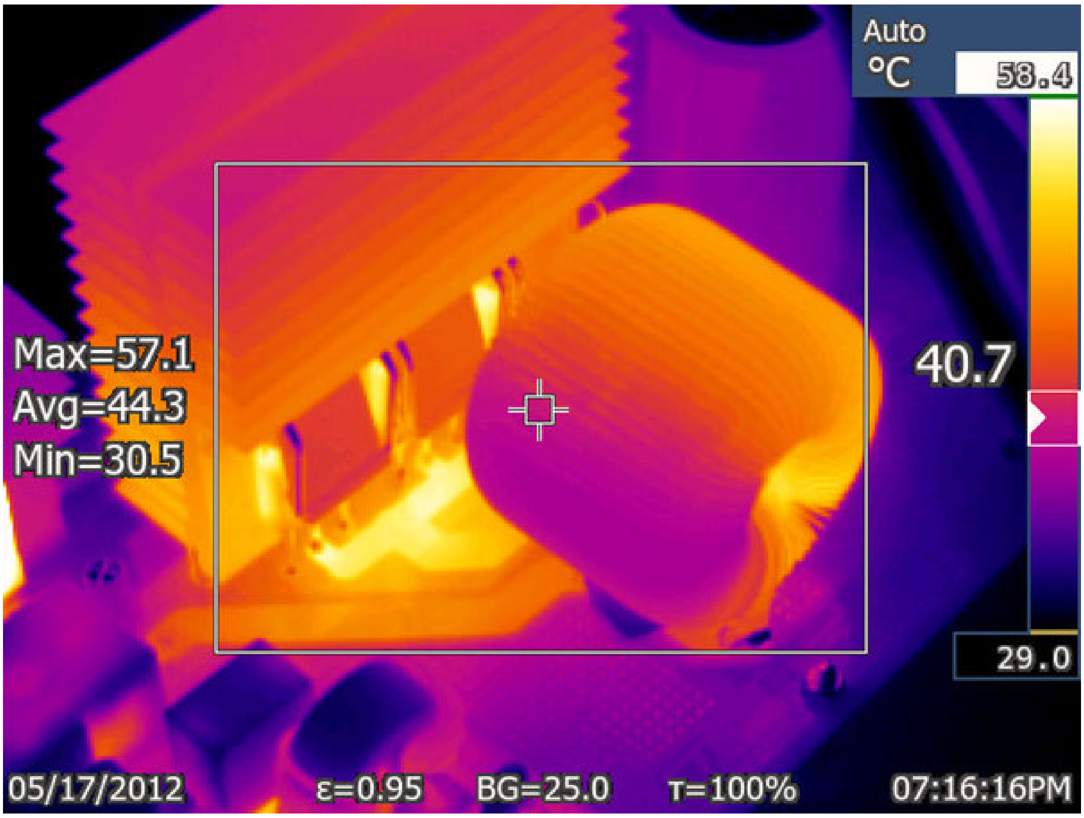


Figure 43. STDES-2KW5CH48V LLC thermal performance

9 Schematic diagrams

Figure 44. STDES-2KW5CH48V circuit schematic (1 of 8)

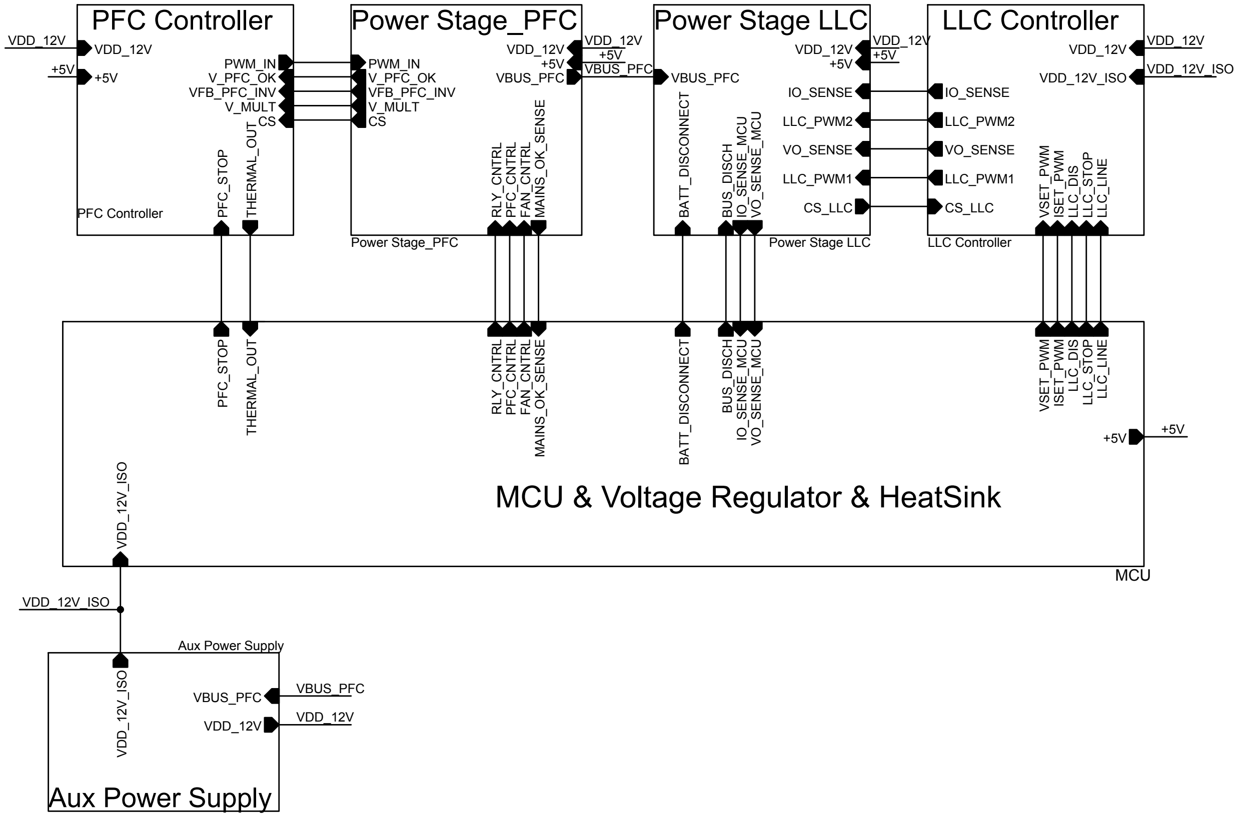


Figure 45. STDES-2KW5CH48V circuit schematic (2 of 8)

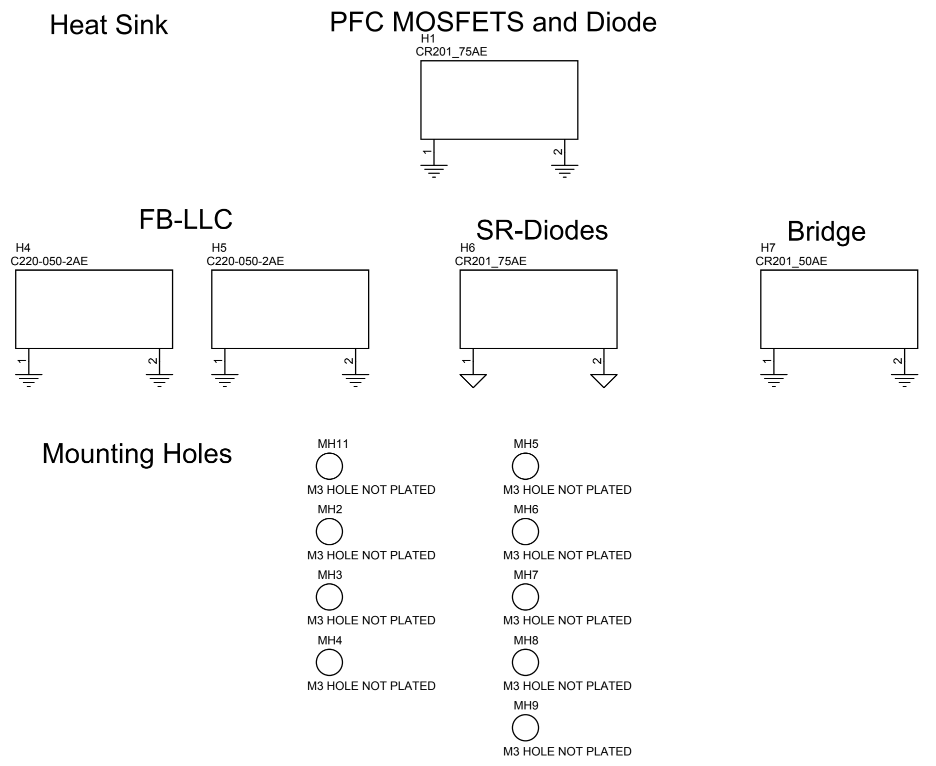


Figure 46. **STDES-2KW5CH48V circuit schematic (3 of 8)**

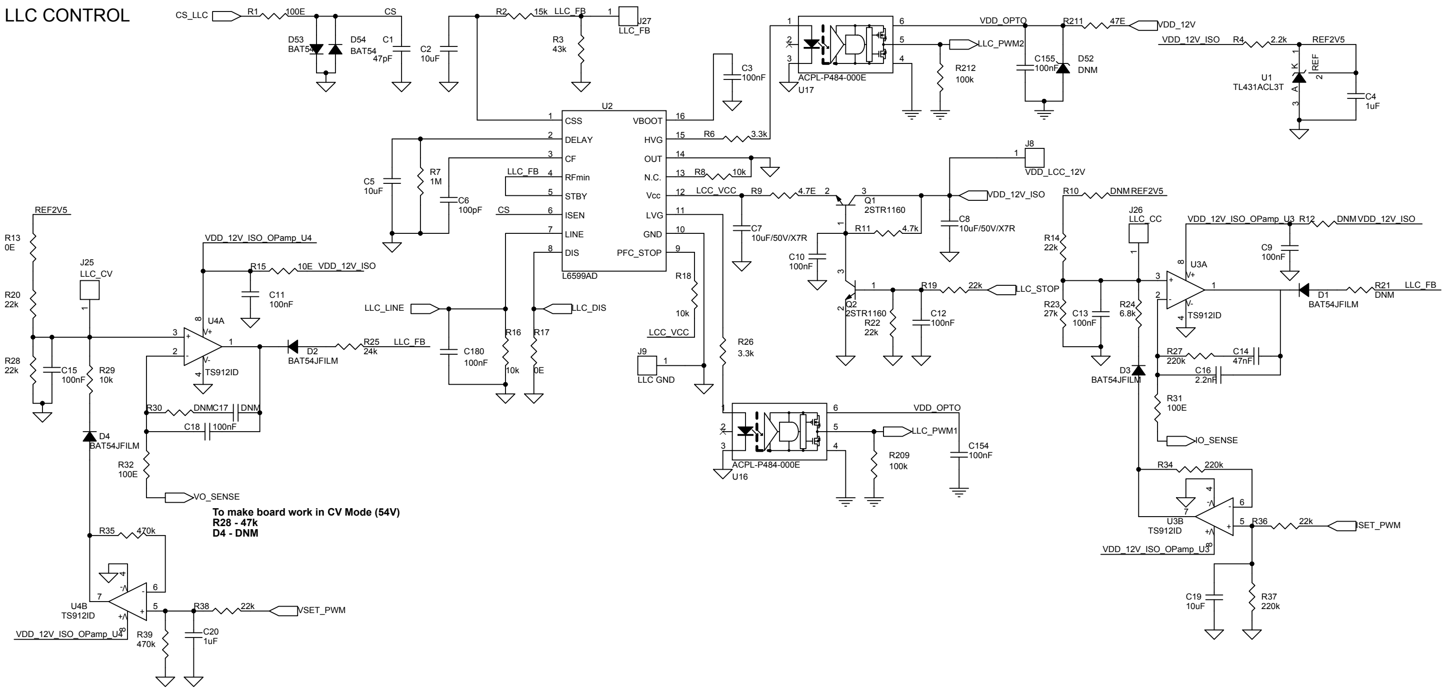


Figure 47. STDES-2KW5CH48V circuit schematic (4 of 8)

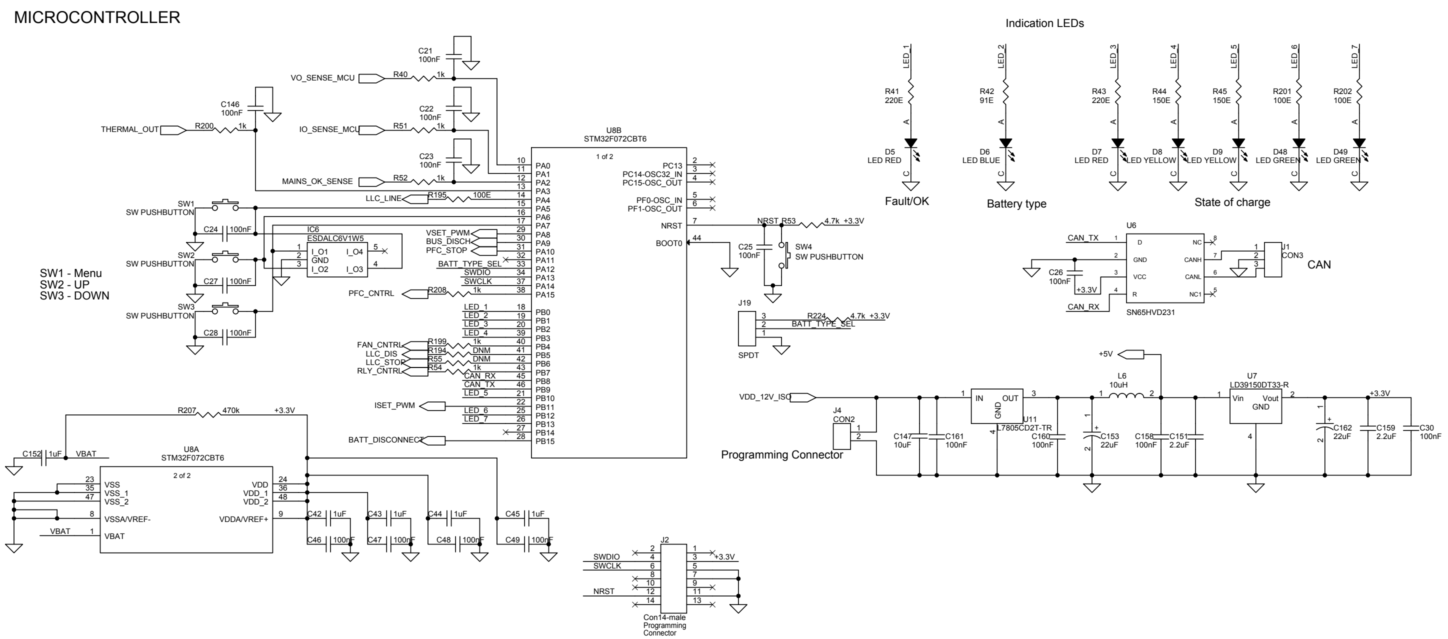


Figure 48. STDES-2KW5CH48V circuit schematic (5 of 8)

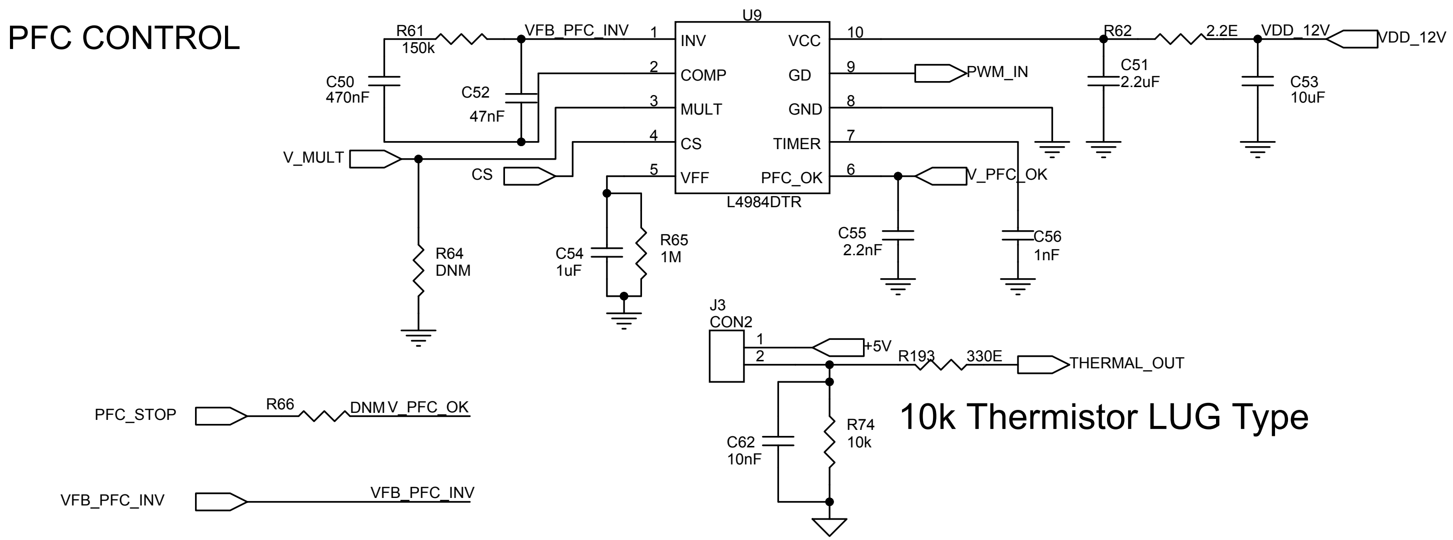


Figure 49. STDES-2KW5CH48V circuit schematic (6 of 8)

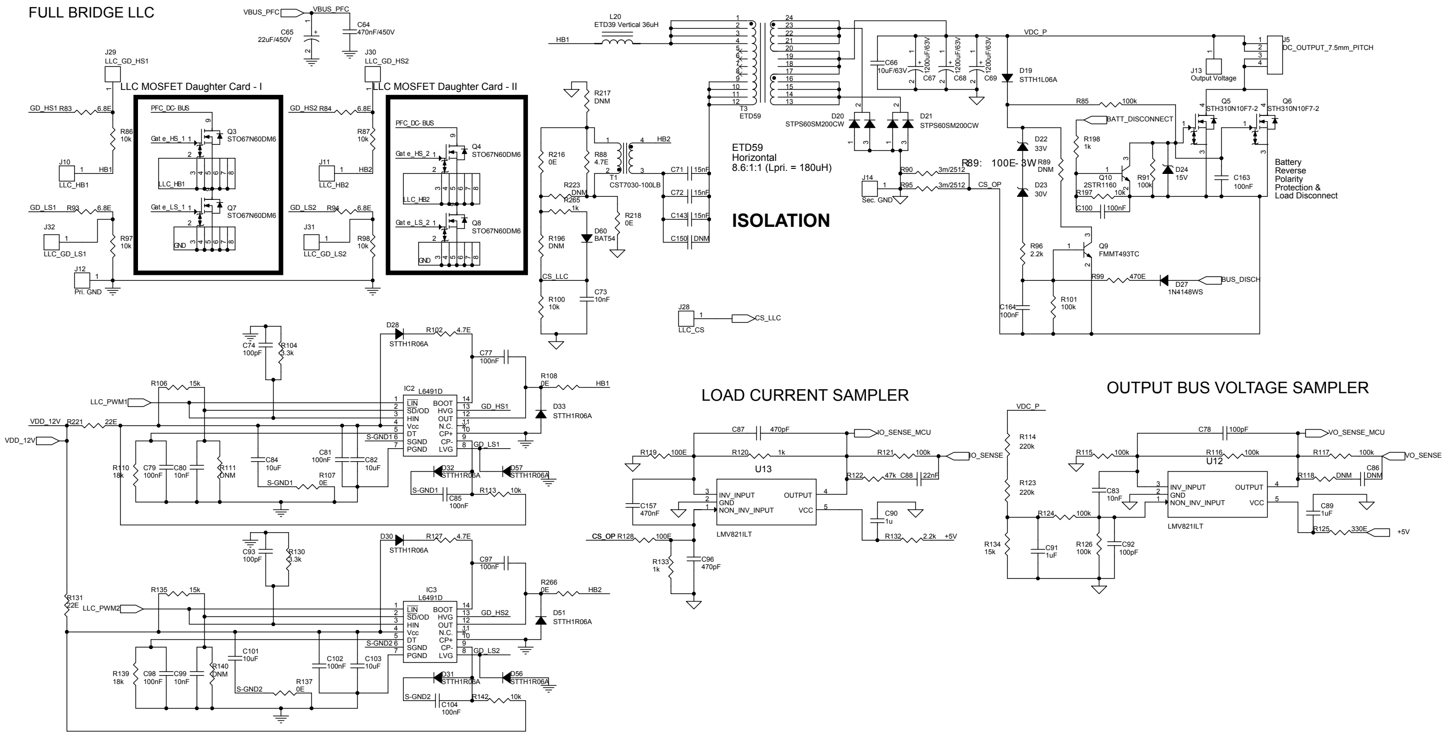


Figure 50. STDES-2KW5CH48V circuit schematic (7 of 8)

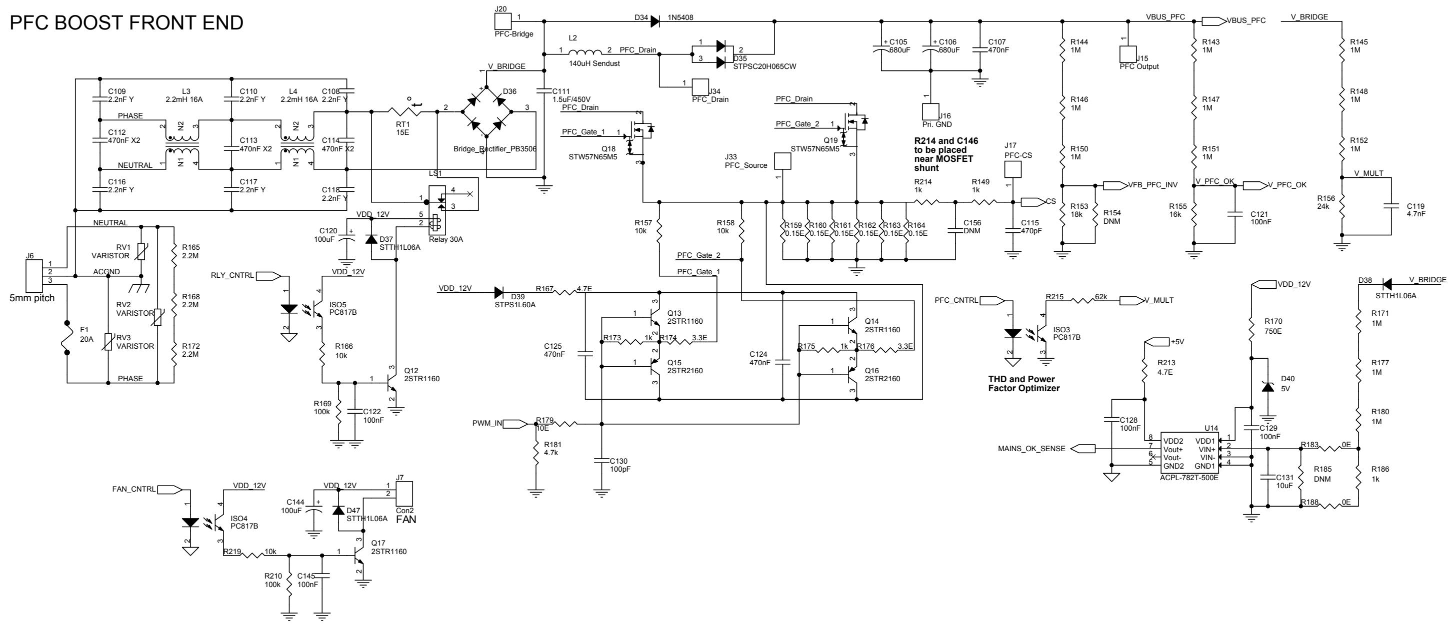
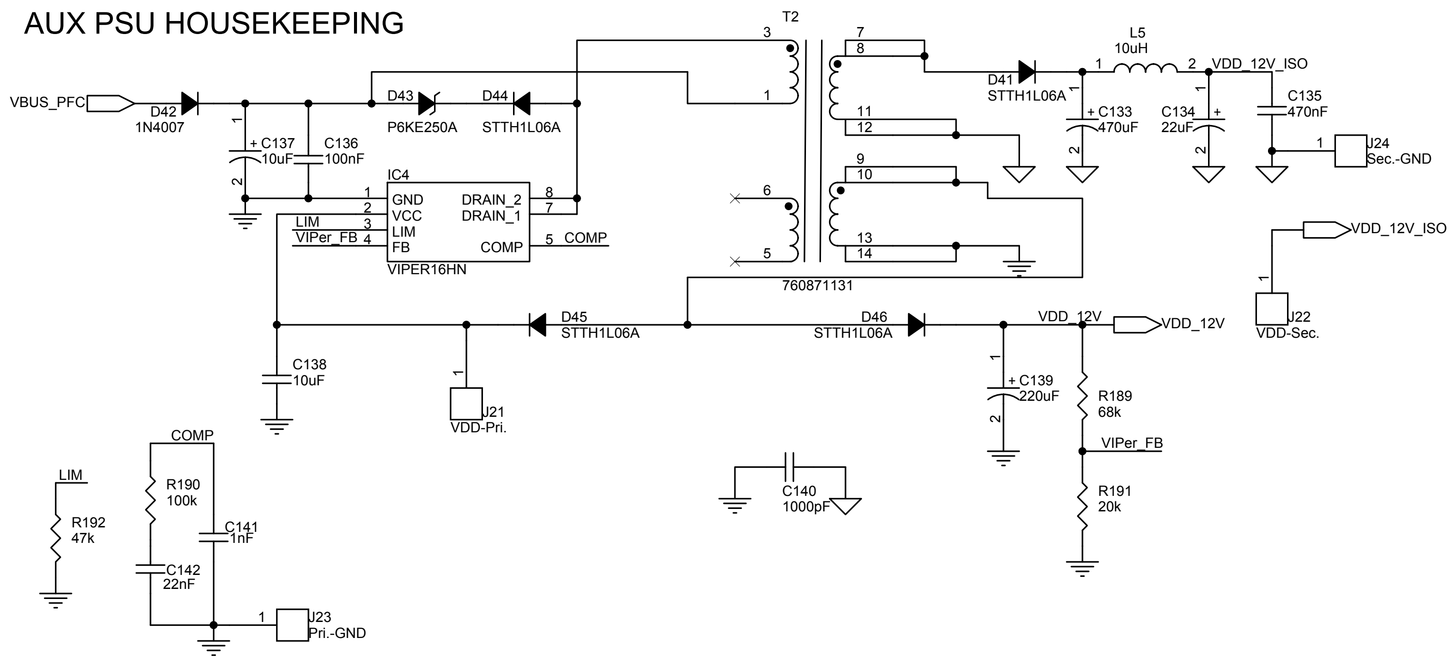


Figure 51. STDES-2KW5CH48V circuit schematic (8 of 8)



10 Bill of materials

Table 10. STDES-2KW5CH48V bill of materials

Item	Q.ty	Ref.	Part/value	Description	Manufacturer	Order code
1	1	C1	47pF, SMD 0805, 25 V, ± 10 %	Ceramic Capacitor, X7R	Any	Any
2	5	C2,C53,C131,C138,C147	10uF, SMD 1206, 50 V, ± 10 %	Ceramic Capacitor, X7R	Any	Any
3	41	C3, C9, C10, C11, C12, C13, C15, C18, C21, C22, C23, C24, C25, C26, C27, C28, C30, C46, C47, C48, C49, C77, C79, C85, C97, C98, C104, C121, C122, C128, C129, C145, C146, C154, C155, C158, C160, C161, C163, C164, C180	100nF , SMD 0805, 50 V, ± 10 %	Ceramic Capacitor, X7R	Any	Any
4	10	C4,C20,C42,C43,C44,C45,C54, C89,C91,C152	1uF, SMD 0805, 25 V, ± 10 %	Ceramic Capacitor, X7R	Any	Any
5	6	C6, C74, C93, C78, C92, C130	100pF, SMD 0805, 50 V	Ceramic Capacitor, COG	Any	Any
6	4	C5,C7,C8,C19	10uF, SMD 0805, 50 V	Ceramic Capacitor, X7R	Any	Any
7	2	C14, C52	47nF, SMD 0805, 50 V, ± 10 %	Ceramic Capacitor, X7R	Any	Any
8	2	C16, C55	2.2nF, SMD 0805, 50 V, ± 10 %	Ceramic Capacitor, X7R	Any	Any
9	3	C17, C86, C156	DNM, SMD 0805	Ceramic Capacitor, X7R	Any	Any
10	4	C50, C124, C125, C135	470nF, SMD 0805, 50 V	Ceramic Capacitor, X7R	Any	Any
11	3	C51, C151, C159	2.2uF, SMD 0805, 50 V	Ceramic Capacitor, X7R	Any	Any
12	2	C56, C141	1nF, SMD 0805, 50 V, ± 10 %	Ceramic Capacitor, X7R	Any	Any
13	4	C62, C73, C80, C99	10nF, SMD 0805, 50 V, ± 10 %	Ceramic Capacitor, X7R	Any	Any
14	5	C64,C107,C112,C113,C114	470nF, 15mm Pitch, Through Hole, 305V(AC)/ 630V(DC) V, ± 20 %	Film Capacitor	EPCOS - TDK Electronics	B32922C3474M000

Item	Q.ty	Ref.	Part/value	Description	Manufacturer	Order code
15	1	C65	22uF, 10mm Pitch, Through Hole, 450 V, ± 20 %,	Electrolytic Capacitor	Nichicon	UCA2W220MHD
16	1	C66	10uF, 15mm Pitch, Through Hole, 63 V, ± 10 %	Film Capacitor	EPCOS - TDK Electronics	B32522C0106K189
17	3	C67,C68,C69	1200uF, 7.5mm Pitch, Through Hole, 63 V, ± 20 %	Electrolytic Capacitor	Rubycon	63ZLH1200MEFC18X25
18	3	C71,C72,C143	15nF, 15mm Pitch, Through hole, 600V(AC)/ 1000V(DC) V, ± 5 %	Film Capacitor	EPCOS - TDK Electronics	B32642B0153J
19	3	C81, C100, C102	100nF, SMD 1206, 50 V, ± 10 %	Ceramic Capacitor, X7R	Any	Any
20	4	C82, C84, C101, C103	10uF, SMD 1206, 50 V, ± 10 %,	Ceramic Capacitor, X7R	Any	Any
22	3	C87, C96, C115	470pF, SMD 0805, 50 V, ± 10 %,	Ceramic Capacitor, X7R	Any	Any
23	2	C88, C142	22nF, SMD 0805, 50 V, ± 10 %	Ceramic Capacitor, X7R	Any	Any
24	1	C90	1uF, SMD 0805, 50 V, ± 10 %	Ceramic Capacitor, X7R	Any	Any
25	2	C105, C106	680uF, 10mm Pitch, Through Hole, 450 V, ± 20 %	Electrolytic Capacitor	Nichicon	LGG2W681MELC50
26	6	C108,C109,C110,C116,C117,C118	2.2nF, 10mm Pitch, Through Hole, 760 V AC V, ± 20 %	Ceramic Capacitor, Y1, Safety Capacitor	Vishay Beyschlag/ Draloric/BC Components	VY1222M43Y5UC63V0
27	1	C111	1.5uF, 15mm Pitch, Through Hole, 450 V, ± 5 %	Film Capacitor	Panasonic Electronic Components	ECW-FE2W155J
28	1	C119	4.7nF, SMD 0805, 50 V, ± 10 %	Ceramic Capacitor, X7R	Any	Any
29	2	C120,C144	100uF , 2.54mm Pitch, 5mm Diameter, Through Hole, 35 V, ± 20 %	Electrolytic Capacitor	Any	Any
30	1	C133	470uF, 5.08mm Pitch, 10mm Diameter, Through Hole, 63 V, ± 20 %	Electrolytic Capacitor	Any	Any

Item	Q.ty	Ref.	Part/value	Description	Manufacturer	Order code
31	3	C134,C153,C162	22uF, 2.5mm Pitch, Through Hole, 100 V, ± 20 %	Electrolytic Capacitor	Nichicon	UVZ2A220MED1TD
34	1	C139	220uF, 5.08mm Pitch, Through Hole, 63 V, ± 20 %	Electrolytic Capacitor	Nichicon	UVR1J221MPD1TD
35	1	C140	1000pF, 7.5mm Pitch, Through Hole, 400 VAC V, ± 20 %	Film Capacitor	KEMET	C907U102MYVDBA7317
36	1	C150	DNM, 15mm Pitch, Through hole	Film Capacitor	Any	Any
38	7	D1, D2, D3, D4, D53, D54, D60	BAT54JFILM, SOD323, 40 V, 300m A	40 V, 300 mA general purpose signal Schottky diodes	ST	BAT54JFILM
39	2	D5, D7	LED RED, SMD 0603	LED	Any	Any
40	1	D6	LED BLUE, SMD 0603	LED	Any	Any
41	2	D8, D9	LED YELLOW, SMD 0603	LED	Any	Any
42	8	D19, D37, D38, D41, D44, D45, D46, D47	STTH1L06A, SMA, 600 V, 1 A	600 V, 1 A low drop ultrafast diode	ST	STTH1L06A
43	2	D20, D21	STPS60SM200CW, TO-247, 200 V, 60 A	200 V, 60 A dual low leakage power Schottky rectifier	ST	STPS60SM200CW
44	1	D22	33V, SOD-323, 33 V, 200m W	Zener diode	Any	Any
45	1	D23	30V, SOD-323, 30 V, 200m W	Zener diode	Any	Any
46	1	D24	15V, SOD-323, 15 V, 200m W	Zener diode	Any	Any
47	1	D27	1N4148WS, SOD-323, 75 V, 150m A	Small signal diode	Fairchild/ON Semiconductor	1N4148WS
48	8	D28, D30, D31, D32, D33, D51, D56, D57	STTH1R06A, SMA, 600 V, 1 A	600 V, 1 A Turbo 2 ultrafast diode	ST	STTH1R06A
49	1	D34	1N5408, DO-201AD, 1000 V, 3 A	General purpose rectifier	Fairchild/ON Semiconductor	1N5408
50	1	D35	STPSC20H065CW, TO-247, 650 V, 20 A	650 V, 20 A dual high surge silicon carbide power Schottky diode	ST	STPSC20H065CW
51	1	D36	PB5006, SIP-4, PB, 600 V, 35 A	Enhanced isoCink+™ Bridge Rectifiers	Vishay Semiconductors	PB5006-E3/45

Item	Q.ty	Ref.	Part/value	Description	Manufacturer	Order code
52	1	D39	STPS1L60A, SMA, 60 V, 1 A	60 V, 1 A low drop power Schottky rectifier	ST	STPS1L60A
53	1	D40	5V, SOD-80, 5 V	5V Zener Diode	Any	Any
54	1	D42	1N4007, DO-41, 1000 V, 1 A	General purpose diode	Any	Any
55	1	D43	P6KE250ARL, DO-15	600 W TVS in DO-15	ST	P6KE250ARL
56	2	D48, D49	LED GREEN, SMD 0603	LED	Any	Any
57	1	D52	DNM	LED	Any	Any
58	1	F1	20A, 5.08mm Pitch, Through Hole, 350 V, 20 A	FUSE BRD MNT 20A 350VAC 72VDC	Bel Fuse Inc.	0697H9200-02
59	1	FAN	12V, To be placed as ashown in diagram, with air flow inwards (toward board), 12 V, 2.26 W	Fan 80mm x 80mm	CUI Devices	CFM-8015V-130-347
60	2	H1,H6	CR201-75AE, 75mm Pitch, Through hole	Heat Sink	Ohmite	CR201-75AE
61	2	H4,H5	C220-050-2AE, 50mm Pitch, Through hole,	Heat Sink	Ohmite	C220-050-2AE
62	1	H7	CR101-50AE, 50mm Pitch, Through hole	Heat Sink	Ohmite	CR101-50AE
63	2	IC2,IC3	L6491D, SO-14	High voltage high and low-side 4 A gate driver	ST	L6491D
64	1	IC4	VIPER16HN, PDIP 7	Fixed frequency VIPer™ plus family	ST	VIPER16HN
65	1	IC6	ESDALC6V1W5 , SOT323-5L	Quad TRANSIL™ array for data protection	ST	ESDALC6V1W5
66	3	ISO3,ISO4,ISO 5	PC817B, DIP-4,	Optoisolator Transistor	American Bright Optoelectronics Corporation	BPC-817 (B BIN)
67	1	J1	CON3, 5.08mm Pitch, Through Hole	3P 5.08mm pitch	Any	Any
68	1	J2	Con14-male	CONN HEADER SMD 14POS 1.27MM	Any	Any
70	2	J3, J4	2-pin berg-stick, Through Hole	2.54mm pitch	Any	Any

Item	Q.ty	Ref.	Part/value	Description	Manufacturer	Order code
71	1	J5	DC_OUTPUT_7.5mm_PITCH, 7.5mm Pitch, Through Hole	Terminal block 4POS 7.5mm	Phoenix Contact	1717046
72	1	J6	V(AC) I/P, 5.08mm Pitch, Through Hole, 16 A	Terminal block 3POS 5.08mm	CUI Devices	TB007-508-03BE
73	1	J8	VDD_LCC_12V, Through Hole	Test Point	Any	Any
74	1	J9	LLC GND, Through Hole	Test Point	Any	Any
75	1	J10	LLC_HB1, Through Hole	Test Point	Any	Any
76	1	J11	LLC_HB2, Through Hole	Test Point	Any	Any
77	2	J12,J16	Pri. GND, Through Hole	Test Point	Any	Any
78	1	J13	Output Voltage, Through Hole	Test Point	Any	Any
79	1	J14	Sec. GND, Through Hole	Test Point	Any	Any
80	1	J15	PFC Output, Through Hole	Test Point	Any	Any
81	1	J17	PFC-CS, Through Hole	Test Point	Any	Any
82	1	J19	SPDT, Through Hole, 12 V, 500mA A	SWITCH SLIDE SPDT	EAO	09.03201.02
83	1	J20	PFC-Bridge, Through Hole	Test Point	Any	Any
84	1	J21	VDD-Pri., Through Hole	Test Point	Any	Any
85	1	J22	VDD-Sec., Through Hole	Test Point	Any	Any
86	1	J23	Pri.-GND, Through Hole	Test Point	Any	Any
87	1	J24	Sec.-GND, Through Hole	Test Point	Any	Any
88	1	J25	LLC_CV, Through Hole	Test Point	Any	Any
89	1	J26	LLC_CC, Through Hole	Test Point	Any	Any
90	1	J27	LLC_FB, Through Hole	Test Point	Any	Any
91	1	J28	LLC_CS, Through Hole	Test Point	Any	Any
92	1	J29	LLC_GD_HS1, Through Hole	Test Point	Any	Any
93	1	J30	LLC_GD_HS2, Through Hole	Test Point	Any	Any
94	1	J31	LLC_GD_LS2, Through Hole	Test Point	Any	Any

Item	Q.ty	Ref.	Part/value	Description	Manufacturer	Order code
95	1	J32	LLC_GD_LS1, Through Hole	Test Point	Any	Any
96	1	J33	PFC_Source, Through Hole	Test Point	Any	Any
97	1	J34	PFC_Drain, Through Hole	Test Point	Any	Any
98	1	LS1	Relay 30A, Through Hole, V, A	General Purpose Relays Industrial Relays	Potter & brumfield	T9AV1L12-12
99	1	L2	160uH, Through Hole	160uH Sendust	Wurth Electronics	750344954
100	2	L3,L4	2.2mH 16A, Though Hole	CMC 2.2MH 16A 2LN 2.6 KOHM TH	Pulse Electronics Power	PH9455.205NL
101	2	L5, L6	10uH , SMD, %	Fixed Inductors 10uH	Bourns	SRR7045-100M
102	1	L20	ETD39 Vertical, Through Hole	36uH LLC resonant inductor	Magsol	L0403901
103	7	Q1, Q2, Q10, Q12, Q13, Q14, Q17	2STR1160, SOT-23	Low voltage fast-switching NPN power transistor	ST	2STR1160
104	4	Q3, Q4, Q7, Q8	STO67N60DM6 , TO-LL	N-channel 600 V, 48 mOhm typ., 58 A MDmesh DM6 Power MOSFET in a TO-LL package	ST	STO67N60DM6
105	2	Q5,Q6	STH310N10F7-2, H2PAK-2	N-channel 100 V, 1.9 mOhm typ., 180 A STripFET F7 Power MOSFET in H2PAK-2 package	ST	STH310N10F7-2
106	1	Q9	FMMT493TC, SOT-23,	100V NPN medium power transistor	Diodes Incorporated	FMMT493TC
107	2	Q15, Q16	2STR2160, SOT-23	Low voltage fast-switching PNP power transistor	ST	2STR1160
108	2	Q18, Q19	STW57N65M5, TO-247	N-channel 650 V, 0.056 Ohm typ., 42 A MDmesh M5 Power MOSFET in TO-247 package	ST	STW57N65M5
109	8	R1, R31, R32, R119, R128, R195, R201, R202	100E, SMD 0805	Thick Film Resistor	Any	Any
110	4	R2,R106, R134, R135	15k, SMD 0805	Thick Film Resistor	Any	Any

Item	Q.ty	Ref.	Part/value	Description	Manufacturer	Order code
111	1	R3	43k, SMD 0805	Thick Film Resistor	Any	Any
112	3	R4,R96,R132	2.2k, SMD 0805	Thick Film Resistor	Any	Any
113	4	R6,R26, R104, R130	3.3k, SMD 0805	Thick Film Resistor	Any	Any
114	14	R7, R65, R143, R144, R145, R146, R147, R148, R150, R151, R152, R171, R177, R180	1M, SMD 0805	Thick Film Resistor	Any	Any
115	17	R8, R16, R18, R29, R74, R86, R87, R97, R98, R100, R113, R142, R157, R158, R166, R197, R219	10k, SMD 0805	Thick Film Resistor	Any	Any
116	6	R9, R88, R102, R127, R167, R213	4.7E, SMD 080	Thick Film Resistor	Any	Any
117	16	R10, R12, R21, R30, R55, R64, R66, R111, R118, R140, R154, R185, R194, R196, R217, R223	DNM	Resistors	Any	Any
118	4	R11, R53, R181, R224	4.7k, SMD 0805	Thick Film Resistor	Any	Any
119	10	R13, R17, R107, R108, R137, R183, R188, R216, R218, R266	0E, SMD 0805	Thick Film Resistor	Any	Any
120	7	R14, R19, R20, R22, R28, R36, R38	22k, SMD 0805	Thick Film Resistor	Any	Any
121	2	R15, R179	10E, SMD 0805	Thick Film Resistor	Any	Any
122	1	R23	27k, SMD 0805	Thick Film Resistor	Any	Any
123	1	R24	6.8k, SMD 0805	Thick Film Resistor	Any	Any
124	2	R25, R156	24k, SMD 0805	Thick Film Resistor	Any	Any
125	5	R27, R34, R37, R114, R123	220k, SMD 0805	Thick Film Resistor	Any	Any
126	3	R35, R39, R207	470k, SMD 0805	Thick Film Resistor	Any	Any

Item	Q.ty	Ref.	Part/value	Description	Manufacturer	Order code
127	16	R40, R51, R52, R54, R120, R133, R149, R173, R175, R195, R198, R199, R200, R208, R214, R265	1k, SMD 0805	Thick Film Resistor	Any	Any
128	2	R41, R43	220E, SMD 0805	Thick Film Resistor	Any	Any
129	1	R42	91E, SMD 0805	Thick Film Resistor	Any	Any
130	2	R44, R45	150E, SMD 0805	Thick Film Resistor	Any	Any
131	1	R61	150k, SMD 0805	Thick Film Resistor	Any	Any
132	1	R62	2.2E, SMD 0805	Thick Film Resistor		
133	4	R83, R84, R93, R94	6.8E, SMD 0805	Thick Film Resistor	Any	Any
134	14	R85, R91, R101, R115, R116, R117, R121, R124, R126, R169, R190, R209, R210, R212	100k, SMD 0805	Thick Film Resistor	Any	Any
135	1	R89	DNM, Through hole	Metal Oxide Resistors	Any	Any
136	2	R90, R95	0.003E, SMD 2512	Thick Film Resistor	Any	Any
137	1	R99	470E, SMD 0805	Thick Film Resistor	Any	Any
138	2	R129, R189	68k, SMD 0805	Thick Film Resistor	Any	Any
139	3	R110, R139, R153	18k, SMD 0805	Thick Film Resistor	Any	Any
140	2	R122, R192	47k, SMD 0805	Thick Film Resistor	Any	Any
141	2	R125, R193	330E, SMD 0805	Thick Film Resistor	Any	Any
142	1	R155	16k, SMD 0805	Thick Film Resistor	Any	Any
143	6	R159, R160, R161, R162, R163, R164	0.15E, SMD 2512	Thick Film Resistor	Any	Any
144	3	R165, R168, R172	2.2M, SMD 1206	Thick Film Resistor	Any	Any
145	1	R170	750E, SMD 1206	Thick Film Resistor	Any	Any
146	2	R174, R176	3.3E, SMD 0805	Thick Film Resistor	Any	Any
147	1	R186	1k, SMD 1206	Thick Film Resistor	Any	Any

Item	Q.ty	Ref.	Part/value	Description	Manufacturer	Order code
149	1	R211	47E, SMD 0805	Thick Film Resistor	Any	Any
150	1	R215	62k, SMD 0805	Thick Film Resistor	Any	Any
151	2	R131, R221	22E, SMD 0805	Thick Film Resistor	Any	Any
152	1	RT1	5E, 7.8mm Pitch, Through Hole	5 Ohm NTC Thermistor	Ametherm	SL32 5R020-B
153	3	RV1,RV2,RV3	VARISTOR, 7.5mm Pitch, Through Hole	Varistor, 14mm diameter	EPCOS / TDK	B72214S0301K101
154	4	SW1, SW2, SW3, SW4	Push Buttons, SMD	SWITCH TACTILE SPST-NO	Panasonic Electronic Components	EVQ-5PN05K
155	1	T1	CST7030-100LB, SMD	Current Transformers 1:100 20A 1.33mH	Coilcraft	CST7030-100LB
156	1	T2	760871131, Through hole	Power Transformers MID-UNIT STM Offline 1.396mH 1.60Ohm	Würth Elektronik	760871131
157	1	T3	LLC Transformer ETD59, Through Hole	LLC converter Transformer	Magsol	T0405901
158	1	U1	TL431ACL3T, SOT23	Adjustable micropower shunt voltage reference	ST	TL431ACL3T
159	1	U2	L6599AD, SO-16	Improved high-voltage resonant controller	ST	L6599AD
160	2	U3,U4	TS912ID, SO-8	Low power with CMOS inputs	ST	TS912ID
161	1	U6	SN65HVD231, SOIC	CAN Transceiver	Texas Instruments	SN65HVD231
162	1	U7	LD39150DT33-R, DPAK	Ultra low drop BiCMOS voltage regulator	ST	LD39150DT33-R
163	1	U8	STM32F072CBT6, LQFP 48 7x7x1.4 mm	Mainstream Arm Cortex-M0 USB line MCU with 128 Kbytes of Flash memory, 48 MHz CPU, USB, CAN and CEC functions	ST	STM32F072CBT6
164	1	U9	L4984DTR, SSOP 10	CCM PFC controller	ST	L4984DTR
165	1	U11	L7805CD2T-TR, D²PAK	Positive voltage regulator IC	ST	L7805CD2T-TR

Item	Q.ty	Ref.	Part/value	Description	Manufacturer	Order code
166	2	U12,U13	LMV821ILT, SOT23-5L	Low power, high accuracy, general-purpose operational amplifier	ST	LMV321ILT
167	1	U14	ACPL-782T-500 E, SMD-8	Automotive Isolation Amplifier with R2Coupler™ Isolation	Broadcom Limited	ACPL-782T-500E
168	2	U16,U17	ACPL-P484-000E, SO-6	Gate Drive Interface Optocoupler	Broadcom Limited	ACPL-P484-000E
169	9	MH2,MH3,MH4, MH5,MH6,MH7, MH8,MH9,MH1 1	Moulting Holes, Spacer and Screw, Through Hole	Spacers (M3x12) Screw (M3x6)	Wakefield-Vette	CD-02-05-247
170	5	Isolation Pad (Q18,Q19,D35, D20,D21)	TO-247	Thermal Pad	Any	Any
171	1	Thermal Isolation Pad (Heat-Sink H7)	Thermal Isolation Pad , Customized cut thermal isolation pad "50mm x 28mm" with 0.5mm thickness	50mm x 28mm	Any	Any
172	2	LLC MOSFET Daughter Card assembled with heat-sink (H4,H5) and isolation pad	STO67N60DM6 , 2 MOSFETs mounted on single Daughter card, TO-LL	N-channel 600 V, 48 mOhm typ., 58 A MDmesh DM6 Power MOSFET in a TO-LL package	ST	STO67N60DM6

Appendix A Reference design warnings, restrictions and disclaimer

Important: *The reference design is not a complete product. It is intended exclusively for evaluation in laboratory/ development environments by technically qualified electronics experts who are familiar with the dangers and application risks associated with handling electrical/mechanical components, systems and subsystems.*

Danger: *Exceeding the specified reference design ratings (including but not limited to input and output voltage, current, power, and environmental ranges) may cause property damage, personal injury or death. If there are questions concerning these ratings, contact an STMicroelectronics field representative prior to connecting interface electronics, including input power and intended loads. Any loads applied outside of the specified output range may result in unintended and/or inaccurate operation and/or possible permanent damage to the reference design and/or interface electronics. During normal operation, some circuit components may reach very high temperatures. These components include but are not limited to linear regulators, switching transistors, pass transistors, and current sense resistors which can be identified in the reference design schematic diagrams.*

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Revision history

Table 11. **Document revision history**

Date	Revision	Changes
17-Oct-2022	1	Initial release.
21-Oct-2022	2	Updated Section 10. Bill of materials.
11-Nov-2022	3	Updated Section 10 Bill of materials.

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