Technical note

STDES-6KWHVDCDC test report

Introduction

This document describes the practical implementation of a 6 KW wide output LLC converter, which is a major building block for any mains-fed power conversion system (EV chargers, telecom power supplies, or general high power SMPS applications). It has a compact form-factor: 225 x 300 x 60 mm^3. It is intended to deliver full power under forced convection cooling and 700-800 V input. Components have been selected to make it housed in a 2U height enclosure used for standard 19” rack mount fitment. The design has been tested up to 6 kW, with a peak efficiency of 98%. However, it is possible to go up to 8 kW under certain conditions using the same components on the board.

The STDES-6KWHVDCDC reference design is a 6 kW high voltage DC-DC converter mainly for battery charging in an EV infrastructure.

The reference design consists of a full bridge LLC resonant converter, digitally controlled.

For the output rectification, SiC diodes have been used. Depending on the output voltage requirement, the LLC transformer output configuration is interchangeable between center tapped and full-wave.

This results in frequency fold-back that increases efficiency by a wide margin over an entire output voltage range.

The dual transformer variant is more suited for limited output voltage: 200-500 or 500-1000 V depending on the secondary winding scheme. This scheme also uses smaller cores. The single transformer variant is usable from 200-1000 V with the frequency foldback scheme.

STW40N95DK5 MDmesh DK5 Power MOSFETs are used in the LLC stage while STPSC40H12CWL SiC diodes are used in rectification. The STM32G474RET6 MCU manages the control functions.

The auxiliary power supply is referred to a secondary GND to supply MOSFET gate driver, microcontroller, and signal conditioning.

The gate driving of LLC MOSFETs is isolated through a gate drive transformer in addition to the PM8834MTR gate driver ICs.

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

The electrical specifications have been derived keeping in mind typical commercial specifications. This reference design allows the engineer to evaluate a wide range of power output options (in a range of 1000-6000 W).

ST offers a wide range of suitable Super junction MOSFETs which are class leading, and also SiC diodes, which are crucial to the high performance witnessed in this board. This eases the designer’s task of getting started with a design that works first time with not many hiccups to resolve. For a detailed design customization, it is advised to get in touch with ST, as certain components even though seemingly trivial, are absolutely critical for reliable performance under all conditions. Substitution or scaling of power levels, must be done carefully to arrive at a reliable design.

1 Precautions for use

Danger: *This reference design has potentially lethal voltages across all stages. Skilled personnel (at least two) must work on the board. Technical know-how and specialistic skills are mandatory for the evaluation of this board in live conditions.*

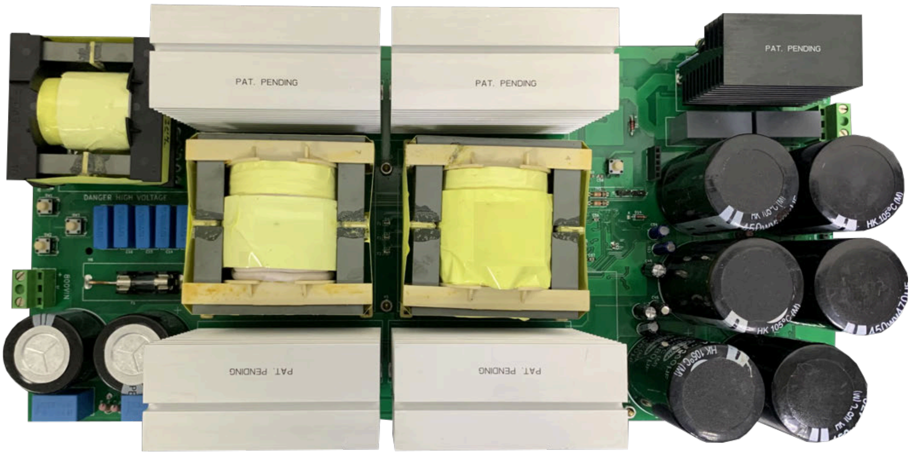
Some stages on the board are not isolated from the HV input. Very high-power density means, some components on the board, copper tracks, as well as the heat sink can cause a burn if touched directly.

Important: It is routine to take advantage of the 150°C to 175°C junction temperatures of new generation devices to achieve high power densities in commercial products. Heat sink temperatures may rise very high in PCBs. Since this is an evaluation board, we have kept the heat sinks larger than needed to minimize the risk for the user. In the worst cases, the heat sink surface would reach 55°C while it could be easily operated to 100°C-110°C inside products with smaller heat sinks to achieve even higher power densities.

2 Overview

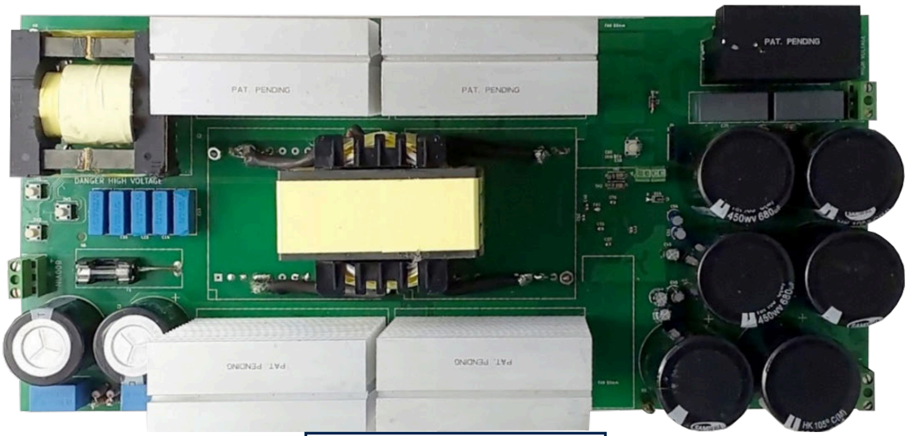
The system is a full bridge LLC converter with either two transformers or a single transformer.

Figure 1. STDES-6KWHVDCDC reference design version 1



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

Figure 2. STDES-6KWHVDCDC reference design version 2



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

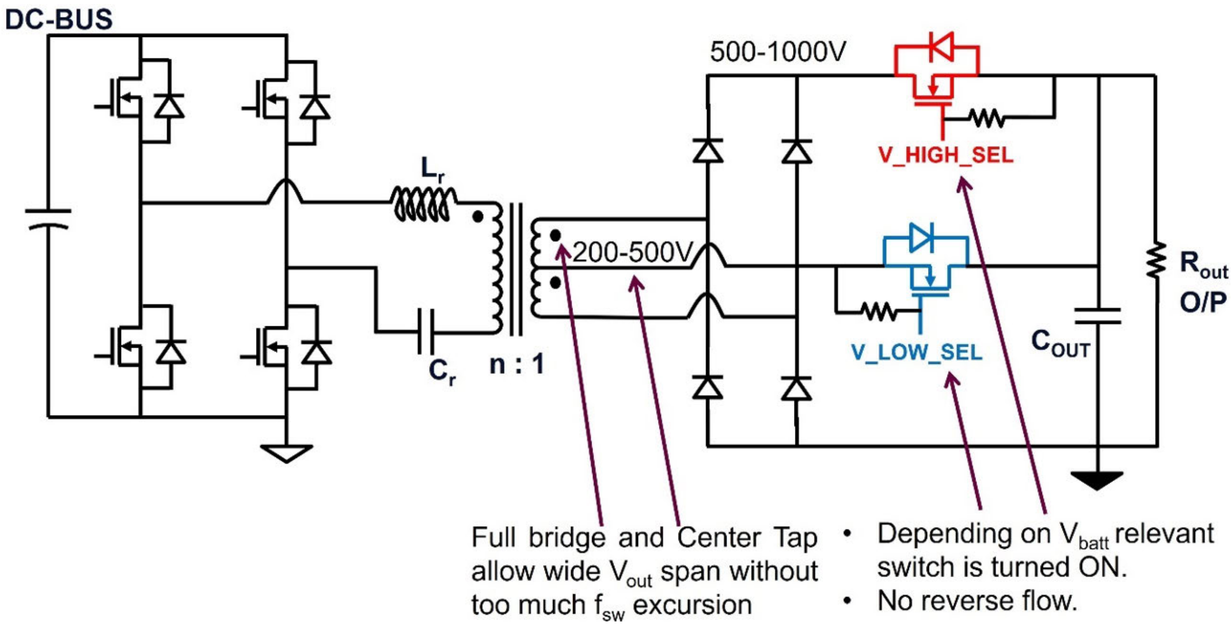
Note: Heatsink patent marking is only for the heatsink.

The two-transformer variant operates in the standard mode starting from 85 kHz up to 190 kHz to cover a span of 200 to 1000 Volts. However, the efficiency starts to taper off as the operating frequency increases beyond resonance. This is due to the fact that to maintain regulation at very low voltages the operating frequency must be increased far beyond resonance. By adjusting the turns ratio in the secondary stage, it is possible to operate this variant for a limited output range with a very high efficiency.

The single transformer variant implements a special scheme in which we have used both the center tap and the full bridge configuration. When the load needs a voltage between 200 and 500 Volts, the center tap configuration is used to feed the load.

When the load needs to be supplied with more than 500 Volts up to 1000 Volts, the center tap mode is disabled and the full bridge mode is used to feed the load. This is implemented using two additional MOSFETS, operating entirely as a DC switch on the two output voltage buses as shown in the diagram below.

Figure 3. STDES-6KWHVDCDC power plant



The board operation should be limited to the maximum voltage of 800 V. This is the typical output of three-phase PFC rectifiers. This represents the isolated downstream converter for applications like EV charger modules. It is recommended to restrict operation from 700 V to 800 V as the magnetics have been designed in such a way. When the MCU on the board detects ranges beyond this limit, it does not start the converter.

Figure 4. STDES-6KWHVDCDC full block diagram

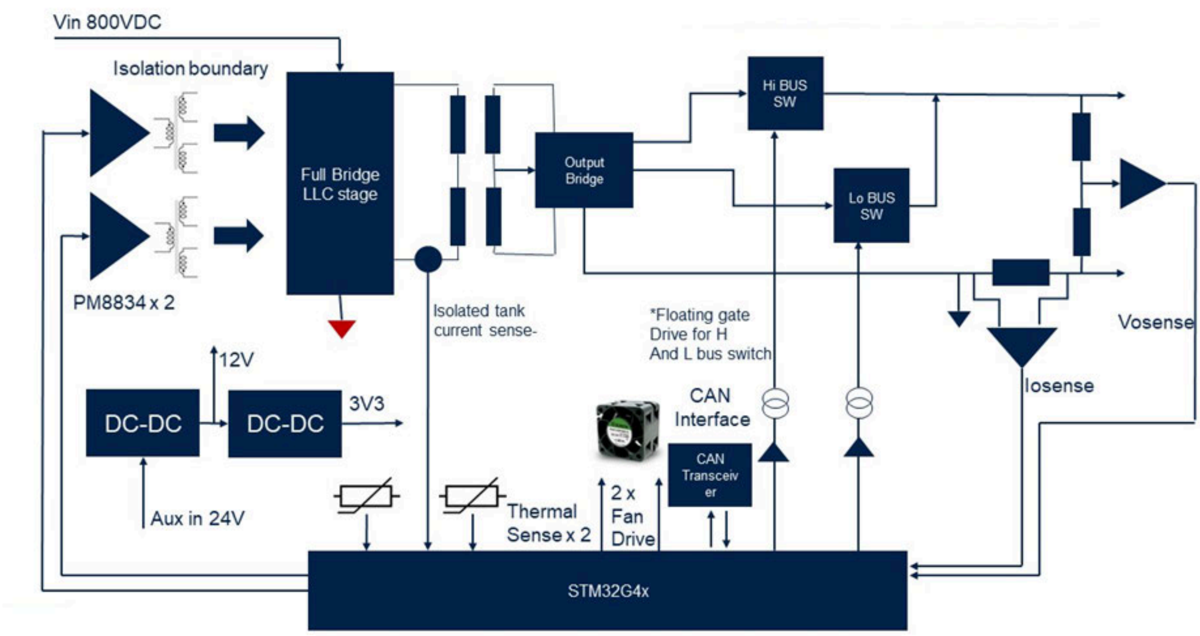


Table 1. **STDES-6KWHVDCDC electrical characteristics**

Parameter	Value/Range/Comments
Input DC voltage	700 to 800 V DC
Peak efficiency	>98% at 3 kW load
Peak efficiency at full load	>97.5%
Output voltage	200 – 1000V DC
Maximum output power	6 kW (with a maximum current of 12 A)
DC-DC converter topology	Full-bridge LLC
LLC power converter frequency range for full voltage span	80 – 270 Khz (with soft-start) 90 – 180 kHz (Version 1) 90 – 140 kHz (Version 2)
Auxiliary power supply input DC voltage	20 – 25 V DC
Startup	Soft start
Rectification topology	Center tapped (200 – 500 V) Full bridge (500 – 1000 V)
Cooling	Forced air

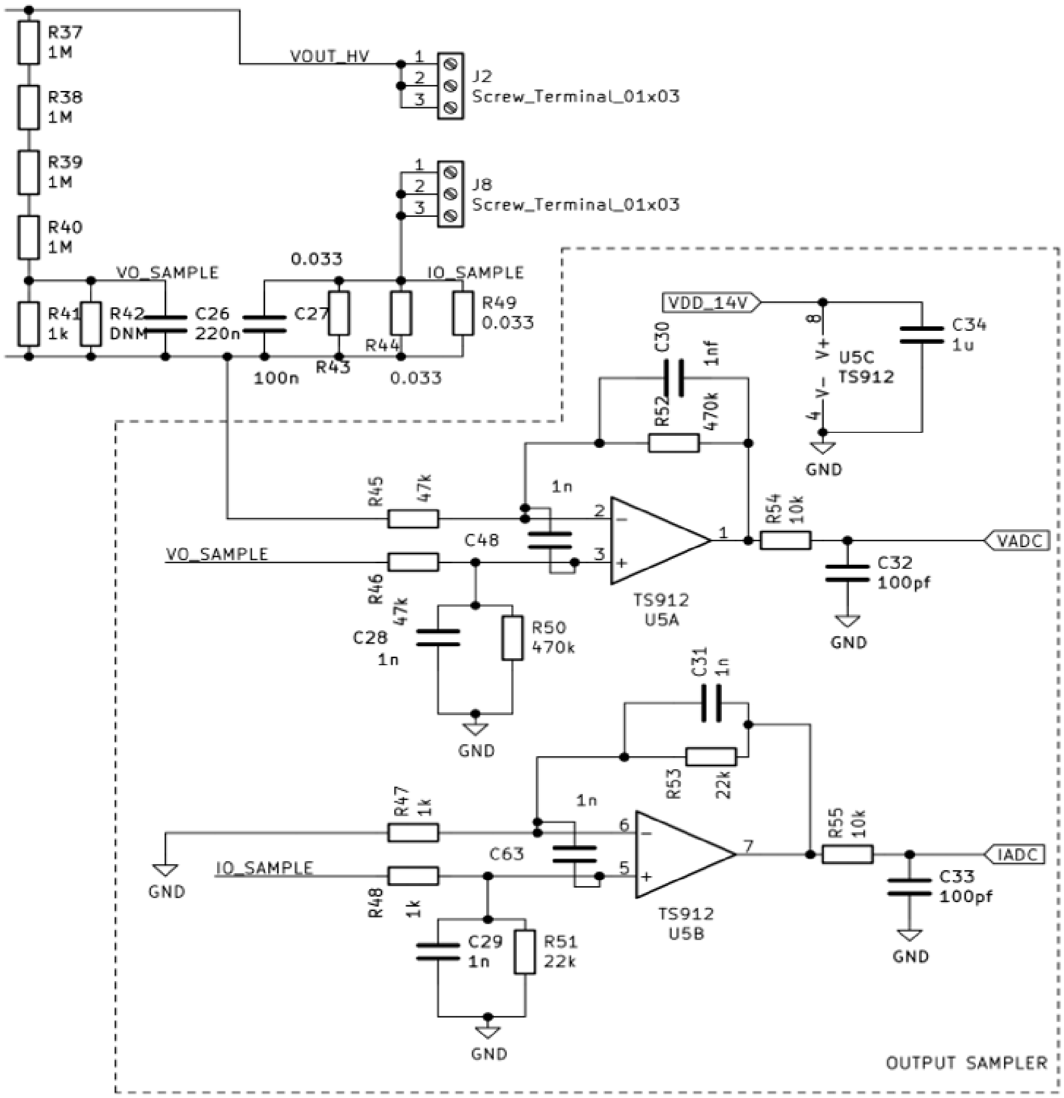
2.1 Startup and operating modes

This reference design has a separate auxiliary power supply from high voltage DC input. When powering the auxiliary supply with 24 V DC using the J3 connector, the microcontroller starts the PWM with a frequency of 270 kHz.

Note: *It is not necessary to give the DC input voltage to the LLC stage for PWM testing. The input DC voltage should be applied only when PWM signals are validated by the user. By default, the firmware works in test mode, where all protections are disabled. Thus, at the input, the user can start with less voltage as per requirement and test various parameters by changing load and frequency. Then, various MCU peripherals can be enabled for protections as per user requirements.*

The evaluation board features the sensing of output voltage and current sensing as shown in the figure below.

Figure 5. **STDES-6KWHVDCDC output voltage and current sampling**



So, the control loop can be closed either in output CC or CV as per user requirement.

The evaluation board also features three push buttons. Using the push buttons SW1 and SW2, the PWM frequency can be decreased or increased in steps of 5 kHz as shown in the table below.

Table 2. **Push button to change the switching frequency**

Push button	LLC converter switching frequency
SW1	Reduces the switching frequency by 5 kHz (min. 80 kHz)
SW2	Increases the switching frequency by 5 kHz (max. 270 kHz)

With reference to Figure 5, the current is sampled through a shunt resistor (a parallel combination of three metallic shunt resistances of 33 mohms each. With a maximum current of 12 A, the loss in the shunt is approximately 1.5 W, which is an insignificant fraction of the total power output and therefore does not contribute much to the overall efficiency loss. We could have used a lower value for the shunt resistance, but this is a tradeoff between noise and a realistic signal level, which can be resolved by the MCU while working under harsh conditions.

The signal from the shunt is amplified by an op-amp in a pseudo-differential configuration to minimize the noise pickup. It has a gain of 22. This means that the MCU ADC input works with a ground-referenced voltage of 24 2mV per ampere. This is well handled by the ADC dynamic range, as the full scale reading at 12 A output current would be 2.9 V, which provides a good upper headroom of 3.3 V when the MCU ADC also operates at 3.3 V.

The voltage is also sampled using a voltage divider, followed by a differential amplifier stage, with a gain of 10. This ensures that the dynamic range seen by the MCU ADC is again in linear region: 0.5 V output for 200 V and 2.5 V output for 1000 V varying in a linear function. This is a good range considering noise immunity and ADC linearity in presence of harsh noise.

The TS912 device is a rail-to-rail CMOS dual operational amplifier designed to operate with a single or dual supply voltage. The input voltage range Vicm includes the two supply rails VCC+ and VCC-. It has a GBP of 0.8 MHz, an extremely low bias current, and a reasonable offset drift vs temperature. For an even better performance, the TSH56 series might also be used at a lower footprint area. However, the TS912 operates at 12 V in this application, which provides better noise immunity and prevents input saturation due to noise spikes.

3 STDES-6KWHVDCDC key components

The STDES-6KWHVDCDC power supply consists of the following key components:

1. LLC resonant choke
2. Rectification SiC diodes mounted on heat-sink
3. Output BUS section MOSFETs mounted on heat-sink
4. Output +ve terminal connector
5. Auxiliary power supply connector
6. Output -ve terminal connector
7. Output bulk capacitor
8. LLC transformer
9. LLC full-bridge MOSFETs mounted on heat-sink
10. LLC resonant capacitor
11. Input connector
12. User interface – switches

Figure 6. **STDES-6KWHVDCDC key components**

3.1 LLC full-bridge resonant converter stage

The LLC stage is based on the DK5 series of super junction MOSFETs. For a power handling of 6000 W, four of these devices have been used in a full-bridge configuration. A total power throughput of up to 8000 W is also possible, with similar efficiency results. In this particular application, the power plant runs between 85 and 180 kHz, depending on the exact load conditions and battery voltage. 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 ~5 span of 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 runs from a regulated PFC front-end. Keeping a judicious L_m to L_r ratio, a 200-500 V output voltage range is achieved. The system is tested at a full load with good efficiency.

The secondary stage is switched between full bridge and center tapped modes to keep the operation near resonance and also increase the efficiency over the entire voltage band. So, the center tap provides a 200-500 V range, while the full bridge rectifier provides the 500-1000 V range.

The LLC operates at a slightly less than 50% duty ratio and a fixed 180° phase shift. The regulation is reached via 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 hard switching. The resonant operation of all switching and commutation components in the LLC converter ensures increased overall efficiency.

The fundamental aspect to consider is: 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 resonance frequency
- Reflected load resistance
- Normalized frequency

The switch gain is 1 for full-bridge and 0.5 for half-bridge configuration. Arriving at the optimal Q and M values is not a trivial task. It requires a couple of iterations even for experienced professionals. So, physical experiments are required, preferably run-in open loop, for an easier conclusion. Refer to AN2450 for further elaborate analysis.

To start the first step design, the value of the maximum Q should be less than 0.7. Q reaches its minimum value at light loads, where the gain curve starts to flatten as the frequency increases. The converter must be able to regulate at these high frequencies, especially when the battery is deep discharged, for example. A ratio of L_m/L_r = 3 and a Q_{max} of 0.3 has been chosen for this application for a limited operating span and a good regulation.

There are three modes of operation:

1. at resonant frequency operation→f_s=f_r. The resonant tank is close to the unity gain and is best fit for high efficiency. The transformer turns ratio is chosen to make the converter operate at this point at the nominal input and output voltages
2. above resonant frequency operation→f_s>f_r. Over resonant mode results in buck operation or reduction of the output voltage to an extent, depending on the resonant tank components, the M ratio, and the output loading degree. The turn-off commutation is no longer ZCS. Losses increase in this mode, depending on the operating point of the primary resonant tank. The use of extremely fast diodes, still Schottky, or SiC Schottky diodes is mandatory for the 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}, with the effective loading reflected to the primary side. There is a boost gain, but the primary to secondary current transfer is discontinuous. Furthermore, operating at lower frequency increases the magnetizing current value. 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. We can move left of 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 operate in all three modes. Each mode operates at 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), with an optimum efficiency. Below resonance, ZVS achieved, DCM on sec, rectifiers are soft switched (ZCS), RMS currents higher for a given power.

In an off-line application with a pre-regulated bus, each primary side MOSFET sees a maximum voltage equal to the bus voltage. Due to the resonant operation, over- and under-shoot is negligible. So, a breakdown voltage rating of 950 V is a an acceptable result. 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 ample pre-programmed deadtime), the 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. STW40N95DK5 MOSFET has been used for this application.

Ideally, a MOSFET for the LLC should operate with zero dead time (maximum power transfer/no duty cycle loss) and no conduction loss. R_{dsON} is obviously important for the latter consideration, but 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}).

Table 3. **DC-DC LLC resonant tank parameters**

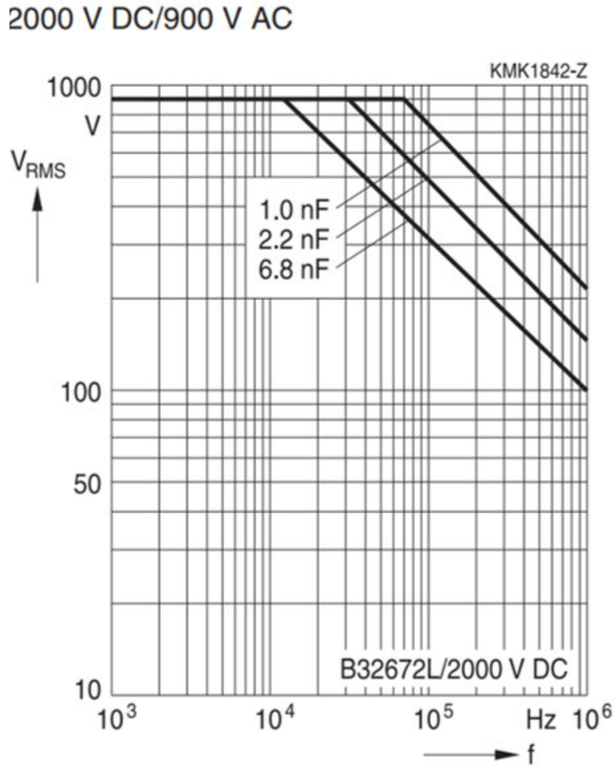
LLC resonant tank parameters	Value
Resonant inductor (Lr)	67 µH
Magnetizing inductance (Lm)	200 µH
Resonant capacitor (Cr)	27 nF
Turns ratio (Np : Ns1 : Ns2)	• 1.08 : 1 for Ver 1 • 2.16 : 1 : 1 V2

3.2 Key devices used in DC-DC LLC resonant converter

- **STM32G474RET6**
  The STM32G474xB/xC/xE devices are based on the high-performance Arm® Cortex®-M4 32-bit RISC core. They operate at a frequency of up to 170 MHz. The Cortex-M4 core features a single-precision floating-point unit (FPU), which supports all the Arm single-precision data-processing instructions and all the data types. It also implements a full set of digital signal processing (DSP) instructions and a memory protection unit (MPU), which enhances the application security. These devices embed high-speed memories (up to 512 Kbytes of flash memory and 128 Kbytes of SRAM), a flexible external memory controller (FSMC) for static memories (for devices with packages of 100 pins and more), a quad-SPI flash memory interface, and an extensive range of enhanced I/Os and peripherals connected to two APB buses, two AHB buses, and a 32-bit multi-AHB bus matrix. The devices also embed several protection mechanisms for embedded flash memory and SRAM: readout protection, write protection, securable memory area, and proprietary code readout protection. The devices embed peripherals allowing mathematical/arithmetic function acceleration (CORDIC for trigonometric functions and FMAC unit for filter functions). They offer five fast 12-bit ADCs (4 Msps), seven comparators, six operational amplifiers, seven DAC channels (3 external and 4 internal), an internal voltage reference buffer, a low-power RTC, two general-purpose 32-bit timers, three 16-bit PWM timers dedicated to motor control, seven general-purpose 16-bit timers, and one 16-bit low-power timer, and high resolution timer with 184 ps resolution.
- **STW40N95DK5: LLC MOSFET**
  These very high voltage N-channel Power MOSFETs are part of the MDmesh DK5 fast-recovery diode series. The MDmesh DK5 combines very low recovery charge (Qrr) and recovery time (trr) with an excellent improvement in Rds(on) * area and one of the most effective switching behaviors, ideal for half bridge and full bridge converters. In the STDES-6KWHVDCDC reference design, a total of four of these MOSFETs have been used. The MOSFETs have been mounted via a thermal pad on an Ohmite CR201-75 heat-sink.
- **STPSC40H12C: output rectification SiC diode**
  The SiC diode, available in a TO-247 LL package, is an ultrahigh performance power Schottky rectifier. It is manufactured using a silicon carbide substrate. The wide band-gap material allows the design of a low VF Schottky diode structure with a 1200 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 temperature. Especially suited to be used in PFC and secondary side applications, this ST SiC diode eases the performance of hard switching conditions. This rectifier enhances the performance of the LLC conditions under all operating modes. Its high forward surge capability ensures a good robustness during transient phases.

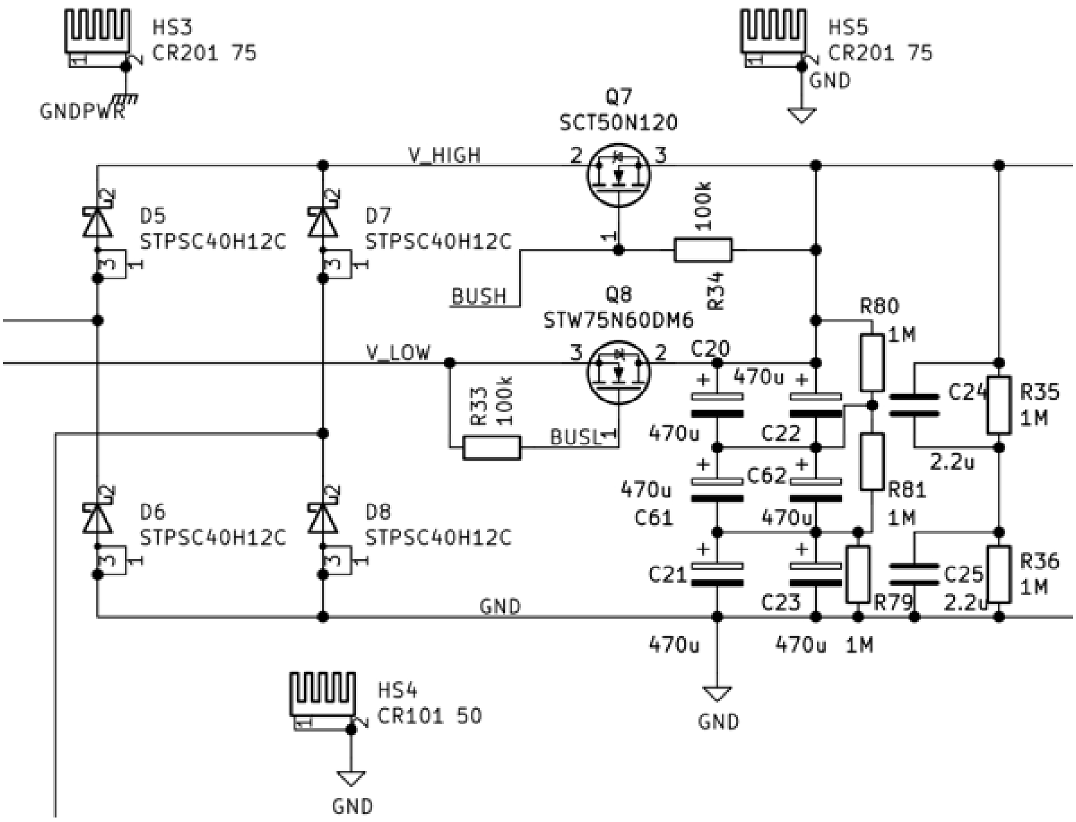
- **Resonant capacitor**
  The resonant capacitor must have a very low dissipation factor (DF) due to its high-frequency operation, and very high sinusoid and non-sinusoid current. Capacitors such as electrolytic or ceramic are unsuitable and even polyester capacitors need a careful look. NP0 capacitors may be used for their low loss, but their maximum capacitance presents limitations and high cost. Capacitors for LLC converters are popularly metalized polypropylene film. These capacitors have a low DF and are capable of handling constant 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. It is better to use many smaller capacitors in parallel than one single large capacitor.

Figure 7. **Capacitor derating with frequency (from 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, although 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 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 maximum possible ripple current rating. In this particular application, capacitors have been connected in a series parallel combination with equalizing resistors to meet the high operating voltage target, volume, and cost.

Figure 8. **Capacitor configuration in output filter**

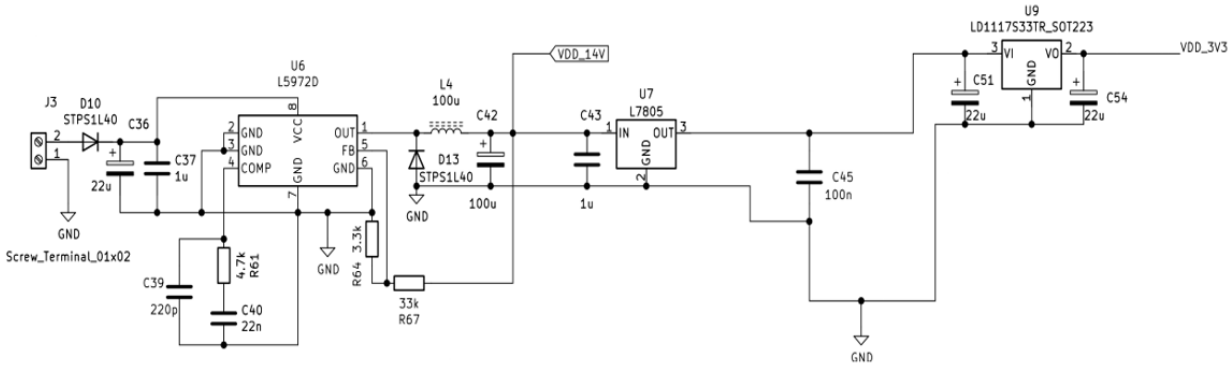


3.3 Auxiliary power supply

The auxiliary power supply has three stages to convert the input 20 – 25 V DC:

- 14 – 15 V for relays, fans and gate drivers
- from 12 V to 5 V for some peripheral devices
- 5 V to 3.3 V for the MCU

Figure 9. Auxiliary power supply



The 24 V to 15 V conversion is taken care of by a switching regulator to minimize losses. The other low current demand regulators are linear: the L78 converting 12 V to 5 V and the LD1117 converting the 5 V to 3.3 V for a ripple free supply to the MCU.

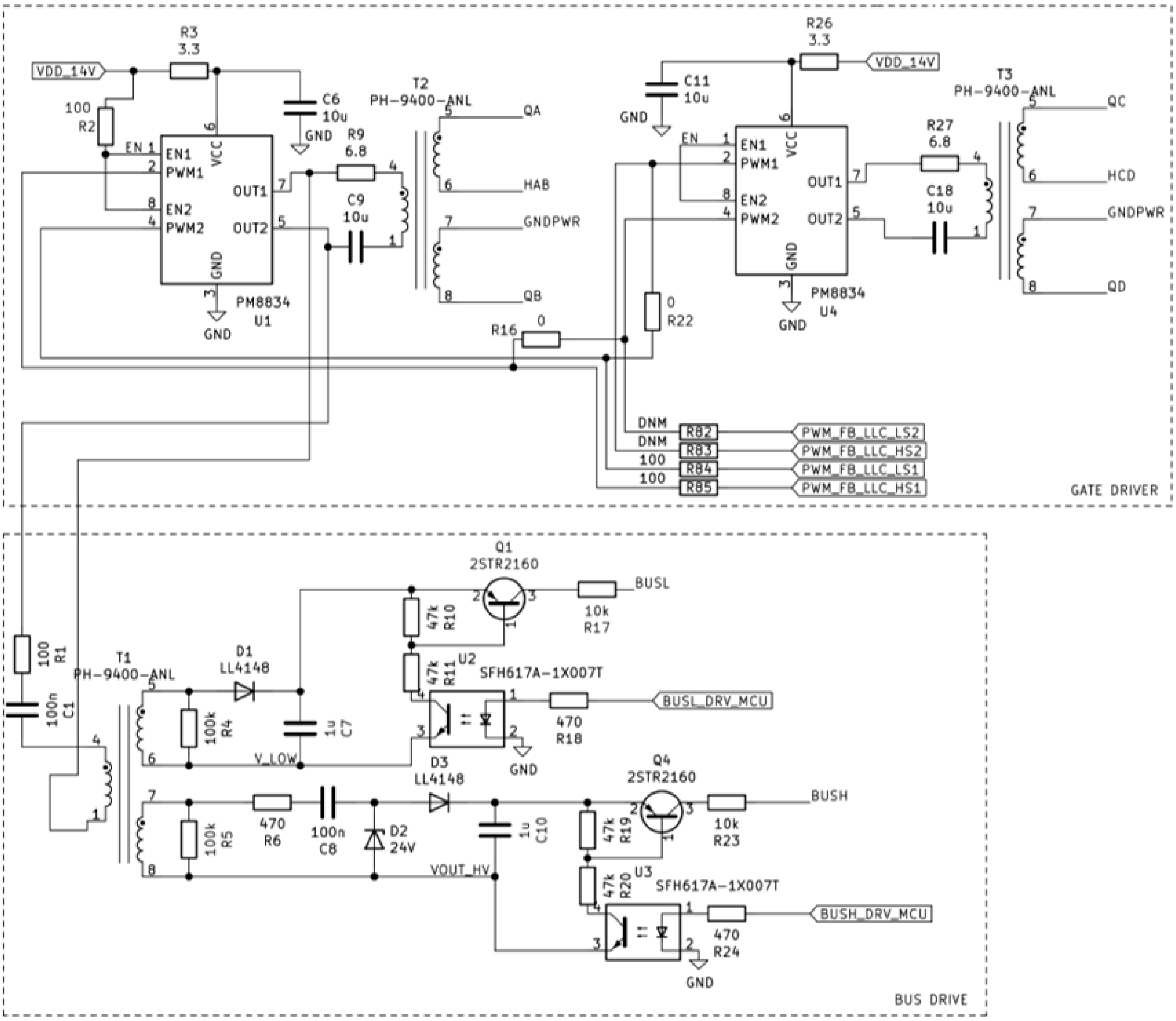
3.4 Gate drive stage

There are two different gate driving schemes. The main LLC power plant PWM coming from the microcontroller is level shifted by the PM8834 gate drivers. One set of gate drive signals from the output of the gate driver ICs is fed to the LLC MOSFETs using gate drive transformers to provide the required isolation between the control side and the power plant side.

There are two MOSFETs on the output DC bus that are referred to the DC bus. This means that the gate drive must be floating with respect to the DC buses.

Another gate drive transformer has been used to derive two floating supplies controlled by an opto-isolator to drive the floating gates. There is an added degree of safety: in case the main PWM stops, there is no way to keep the DC bus switches active. They shut off automatically as shown below.

Figure 10. **Gate driving circuitry**



4 Experimental results

The STDES-6KWHVDCDC reference design has been tested with center tapped and full bridge configuration with an input voltage ranging from 700 to 800 V DC.

4.1 Test setup and waveforms

Figure 11. STDES-6KWHVDCDC test setup

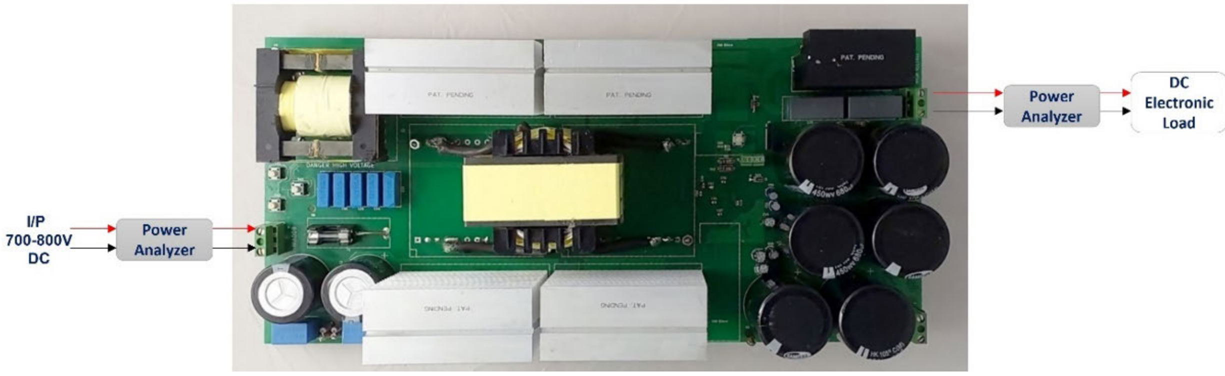
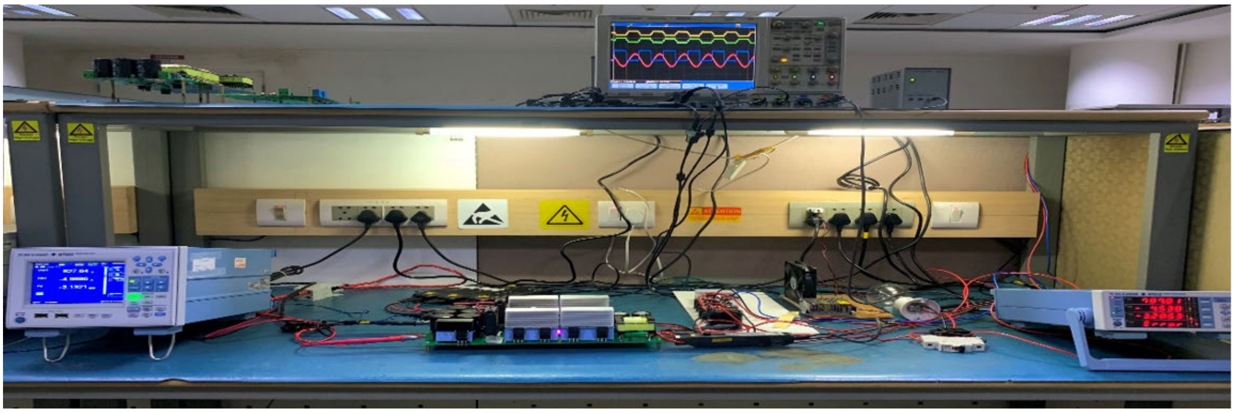
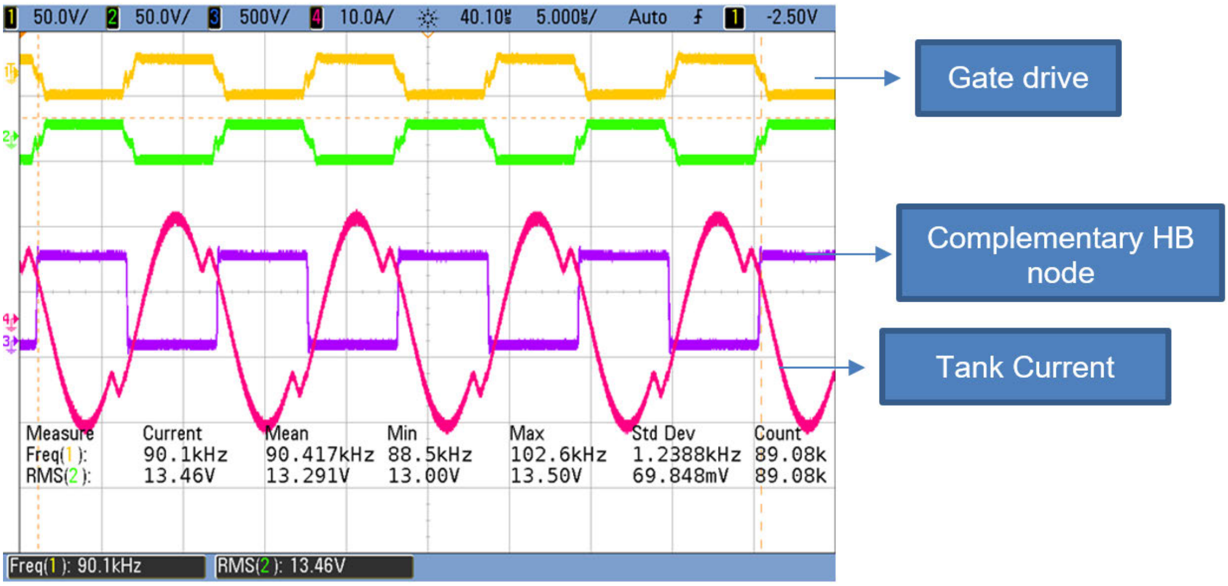


Figure 12. STDES-6KWHVDCDC actual test setup



The various operating modes are shown below.

Figure 13. **800 V output, 90 kHz**



Note the bipolar nature of the gate drive due to the usage of the gate drive transformer. The "notch" halfway of the gate drive is not to be mistaken with the Miller plateau (non ZVS). It is the deadtime region in a gate drive transformer. Effectively, the gate drive voltage is +/-12 V that leads to a faster turn-off than a unipolar gate drive swing. This adds a slight efficiency increase thanks to the faster turn-off. These measurements are taken at the maximum power for that voltage band. Ranging from 2400 W (at 200 V) to 6000 W (at 900 V).

Figure 14. **700 V output, 100 kHz**

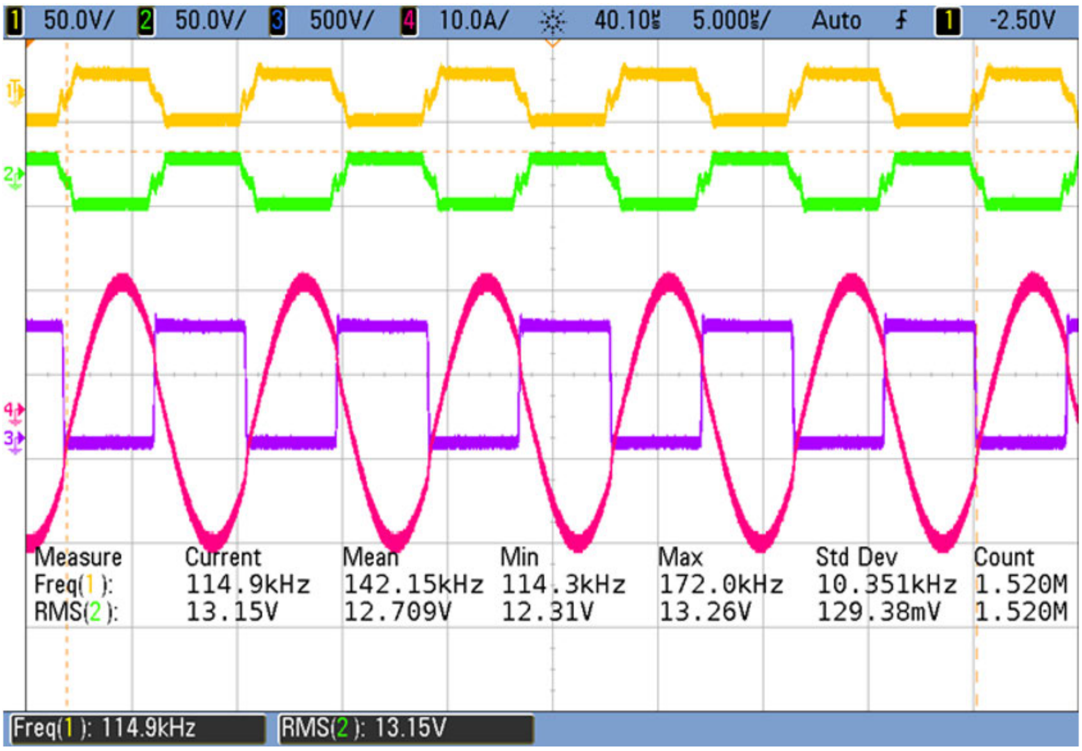


Figure 15. 500 V output, 135 kHz

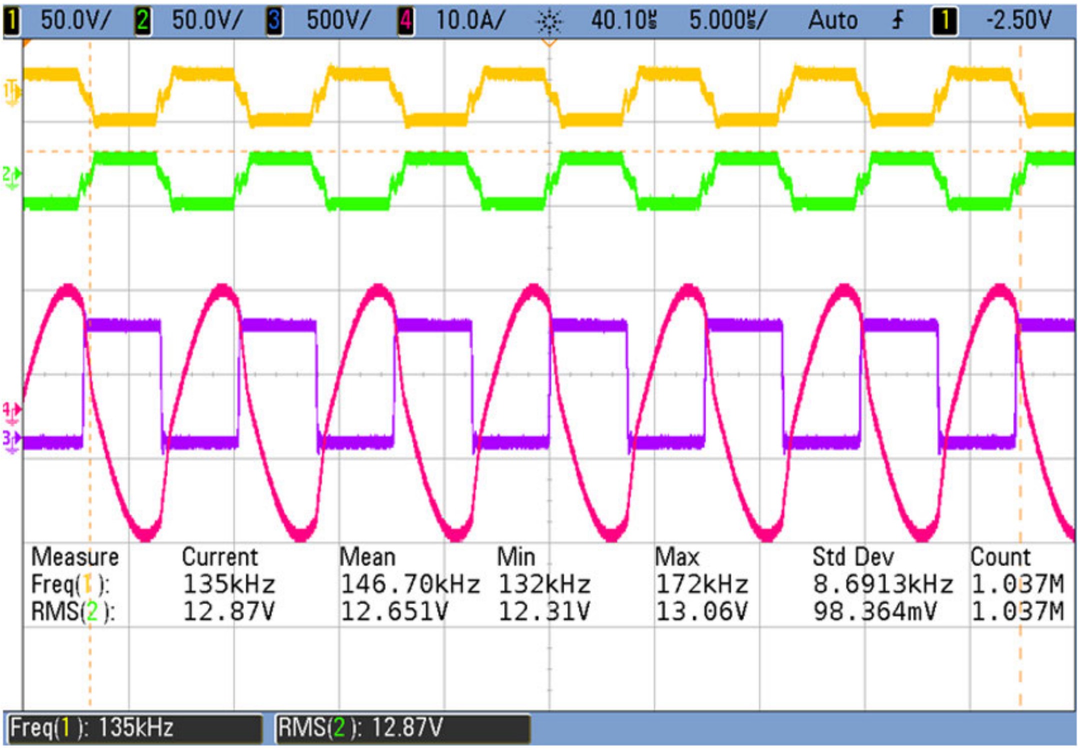


Figure 16. 400 V output, 145 kHz shifts to 90 kHz with the bus switching scheme

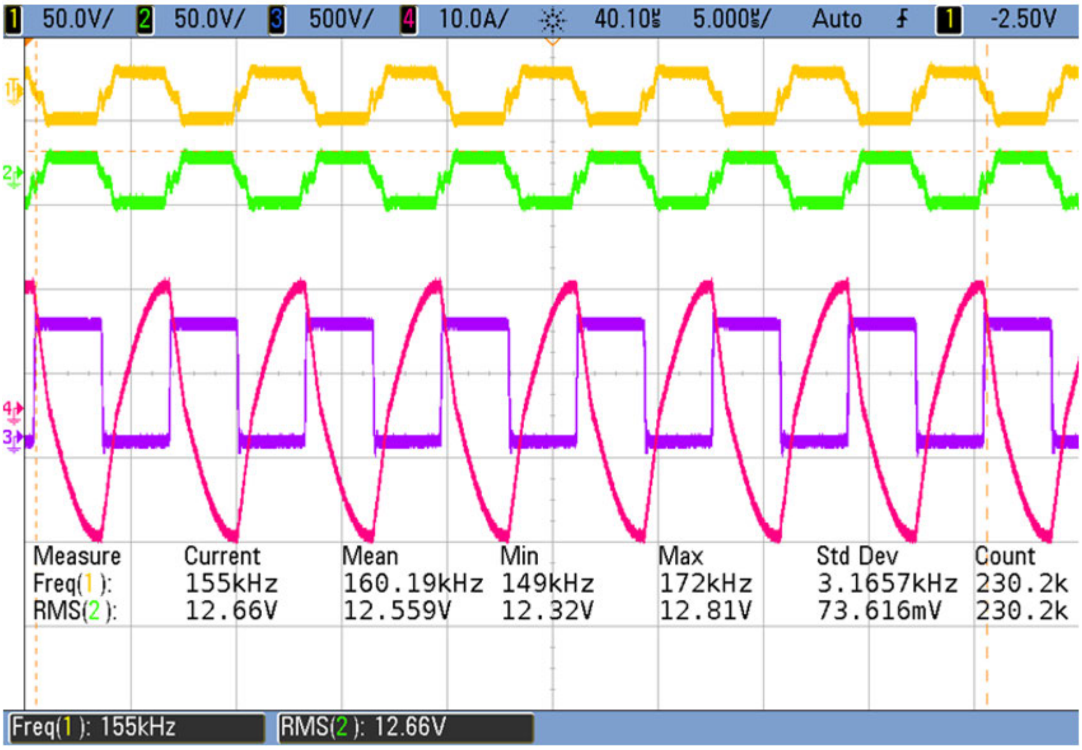


Figure 17. **300 V output, 165 kHz shifts to 120 kHz with the bus switching scheme**

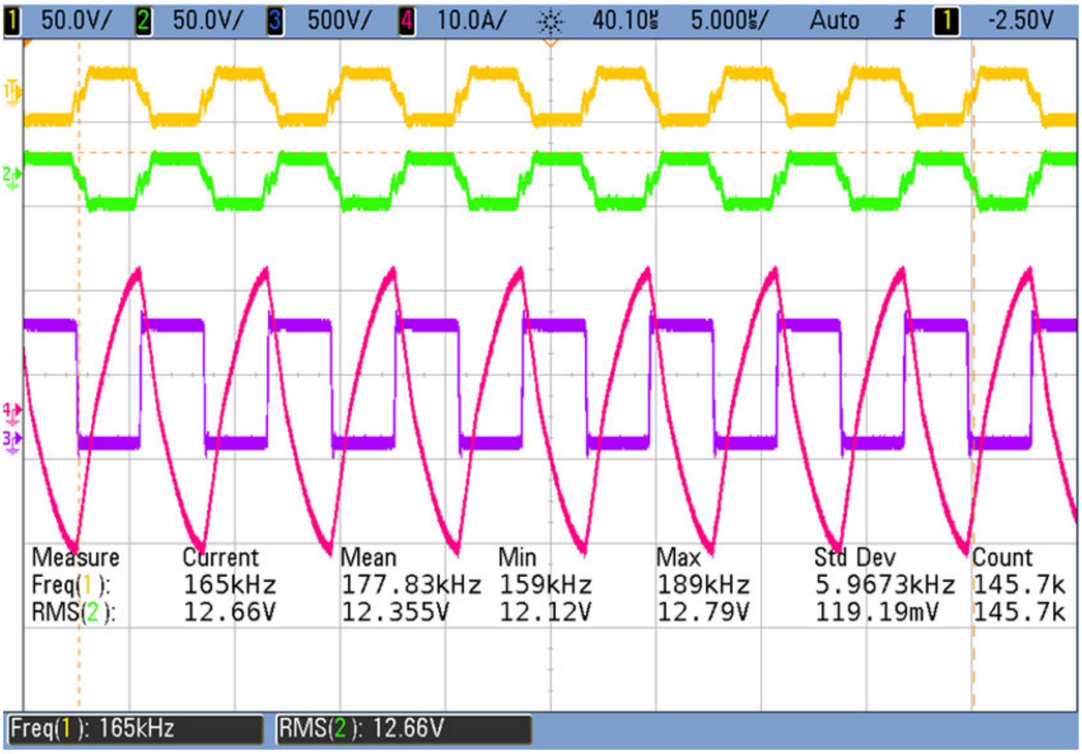
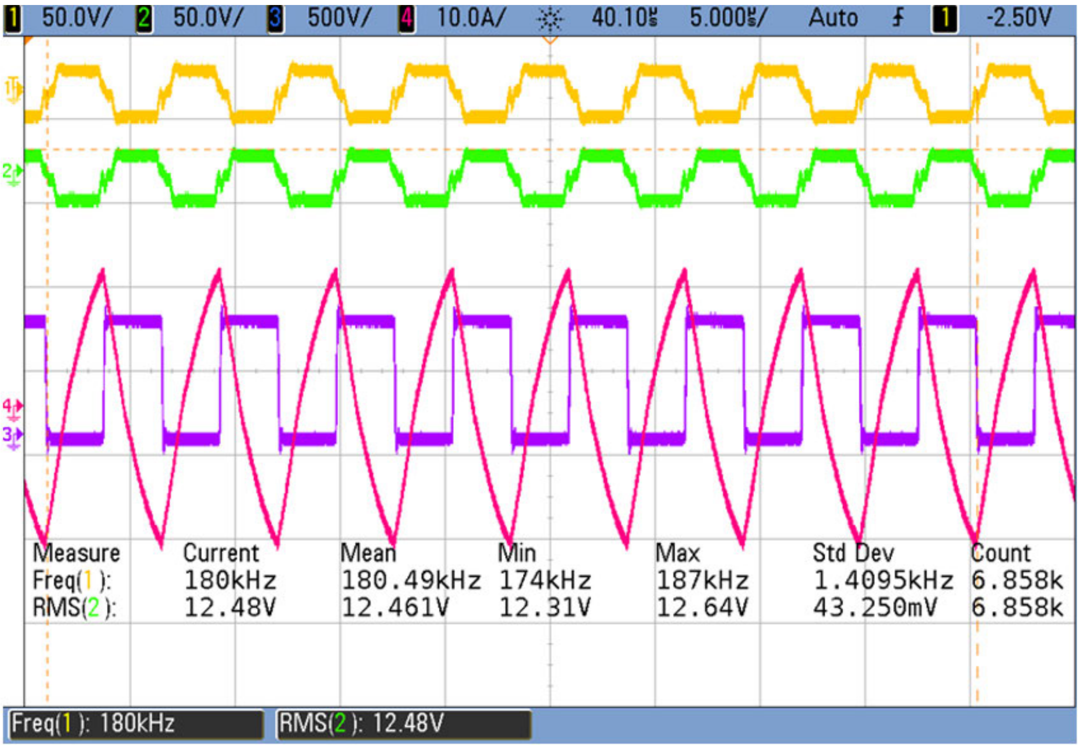
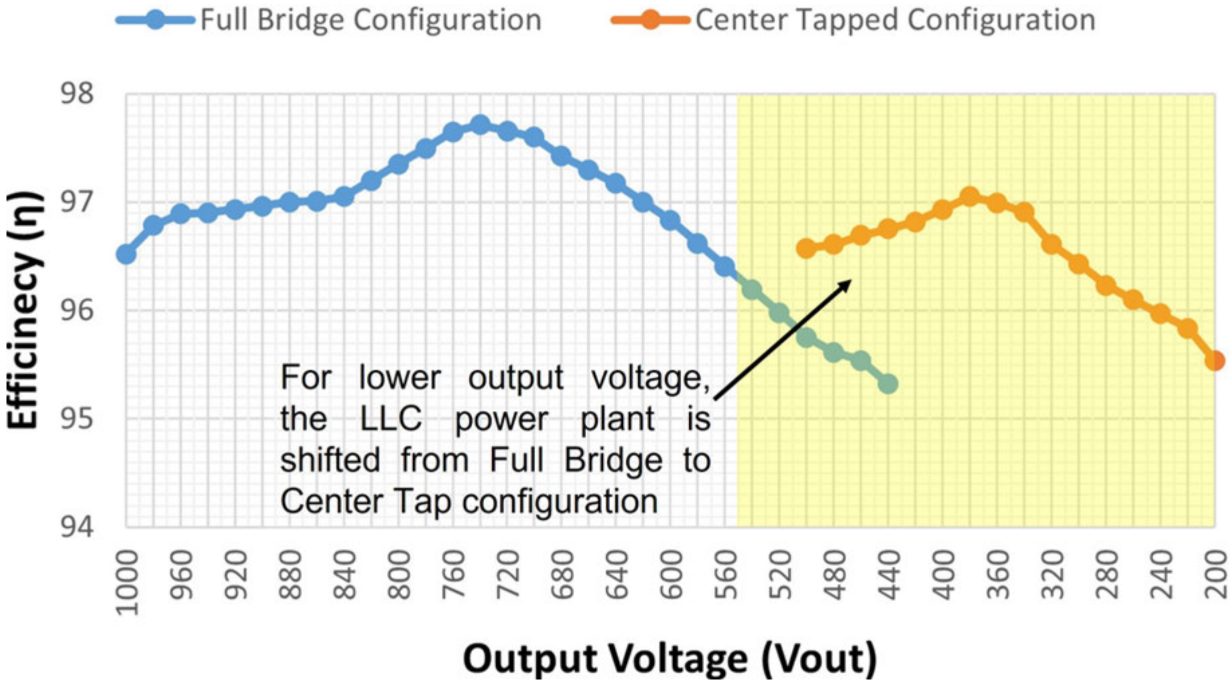


Figure 18. **200 V output, 180 kHz shifts to 130 kHz with the bus switching scheme**



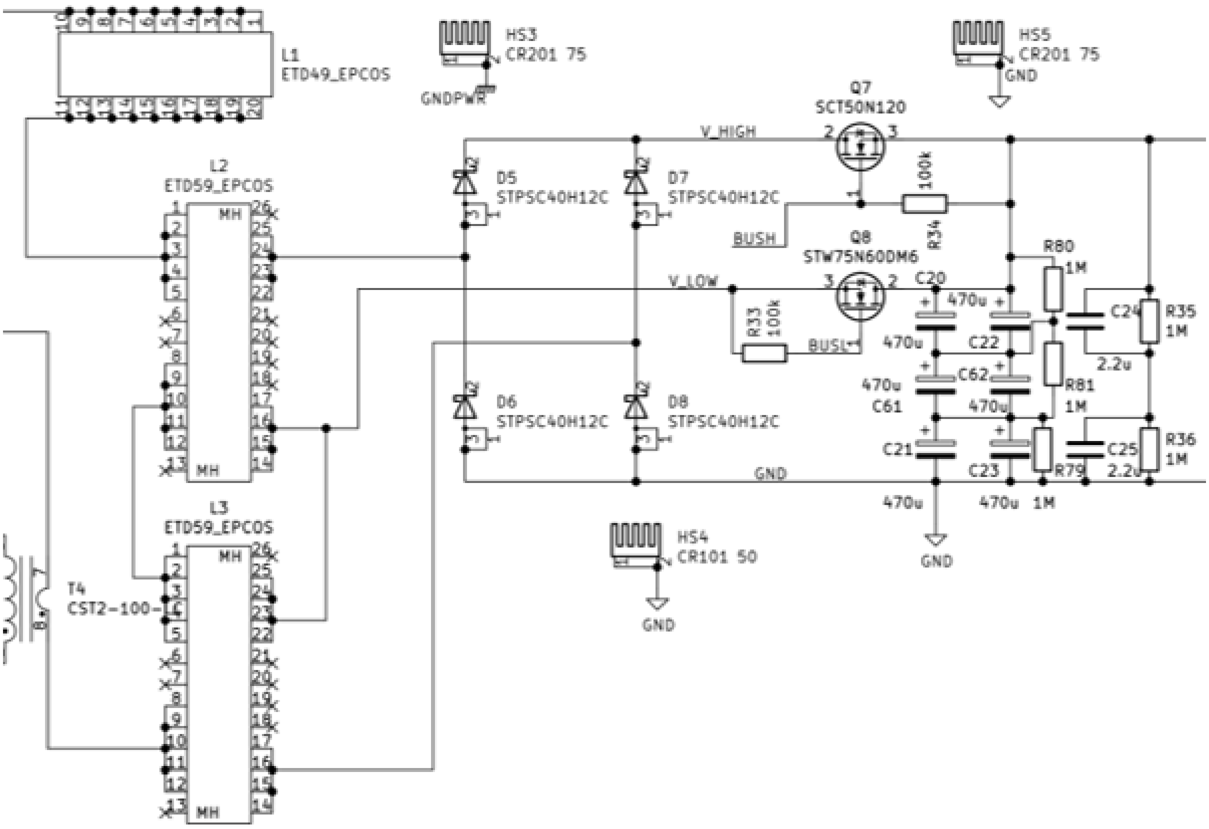
Regarding the improvement with the bus switching scheme with a single transformer vs a traditional dual transformer LLC, it is possible to notice how a significant gain in terms of efficiency is obtained by using the bus switching scheme (frequency foldback). The operating curves are exactly identical as shown above but the frequency excursion at lower voltages is minimized, increasing efficiency.

Figure 19. **Efficiency (%) vs output voltage**



The bus switching consists of two MOSFETs in the Vbush and Vbusl lines as shown below.

Figure 20. **Bus switching**



Note that the gate drives are floating and referred to the source of the respective MOSFET. The unique arrangement of the MOSFETs always prevent reverse flow of any current. This is also an added advantage. The upper MOSFET may support the full output voltage of 1000 V. So, a 1200 V device has been chosen. As the lower MOSFET supports up to 500 V, a 650 V MOSFET is chosen. The upper MOSFET is always at double the voltage level of the lower MOSFET voltage. So, the body diode of the upper MOSFET is always reverse biased, causing no reverse flow of current. When both the MOSFETs are off, there is no current flowing from the load (battery) towards the charger.

The following table shows the performance at some typical operating points:

- V_{IN} = 700 V
- MOSFET case temperature: worst < 50°C with forced air cooling, 30 minutes warmup

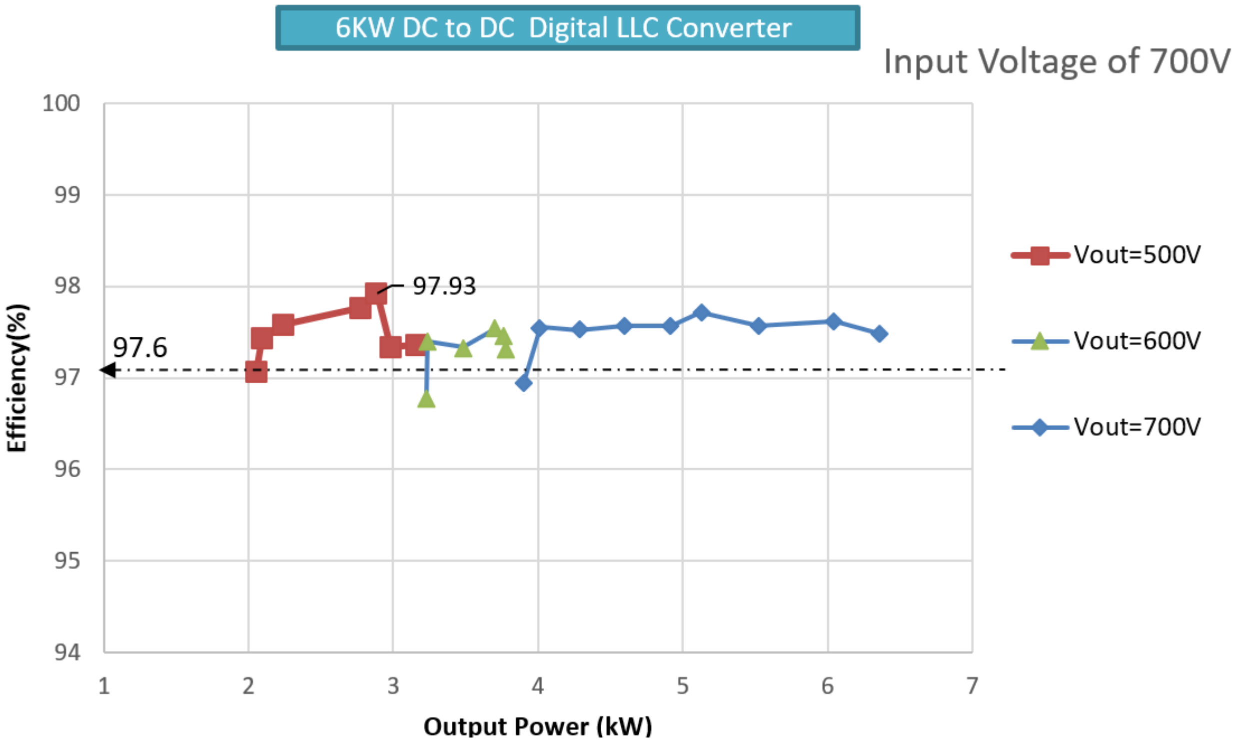
: (

Table 4. Typical performance

Input voltage (V)	Input current (A)	Input power (KW)	Switching frequency (kHz)	Output voltage (V)	Output current (A)	Output power (KW)	Efficiency (%)	Load (ohm)
711.3	3.204	2.2788	180	210.9	9.572	2.0195	88.6212	21
706.75	4.943	3.4934	165	307.95	10.413	3.207	91.8016	28
704.93	5.515	4.1012	155	396.29	9.791	3.8815	94.6430	38
701.57	7.529	5.2827	135	508.47	10.013	5.0929	96.4071	48
698.76	9.37	6.5249	115	608.17	10.455	6.3606	97.4819	54
702.44	7.049	4.952	100	692.9	6.962	4.825	97.4353	92
686.07	8.998	6.1736	90	775.5	4.759	6.019	97.4957	92
708.05	4.38	3.1016	115	625.38	4.8583	3.0351	97.8559	122

Some typical “emulated” battery charging conditions and power profiles and efficiency have been plotted. These indicate typical “discharged to charged” stages a battery is going through during a charge cycle. When it is at a 700 V band, it typically means from 660 V to 740 V as the battery voltage rises with charging and so the power (V * I, with V increasing and I constant).

Figure 21. STDES-6KWHVDCDC efficiency based on different conditions



5 STDES-6KWHVDCDC magnetics

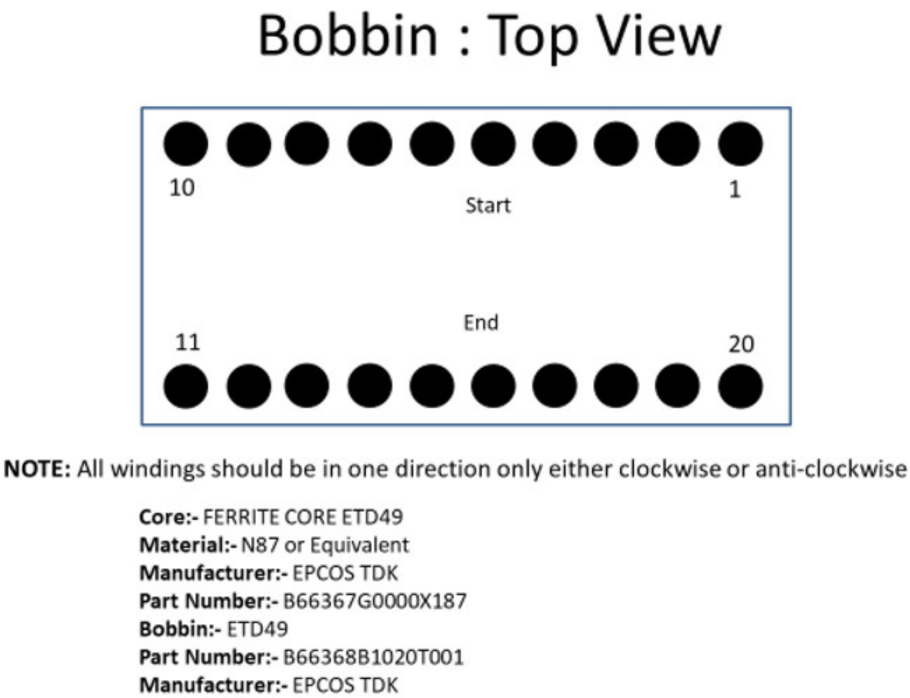
In the STDES-6KWHVDCDC reference design, there are several customized transformer and inductor involved. The magnetics design specifications are detailed in the following sections.

5.1 LLC choke/inductor common for both variants

Table 5. LLC choke/inductor

Parameter	Value/name
Number of turns	20
Inductance	60 µH
Wire gauge (primary)	Litz wire (42*300), silk leads
Standard	UL94, EN60950

Figure 22. LLC choke/inductor

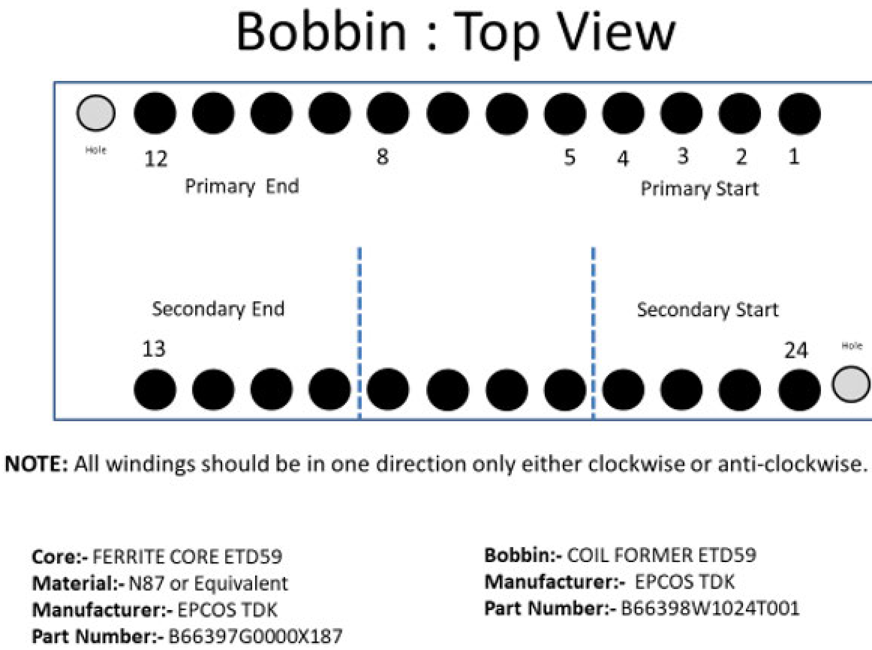


5.2 LLC transformer winding for dual transformer version 1

Table 6. LLC transformer winding for dual transformer version 1

Parameter	Value/name
Number of turns (primary)	25
Number of turns (secondary)	20
Inductance (primary)	100 µH
Wire gauge (primary)	Litz wire (42*300), silk leads
Wire gauge (secondary)	Litz wire (42*300), silk leads
Standard	UL94, EN60950

Figure 23. LLC transformer winding for dual transformer version 1



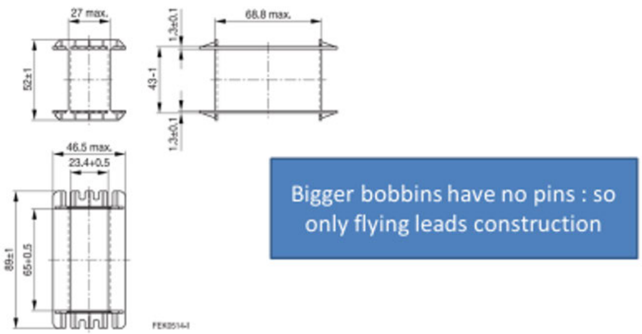
5.3 LLC transformer winding for single transformer version 2

Table 7. LLC transformer winding for single transformer version 2

Parameter	Value/name
Number of turns (primary)	21
Number of turns (secondary)	10+10 (center tap)
Inductance (primary)	200 µH
Wire gauge (primary)	Litz wire (42*300), silk leads
Wire gauge (secondary)	Litz wire (42*300), silk leads
Standard	UL94, EN60950

Figure 24. LLC transformer winding for single transformer version 2

EE70 transformer



NOTE: All windings should be in one direction only either clockwise or anti-clockwise.

Core:- FERRITE CORE E70
Material:- N87 or Equivalent
Manufacturer:- EPCOS TDK
Part Number:- B66371G0000X187

Bobbin:- COIL FORMER E70
Manufacturer:- EPCOS TDK
Part Number:- B66372A2000T001

6 STDES-6KWHVDCDC modifications version 1 or version 2

Version 1

This reference design can operate in two modes. The first mode or the default mode is the dual transformer variant.

In this particular case, the board behaves like a standard LLC converter with a full-bridge secondary rectifier scheme.

The bus switching MOSFETs are redundant. So, the high bus switch MOSFET has to be replaced with a wire jumper to short the train and the source pins. The lower bus MOSFET has to be removed out of the circuit. The effective circuit behaves like a standard full-bridge converter with a full-bridge rectifier at the secondary followed by a capacitive filter.

All the other functions remain the same except the bus switching logic and the converter that still operate from 200 to 1000 V at the output with an input of 750 V DC. However, the efficiency would peak around the resonant frequency to about 98% at an output voltage of 800 V and 6 kilowatts, gradually decreasing to 91% at 200 V and 2.5 kilowatts output.

At 85 kHz the output voltage of the converter would be 1000 V and it would reach 200 V at 160 kHz. The sweet spot is at 110 kHz.

The secondary winding of the transformer can be adjusted as per user's need as the suitable voltage rating and the operating range can be narrowed for a higher efficiency. So, we suggest using this configuration for a limited voltage swing application. For a wide voltage swing, we use the scheme of version 2.

Figure 25. Modification for version 1 configuration

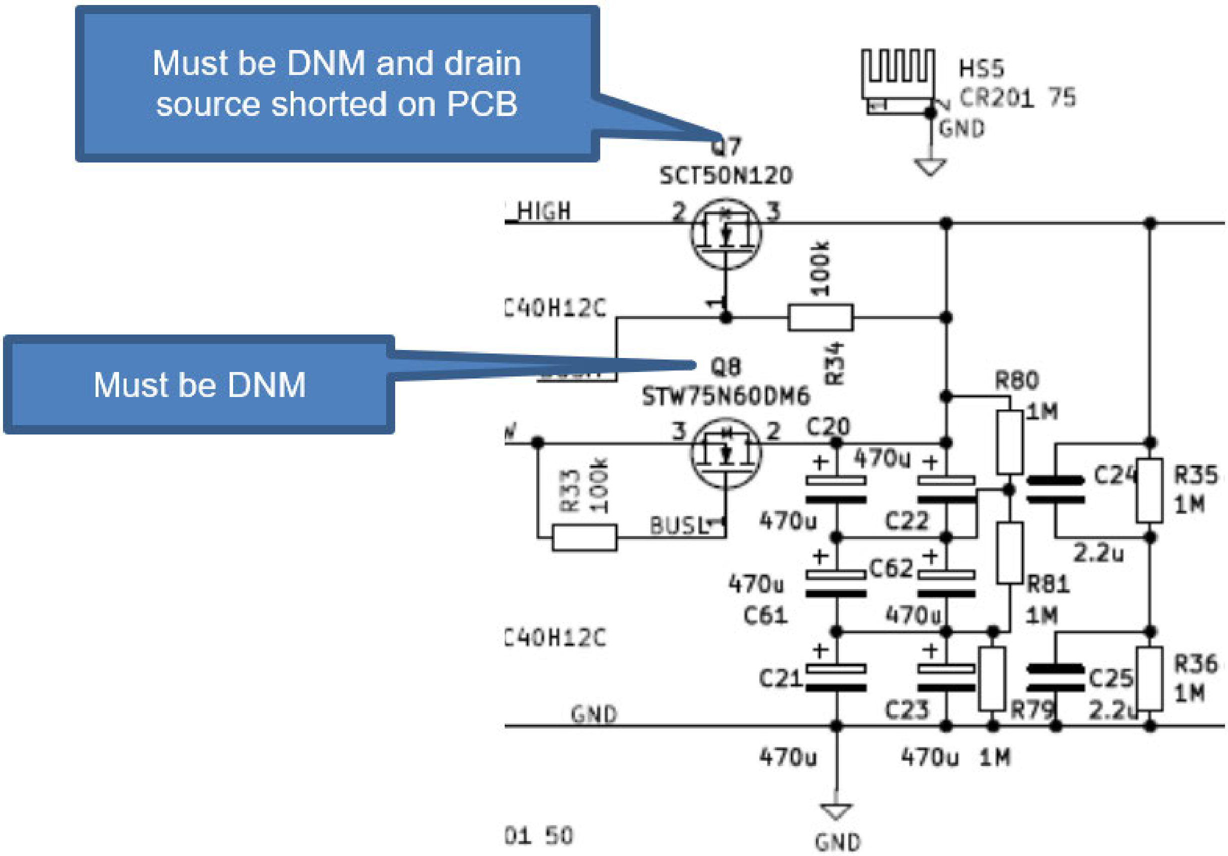
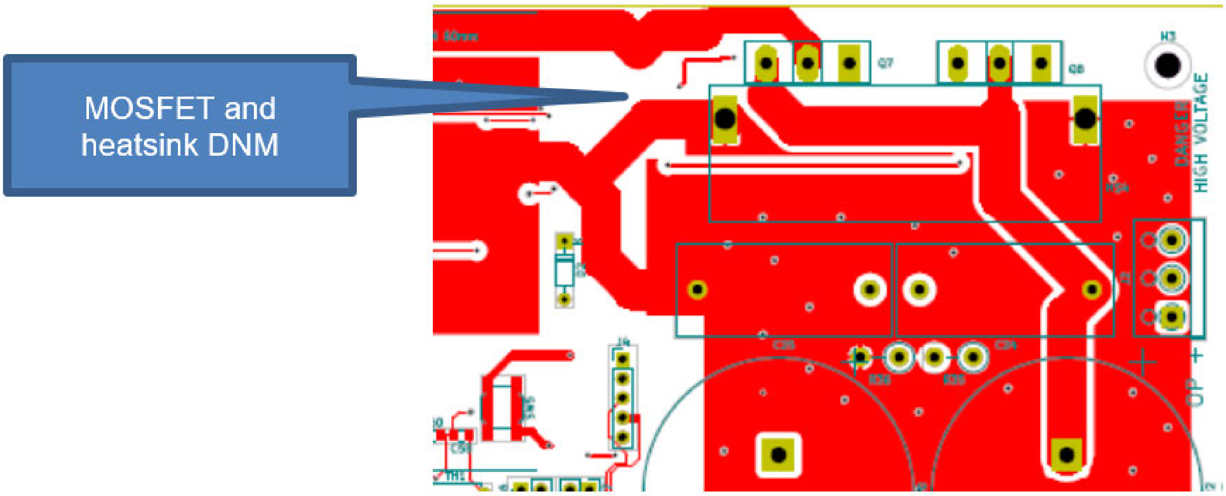


Figure 26. **Location of related components**

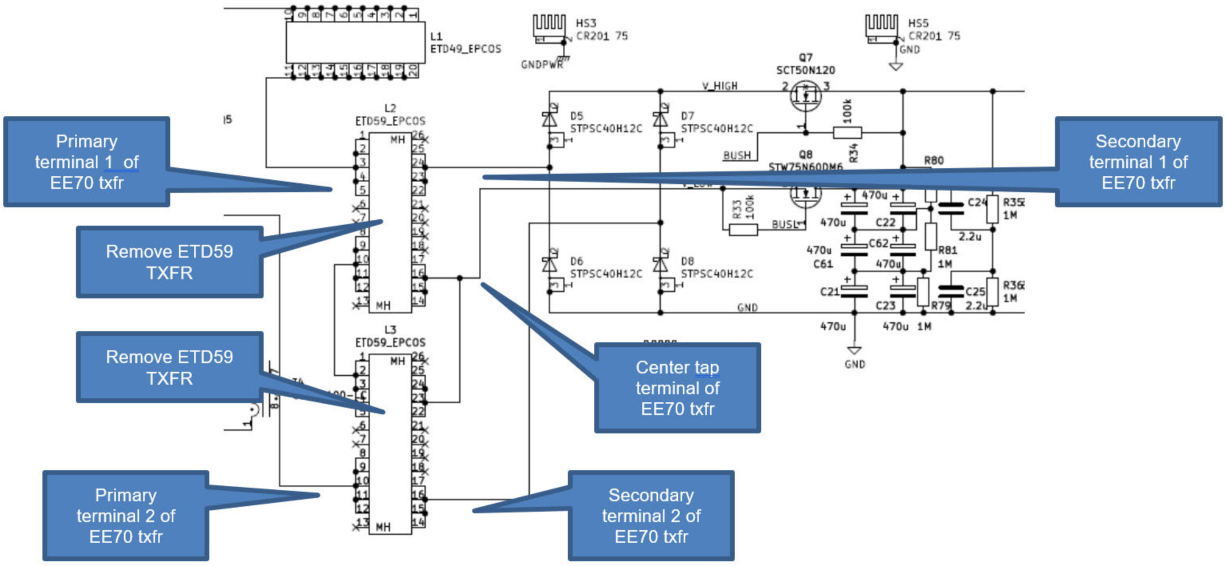


With this configuration, we need to mount both transformers, which are smaller in size (ETD 59 size) with a core material N97 from EPCOS TDK, for the best performance.

Version 2

This is the dual transformer version. In this configuration, instead of two transformers, we use a single transformer wound on a double E70 core for the required power handling. The secondary is center tapped and this transformer must be fixed on the same PCB as shown in the diagram below.

Figure 27. **Location of related components for version 2**



All the other components must be mounted. The steps mentioned in the modification for version 1 must be ignored in this particular case.

The figure below shows the modifications for version 2.

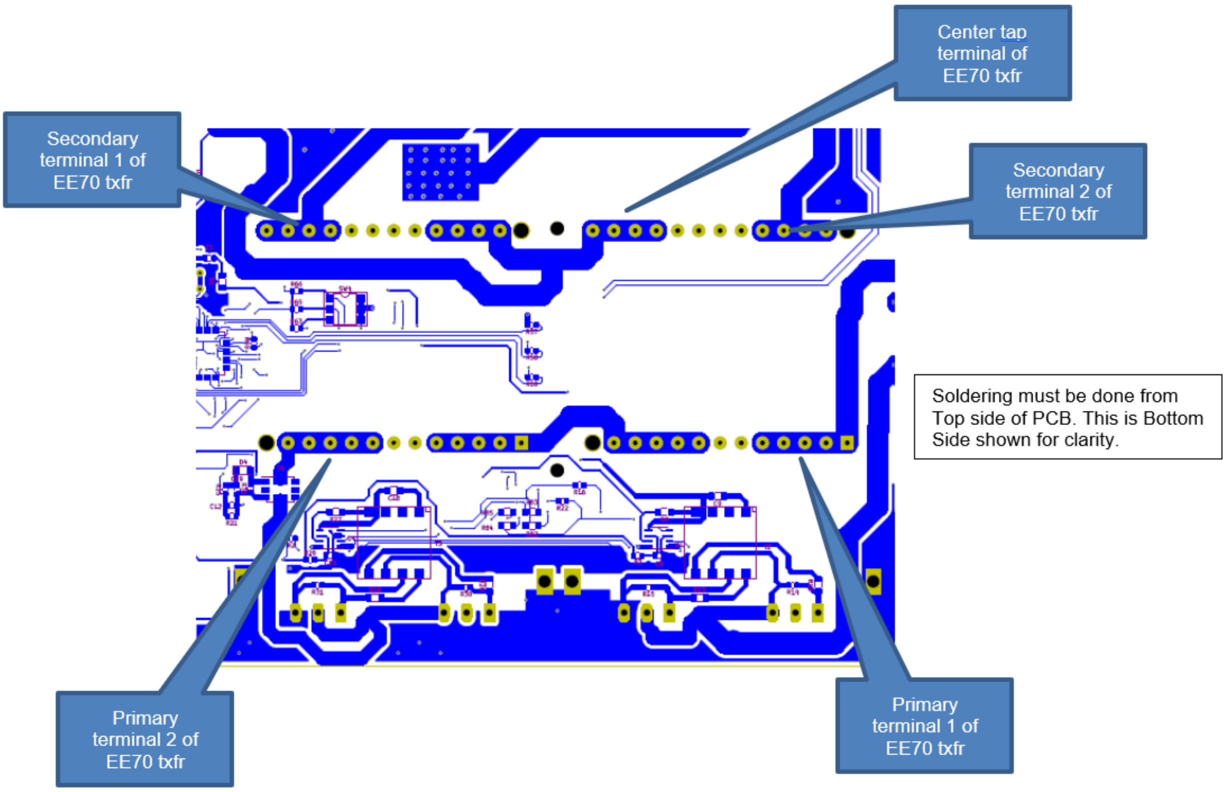
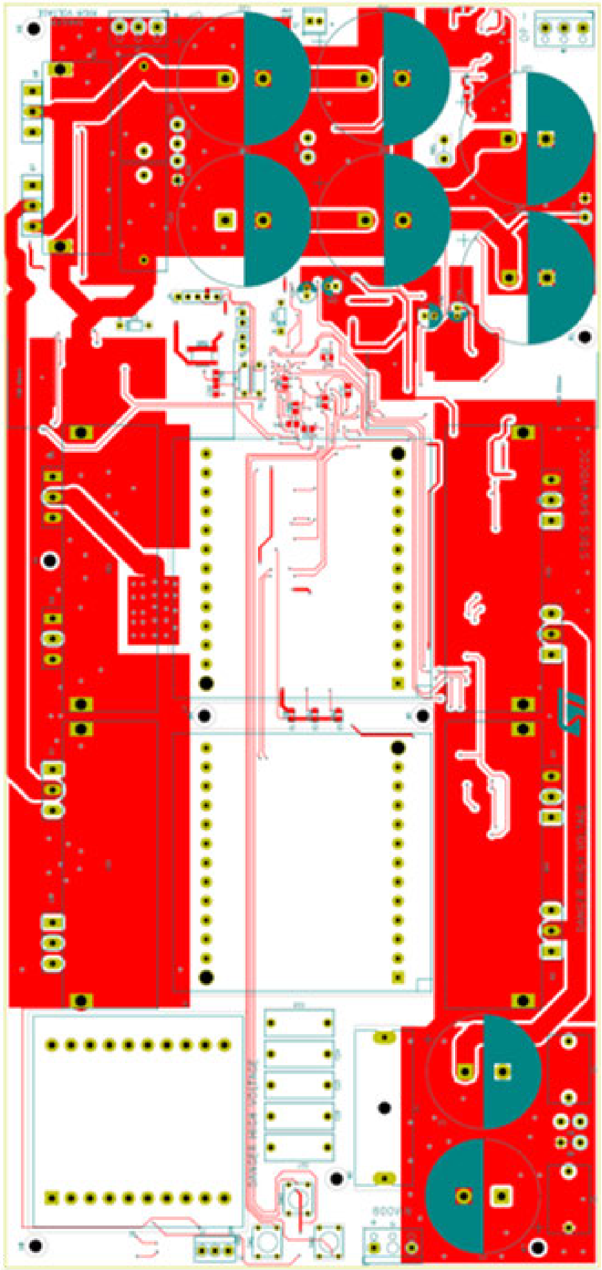


Figure 28. Location of EE70 transformer connection for version 2

7 STDES-6KWHVDCDC PCB layout

Figure 29. STDES-6KWHVDCDC PCB top layer



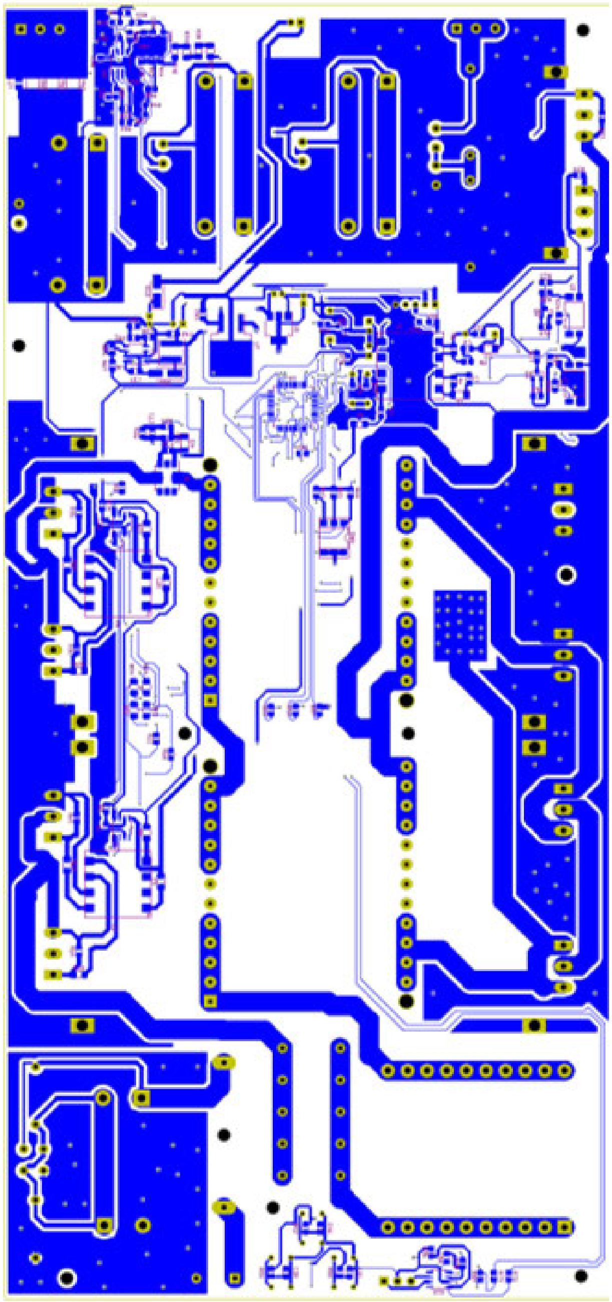


Figure 30. STDES-6KWHVDCDC PCB bottom layer

8 Schematic diagrams

Figure 31. STDES-6KWHVDCDC circuit schematic (1 of 2)

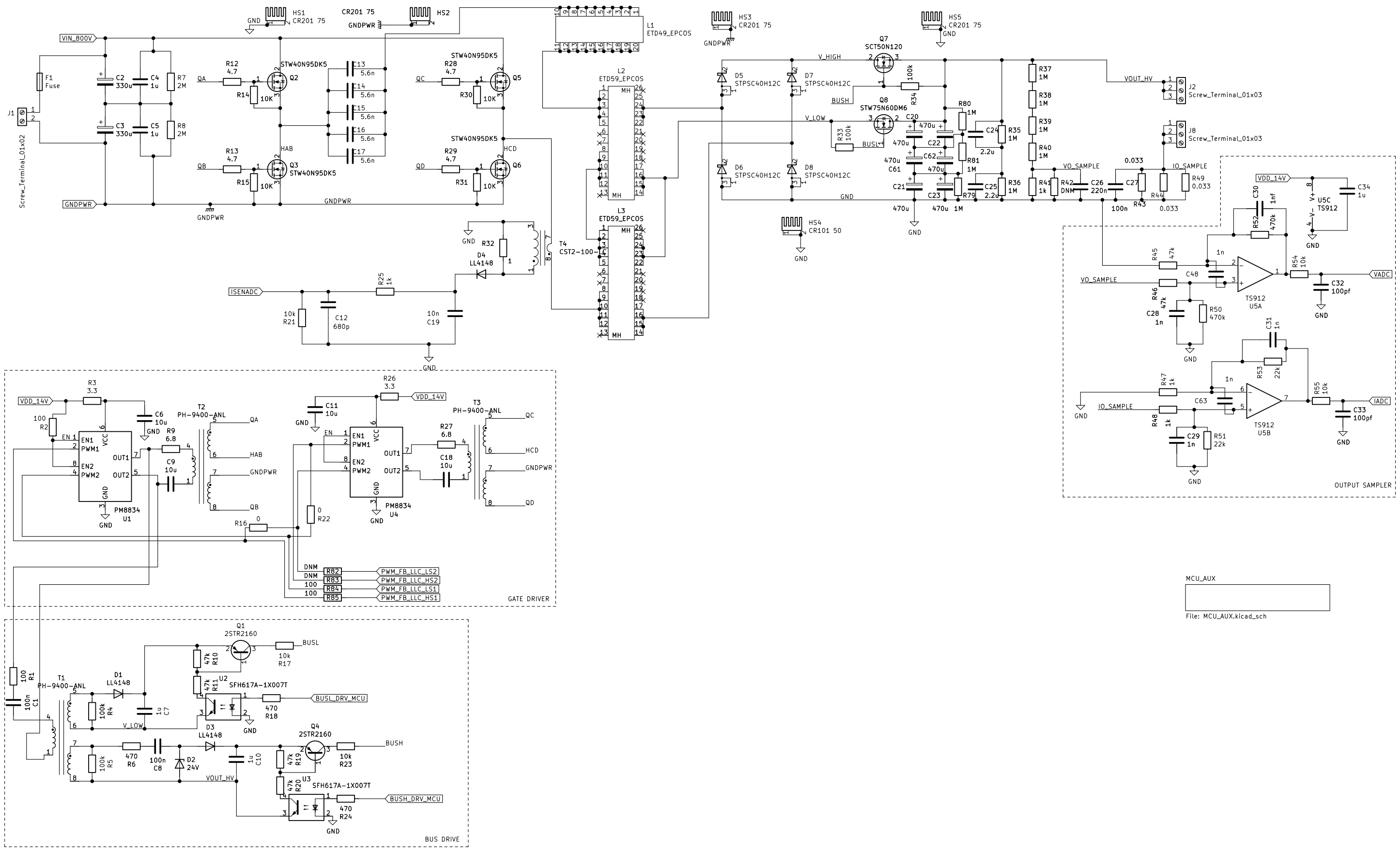
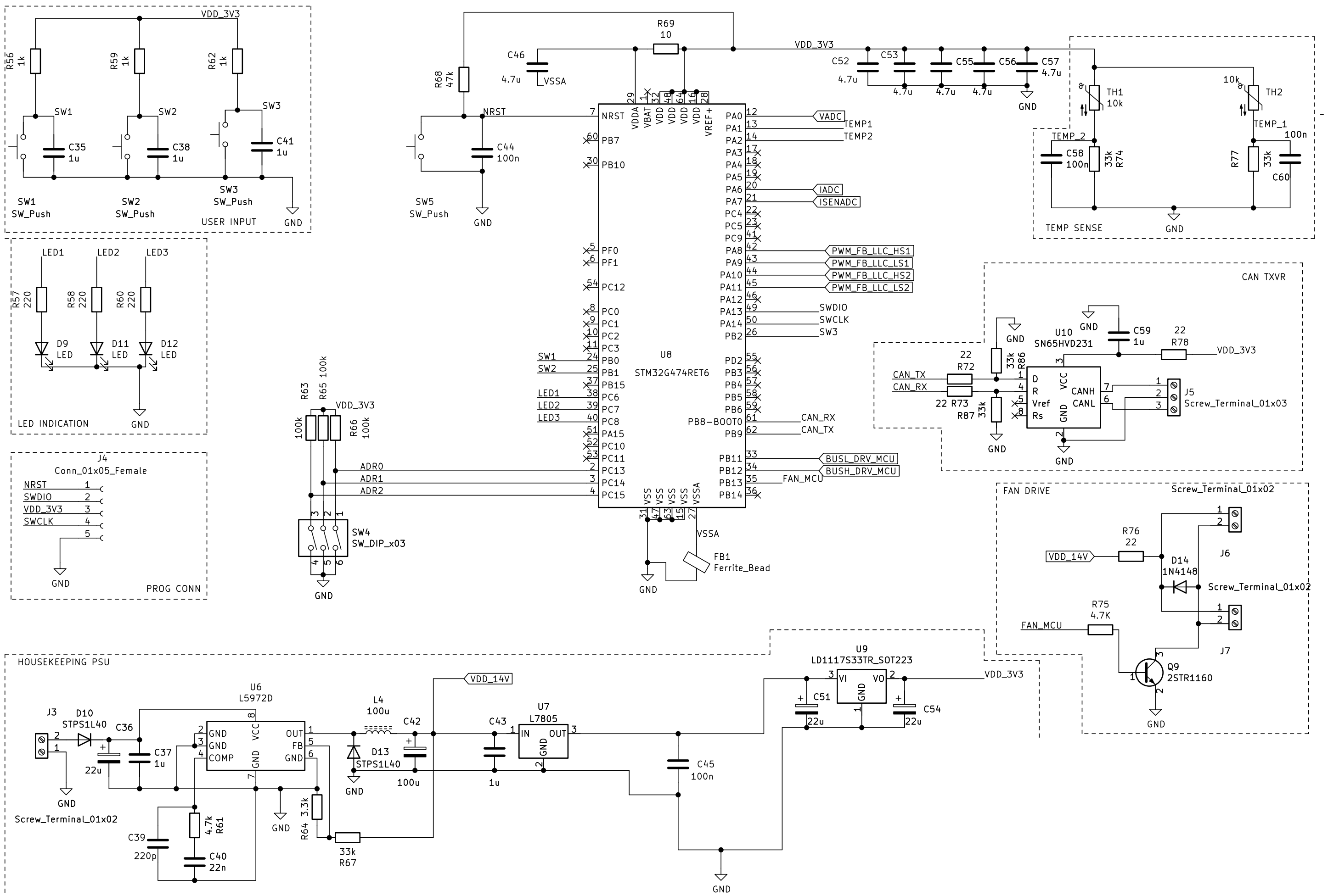


Figure 32. STDES-6KWHVDCDC circuit schematic (2 of 2)



9 Bill of materials

Table 8. **STDES-6KWHVDCDC bill of materials**

Item	Q.ty	Ref.	Part/value	Description	Manufacturer	Order code
1	4	D5, D6, D7, D8	STPSC40H12CWL, TO-247 LL 1200 V 40 A	1200 V power Schottky silicon carbide diode	ST	STPSC40H12CWL
2	2	Q1, Q4	2STR2160 SOT-23 60V 1A	Low voltage fast-switching PNP power transistor	ST	2STR2160
3	4	Q2, Q3, Q5, Q6	STW40N95DK5 TO-247 950V 38 A	N-channel 950 V, 120 mΩ, 38 A	ST	STW40N95DK5
4	1	Q7	SCT50N120 HIP247 1200 V 65 A	Silicon carbide Power MOSFET 1200 V,59 mΩ, 65 A	ST	SCT50N120
5	1	Q8	STW75N60DM6 TO-247 600 V 72A	N-channel 600 V, 32 mΩ, 72 A	ST	STW75N60DM6
6	1	Q9	2STR1160 SOT-23 60 V 1A	Low voltage fast-switching NPN power transistor	ST	2STR1160
7	2	D10, D13	STPS1L40A SMA 40 V 1A	40 V, 1 A low drop power Schottky rectifier	ST	STPS1L40A
8	1	U5	TS912ID SO-8	Low power with CMOS inputs	ST	TS912ID
9	2	U1, U4	PM8834TR MINI SO8	4 A dual low-side MOSFET driver	ST	PM8834TR
10	1	U6	L5972D SO-8	2A switch step down switching regulator	ST	L5972D
11	1	U7	L7805ACD2T-TR D2PAK	Positive voltage regulator ICs	ST	L7805ACD2T-TR
12	1	U8	STM32G474RET6 LQFP64	Mainstream Arm Cortex-M4 MCU	ST	STM32G474RET6
13	1	U9	LD1117S33TR SOT-223	Adjustable and fixed low drop positive voltage regulator	ST	LD1117S33TR
14	6	C1,C8, C44,C45,C58,C60	100nF SMD 0805 25 V ±10%	Ceramic Capacitor, X7R	Any	Any
15	2	C2, C3	330uF 10mm Pitch, Through Hole 450 VDC ±20%	Electrolytic Capacitor	EPCOS(TDK)	B43647B5337M057
16	2	C4, C5	1uF 15mm Pitch, Through hole 450 VDC ±5%	Film Capacitor	EPCOS(TDK)	B32672Z4105J000

Item	Q.ty	Ref.	Part/value	Description	Manufacturer	Order code
17	2	C6,C11	10uF SMD 0805 50 V ±10%	Ceramic Capacitor, X7R	Any	Any
18	8	C7,C10,C34,C35,C38,C41,C43, C59	1uF SMD 0805 25 V ±10%	Ceramic Capacitor, X7R	Any	Any
19	2	C9, C18	10uF SMD 1206 50 V ±10%	Ceramic Capacitor, X7R	Any	Any
20	1	C12	680pF SMD 0805 50 V ±10%	Ceramic Capacitor, X7R	Any	Any
21	5	C13, C14, C15, C16, C17	5.6nF 15mm Pitch, Through hole 700 VAC ±10%	Film Capacitor	EPCOS(TDK)	B32672L8562K000
22	1	C19	10nF SMD 0805 50V ±10%	Ceramic Capacitor, X7R	Any	Any
23	6	C20, C21, C22, C23, C61, C62	470uF 10mm Pitch, Through Hole 450 VDC ±20%	Electrolytic Capacitor	Any	Any
24	2	C24, C25	2.2uF 22.5mm Pitch, Through hole 630 VDC ±10%	Film Capacitor	EPCOS(TDK)	R71PN422050H6K
25	1	C26	220nF SMD 0805 50 V ±10%	Ceramic Capacitor, X7R	Any	Any
26	1	C27	100nF SMD 0805 50 V ±10%	Ceramic Capacitor, X7R	Any	Any
27	2	C32, C33	100pF SMD 0805 50 V ±10%	Ceramic Capacitor, X7R	Any	Any
28	6	C28,C29,C30, C31.C48,C63	1nF SMD 0805 25 V ±10%	Ceramic Capacitor, X7R	Any	Any
29	1	C36	22uF 2.54mm Pitch,Through Hole 100 V ±20%	Electrolytic Capacitor	Nichicon	UVR2A220MED
30	1	C37	1uF SMD 0805 50 V ±10%	Ceramic Capacitor, X7R	Any	Any
31	1	C39	220pF SMD 0805 50 V ±10%	Ceramic Capacitor, X7R	Any	Any
32	1	C40	22nF SMD 0805 50 V ±10%	Ceramic Capacitor, X7R	Any	Any
33	1	C42	100uF 2.54mm Pitch,Through Hole 35 V ±20%	Electrolytic Capacitor	Nichicon	UHV1V101MED
34	6	C46, C52, C53, C55, C56, C57	4.7uF SMD 0805 10V ±10%	Ceramic Capacitor, X7R	Any	Any
35	2	C51, C54	22uF 2mm Pitch, Through Hole 63 V ±20%	Electrolytic Capacitor	Panasonic Electronic Components	ECA-1JM220

Item	Q.ty	Ref.	Part/value	Description	Manufacturer	Order code
36	3	D1, D3, D4	LL4148 SOD-80 75V 300mA	Small Signal Fast Switching Diodes	Vishay Semiconductors	LL4148-GS08
37	1	D2	24V Zener SOD27 24V 500mW	Zener diode	Nexperia USA Inc.	NZX24A,133
38	3	D9, D11, D12	LED SMD 0805	LED	Any	Any
39	1	D14	1N4148 DO-35 100 V 200 mA	Small Signal Fast Switching Diodes	Onsemi	1N4148TA
40	1	F1	15A 37mm Pitch, Through Hole 15 A	15 A fuse	Any	Any
41	2	DC FANS	CFM-6015V-154-362	DC Fans 60mm, 12Vdc 2.22W 30.4CFM	CUI Devices	CFM-6015V-154-362
42	1	FB1	Ferrite Bead SMD 0805 250mA ±25%	470 Ohms @ 100 MHz	Any	Any
43	4	HS1, HS2, HS3, HS5	CR201-75AE 75mm Pitch, Through Hole	Heat Sink	Ohmite	CR201-75AE
44	1	HS4	CR101-50AE 50mm Pitch, Through Hole	Heat Sink	Ohmite	CR101-50AE
45	1	J1	800 VIN 10mm Pitch, Through Hole	Terminal block 2POS 10mm	Any	Any
46	1	J2	OP+ 5.08mm Pitch, Through Hole	Terminal block 3POS 5mm	Any	Any
47	1	J8	OP- 5.08mm Pitch, Through Hole	Terminal block 3POS 5mm	Any	Any
48	1	J3	AUX 24 2.54mm Pitch, Through Hole	Terminal block 2POS 2.54mm	Phoenix Contact	1725656
49	1	J4	Program connector 2.54mm Pitch, Through Hole	Female header strip 5 pin 2.54mm	Any	Any
50	1	J5	CAN 3.5mm Pitch, Through Hole	Terminal block 3POS 3.5mm	Any	Any
51	2	J6, J7	Fan connectors 2.54mm Pitch, Through Hole	Male header strip 2 pin 2.54mm	Any	Any
52	1	L1	ETD49 Through Hole	LLC Choke (refer to TN1438)	-	-
53	2	L2, L3	ETD59/EE70 Through Hole	LLC Transformer (refer to TN1438)	-	-
54	1	L4	100uH SMD 450mA ±30%	Fixed Inductor	Bourns Inc.	SRR5028-101Y

Item	Q.ty	Ref.	Part/value	Description	Manufacturer	Order code
55	2	R16,R22	0E SMD 1206 1/4 W ±5%	Thick Film Resistor	Any	Any
56	1	R1	100E SMD 1206 1/4 W ±5%	Thick Film Resistor	Any	Any
57	1	R2	100E SMD 0805 1/8 W ±1%	Thick Film Resistor	Any	Any
58	9	R14, R15, R17, R21, R23, R30, R31, R54, R55	10K SMD 0805 1/8 W ±1%	Thick Film Resistor	Any	Any
59	2	R3, R26	3.3E SMD 0805 1/10 W ±5%	Thick Film Resistor	Any	Any
60	7	R4, R5, R33, R34, R63, R65, R66	100K SMD 0805 1/8 W ±5%	Thick Film Resistor	Any	Any
61	3	R6, R18, R24	470E SMD 0805 1/8 W ±5%	Thick Film Resistor	Any	Any
62	2	R7, R8	2M Through Hole 1 W ±5%	Metal Oxide Resistors	YAGEO	RSF1WSJT-52-1M
63	2	R9, R27	6.8E SMD 1206 1/4 W ±5%	Thick Film Resistor	Any	Any
64	7	R10, R11, R19, R20,R45,R46, R68	47K SMD 0805 1/4 W ±0.5%	Thick Film Resistor	Any	Any
65	4	R12, R13, R28, R29	4.7E SMD 1206 1/4 W ±5%	Thick Film Resistor	Any	Any
66	7	R25,R41, R47, R48, R56, R59, R62	1K SMD 0805 1/8 W ±5%	Thick Film Resistor	Any	Any
67	1	R32	1E SMD 0805 1/10 W ±5%	Thick Film Resistor	Any	Any
68	5	R35,R36, R79, R80, R81	1M Through Hole 1 W ±5%	Metal Oxide Resistors	YAGEO	RSF1WSJT-52-1M
69	2	R84,R85	100E SMD 1206 1/4 W ±1%	Thick Film Resistor	Any	Any
70	2	R82,R83	DNM SMD 1206	Thick Film Resistor	Any	Any
71	4	R37, R38, R39, R40	1M SMD 1206 1/4 W ±1%	Thick Film Resistor	Any	Any
72	1	R42	DNM SMD 0805	Thick Film Resistor	Any	Any
73	3	R43, R44, R49	0.033E SMD 2512 3W ±0.1%	Thick Film Resistor	Any	Any
74	2	R51,R53	22K SMD 0805 1/8 W ±5%	Thick Film Resistor	Any	Any
75	2	R50, R52	470K SMD 0805 1/8 W ±5%	Thick Film Resistor	Any	Any
76	3	R57, R58, R60	220E SMD 0805 1/10 W ±5%	Thick Film Resistor	Any	Any

Item	Q.ty	Ref.	Part/value	Description	Manufacturer	Order code
77	2	R61, R75	4.7K SMD 0805 1/8 W ±5%	Thick Film Resistor	Any	Any
78	1	R64	3.3k SMD 0805 1/8 W ±5%	Thick Film Resistor	Any	Any
79	5	R67, R74, R77, R86, R87	33k SMD 0805 1/8 W ±5%	Thick Film Resistor	Any	Any
80	1	R69	10E SMD 0805 1/8 W ±5%	Thick Film Resistor	Any	Any
81	4	R72, R73, R76, R78	22E SMD 0805 1/8 W ±5%	Thick Film Resistor	Any	Any
82	4	SW1, SW2, SW3, SW5	Push Button Through Hole 24V 0.05A	Tactile Switch SPST-NO	TE Connectivity ALCOSWITCH Switches	FSM10JH
83	1	SW4	Dip switch SMD	3 Way DIP Switch	Any	Any
84	3	T1, T2, T3	PH9400-ANL SMD	1.21mH 5kV Iso 1:1:1 pulse transformer	Pulse Electronics	PH9400.111ANLT
85	1	T4	CST2-100LC SMD	Current Transformers CST2 1:100 20A 2KuH	Coilcraft	CST2-100LC
86	2	TH1, TH2	10k Through Hole	Thermistor	Any	Any
87	2	U2 , U3	SFH617A SMD	Optocoupler	Vishay Semiconductors	SFH617A-1X007T
88	1	U10	SN65HVD231 SOIC	CAN Transceiver	Texas Instruments	SN65HVD231

10 Conclusions

A 6 kW LLC converter with a very wide range has been successfully demonstrated. It is a combination of simplistic and robust design, both from electrical and magnetic point of views.

The bus switching scheme, as explained in the design note, is an effective method of addressing wide voltage range in an LLC converter without sacrificing efficiency.

The frequency fold back ensures that the operation frequency excursion is minimized around resonance.

It has also been established that it is possible to operate LLC converters with a low Lm/Lr ratio in high power applications, without a significant reduction in efficiency.

This board is an experimental platform. It must be optimized for end usage considering radiated and conducted EMI. It is possible to use much smaller heat-sinks in an end application for enhanced power density. This design scheme can be extended for other power and voltage levels.

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 9. Document revision history

Date	Revision	Changes
20-Dec-2022	1	Initial release.

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Figure 31. STDES-6KWHVDCDC circuit schematic (1 of 2) . . . 30
Figure 32. STDES-6KWHVDCDC circuit schematic (2 of 2) . . . 31