Easy-Automotive Modules

Application Note

HV to LV DC/DC-Converter Evaluation Kit with Easy Automotive Module F4-50R07W1H3_B11A

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1 Introduction

The Evaluation Kit *"EASYKIT DCDC"* was developed to support customers during their first steps in designing applications with the Easy Automotive H-Bridge power module. This Easy Module contains HighSpeed IGBT3 and Rapid Diode and is e.g. well suited for HV to LV DC/DC-converters in phase shift full bridge zero voltage transition (ZVT) DC/DC-converters up to 100 kHz and 3 kW. Such a phase shifted converter system is demonstrated in the Evaluation Kit and gives the customers important information about the specific characteristics of this HighSpeed IGBT Technology in this particular application.

The application note contains general information about the operation of phase shift full bridge ZVT DC/DC converters, schematics as well as detailed experimental results from the Evaluation Kit. The information is intended to enable the customers to re-use and modify the Evaluation Kit design for their own specific requirements.

1.1 Safety Warning for Evaluation KIT

Please read and understand the manual and the following safety warnings.

The design operates with unprotected high voltages. Therefore, the Evaluation Kit may only be handled by persons with sufficient electrical engineering training and experience. The customer assumes all responsibility and liability for its correct handling and/or use of the Evaluation Kit and undertakes to indemnify and hold Infineon Technologies harmless from any third party claim in connection with or arising out of the use and/or handling of the Evaluation Kit by the customer.

The Evaluation Kit is a sample to be used by the customer solely for the purpose of evaluation and testing. It is not a commercialized product and shall not be used for series production.. The Evaluation Kit is thus not intended to meet any automotive qualifications. Due to the purpose of the system, it is not subjected to the same procedures regarding Returned Material Analysis (RMA), Process Change Notification (PCN) and Product Withdraw (PWD) as regular products. See Legal Disclaimer and Warnings for further restrictions on Infineon Technologies warranty and liability.

European legislation in relation to inter alia the restriction of hazardous substances (RoHS), waste from electrical and electronic equipment (WEEE), electromagnetic compatibility, as well as duties to comply with CE, FCC or UL standards do not apply to the Evaluation Kit and the Evaluation Kit may not fulfill such requirements..

1.2 How to Order the Evaluation Kit

The Evaluation Kit has Infineon Technologies Sales Product Number and can be ordered via Infineon Sales Partners. **EASYKIT DCDC** Order Number: **SP001007734**

The kit is also available in the online web shop: http://ehitex.com/Easy-Kit-DCDC_detail_451.html

Figure 1 Picture of the "EASYKIT DCDC" Evaluation Kit.

2 Quick Start Guide

Before operating this Evaluation Kit two steps are necessary:

1. Mount system on a cooling plate
2. Connect aux supply, HV supply and LV load

Please read the following instructions carefully in order to prevent damage on the Evaluation Kit.

2.1 Mount System on a Cooling Plate

The power module can be attached directly on a cooling plate with a 50 um thick applied thermal grease (e.g. Fischer WLP). Detailed information on the mounting of the Easy Automotive Module can be found in [2].

The LV secondary side PCB area has to handle high currents up to 170 A and has to be cooled. The PCB is designed with thermal vias in the areas of the synchronous rectifier MOSFETs. A mounting on a cooling plate via a gap pad is recommended (e.g. Bergquist GapPad VO Ultra Soft 0.5mm or Kunze Ku-TCS50 0.5mm). Please take care that the pins of the connectors and capacitors do not generate a short circuit to the cooling plate.

Please note that it is also required to cool the transformer windings as well as the core if the Evaluation Kit should run continuously at high load currents. Please contact Epcos/TDK for more information about mounting and cooling of the passive components.

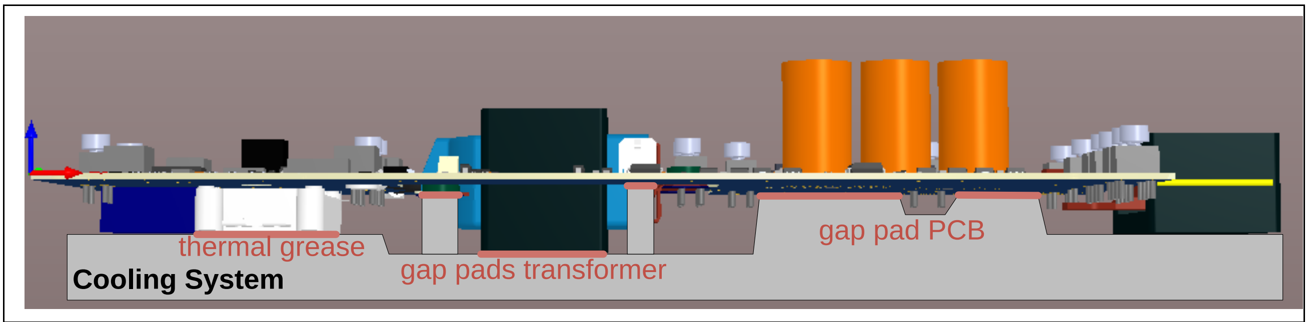


Figure 2 Recommended mounting concept of the Evaluation Kit. The module is mounted with standard thermal grease on the cooling system. The transformer core, windings as well as PCB area, where the secondary side MOSFETs are located, are connected via gap pads to the cooling system.

A 3D file of a flat cooling plate according to Figure 2 can be requested from Infineon. The flat cooling plate can than be mounted easily e.g. on a water cooling system or the design files can be used as a starting point for a customer specific cooling system.

For short term operation tests, it is also possible to operate the Evaluation Kit with active cooling of the power module only. The LV secondary side as well as the transformer is cooled from the intrinsic thermal capacitances only. Please take note that such an operation has certain risks as the design is not protected against any overtemperature events and thus it is only recommended for very experienced developers.

The experimental results of Figure 3 with 45K delta T after running at 100A just 30s make clear that operation at high output current will be possible only for some seconds if the secondary side is cooled with free convection only!

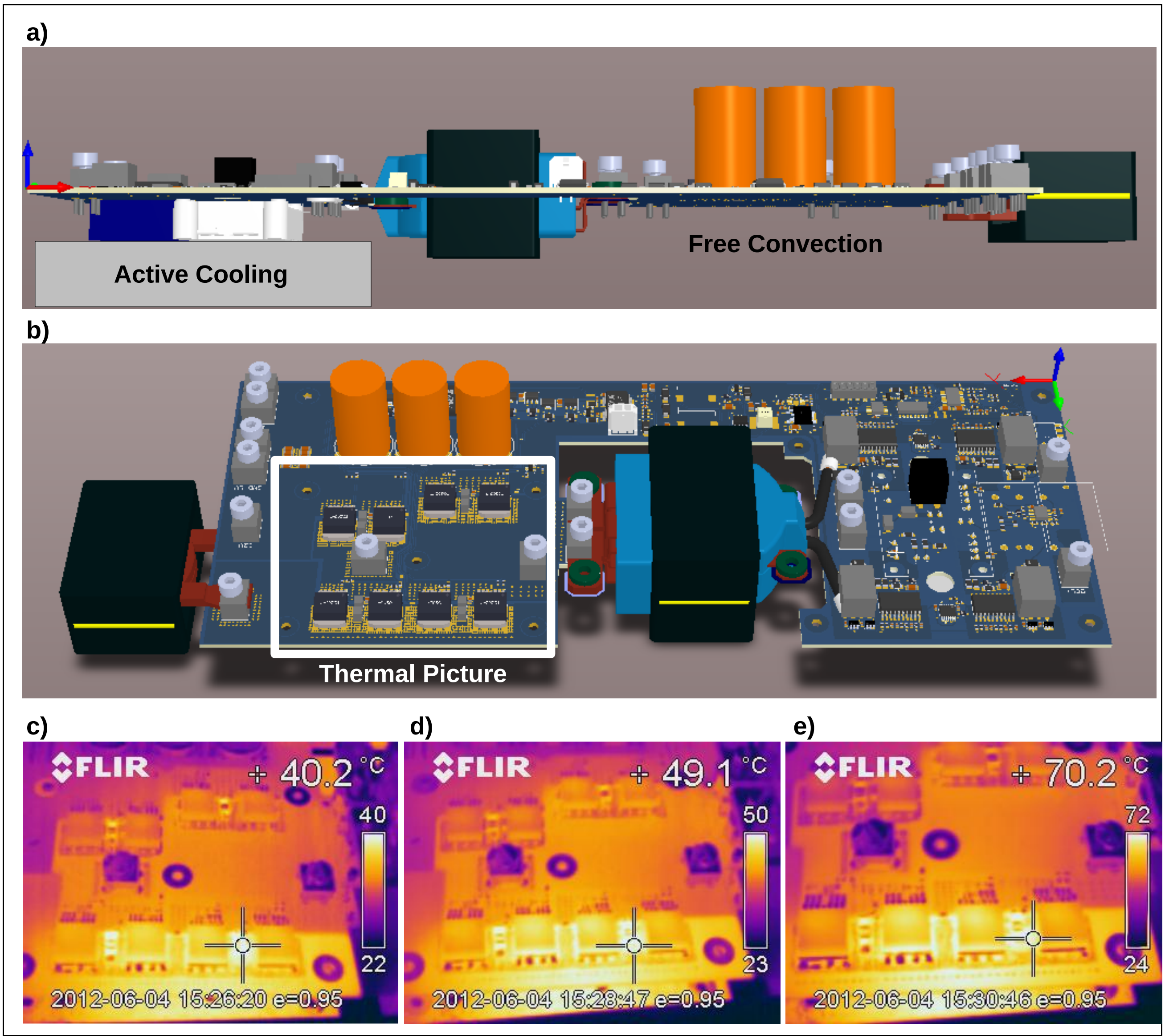


Figure 3 Only for short term operation! Module mounted on cooling plate, passive components and secondary side PCB area in free convection (a). Illustrated window of the thermal picture (b). Thermal picture at 20°C room temperature after running 30 seconds at 50A/700W (c), 75A/1050W (d), and 100A/1.4kW output load (e).

2.2 Connect Supplies and Load

The Evaluation KIT has to be connected to a high voltage source (<350V, 20A) an auxillary supply (8..18V/1A) as well as a load (electric controlled or passive) with minimum 20V and up to 170A.

Please take note that only the aux supply is reverse polarity protected up to -20V. The power terminals for the <350V DCL supply as well as the the 14V load are not protected against reverse polarity events. Thus the correct polarization according to Figure 4 is required.

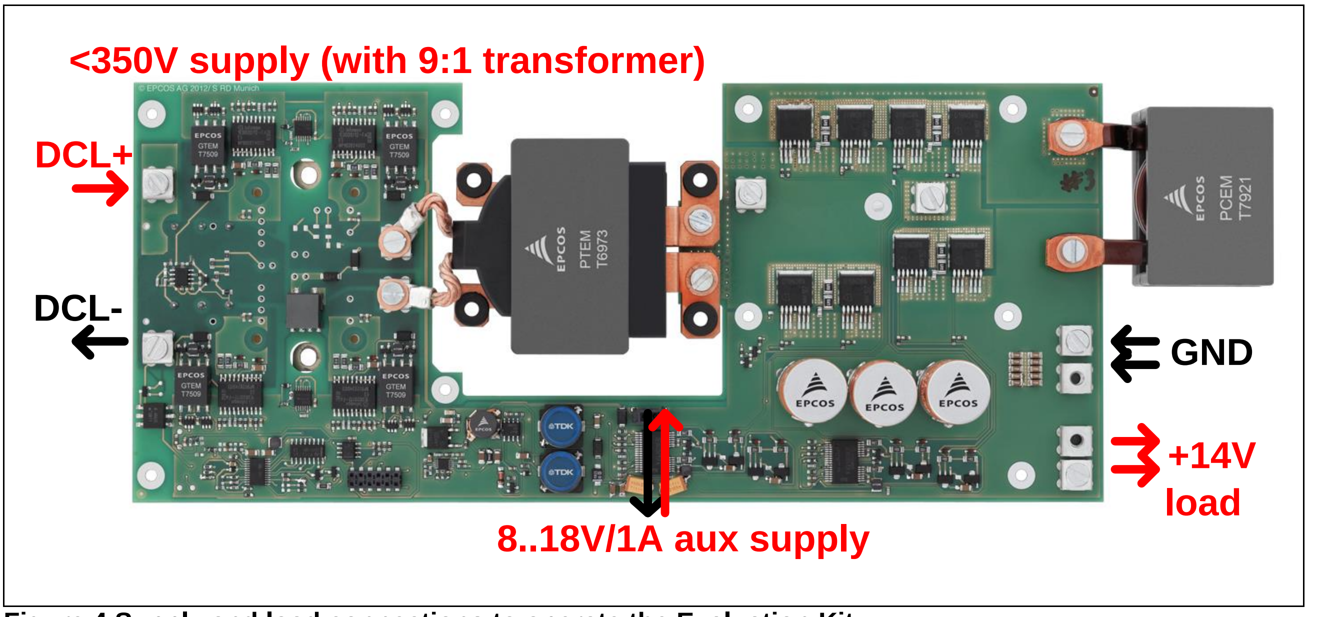


Figure 4 Supply and load connections to operate the Evaluation Kit.

2.3 Recommended Test Setup and Equipment

Minimum to operate the Evaluation Kit:

- 400V 20A DC source
- 20V 1A DC source
- 40V >=170A DC electronic load
- Cooler plate, thermal grease, gap pads (see section 2.1)

For investigations on the switching behavior additional:

- 4 channel scope (min. 100Mhz)
- Voltage probes (capable for measuring 650V), differential probes preferred.
- Rogowski current probe (e.g. CWT1)

For investigations on the efficiency additional:

- 3 channel power analyzer
  OR
- 10mΩ 3W precision shunt
- 0.25mΩ precision shunt or 200A compensated current transducer
- 4 V-Meter with milli-volt rage

3 Feature Description

3.1 Key Features

- Full Bridge Phase Shift Converter with Synchronous Rectification (see Figure 5)
- 100 kHz Switching Frequency with HighSpeed IGBT3 and Rapid Diode
- Wide Input Voltage Range (160 V…350 V with 9:1 transformer)
- Output currents up to 170 A @14 V (limit of secondary side)
- High efficiency up to 93% incl. all aux supplies
- High efficiency over wide load and temp conditions e.g. >90% @160 V from 150 W to 2.3 kW
- Low system BOM (e.g. no resonating inductance, no active components in sec side snubber,…)

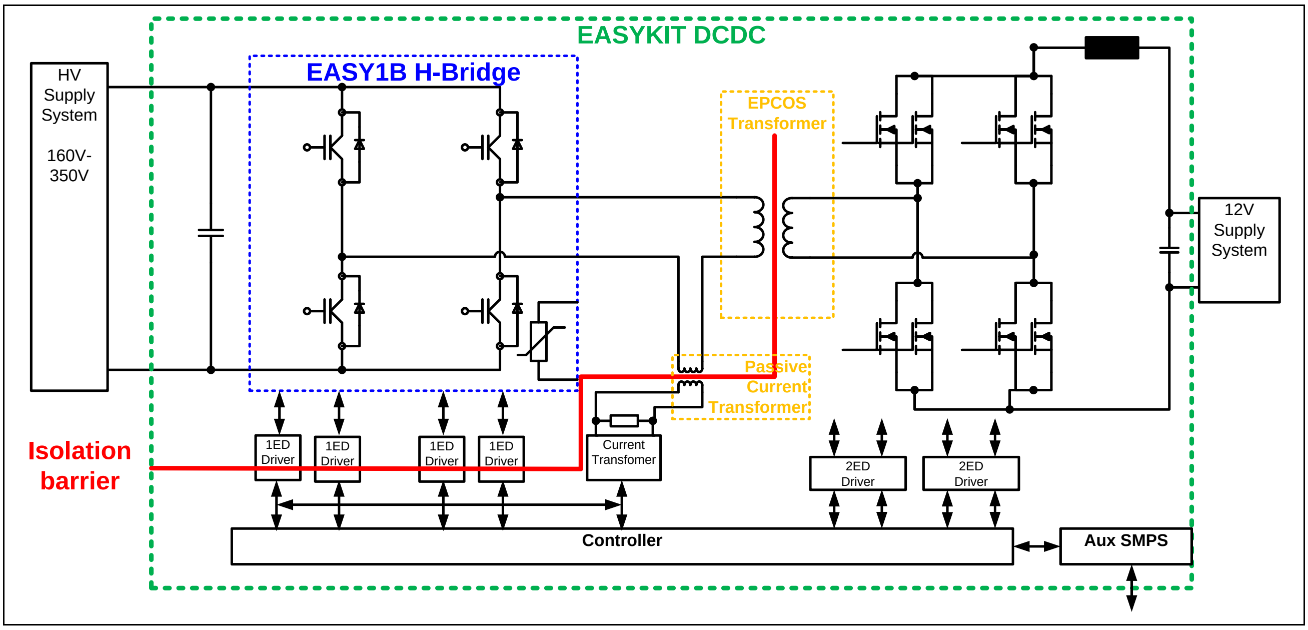


Figure 5 Topology of the EASYKIT DCDC Evaluation Kit.

3.2 Protection Features

The protection features in this Evaluation KIT are very limited. This allows easier adoptions to different requirements. Please take note that testing beyond maximum rating may lead to device failures and thus is not recommended. Infineon will not take any liability for failures on the Evaluation KIT as well as damage on lab equipments.

The design is not protected against:

X Overtemperature (HV and LV side)
X Overvoltage (HV and LV side)
X Reverse energy flow (Energy transfer from LV to HV)*
X Reverse polarity on power connectors
X Short circuit (transformer and LV output short circuit protection is implemented)

**the power stage is suitable for reverse energy transfer but the control can cause wrong PWM patterns, which can lead to failure of sync rectifier MOSFETs as well as the HighSpeed IGBT Module.*

Following protection features are implemented and activated:

- Gate Driver Undervoltage Lockout (UVLO)
- Gate Driver not Ready event locks all other Channels to avoid transformer saturation
- Overcurrent redundant in peak current mode control and emergency turn-off
- Aux supply short circuit and overcurrent with self restart (hiccup mode)
- Power transformer and LV output short circuit with self restart (hiccup mode)

3.2.1 Gate Driver not Ready and emergency turn-off implementation

Transformer saturation is one of the most critical points in isolated DC/DC-converters. A transformer saturates at a certain B field which can be calculated with the volt-second product on the transformer divided by the effective core area and turn ratio (B=Vtrans*t/Ae*N). At Bsat the transformer saturates and causes a short circuit. Therefore, it is crucial to keep the transformer positive and negative magnetized with exact the same field strength.

With this background it is now easy to understand that all gate drivers have to be turned-off immediately if one channel is not ready (e.g. in undervoltage lockout). Otherwise, if the others continue with switching operation, it will take typically only few µs until the transformer saturates and generates the next failure – a short circuit (worst case repetitive).

In order to avoid such failures, it is common to implement several turn-off mechanisms in parallel. One possible concept is shown in Figure 6. Please note that only the basic concept is shown in an extract of one phase leg. An exemplarily dimensioning with all required filter elements can be seen in chapter 5. The concept is implemented with analog circuits but it can be transferred also to digital controlled converters.

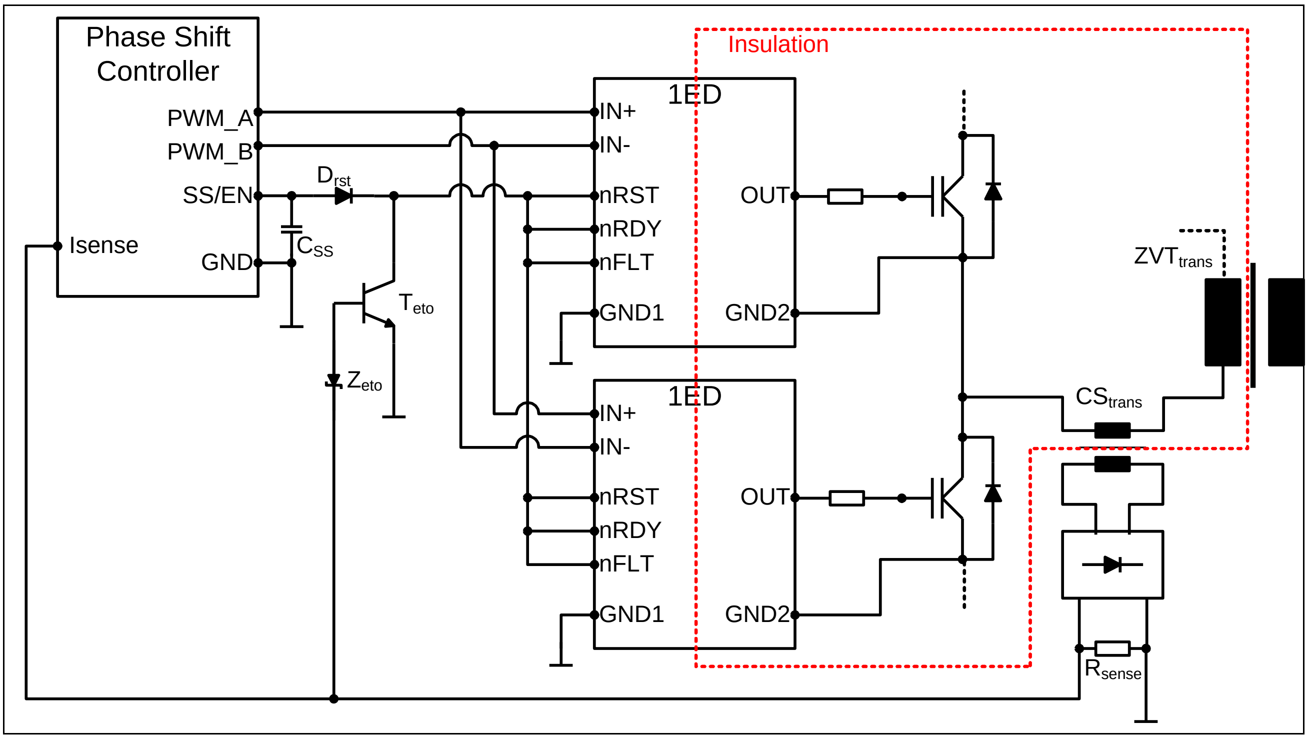


Figure 6 Gate not ready and emergency turn-off concept.

A small current sense transformer (CS_{trans}) transfers via the sense resistor a current signal from the transformer primary current to the phase shift controller. With this signal it is possible to control the converter in peak current mode, which can avoid in general DC voltages on the transformer and saturation.

But if one gate driver is not ready and thus is not able to turn-on than it is not useful to wait until the saturation happens. In this case the nRDY/nFLT output pulls all nRST inputs of the gate drivers to a low signal (all gate drivers turn-off immediately) and disables also via the diode (D_{rst}) the controller. If all gate drivers are ready again, than the phase shift controller can start according to the programmed soft-start ramp with C_{SS}.

Due to the fact that saturation and short circuit is the major problem in such converters, an additional emergency turn-off loop is implemented. If the sensed current (Rsense) rises to excessive values (typ 150%..200% of the nominal turn-off current), than all the nRST of the gate drivers as well as the enable/softstart pin of the controller are pulled to zero immediately. This event can occur also in peak current mode controlled converters if e.g. the synchronous rectifier timing is not matching to the primary side and thus the primary side IGBTs are switching against the LV MOSFETs.

After the failure is fixed, the controller can start again with the programmed soft start ramp.

Figure 7 shows a measurement where the control of the converter was deactivated and the IN+ of the gate driver turned-on with a long single pulse (see black curve in the lower diagram). The transformer secondary side was short circuited for this experiment with a copper plate. After the gate driver and IGBT propagation delay the IGBT turn-on at approx 200ns (see low Vce voltage in black and rising Ic current in blue). At 400ns the threshold for the emergency turn-off is exceeded at about 50A. The softstart capacitor and thus the nRST Pin is discharged (see red curve). At 2000ns the IGBT is turned off. The gate driver discharges the Vge voltage and as a consequence the IGBT starts to desaturate at 2000ns. The gate driver continues to discharge the gate. In order to avoid device failure, it is important to turn-off the IGBT faster than the specified allowed short circuit time (typ. 5us). In this example the IGBT is switched off after being only 600ns in desaturation mode. This was a save turn-off event for the HighSpeed IGBT3 without the need for complex measures like soft turn-off. Please note that such events should not occur in common operating mode and not repetitive (<1000 times with 1s wait time is recommended).

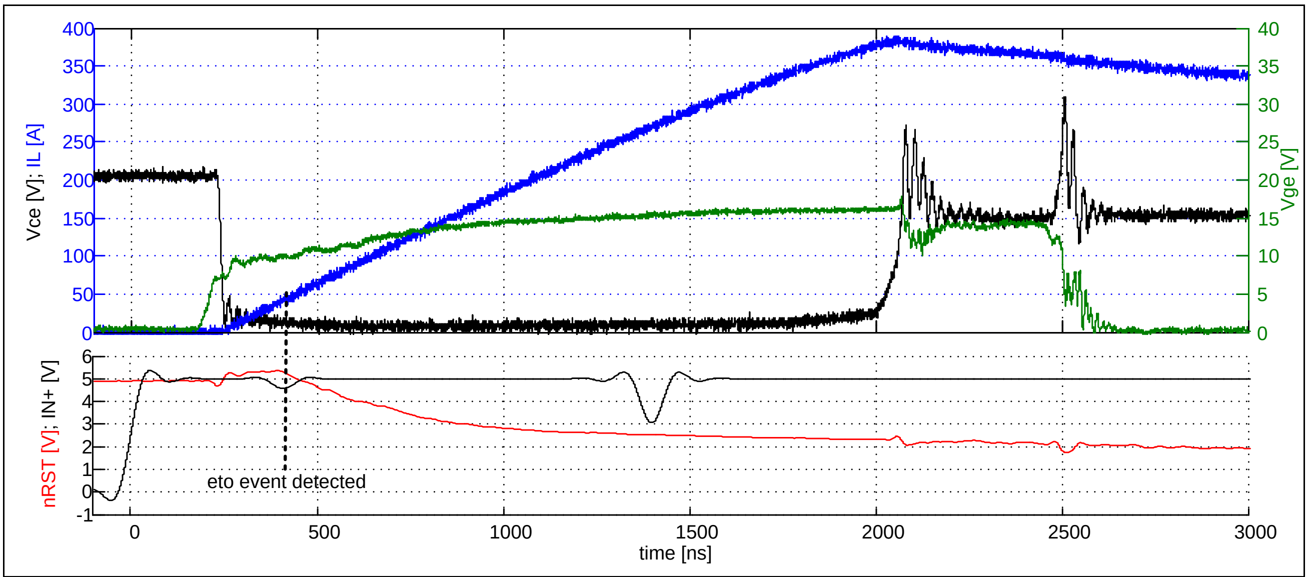


Figure 7 Emergency turn-off measurement at transformer short circuit on secondary side.

3.3 Key Components BOM

Part	Description	Manufacturer	Status
F4-50R07W1H3_B11A	Easy 1B Automotive H-bridge with HighSpeed IGBT3 and Rapid Diode 650V	Infineon	In development
1ED020I12FA	EiceDriver™ 2A Single Channel Gate Driver	Infineon	Productive
IPB180N08S4-02	80V 2.2mΩ OptiMOS™ in TO263-7	Infineon	In development
2ED020I12FA	EiceDriver™ 2A Dual Channel Gate Driver	Infineon	Productive
CRS Capacitor	PressFIT Ceramic Ripple Suppressor Vmax=450V; Ceff=10uF	TDK/Epcos	*
T6973	3kW Phase Shift ZVT Transformer 9:1	TDK/Epcos	*
T7509	SMD Gate Driver Supply Transformers 1:1.1 5mm clearance/creepage	TDK/Epcos	*
T7078	SMD Current Sense Transformer 1:100 5mm clearance/creepage	TDK/Epcos	*
T7921-51	Output Choke 2.1uH, Isat=170A	TDK/Epcos	*

* For status and datasheets of the passive TDK/Epcos components please ask design-solutions@epcos.com.

4 Function Description and Measurement Results

4.1 Function Principle of Phase Shift ZVT Converter

The phase shift ZVT converter operates at a fixed switching frequency and achieves, in an ideal operation, a lossless turn-on (zero voltage transition) due to intrinsic and optional external parasitic elements. In following only intrinsic elements are considered as it is implemented in the Evaluation Kit. How parasitic elements can help to avoid switching losses will be more understandable after a brief review of the switching states of the converter (see Figure 8).

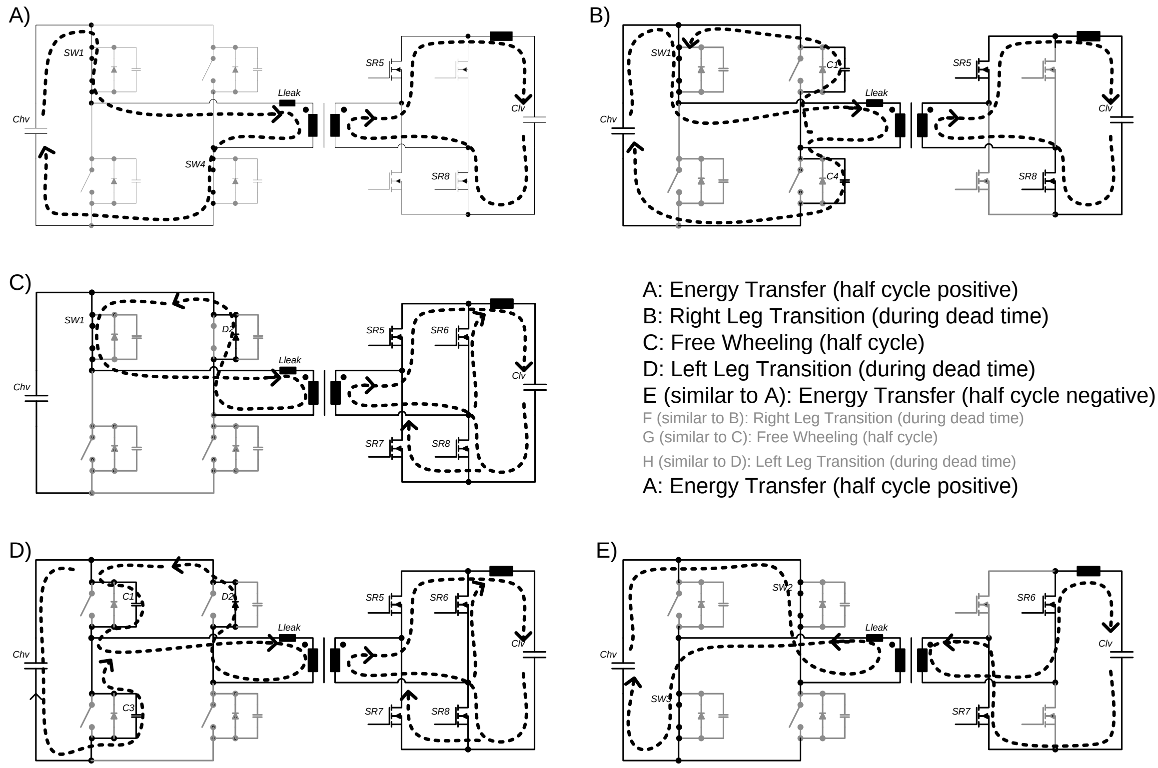


Figure 8 Phase shift ZVT full-bridge DC/DC-converter topology with active H-bridge rectification. State A to H shows the current flow in half of a switching period.

A) Energy Transfer (half cycle positive)

The diagonal switches in the H-bridge are turned-on and energy from HV side is transferred via the transformer to the LV side. The transformer is magnetized in positive direction and the leakage inductance of the transformer (or optional an external Lres) is charged.

B) Right/Leading Leg Transition (during dead time)

After the energy transfer phase the right low-side switch is “hard” turned-off. The voltage across the switch is not changing immediately, as the output capacitances of the switches in the right leg clamps it. However, the parasitic capacitances of both low- and high-side switch are charged/discharged by the stored energy in the leakage inductance of the transformer. The ZVT condition is achieved if the stored energy in the leakage inductance is higher than the required energy to charge/discharge the capacitors.

C) Freewheeling (half cycle)

If the leakage inductance had enough stored energy the diode of the right high-side switch (D2) conducts. Otherwise, the switch (SW2) turn-on without ZVT, which is the case for light load conditions. During the freewheeling, the transformer windings on primary and secondary side are shorted.

D) Left/Trailing Leg Transition (during dead time)

Before entering the next energy transfer phase, the left leg transition is required. The left high-side switch is turned-off. Similar to the right leg transition, the parasitic capacitances clamps again the voltage slope. The parasitic capacitances of both switches are charged/discharged, respectively.

E) Energy Transfer (half cycle positive)

If the leakage inductance had enough stored energy to charge/discharge the parasitic capacitances of the left leg switches, the left low-side switch can turn-on at zero-voltage and the second half of the energy transfer phase starts (similar to state A). In this state the transformer is magnetized in the negative direction.

The states F, G, H are similar to the explained states B, C, D but in reverse current direction from the point of view of the transformer.

The corresponding current waveform on the primary side of the transformer (and thus leakage inductance) as well as the gate signals for the HV switches are shown in Figure 9.
Each half bridge leg is driven by a quasi-complementary 50% PWM pulse pattern. In this example the right leg is phase-shifted to the left leg, which is in this topology the duty cycle command.
The resulting half cycles (T/2) with this gate driving pattern can be clearly seen. The result is that the transformer, filter inductor, HV and LV capacitor is driven at two times of the switching frequency. The leakage inductance, which was required to achieve ZVT, limits the current slope when the transformer is switched from positive to negative cycle and vice versa. During this state the transformer is not transferring energy to the output. Consequently, the leakage inductance causes a “loss of duty cycle” (D_{Loss}) at each half cycle.

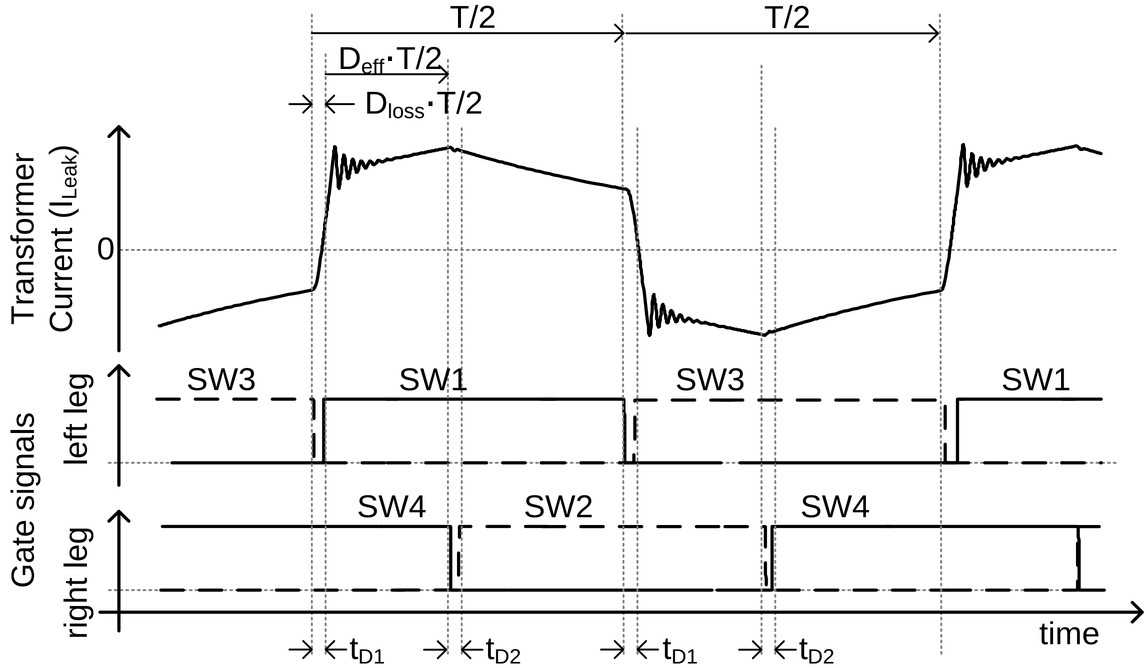


Figure 9 Current waveform of the transformer primary side with the corresponding gate control signals of the 4 HV switches. Each half bridge leg is driven by constant 50% duty cycle. The phase shift of the right leg is here the duty cycle command for the converter energy transfer. The leakage inductance of the transformer leads to a loss of duty cycle (D_{loss}).

The dead times are not only required to a avoid shoot through. As explained before, the parasitic capacitance has to be charged before the corresponding switch is turned-on. At “too short” dead times the converter generate hard switching conditions and will cause additional turn-on power losses.

4.2 IGBT Leading Leg Transition

The IGBT leading leg transition is the transition from energy transfer into the freewheeling state. The leading leg turn-off event is indicated in Figure 10.

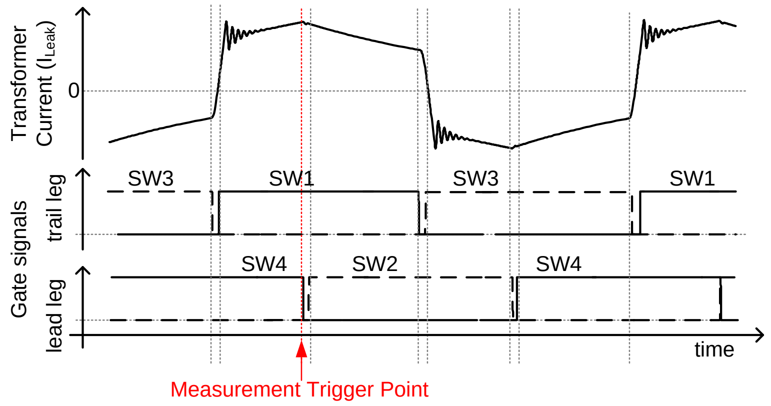


Figure 10 Leading leg turn-off transition in the converter operation cycle. DUT is SW4.

The measured current and voltage waveforms of the IGBT (SW4) during this hard turn-off event are shown in Figure 11 for different input voltages and load currents. The turn-off overvoltage increases with higher currents and voltages. The tail current fall to zero within approximately 200ns and leads to very low switching losses. The approx. 70V voltage overshoot is quite low at 300V input voltage and high output load of 150A. The corresponding switching losses can be calculated with the given Eoff switching energy in the datasheet as this transition is equivalent to a standard inductive turn-off switching event.

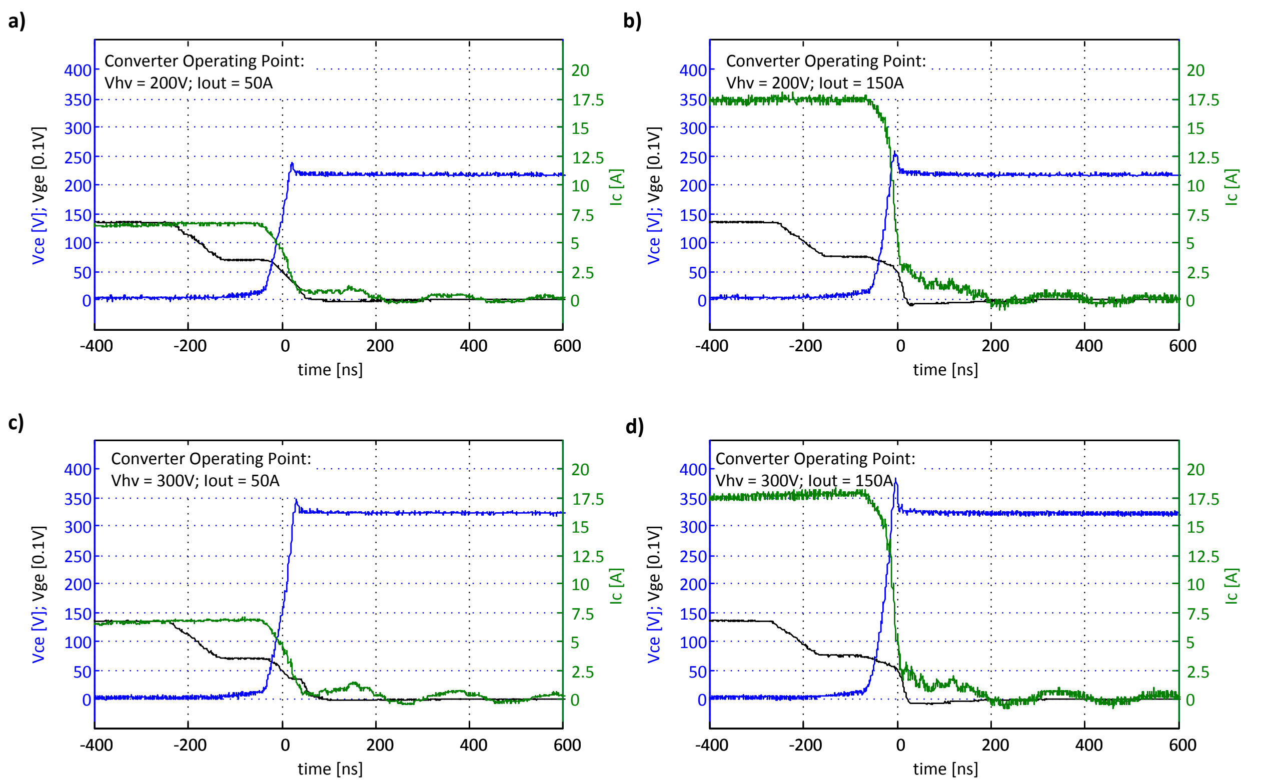


Figure 11 IGBT turn-off in the leading leg transition at V_{HV}=200V, I_{LV}=50A (a); V_{HV}=200V, I_{LV}=150A (b); V_{HV}=300V, I_{LV}=50A (c); V_{HV}=300V, I_{LV}=150A (d).

The leading leg turn-on event occurs within the dead time as indicated in Figure 12.

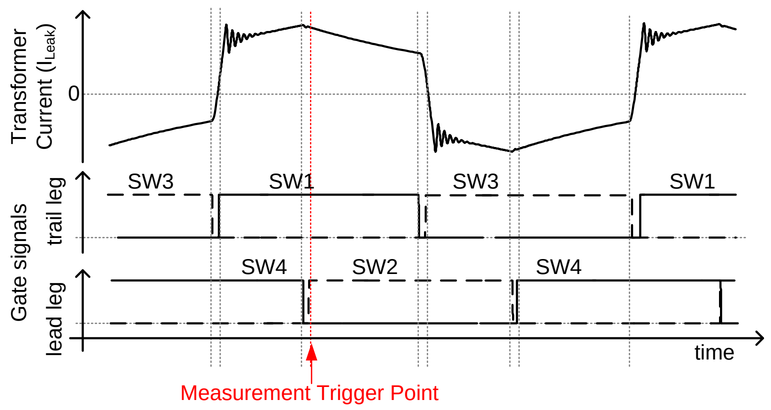


Figure 12 Leading leg turn-on transition in the converter operation cycle. DUT is SW2.

The most interesting case is at very light load conditions in order to validate that the IGBT is switching at zero voltage conditions and therefore is without turn-on losses for leading leg. Figure 13 shows the voltage waveforms across the switch as well as the transformer primary current. It can be seen that zero voltage transition is achieved at very light output load of <30 W. The voltage Vce decreases to zero (and diode conducts) before the IGBT is turned-on (see Vge plateau voltage). As a result, the Evaluation Kit will switch in ZVT condition for the leading leg from about 1% to 100% output load.

Contrary to MOSFETs, if the dead times are slightly increased, it will not have any impact on the switching efficiency as the IGBT does not reverse conduct.

Due to such a zero voltage transition and conduction of the antiparallel diode, this transition is different to the specified Eon in the datasheet (datasheet is specifying hard turn-on incl. diode reverse recovery). For calculation of power losses it is recommended to neglect turn-on power losses of the leading leg completely.

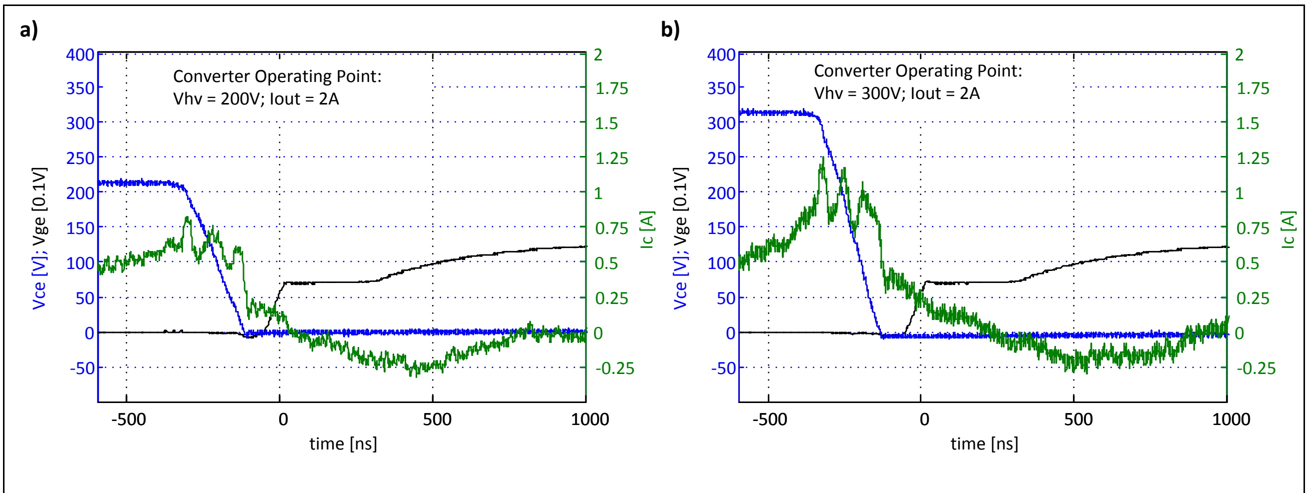


Figure 13 IGBT turn-on in the leading leg transition at very light load conditions V_{HV}=200V, I_{LV}=2A (a); V_{HV}=300V, I_{LV}=2A (b). Zero voltage transition (ZVT) is achieved from 1% to 100% load in leading leg. This transition is lossless for the IGBT. Note: the current was measured with a Rogowski coil suitable for 600A peak; the SNR ratio is very low in this 1A measurement.

4.3 IGBT Trailing Leg Transition

The IGBT trailing leg transition is the transition from freewheeling into the next energy transfer state. The trailing leg turn-off event is indicated in Figure 14.

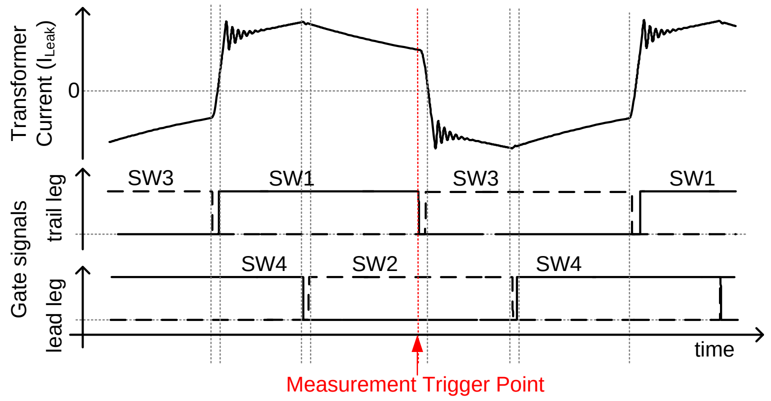


Figure 14 Trailing leg turn-off transition in the converter operation cycle. DUT is SW1.

Figure 15 shows the corresponding experimental results in the Evaluation Kit at different DCL voltages and converter output load currents. The IGBT is turned-off (see Vge and Ic) but the voltage is not rising to the DCL-voltage. This is because the secondary side transition is still ongoing and therefore clamping the voltage on the primary side. Compared to standard turn-off losses, as characterized in the datasheet, this transition is much more efficient as the turn-off voltage is much lower than the DCL-voltage.

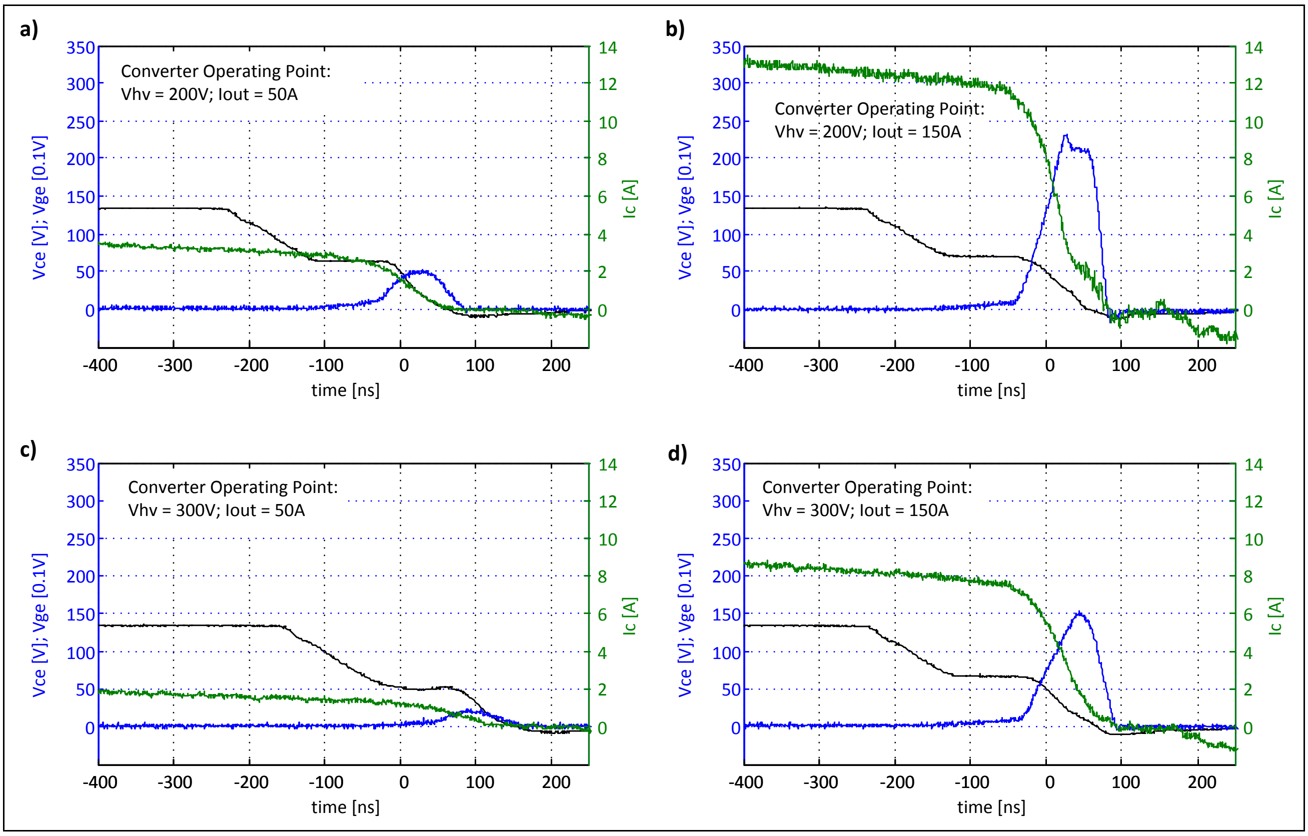


Figure 15 IGBT turn-off in the trailing leg transition at V_{HV}=200V, I_{LV}=50A (a); V_{HV}=200V, I_{LV}=150A (b); V_{HV}=300V, I_{LV}=50A (c); V_{HV}=300V, I_{LV}=150A (d). The turn-off losses are reduced as the primary side transformer voltage (i.e. the voltage across the switch) is clamped by the parasitic elements in the secondary side.

As the voltage clamping characteristic depends on system parameters, like secondary side stray inductance, parasitic capacitances, transformer leakage inductance, a general indication for those losses cannot be given from semiconductor manufacturers. The customer has to determine the trailing leg turn-off losses in the final setup. However, higher losses than the Eoff in standard inductive switching testbench will not occur and thus can be used as an indication of an absolute maximum value for this transition.

The trailing leg turn-on event is shown in Figure 16. Ideally, the IGBT is turned-on again when the Vce voltage is zero but, as it can be seen from Figure 15, the voltage after the turn-off of the complementary switch was swinging back to zero and thus the DUT has to switch now at not ZVT conditions.

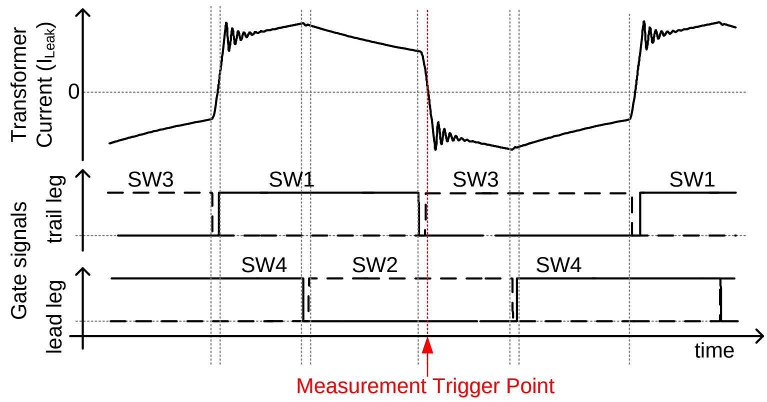


Figure 16 Trailing leg turn-on transition in the converter operation cycle. DUT is SW3.

Figure 17 shows the measured voltage and current waveforms of the trailing leg turn-on IGBT (SW3). It can be clearly seen that the IGBT is switching the full DCL-voltage (no ZVT). But on the other hand the IGBT is always turning on when the current is zero. This is also a very efficient switching transition for the HighSpeed IGBTs because the power losses are caused only by the very low output capacitance of this technology as well as other parasitic capacitances in the setup. Furthermore, the HighSpeed IGBT3 switches relatively soft comparing to MOSFETs, which are typically applied in such applications and often lead to excessive ringing if ZVT is not achieved.

Due to this efficient and smooth turn-on behavior it is recommenced not to increase the leakage inductance of the transformer, which leads just to minor improvements of the turn-on losses but increasing the turn-off losses in the trailing leg. Therefore, with respect to total system power losses an ideal ZVT transition (as always noted in literature targeting MOSFET designs) will not bring major advantages. Furthermore, no external Lres and optimized transformer leakage inductance gives the customers benefit in terms of system cost as well as effective duty cycle.

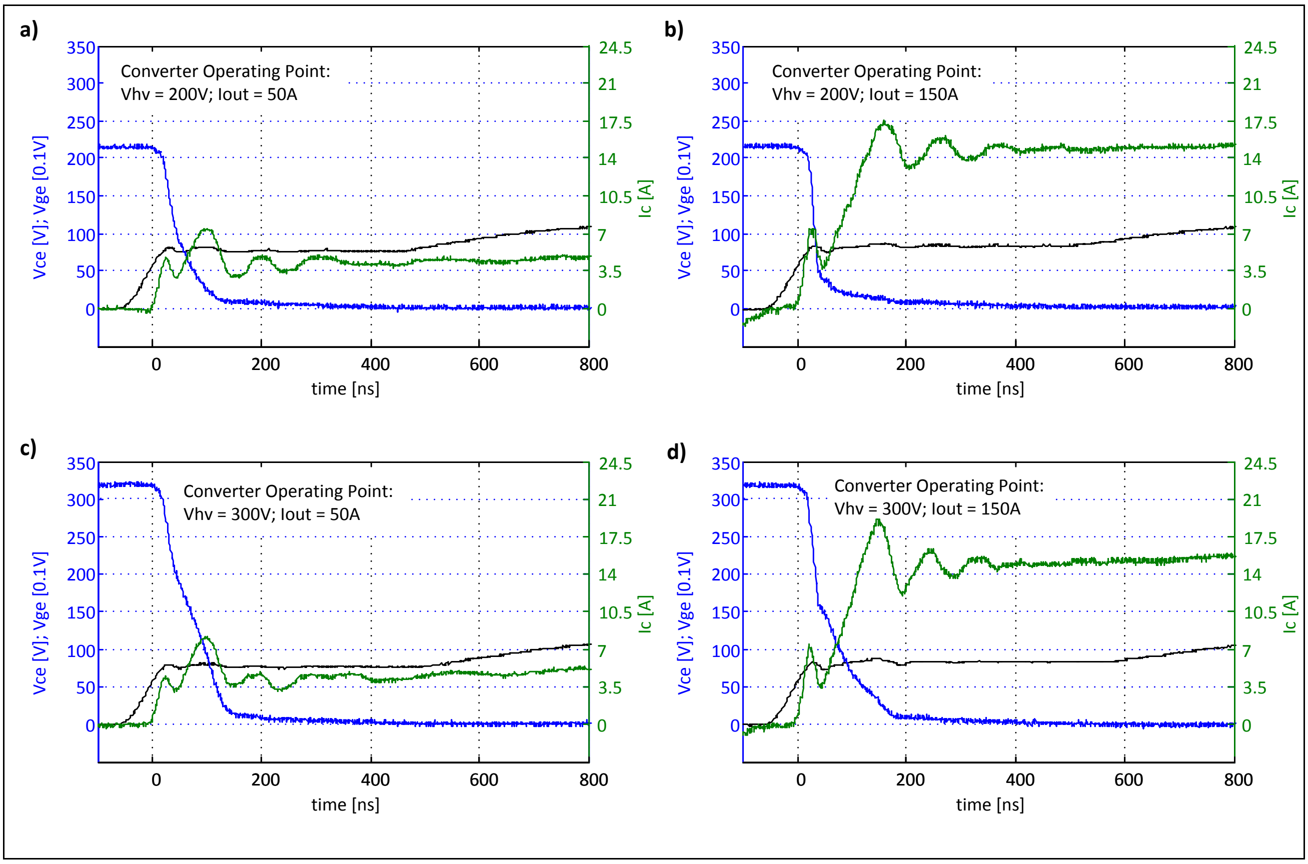


Figure 17 IGBT turn-on in the trailing leg transition at V_{HV}=200V, I_{LV}=50A (a); V_{HV}=200V, I_{LV}=150A (b); V_{HV}=300V, I_{LV}=50A (c); V_{HV}=300V, I_{LV}=150A (d). The IGBT turn-on at zero current and only the charge/discharge of the parasitic capacitance causes very low turn-on losses.

4.4 Short Circuit Tests

A typical requirement in automotive DCDC converters is ruggedness against short circuits in the application. The case, where the control IC generates wrong or continues on output pulse patterns was already discussed in section 3.2.1. This chapter shows the results with a normal working control IC, gate driver and protection features, and the converter system was operated in typical short circuit conditions.

Two examples of application short circuits are discussed in following:

- Short circuit of the power transformer (i.e. similar to transformer saturation)
- Short circuit in the wiring harness at the 12V converter output (i.e. similar to a short circuit in a load on LV power net)

Figure 18 shows the location and the IGBT current/voltage waveforms under an operation where a short circuit is applied at the transformer output. The IGBT is turned-on and the collector current Ic increases. The slope of the current is limited by the stray inductance of the transformer (about 1.2uH). After 200ns the overcurrent (short circuit) is detected and the IGBT turned-off. The maximum measured IGBT current in this design was about 50A, which is the implemented chip current of the power module and thus not critical in terms of current (also repetitive). The turn-off overvoltage at this measured 300V working voltage was about 450V. As the allowed peak voltage is specified 650V for the IGBT module, this event is also not critical.

Due to the hiccup mode of the control IC the IGBT is switched repetitively (lower than 100kHz) into this application short circuit and thus the operation will be continued normally when the short circuit at the transformer is removed.

Please note that the Evaluation Kit is not protected against overtemperature and thus long term operation under these conditions and insufficient cooling can damage the Evaluation Kit.

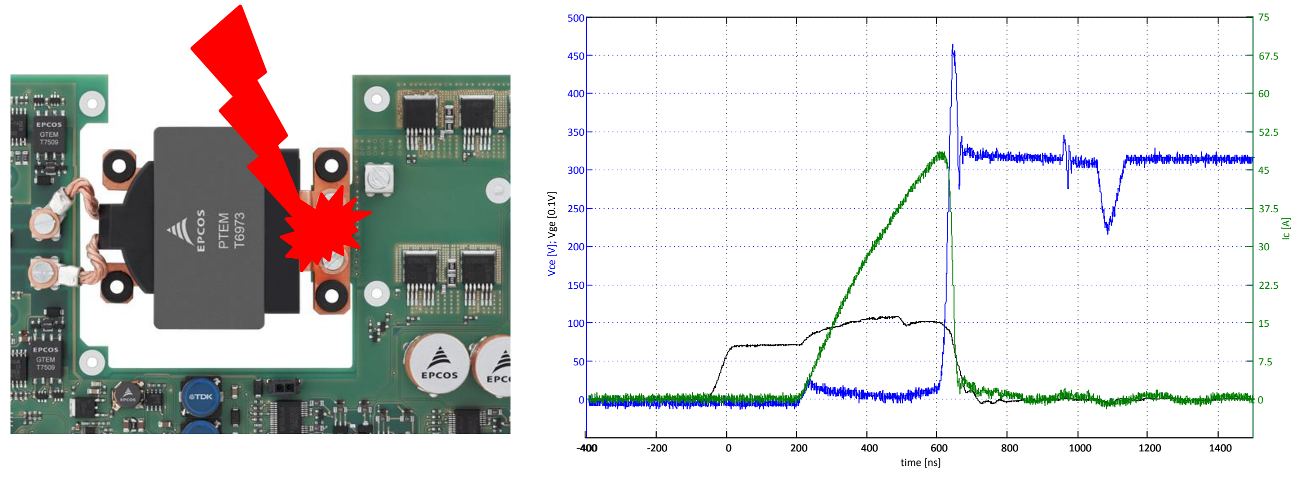


Figure 18 Short circuit at transformer LV winding and measured waveform of IGBT leading leg at converter startup. The control IC is operating in hiccup mode and turn-on repetitive with lower than 100kHz the IGBTs into the short circuit.

Figure 19 shows the most likely short circuit in typical applications, which is a short circuit in the cables or a load connected to the 12V output of the converter. After the short circuit occurs, the output voltage starts to decrease as the short circuit current discharges the output capacitors of the converter. The control loop detects this event first as a normal load step and thus increases the duty cycle. As the short circuit current is higher than the converter output current, the capacitors continuously discharges. After about 250us the control loop detects that despite transferring the maximum output current to the converter output node the output voltage further decreases. Thus, the converter operation is stopped and then the control try to restart the operation continuously with the hiccup mode (<< 100kHz).

During this application short circuit test no critical turn-off overvoltage or high turn-off current (not higher than nominal current) was observed.

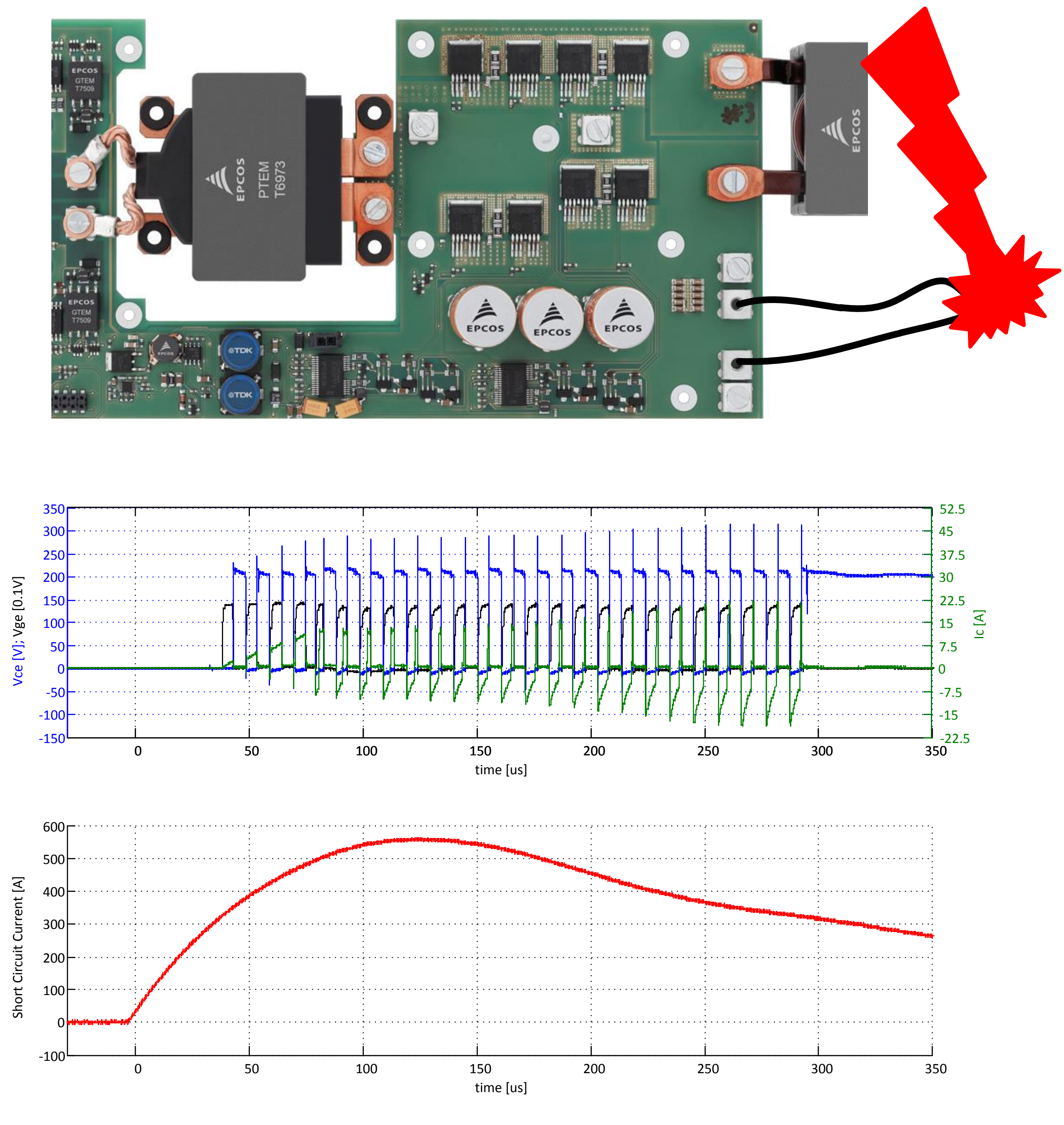


Figure 19 Short circuit at LV output cables. As the LV output voltage decreases rapidly after the short circuit occurs, the control loop starts with pulses at high phase shift (30 to 70us) than the phase shift (i.e. duty cycle) is reduced due to high currents and peak current mode control (70 to 280us) and finally at 300us the control IC stops operation into the short circuit. The highest current for the IGBT power module (leading leg half bridge) was measured <25A.

4.5 Efficiency

The measured efficiency is shown in Figure 20. At light load conditions, constant losses (auxiliary power supply, core losses etc.) are dominant and cause low efficiency. Their impact on the efficiency is relatively low at higher output power. On the other hand, the resistive losses become then more dominant as these losses are proportional to the square of RMS output current

The highest efficiency is reached at partial load, where the best balance of different losses relatively to the output power is achieved. The highest measured efficiency was 92.5% (at Vin = 160V and Iload = 50A). At a wide range of load currents from ~30A to full load, efficiency higher than 90% is achieved. The efficiency is very high taken into account that the power module was designed for best cost/performance ratio. For highest possible efficiency the HighSpeed IGBT should be replaced by the leading CoolMOS technology with lowest Rdson.

Efficiency curves in Figure 20 are shifted to lower values when the input voltage of the converter is increased. This is caused by the lower phase shift (duty cycle) and longer freewheeling period followed by increased losses. In the design process, transformer turn ratio is determined by the maximum allowed duty cycle (minimum input voltage) and because of the wide range of input voltages, duty cycle is considerably shorter at the maximum input voltages. If the transformer turn ratio would be adapted for other input voltage range, a higher efficiency at high input voltages can be achieved.

Due to the controller functionality (light load efficiency management), synchronous rectifier control is starting at load current of approximately 12 A output load. Up to this current only body diodes are conducting.

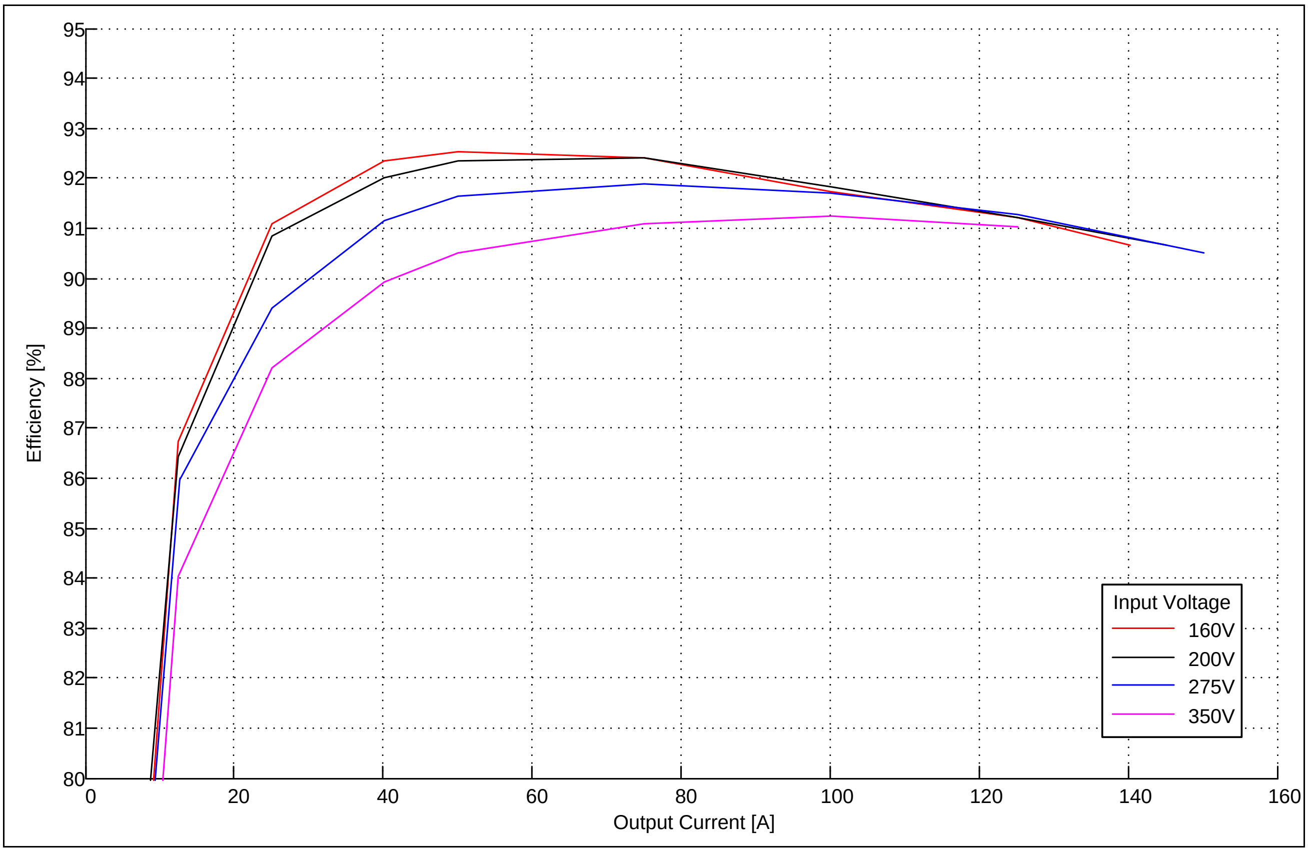


Figure 20 Efficiency incl. all aux power supplies at V_{LV}=14V output voltage and 85°C cooling plate temperature under the Easy Automotive power module.

4.6 Efficiency with different Transformer Turn-Ratio (converter input voltage range adaption)

The EASYKIT DCDC is a demonstrator only and thus is not optimized to customer specific application operating conditions. This section explains the relationship between different application input voltage ranges, transformer turn-ratio and efficiency.

The best operating condition for a full bridge phase shift converter is achieved at a phase shift close to 180° (i.e. duty cycle 100%). In this condition the converter is operated nearly without freewheeling periods and is switching from energy transfer (diagonal switches on) to next energy transfer phase (the transitions are performed in the dead time).
The phase shift full bridge converter is a buck derived topology and thus the highest voltage conversion ratio is also at phase shift 180° (duty cycle 1). As a consequence for a given input voltage range and output voltage range the transformer turn-ratio should be designed in a way that the converter is still able to transfer power from minimum HV input voltage to max required output voltage at this condition. At higher input voltages the efficiency decreases due to the lower phase shift.

Therefore, in order to achieve the best performance, a final converter design should be always optimized to match the input/output voltage ranges. Table 1 notes some transformer turn-ratio suggestions for different operating ranges and explains the origin of the operation limits.

Table 1 Suggested transformer turn-ratios for different operating conditions.

HV input Voltage range	Required LV output voltage at min HV input	Suggested Transformer turn-ratio (+)	Typ application
160V(*)..350V(#) / 14V	14V	9:1	Mild hybrid
250V(*)..450V(°) / 14V	14V	14:1	Full hybrid and EV
300V(*)..450V(°) / 14V	14V	17:1	DCDC after PFC stages

(+) Equal characteristic (Ls, Bmax,…) to transformer platform family Epcos/TDK T6973.
(*) limited by max duty cycle (i.e. close to 180° or 100%)
(#) limited by turn-off overvoltage of LV rectifier switches and blocking voltage (80V MOSFETs in H-bridge configuration with small RC damping snubber in EASYKIT)
(°) limited by voltage rating of HV capacitor

Figure 21 shows the measured DCDC converter efficiency including all auxiliary supply with 9:1 and with 17:1 transformer at different input voltages. In this example just the transformer was replaced and all other parts were kept constant. Is can be clearly seen that an increasing HV input voltage leads to reduced efficiency, which is a result of reduced phase shift (duty cycle) at these higher input voltages (equivalent to lower voltage conversion ratio and thus longer freewheeling periods).

With the changed transformer turn-ratio of 17:1 it is no more possible to transfer power at e.g. 200V input voltage (duty cycle > 100% is not possible). But due to the adjusted voltage conversion ratio, the operation at 300V or 350V is now closer to the ideal operation of 180° phase shift and leads to a much increased efficiency. This measurement demonstrates clearly that it is important to choose in a final system an adequate transformer turn ratio.

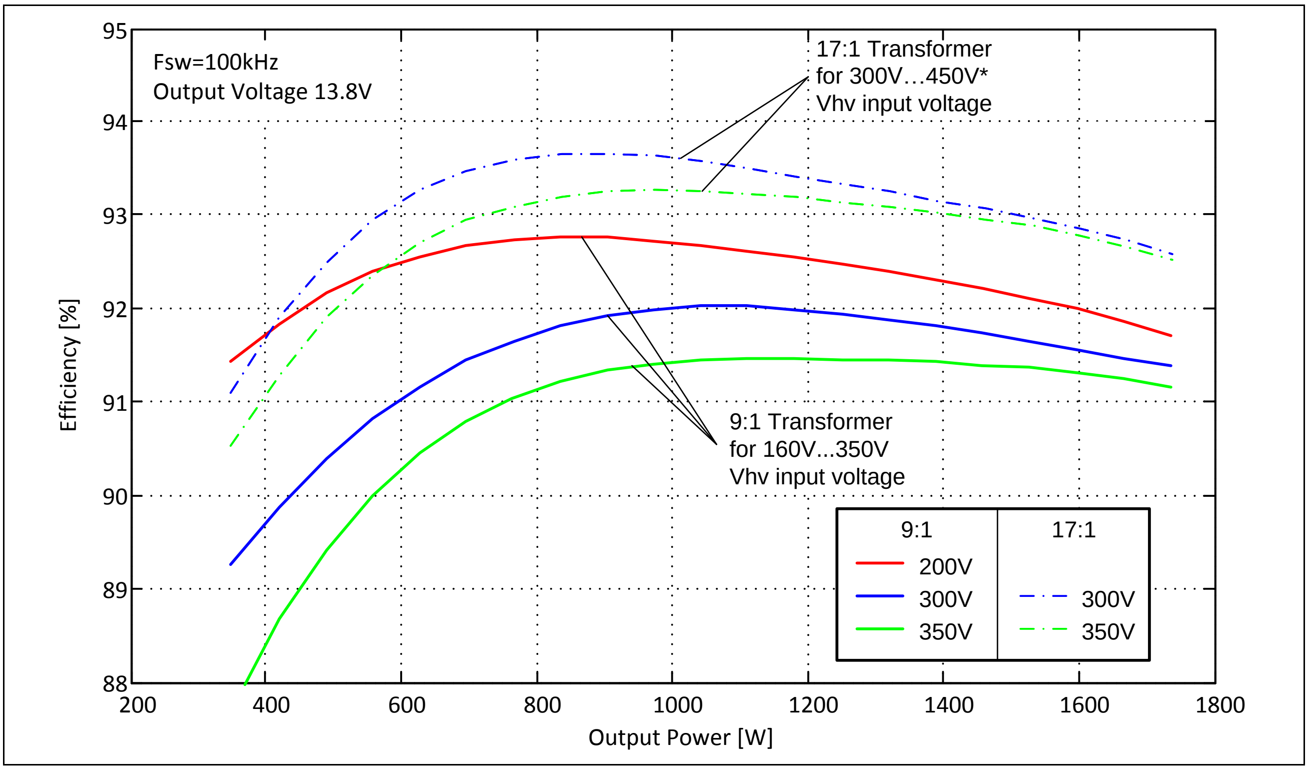
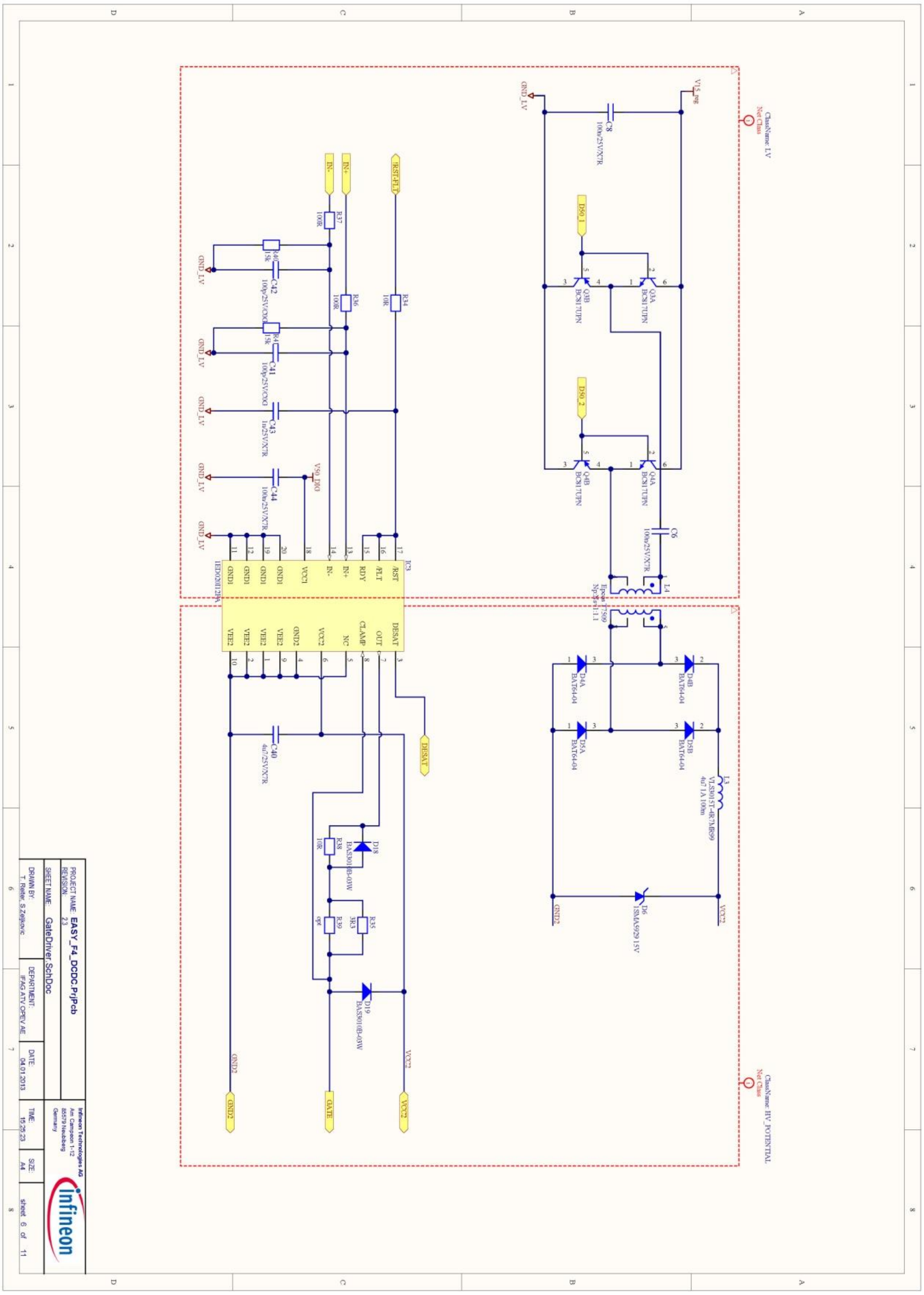


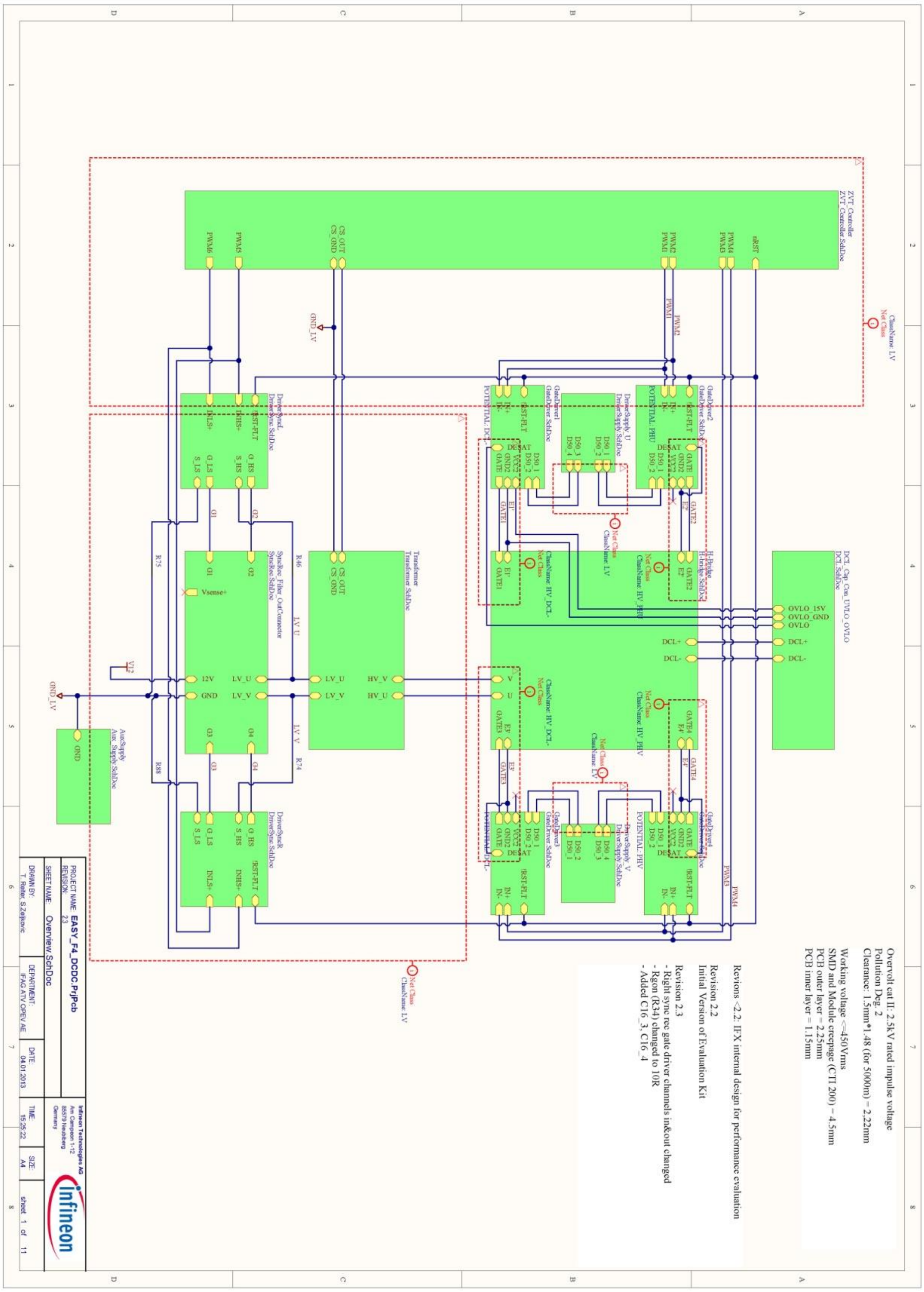
Figure 21 Efficiency incl. all aux power supplies. With the transformer turn ratio it is possible to optimize the converter efficiency for specific application operating requirements. Note 450V(*): higher input voltages may damage the DCL capacitor.

5 Schematics

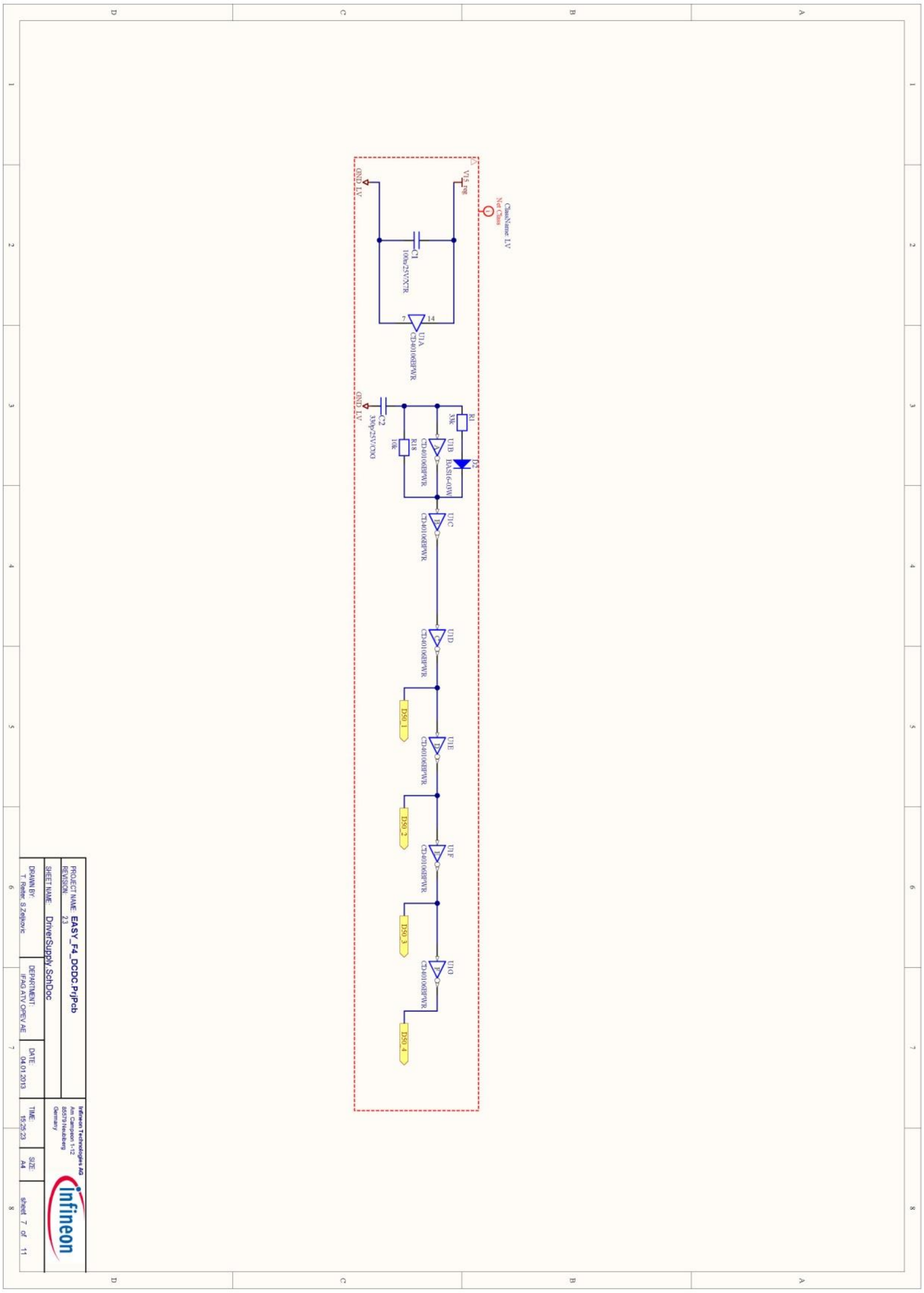
5.1 Overview



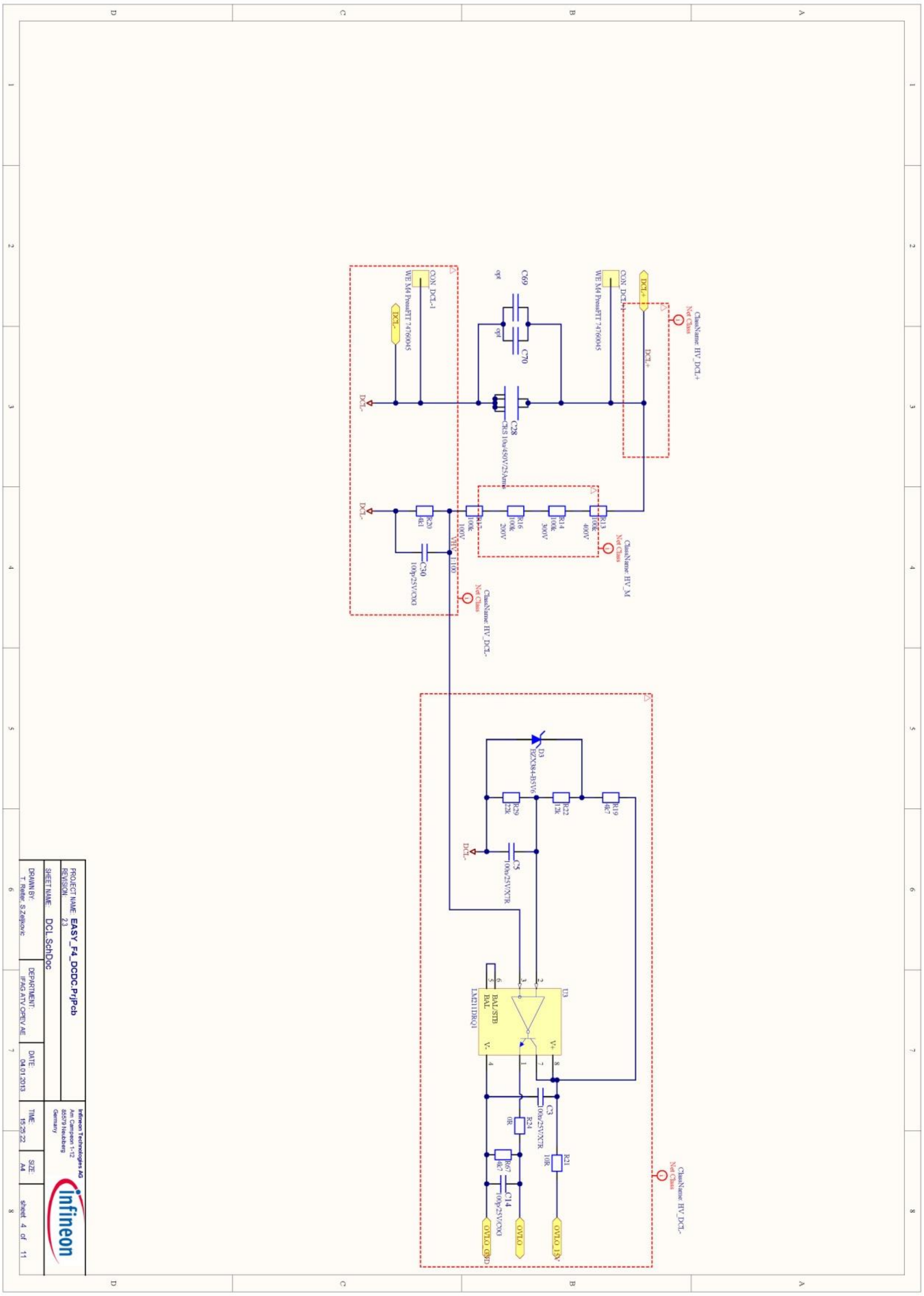
5.2 Gate Driver IGBT



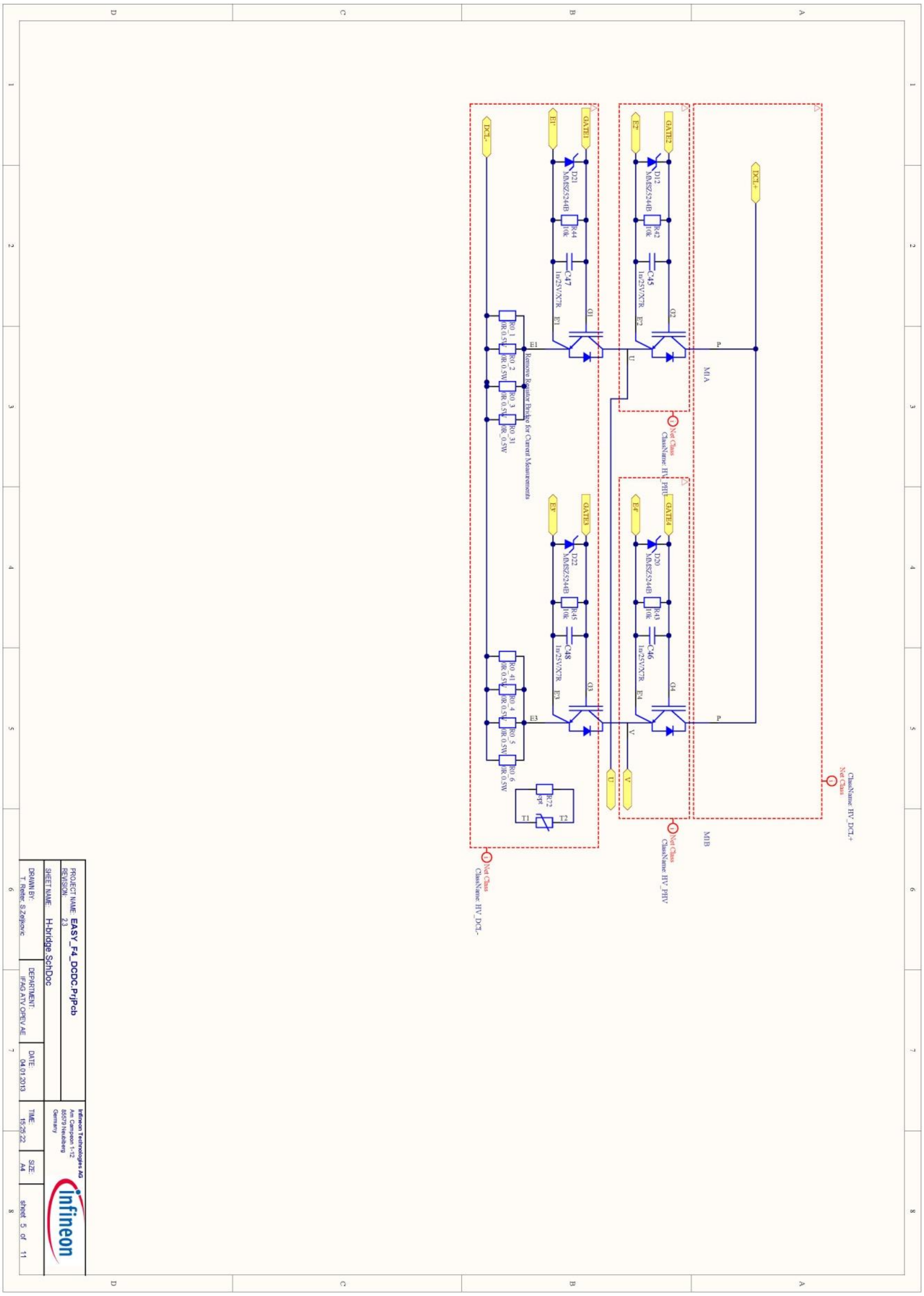
5.3 Oscillator



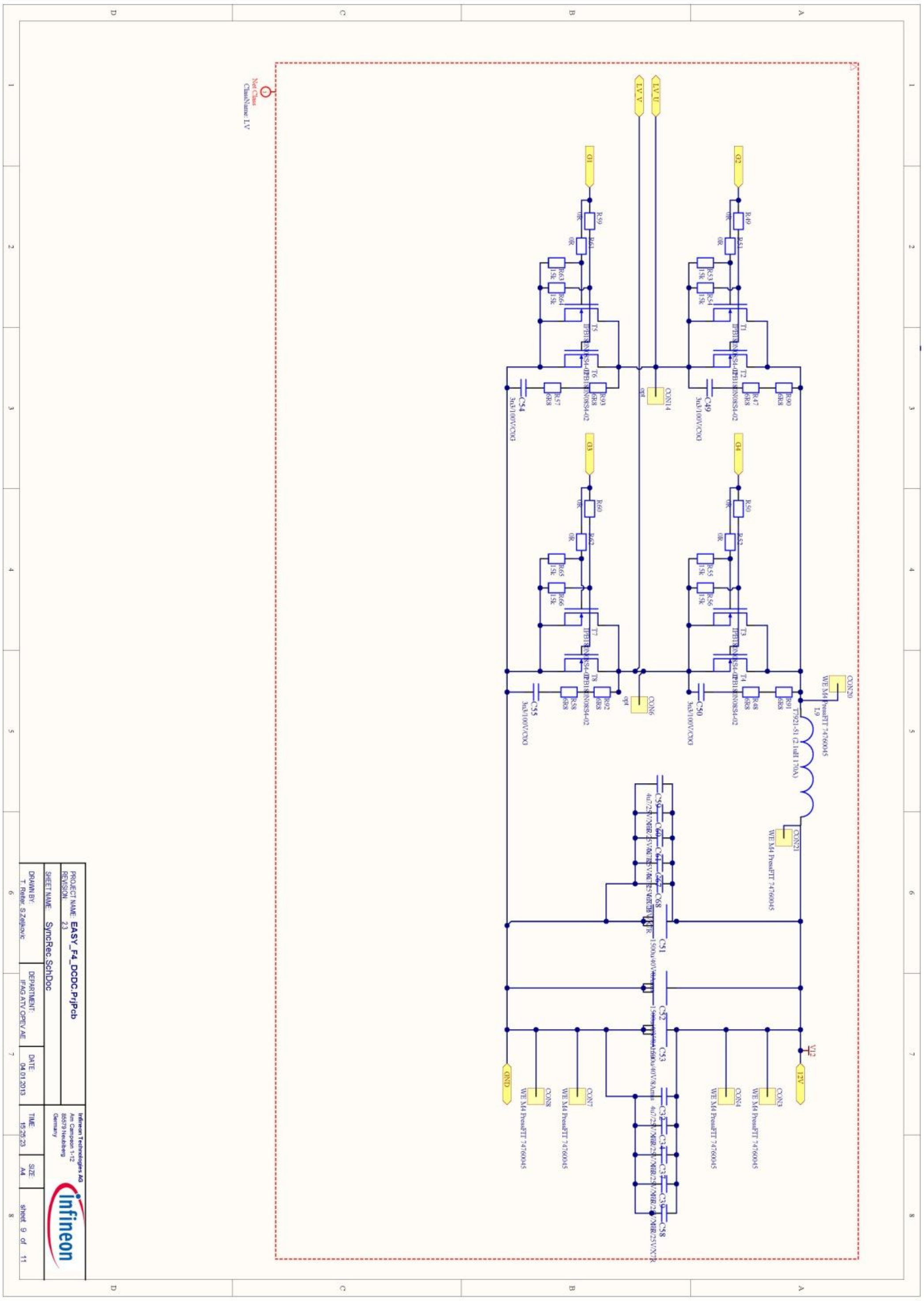
5.4 DCL capacitor



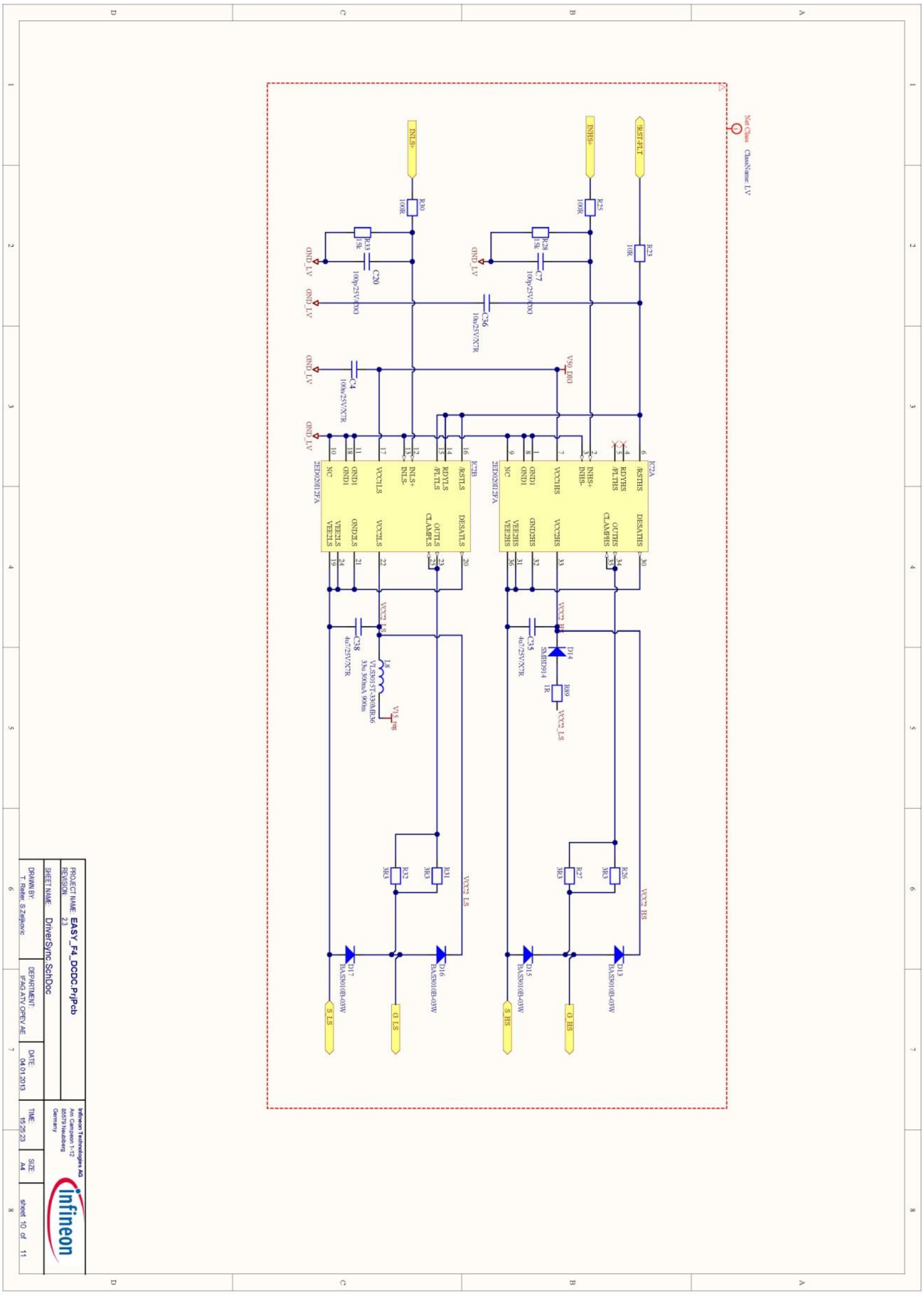
5.5 H-Bridge IGBT



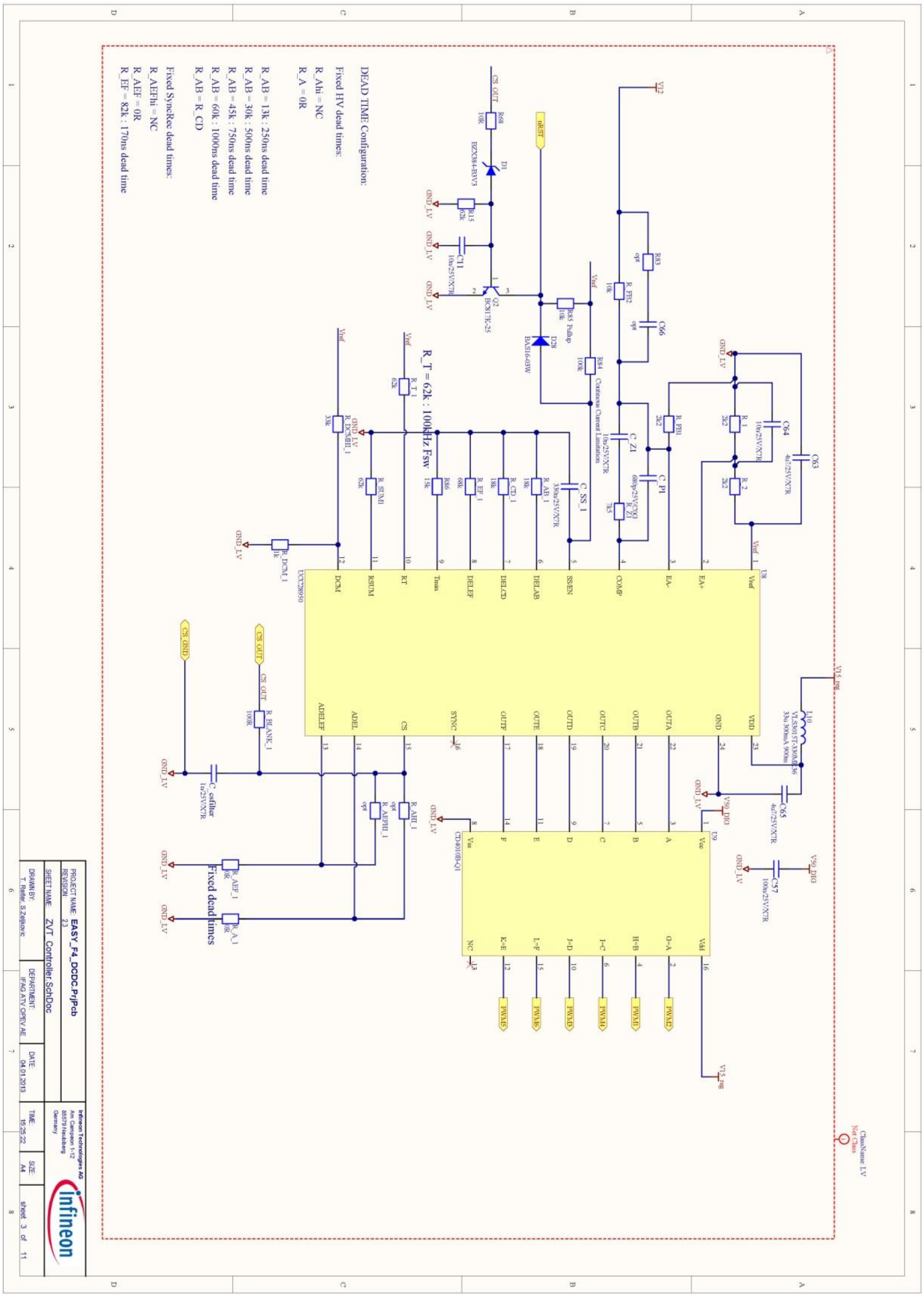
5.6 Synchronous Rectifier



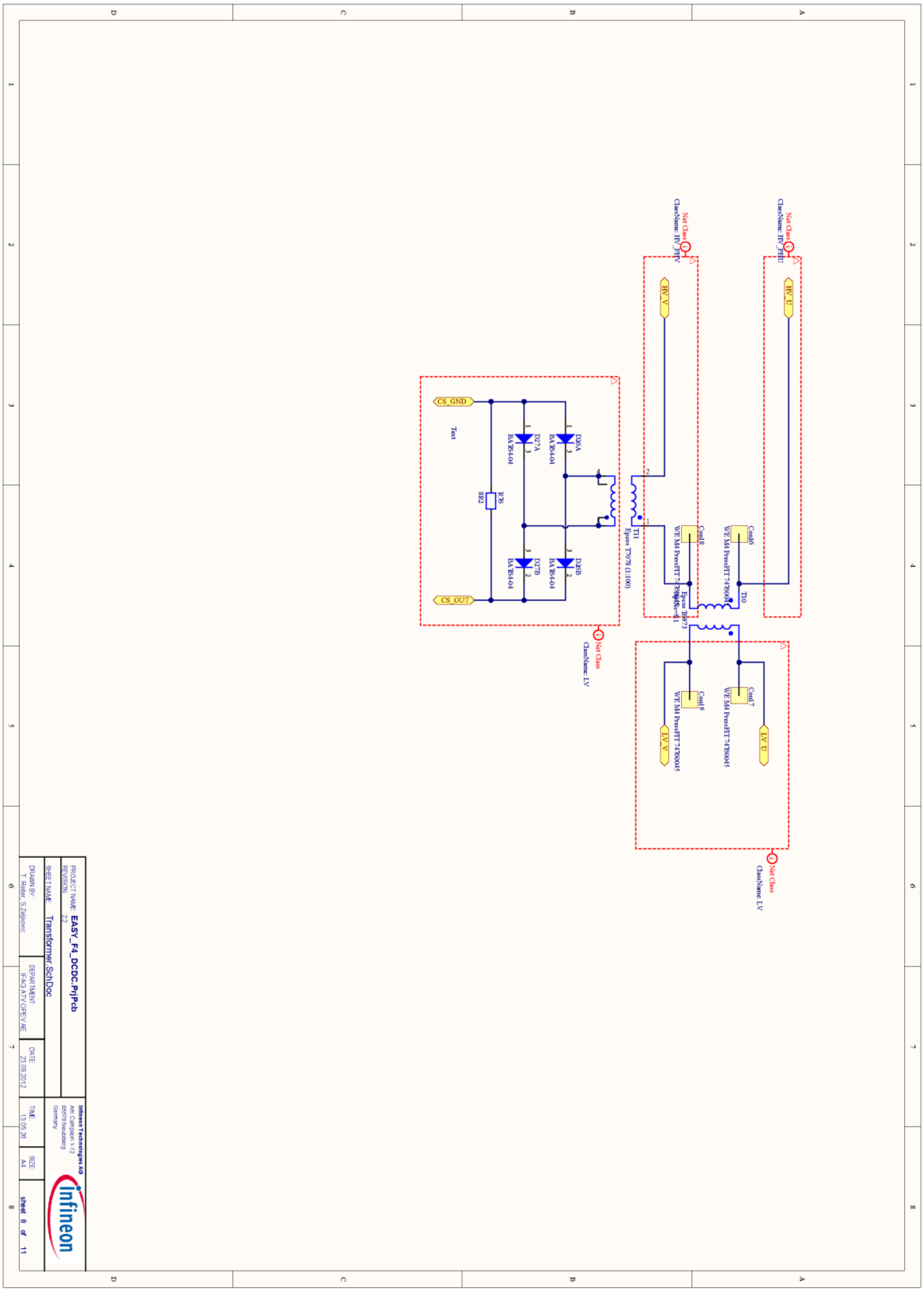
5.7 Gate Driver Synchronous Rectifier



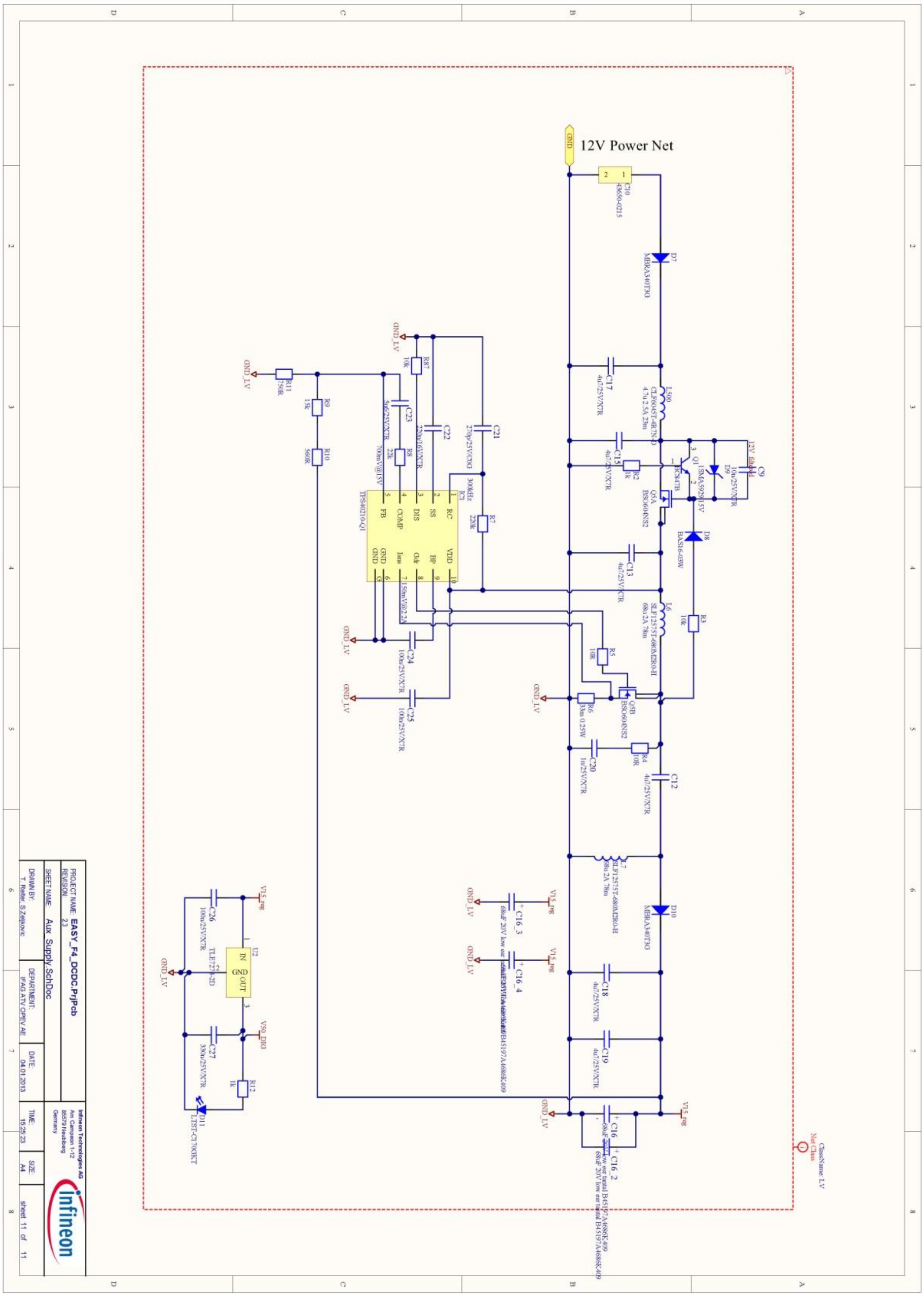
5.8 ZVT Controller



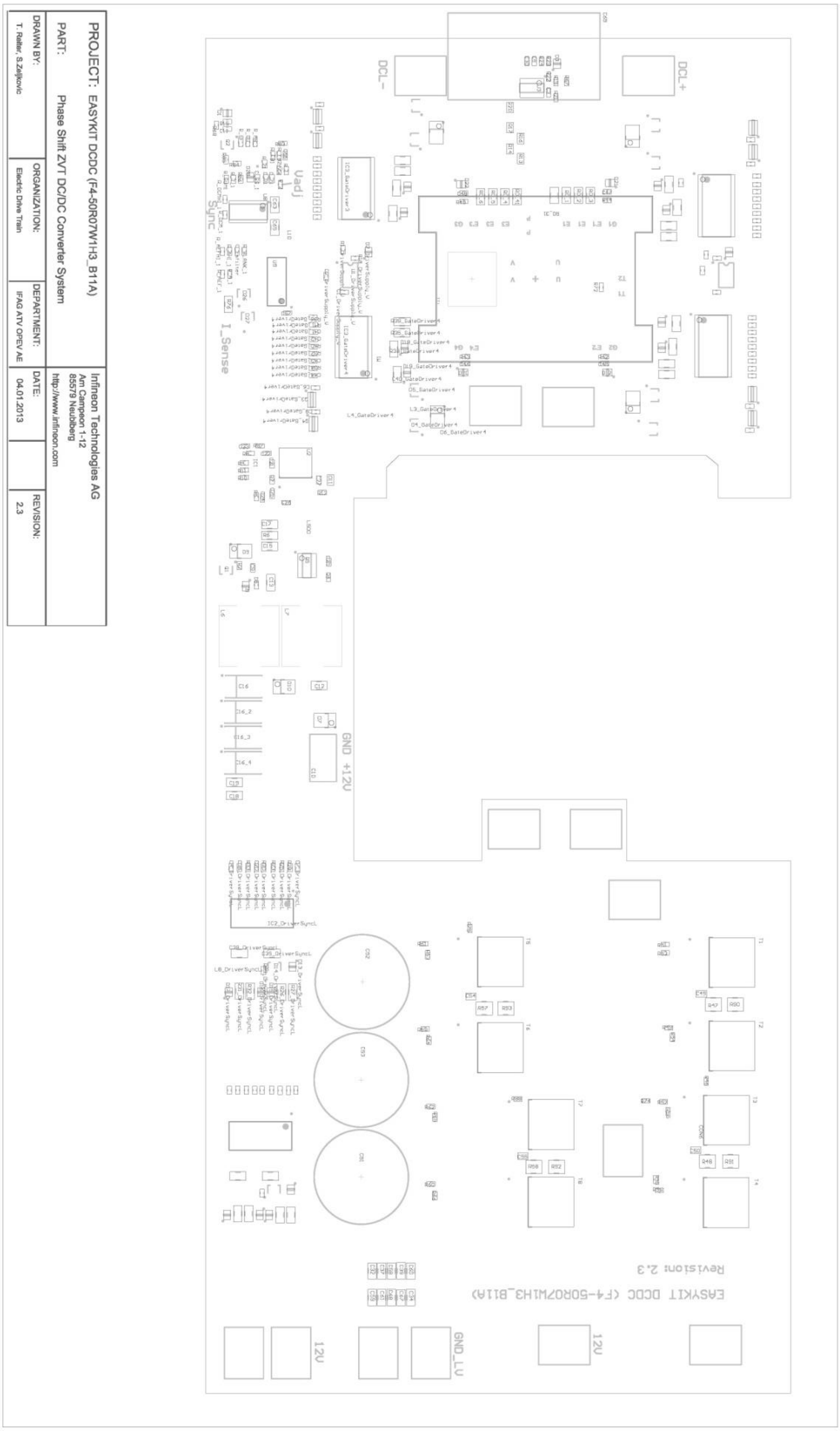
5.9 Transformer



5.10 Aux Supply



5.11 Assembly and Layout



6 References

The referenced application notes can be found at http://www.infineon.com
Direct link to the Easy Automotive site:
http://www.infineon.com/autoeasy

[1] Infineon Application Note AN2010-09, “Explanation of Technical Information”.

[2] Infineon Application Note AN2009-01, “Easy PressFIT Assembly Instructions”.

[3] Infineon Application Note AN2011-11, “Explanation for Traceability of the Easy Automotive Modules”.

[4] T. Reiter, S. Zeljkovic, “Design of an Automotive 2.5kW HV to LV DC/DC-converter using HighSpeed IGBTs” EEHE Conference Electric/Electronic in Hybrid and Electric Vehicles, April 2012.

[5] Zeljkovic; T. Reiter, D. Gerling, “Analysis of Rectifier Topologies for Automotive HV to LV Phase Shift ZVT DC/DC Converter” EPE-PEMC 2012.

[6] S. Zeljkovic; T. Reiter, D. Gerling “Switching Behavior of IGBTs in Phase Shift Full Bridge ZVT DC/DC Converter” PCIM 2013.

[7] A. Kopetz, D. Graovac, T. Reiter, “IGBT power modules update” Electric & Hybrid Vehicle Technology International, Jan 2013.

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