SEC-6K6W-CLLC-GEVK: 6.6/7.2 kW On Board Charger (OBC) CLLC Reference Design Kit Power Board (SEC-6K6W-CLLC-PB-GEVB)

TND6378/D

Use together with the *6.6/7.2 kW OBC CLLC Control Board.*

SPECIFICATIONS

Device	Application	Input Voltage	Output Power	Topology	I/O Isolation
NVHL020N090SC1 NVHL040N120SC1 NCV57000DWR2G NCV4274CST33T3G NCV2901DR2G NCV890100PDR2G NCV210RSQT2G NCV2003SN2T1G NCV8715SQ33T2G NCV431AIDR2G SC431AVSNT1G NCID9401 NCD98010XDPT3G FSL538APG FSL4110LRN …	On Board EV Charger	350 − 750 Vdc G (Grid) to B (Battery) mode 250 − 450 Vdc B (Battery) to G (Grid) mode	7.2 kW	Full bridge CLLC in main converter Flyback, Buck−boost, and Buck in auxiliary power	Yes

OTHER SPECIFICATIONS

Output Voltage (G to B Mode)	250 – 450 Vdc adjustable
Output Current (G to B Mode)	0 – 20 A adjustable
Typical Efficiency	97%
Dimension	229 x 178 x 70 mm + Transformer + Resonant Capacitor Boards + Controller Board

PHOTOGRAPH OF THE REFERENCE DESIGN BOARDS

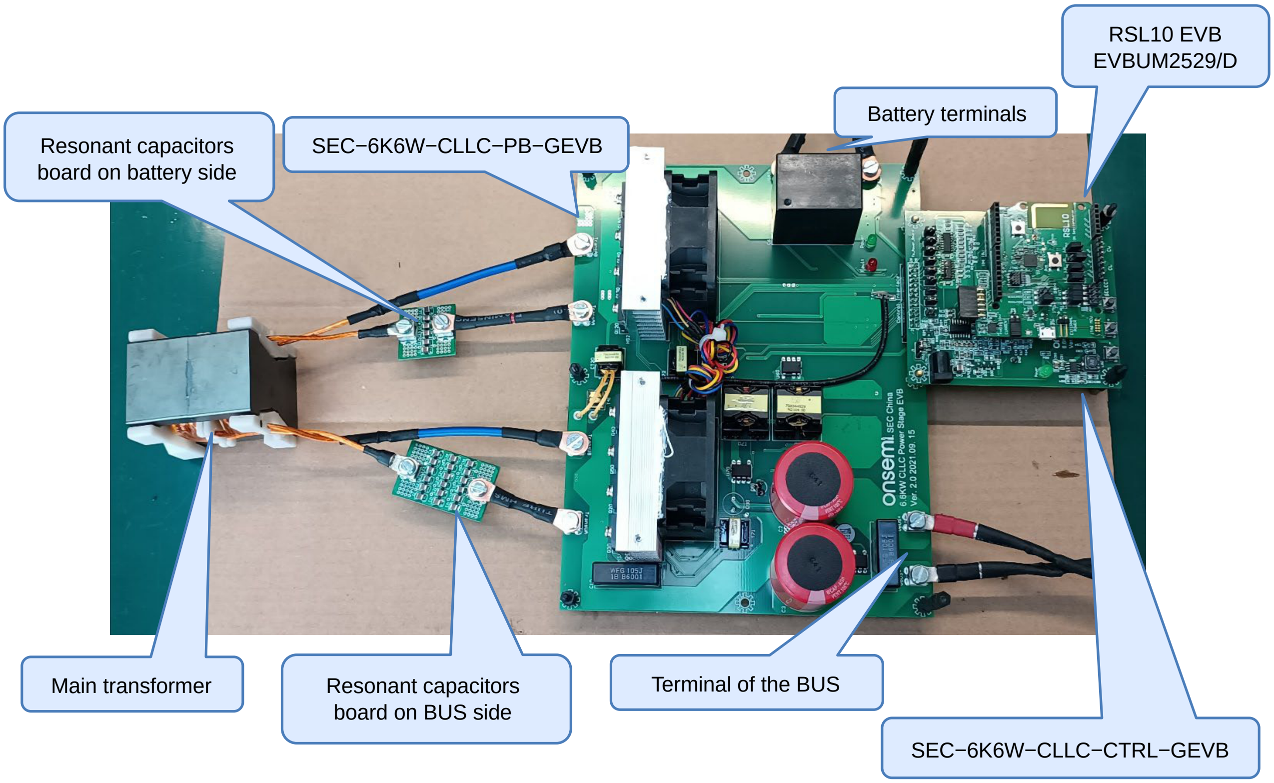


Figure 1. Whole System

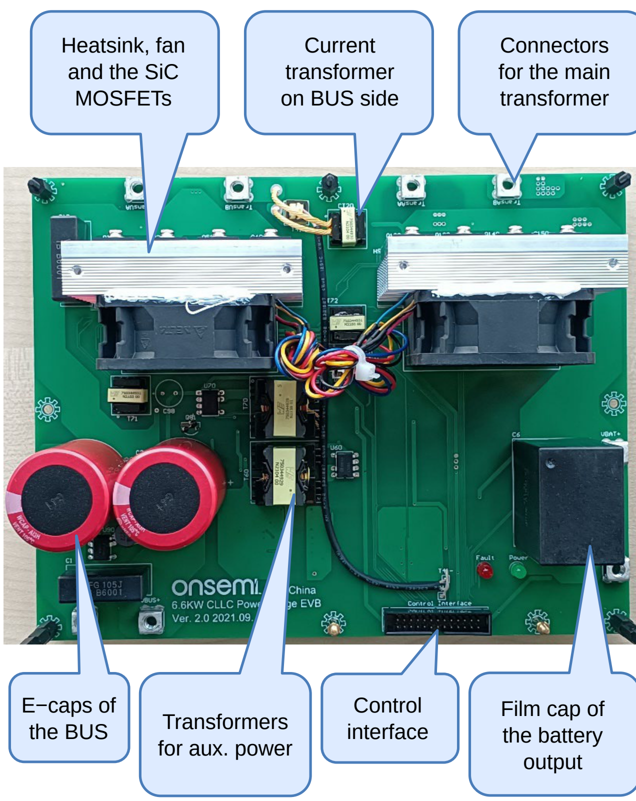


Figure 2. Top Side of the Power Board

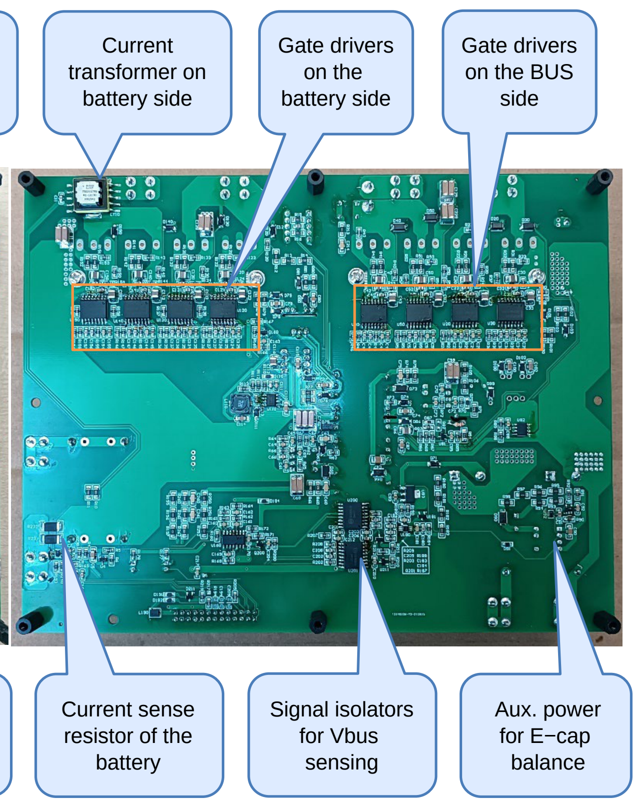


Figure 3. Bottom Side of the Power Board

SYSTEM OVERVIEW

Key Features

- Full bridge SiC MOSFETs on both sides allowing for operational modes such as Pulse Frequency Modulation, Pulse Width Modulation, Phase Shifted Full Bridge modulation and mixed operation.
- Flexible control interface to allow for adaptation to different controller boards.
- Hardware protection on both sides for over−voltage, battery port over−current, and DESAT of each SiC MOSFET.
- Onboard auxiliary power system to supply every circuit on the board and the control board. No outside DC source required.
- Innovative active Bus Capacitor Voltage Balancing circuit combined with the auxiliary power supply provides an economical solution for safely balancing the voltages across the capacitors, while minimizing additional power losses in the circuit.

Block Diagram of Hardware

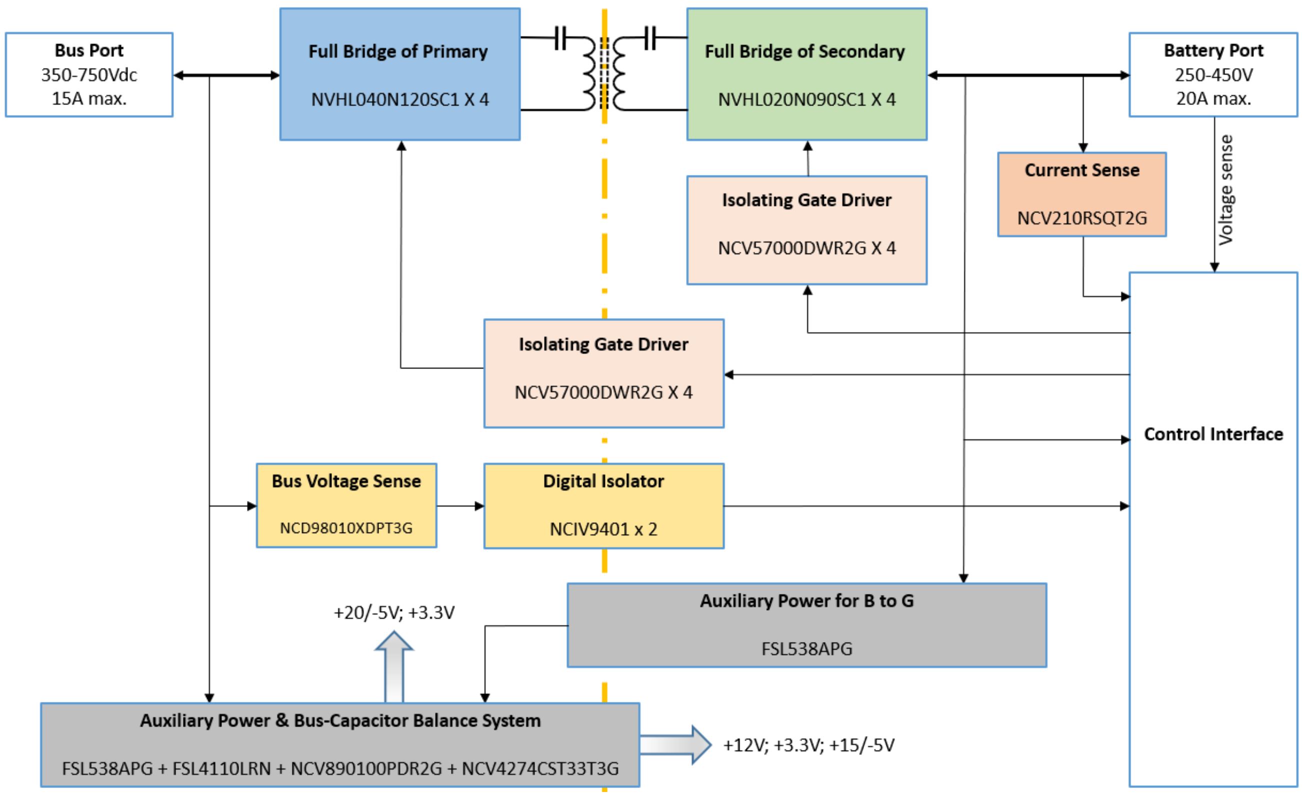


Figure 4. Block Diagram of Hardware

SCHEMATICS AND CIRCUIT DESCRIPTION

Full Bridges, Drivers and the Resonate Tank

Figure 5 shows the schematic with full bridges on both the Bus side (Primary) and the Battery side (secondary). The full bridge on the Bus side is realized by using 40 mΩ SiC MOSFETs (1200 V rated) for Q20, Q30, Q40 & Q50 being driven by +20 V/−5 V. This implementation can accept up to 750 V or even higher bus voltage but is limited by the E−caps. The full bridge on the Battery side is realized by using 20 mΩ SiC MOSFETs (900 V rated) for Q120, Q130, Q140 & Q150 being driven by +15 V/−5 V. This implementation is designed for 400 V battery systems and can accept up to 450 V for a typical system but is capable of handling battery voltages up to 600 V. For 800 V battery systems the main change required would be to update the Battery side (secondary) SiC MOSFETs to 1200 V from 900 V.

Each SiC MOSFET is driven by an AEC qualified NCV57000DWR2G which is a galvanically isolated high−current, high−performance gate driver. The NCV57000 series gate driver was originally designed to drive IGBTs, but the device is capable of driving SiC MOSFETs. The built−in the desaturation protection function of the NCV57000DWR2G, in case of short−circuit or over−current fault happening, will pull the gate voltage low and pull the FLT pin low at same time. The FLT pins of each NCV57000DWR2G are tied to the FLT node. The FLT pin is a fault indication signal, we will talk it more on the following content.

Figure 6 shows the schematic of the resonant tank and the main transformer. The resonant capacitors on both sides are assembled in separated small PCBs for ease of location. Multiple capacitors are installed in a series and parallel configuration on the Bus side to provide enough margin for current and voltage. The resonant inductor is integrated into the main transformer for cost and form factor improvements. The specifications of the transformer from two different suppliers are shown in the figures 7a and 7b.

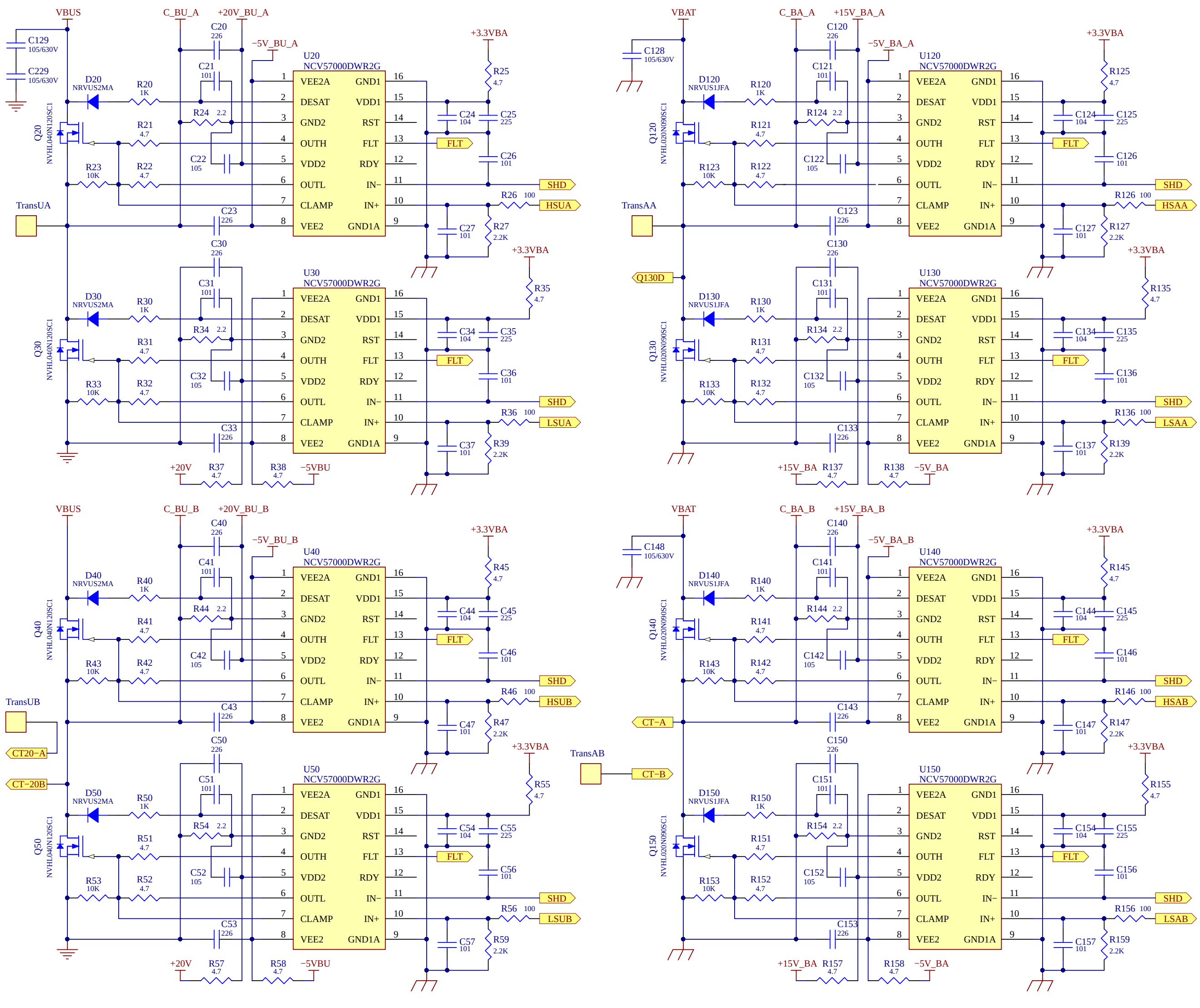


Figure 5. Schematic of the Full Bridges and the Drivers

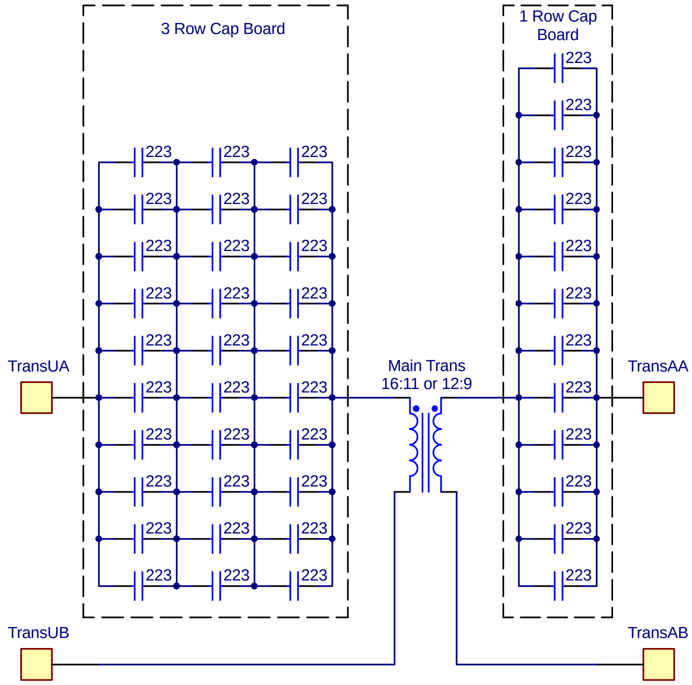


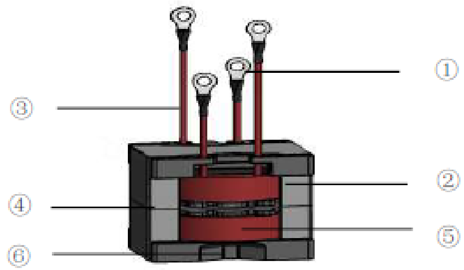
Figure 6. Schematic of the Resonant Tank

Sunlord www.sunlordinc.com

Proposal of Automotive Electronics Transformers for ATWPPQ655462B202T

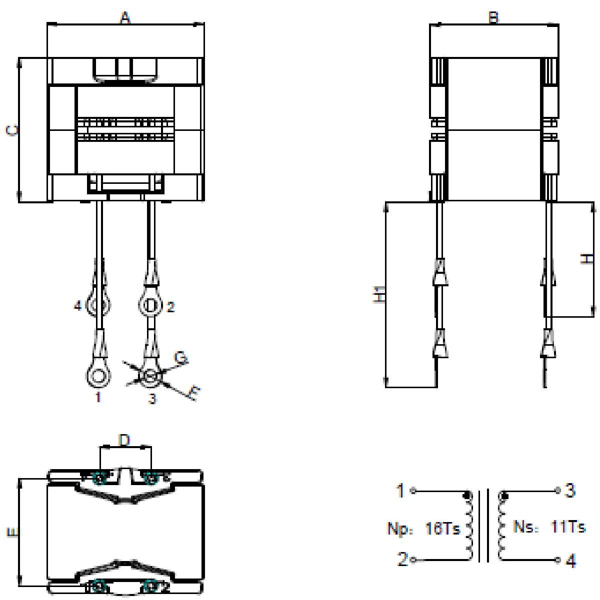
Approved By	Checked By	Prepared By
Jinbo Cai	Teresa Luo	Dingwei Zhu
2021/11/17	2021/11/17	2021/11/17

1.Structure and Material



No.	Part Name	Material Name	UL. NO
①	Terminal	C1100	/
②	Core	Mn-Zn Ferrite	/
③	Wire	Mylar Wire (Ø0.1mm*300P)	/
④	Glue	Epoxy	/
⑤	Tape	Kapton Tape (180℃)	E24883
⑥	Bobbin	PM-9630	E39252

2. Shape and Dimensions (unit: mm)



Note : For RoHS compliant products:
1. Solder : Sn /Ag /Cu .
2.Marking Code: A2111012 Sunlord Code
3.Date Code: : ** ** ****
① ② ③
① Year
② Week
③ Trace Code

Shape and Dimensions

Item	A	B	C	D	E	F	G	H	H1
Sunlord Spec	66.2Max	54.0Max	62.0Max	22.0Ref	45.0Ref	9.3Ref	5.3Ref	65.0Ref	165.0Ref

3. Electrical Characteristics @ 25 ℃: (Operating Temperature: - 40℃ to + 125℃; Operating Frequence:150kHz)

Sunlord P/N:ATWPPQ655462B202T

Parameters	Inductance (Lp)	Leakage Inductance (Lk)	DCR		TURNS RATIO	HI-POT
Unit	μH	μH	mΩ	mΩ	Ts	/
Test Terminal	Pin(1-2)	Pin(1-2), shorted Pin（3-4）	Pin(1-2)	Pin(3-4)	Pin(1-2):(3-4)	Pri to Sec
Sunlord Design	170.0±10%	25.0uH±10%	30.0 Max	20.0 Max	16:11±0.5	3000Vac/50Hz/ 5mA/2s
Test Condition	Measured at 150KHz,0.1V 25°C	Measured at 150KHz,1.0V 25°C	Measured at 25°C	Measured at 25°C	Measured at 15.75KHz,1V, 25°C	Measured at 25°C

Note: •Wave soldering reference JB/T 7488-2008, the soldering time is 3s~5s at the soldering temperature of 250±2℃
• MLS level 1 • RoHS compatible

Revision:01

Figure 7a. Specification of the Main Transformer from Sunlord

MAGSONDER

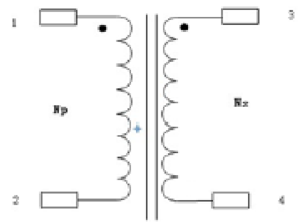
Magsonder Innovation (Shanghai) Co., Ltd

墨尚电子技术(上海)有限公司

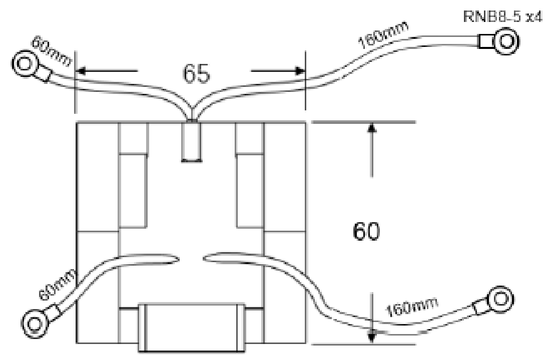
Page : **1 / 1**

P/N:PTX6R6K-17025-r

SCHEMATIC



DIMENSION(unit:mm)



SPECIFICATION

Core: PC95

Type: PQ65/60

Inductance： 175uH±10%

Leakage： 25uH±10%

Turns Ratio： Np:Ns =12:9

DCRp： 9 mΩ MAX

DCRs： 7 mΩ MAX

Insulation Level : CLASS F

HI-POT: 3.3kVac/rms

Primary coils: 0.05*900*2 Litz Wire

Secondary coils: 0.05*900*2 Litz Wire

Figure 7b. Specification of the Main Transformer from Magsonder

Sensing, Protection, and the Control Interface

Figure 8 shows the schematic of the voltage, current sensing, over−current, voltage protection, and the control interface.

The battery voltage VBAT is divided down by 3 different resistor strings for various measurements.

- Resistors R195, R196 & R197 divide VBAT down to the voltage signal VSAM which is sent to the control board for battery voltage monitoring. The lower divider resistor is located on the control board for better noise immunity. Additionally, the signal is clamped to +12 V by D191 to prevent high−voltage in the case where the control board is not connected.
- Like VSAM, the VSAF voltage signal is derived from VBAT by the divider of R260, R261 & R262 which is clamped by D192. The VSAF signal is for feedback of the output voltage for the analog control method. The capacitors C260 and C261 help to speed up the response of the control loop.
- VTHH is divided by R160 and R161+R162 from the reference voltage of +6 V, providing a stable reference of 1.825 V.
- The divider made by R250, R251, R252 and R168 is for over−voltage protection. Once VBAT goes higher than 477 V (1.825 x 3011.5 / 11.5) the FLT pin is pulled low by the comparator U160C and the shutdown signal SHD is pulled high by Q160. From the datasheet of NCV57000 gate driver, if the IN− (SHD) is high, then the output of the gate drivers will be low and the converter stops working.

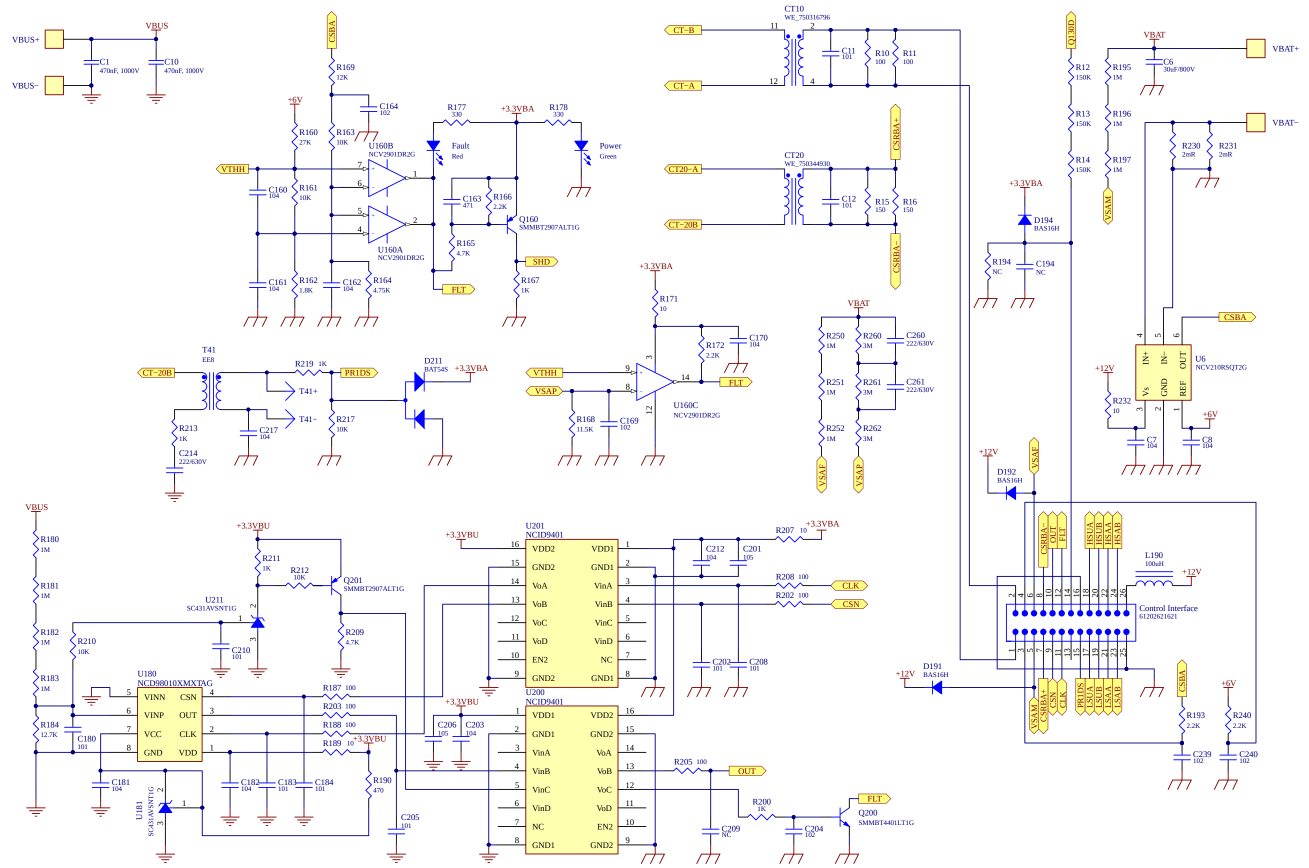
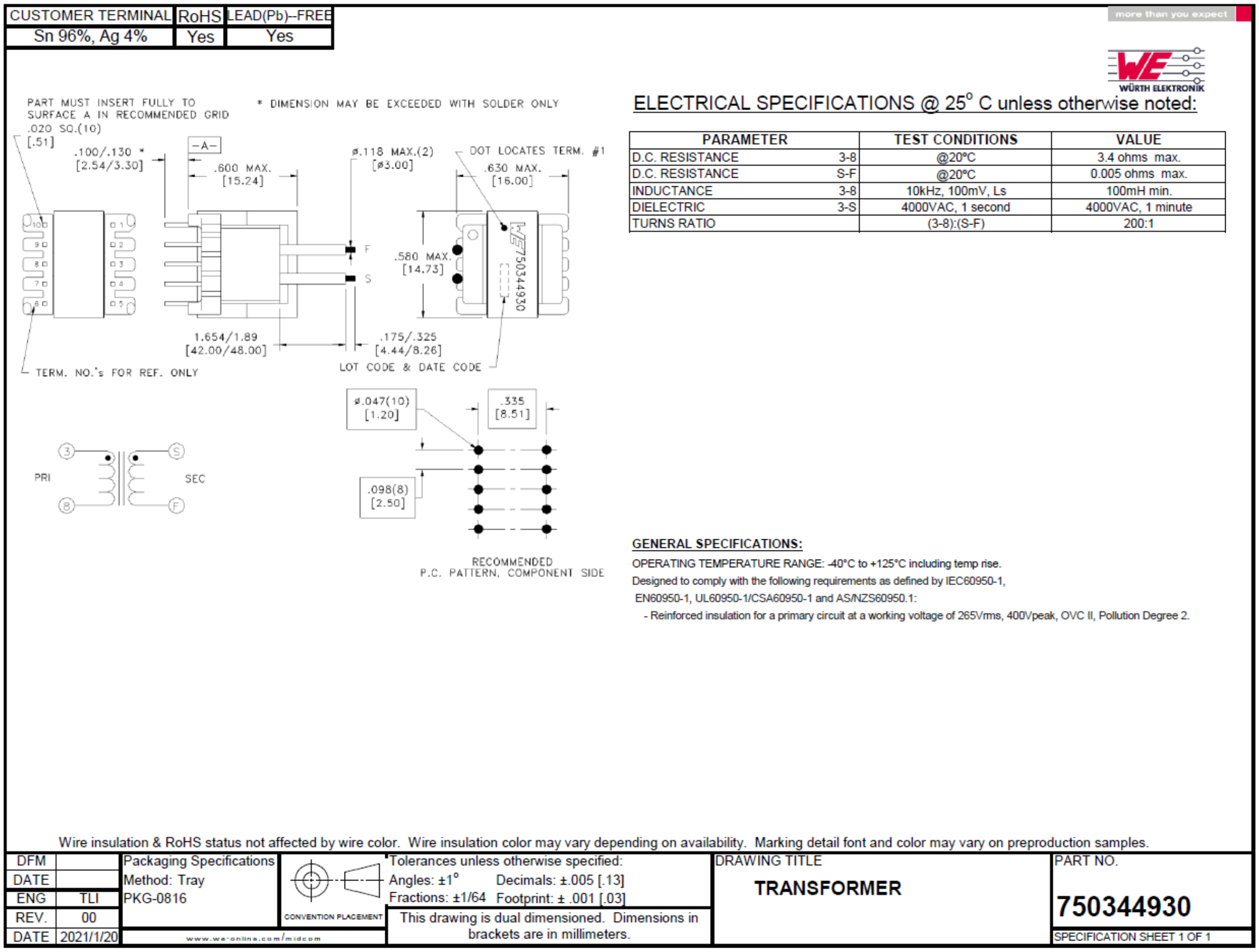


Figure 8. Schematic of the Sensing, Protection, and the Control Interface

Sensing the VBUS voltage is more challenging than sensing VBAT due to the isolation requirement. Thanks to the [High−Speed Quad−Channel Digital Isolator NCID9401](), we can digitize the VBUS measurement and send this value across the isolation boundary from the bus side to the battery side. The VBUS measurement is digitized by using the [12−Bit Low Power SAR ADC NCD98010XMXTAG](). This SAR ADC with 3−wire SPI interface performs the analog to digital conversion and this information is easier to transmit by NCID9401 than the I^2C bus. The analog supply and ADC reference voltage Vcc (pin7 of U180) are regulated by the 2.5 V reference U181. VBUS is divided by R180, R181, R182, R183 and R184 with a maximum sensing input voltage of 800 V. Once VBUS becomes greater than 800 V, U211 turns on Q201 and pulls the VinC pin of U200 high. The FLT pin is also pulled low by Q200 and the converter shuts down.

The battery terminal current is sensed by the shunt resistors R230 and R231,then amplified 200 times by the AEC qualified [Current Sense Amplifier NCV210RSQT2G](#) for power loss reduction on the resistors. The window comparator made by U160 A and B protects for an over−current fault on the battery terminal. If the current is larger than ±20 A, the FLT pin will be pulled low.

The bus and battery side currents from the resonant tank are sensed by the current transformers CT20 and CT10. The turns ratio of each current transformer is 1:200. The key difference between two transformers is that CT20 needs reinforced insulation, while CT10 only needs functional insulation. For more information about the current transformers, please check the specifications from the supplier in figures 9 and 10.



CUSTOMER TERMINAL	RoHS	LEAD(Pb)–FREE
Sn 96%, Ag 4%	Yes	Yes

ELECTRICAL SPECIFICATIONS @ 25° C unless otherwise noted:

PARAMETER		TEST CONDITIONS	VALUE
D.C. RESISTANCE	3-8	@20°C	3.4 ohms max.
D.C. RESISTANCE	S-F	@20°C	0.005 ohms max.
INDUCTANCE	3-8	10kHz, 100mV, Ls	100mH min.
DIELECTRIC	3-S	4000VAC, 1 second	4000VAC, 1 minute
TURNS RATIO		(3-8):(S-F)	200:1

GENERAL SPECIFICATIONS:

OPERATING TEMPERATURE RANGE: -40°C to +125°C including temp rise.

Designed to comply with the following requirements as defined by IEC60950-1, EN60950-1, UL60950-1/CSA60950-1 and AS/NZS60950.1:

- Reinforced insulation for a primary circuit at a working voltage of 265Vrms, 400Vpeak, OVC II, Pollution Degree 2.

Wire insulation & RoHS status not affected by wire color. Wire insulation color may vary depending on availability. Marking detail font and color may vary on preproduction samples.

DFM		Packaging Specifications	Tolerances unless otherwise specified:
DATE		Method: Tray	Angles: ±1° Decimals: ±.005 [.13]
ENG	TLI	PKG-0816	Fractions: ±1/64 Footprint: ± .001 [.03]
REV.	00	CONVENTION PLACEMENT	This drawing is dual dimensioned. Dimensions in brackets are in millimeters.
DATE	2021/1/20	www.we-online.com/midcom	

DRAWING TITLE: TRANSFORMER

PART NO. 750344930

SPECIFICATION SHEET 1 OF 1

Figure 9. Specification of the Current Transformer CT20. 750344930

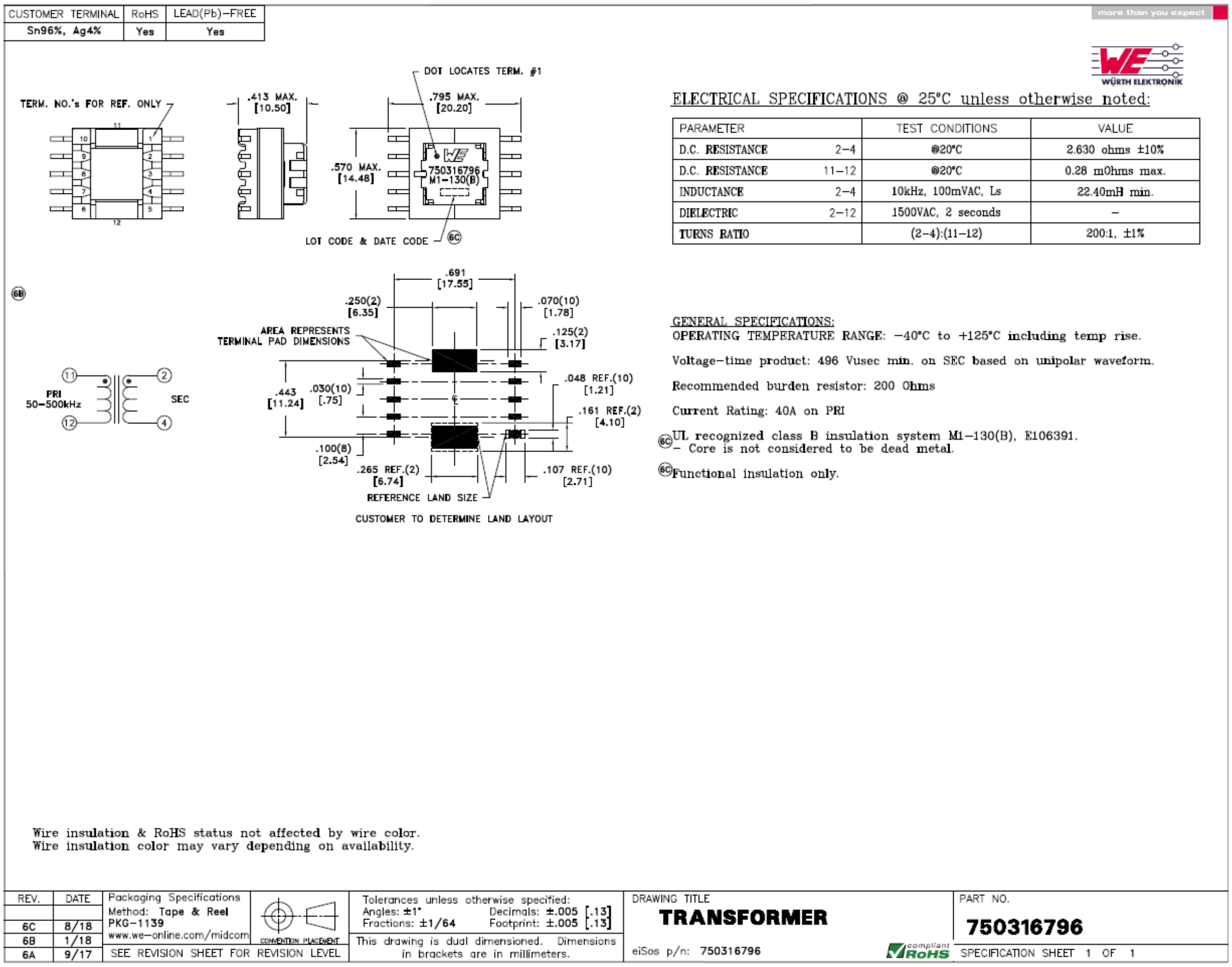


Figure 10. Specification of the Current Transformer CT10. 750316796

The DC current of the bus terminal is not sensed directly. If you need this signal, it is available for monitoring from the Bus (primary) side resonant tank current via the control interface header pins.

For a synchronous rectifier, some control methods need to sense the Vds signals. The Vds signals from both the primary and secondary sides are sent to the control interface for this usage. The Vds of battery side (SR1DS) comes from the drain of Q130 and is divided by R12, R13 and R14. The lower divider resistor is located on the control board for noise immunity and the signal is clamped to 3.3 V by D194. The Vds of bus side (PR1DS) comes from the drain of Q50 (CT−20B). The pulse transformer T41 scales down and provides reinforced insulation for the signal, with D211 clamping the signal between 0 − 3.3 V. Figure 11 shows the details of the T41.

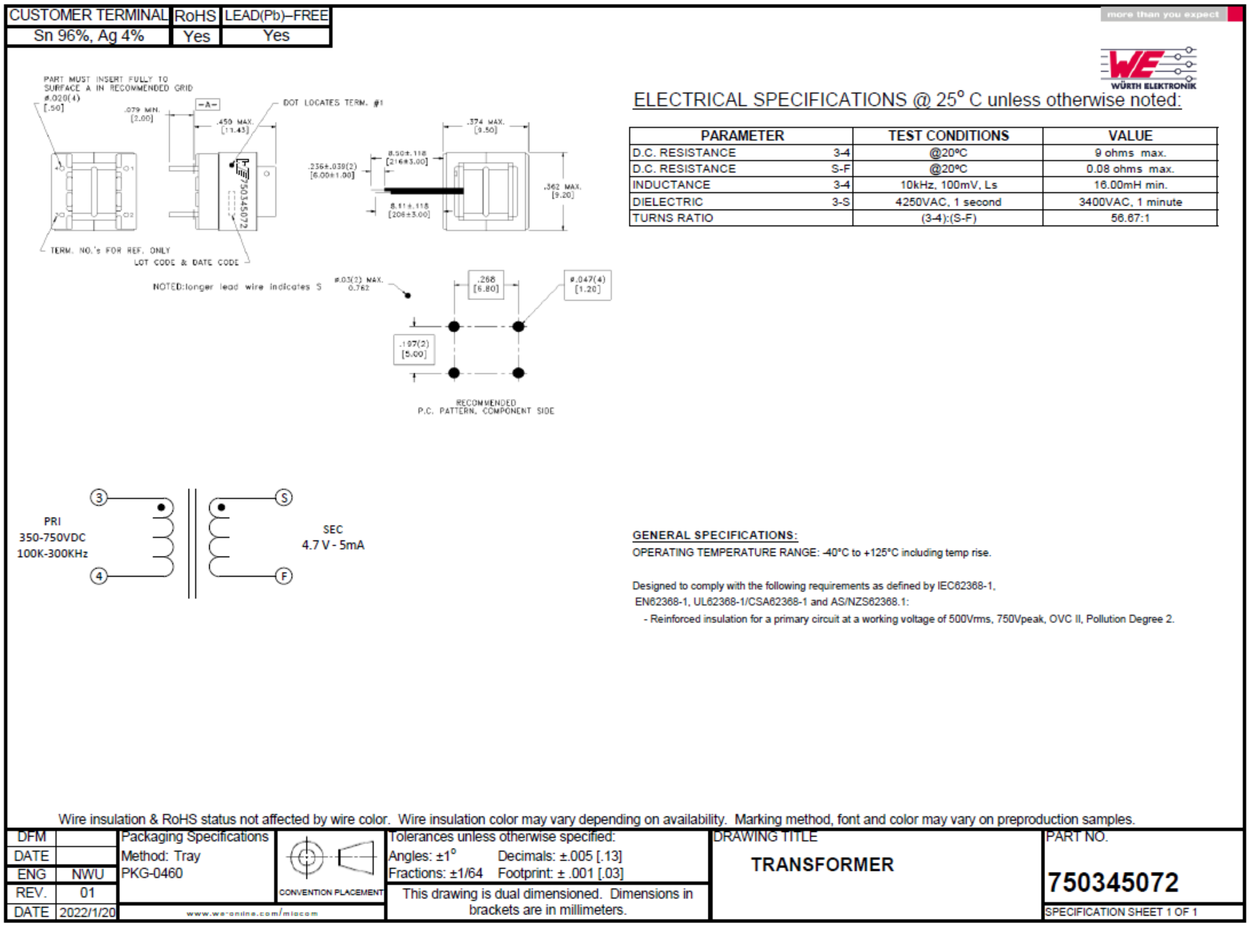


Figure 11. Specification of the Pulse Transformer T41. 750345072

The 26−pin dual row connector connects the power board and the control board. Table 1 show the pin definitions.

Table 1. SIGNALS OF THE CONTROL INTERFACE

Pin	Name	Type	Direction*	Description
1	CSRBU+	Analog	Output	Positive current of Resonant tank of Battery side.
2	CSRBU−	Analog	Output	Negative current of Resonant tank of Battery side.
3	CSA+	Analog	Output	Positive current on Battery terminal.
4	CSA−	Analog	Output	Negative current on Battery terminal (Reference).
5	VSAM	Analog	Output	Voltage of the Battery for Measurement.
6	VSAF	Analog	Output	Voltage of the Battery for Feedback.
7	CSRBA+	Analog	Output	Positive current of Resonant tank of Bus side.
8	CSRBA−	Analog	Output	Negative current of Resonant tank of Bus side.
9	CSN	Digital	Input	Chip select of the ADC (Read Vbus from battery side. Active low).
10	OUT	Digital	Output	Data output of the ADC (Read Vbus from battery side).
11	CLK	Digital	Input	Clock of the ADC (Read Vbus from battery side).
12	FLT	Digital	I/O	Fault output. Open drain with 2.2 kΩ pull high resistor. Active Low.
13	NC	−	−	
14	SR1DS	Digital	Output	Battery side switching edge. Clamp to 3.3 V.
15	PR1DS	Digital	Output	BUS side switching edge. Transferred to Battery side and clamped to 3.3 V.
16	GND	−	−	GND
17	LSUA	Digital	Input	Low side PWM signal of Bus side half bridge A.
18	HSUA	Digital	Input	High side PWM signal of Bus side half bridge A.
19	LSUB	Digital	Input	Low side PWM signal of Bus side half bridge B.
20	HSUB	Digital	Input	High side PWM signal of Bus side half bridge B.
21	LSAA	Digital	Input	Low side PWM signal of Battery side half bridge A.
22	HSAA	Digital	Input	High side PWM signal of Battery side half bridge A.
23	LSAB	Digital	Input	Low side PWM signal of Battery side half bridge B.
24	HSAB	Digital	Input	High side PWM signal of Battery side half bridge B.
25	GND	−	−	GND
26	+12V	Power	Output	±1 V; 0 − 0.2 A

*The signal Direction Input/Output is based on the power board.
*Voltage level of all digital signals = 3.3 V.

Auxiliary Power Supply and Electrolytic Capacitors Balancing

The bus voltage on this board can be as high as 800 V before OVP. This design challenge affects both the auxiliary power circuit and the electrolytic capacitors. If we use a traditional flyback converter for the auxiliary power, a 1200 V switching device should be used which will make the cost higher. On the other hand, the maximum voltage rating of standard electrolytic capacitors is 450 Vdc. In the case where the bus voltage is higher than 400 V, frequently 2 or more electrolytic capacitors will be connected in series. When the electrolytic capacitors are in series, leakage current differences between each capacitor can't be ignored, which can make the voltage on the capacitors unbalanced and may damage a capacitor in the worst case. The traditional solution is to parallel the balancing resistors on each capacitor. For this type of solution, choosing the suitable resistance is a design challenge. When choosing lower resistance the balancing effect is better, but the resistors consume larger amounts power. If choosing larger resistance the power consumption on the resistors is lower, but the balancing effect is not good enough. In this reference design, a creative solution was used to solve these two problems simultaneously.

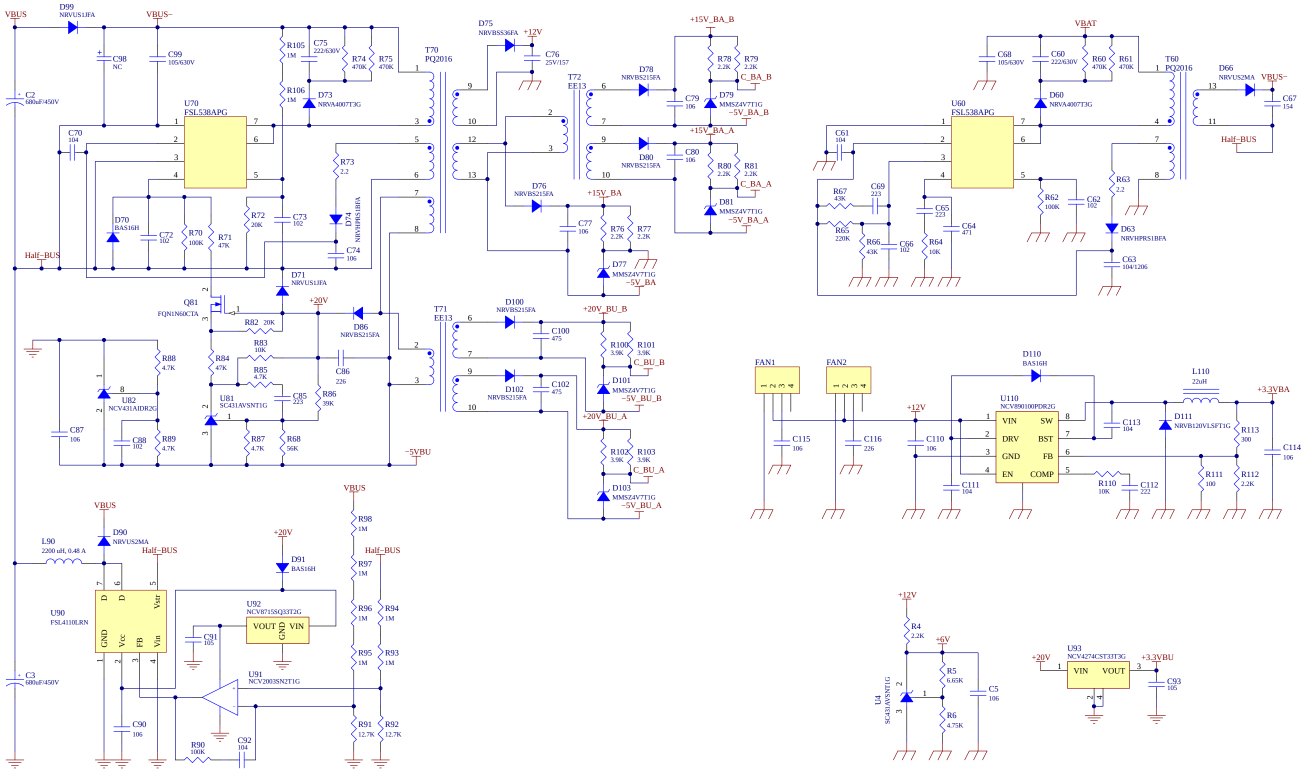
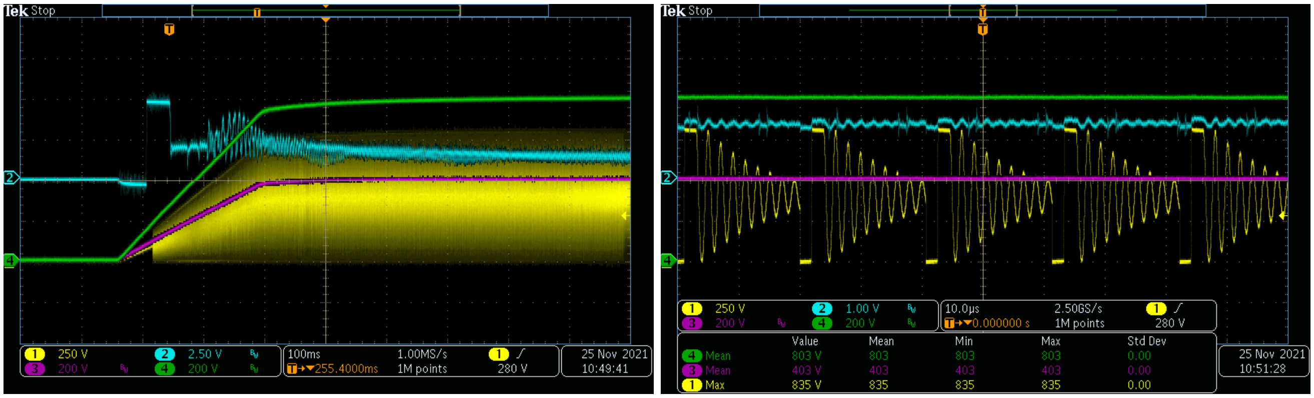


Figure 12. Schematic of the Auxiliary Power Supply

Figure 12 shows the schematic of the auxiliary power of the board, and C2 along with C3 are the electrolytic capacitors in series connected to VBUS. The main flyback converter U70 derives input power from across C2, rather than the whole bus which is different from a traditional solution. When the voltage on C2 and C3 is balanced, the maximum voltage on C2 will be 400 Vdc. U70 drawing power from C2 can make the voltage on C2 drop, and another source is needed to maintain the voltage balance. A solution to this design challenge is provided by U90, U91, and U92. U90 along with L90 and D90 compose a Buck−boost converter, providing a mechanism to balance the voltage between C3 to C2. U91 compares the voltage on C3 (Half−bus) with VBUS and then adjusts the PWM duty cycle accordingly. The target is to make the Half−BUS node equal to 1/2 of the actual VBUS voltage, and as long as the loop is closed the voltage will be balanced across C2 and C3.

For this design the 1000 V Integrated Power Switcher FSL4110LRN was chosen to meet the voltage stress requirements for the buck−boost converter which is Vin + Vout. From the waveforms on figure 13 we can see the voltage spike is under 835 V during steady state operation when VBUS = 800 V. The solution provided by U90, U91 and U92 keeps the voltage balanced during both startup and steady state. For more information please click the FSL4110LRN link.



*CH1: Vds of U90; CH2: Vfb (Pin 3) of U90; CH3: Half−bus; CH4: VBUS.

Figure 13. Key Waveforms on the Buck−boost Converter (U90)

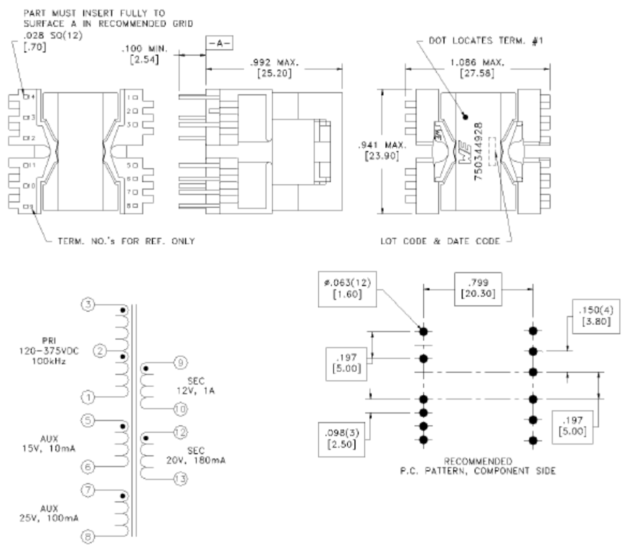
On the main flyback converter (U70), we chose the High Performance 800 V Off−line Switcher FSL538APG. The whole board needs 7 power rails which are listed on table 2.

Table 2. OUTPUT RAILS OF THE MAIN AUXILIARY POWER U70

No.	Name	Rating Current	Load
1	+12V	1 A	Cooling fan, control board, sensing and protection circuits.
2	+20V – −5VBU	0.2 A	Vdd2 – Vee2 of U30 and U50.
3	+20V_BU_A – −5V_BU_A		Vdd2 – Vee2 of U20.
4	+20V_BU_B – −5V_BU_B		Vdd2 – Vee2 of U40.
5	+15V_BA – −5V_BA	0.25 A	Vdd2 – Vee2 of U130 and U150.
6	+15V_BA_A – −5V_BA_A		Vdd2 – Vee2 of U120.
7	+15V_BA_B – −5V_BA_B		Vdd2 – Vee2 of U140.

The rails for No. 1, 2 and 5 come directly from the main transformer T70. The specification of T70 is shown in figure 14. Due to pin count limitations, the rails for No. 3, 4, 6 and 7 are derived from the pulse transformers T71 and T72. The specification for T71/T72 is shown in figure 15.

CUSTOMER TERMINAL	RoHS	LEAD(Pb)–FREE
Sn 96%, Ag 4%	Yes	Yes



ELECTRICAL SPECIFICATIONS @ 25° C unless otherwise noted:

PARAMETER		TEST CONDITIONS	VALUE
D.C. RESISTANCE	3-1	@20°C	0.550 ohms max.
D.C. RESISTANCE	5-6	@20°C	0.050 ohms max.
D.C. RESISTANCE	7-8	@20°C	0.090 ohms max.
D.C. RESISTANCE	9-10	@20°C	0.015 ohms max.
D.C. RESISTANCE	12-13	@20°C	0.070 ohms max.
INDUCTANCE	3-1	10kHz, 100mV, Ls	930μH ±10%
SATURATION CURRENT	3-1	20% rolloff from initial	750mA
LEAKAGE INDUCTANCE	3-1	tie(9+10+12+13),100kHz, 100mV, Ls	10μH max.
DIELECTRIC	1-13	tie(3+5+7,10+12), 4000VAC, 1 second	4000VAC, 1 minute
TURNS RATIO		(3-1):(5-6)	14.33:1
TURNS RATIO		(3-1):(7-8)	7.17:1
TURNS RATIO		(3-1):(9-10)	14.33:1
TURNS RATIO		(3-1):(12-13)	8.6:1

GENERAL SPECIFICATIONS:

OPERATING TEMPERATURE RANGE: -40°C to +125°C including temp rise.

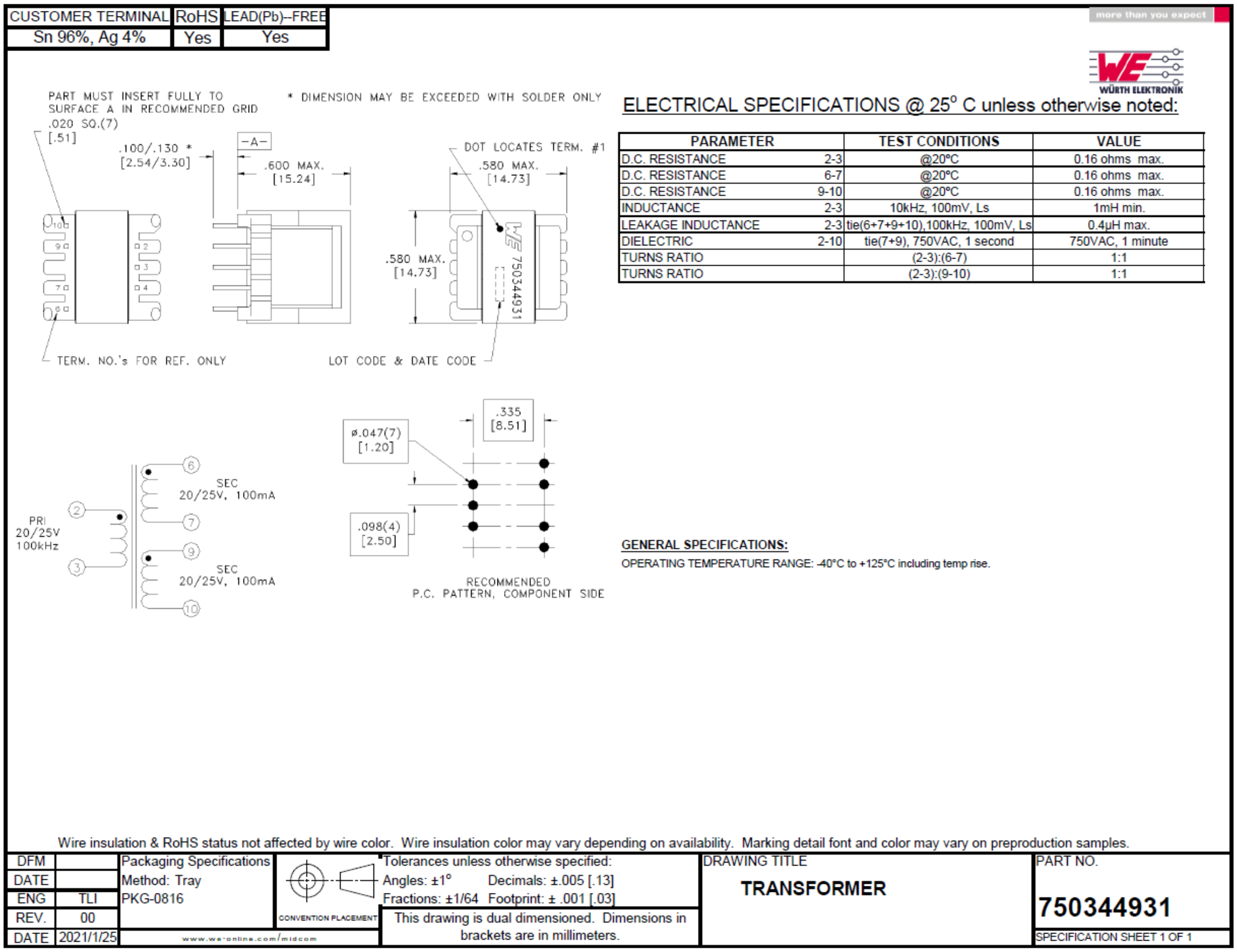
Designed to comply with the following requirements as defined by IEC62368-1, EN62368-1, UL62368-1/CSA62368-1 and AS/NZS62368.1:

- Reinforced insulation for a primary circuit at a working voltage of 265Vrms, 400Vpeak, OVC II, Pollution Degree 2.

Wire insulation & RoHS status not affected by wire color. Wire insulation color may vary depending on availability. Marking method, font and color may vary on preproduction samples.

DFM		Packaging Specifications	Tolerances unless otherwise specified:	DRAWING TITLE
DATE		Method: Tray	Angles: ±1° Decimals: ±.005 [.13]	TRANSFORMER
ENG	TLI	PKG-0239	Fractions: ±1/64 Footprint: ± .001 [.03]	
REV.	01	CONVENTION PLACEMENT	This drawing is dual dimensioned. Dimensions in brackets are in millimeters.	PART NO. 750344928
DATE	2021/9/17	www.we-online.com/midcom		SPECIFICATION SHEET 1 OF 1

Figure 14. Specification of the Main (G to B) Transformer T70. 750344928



PARAMETER		TEST CONDITIONS	VALUE
D.C. RESISTANCE	2-3	@20°C	0.16 ohms max.
D.C. RESISTANCE	6-7	@20°C	0.16 ohms max.
D.C. RESISTANCE	9-10	@20°C	0.16 ohms max.
INDUCTANCE	2-3	10kHz, 100mV, Ls	1mH min.
LEAKAGE INDUCTANCE	2-3	tie(6+7+9+10),100kHz, 100mV, Ls	0.4µH max.
DIELECTRIC	2-10	tie(7+9), 750VAC, 1 second	750VAC, 1 minute
TURNS RATIO		(2-3):(6-7)	1:1
TURNS RATIO		(2-3):(9-10)	1:1

Figure 15. Specification of the Pulse Transformer T71, T72, 750344931

For the SiC MOSFETs to remain in a stable and safe operating condition, the gate driver voltage needs to be well regulated. Since the performance of an opto−coupler is not optimal for use in an automotive design, we feedback the +20V and −5VBU outputs and use Q81 to transfer the error signal from the primary GND rail to the U70 GND (Half_BUS) rail. In B to G mode D71 charges C3 to 20 V to ensure Q81 functions properly, while during G to B mode C2 must charge to >101 Vdc (the brown−in level) for U70 to startup.

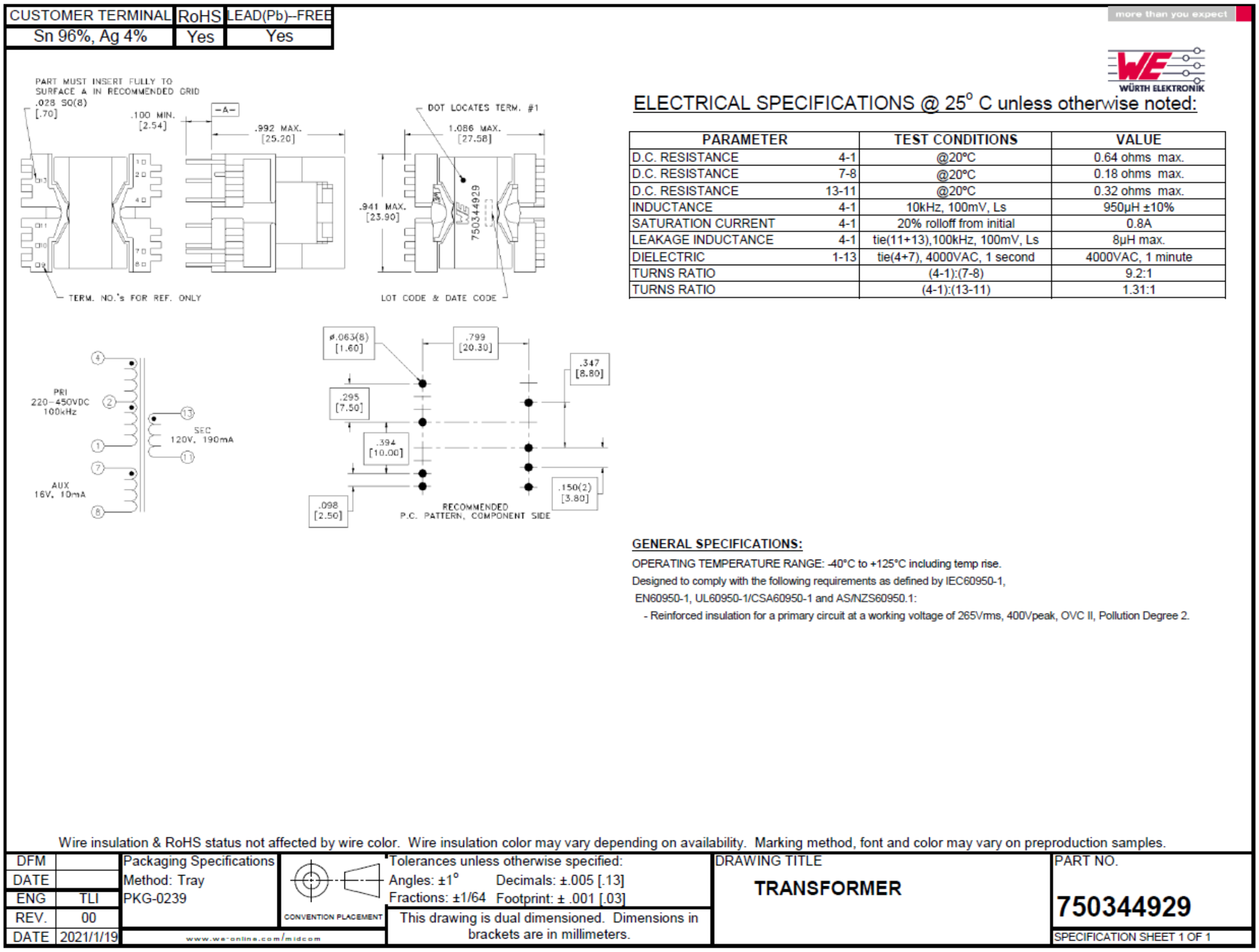
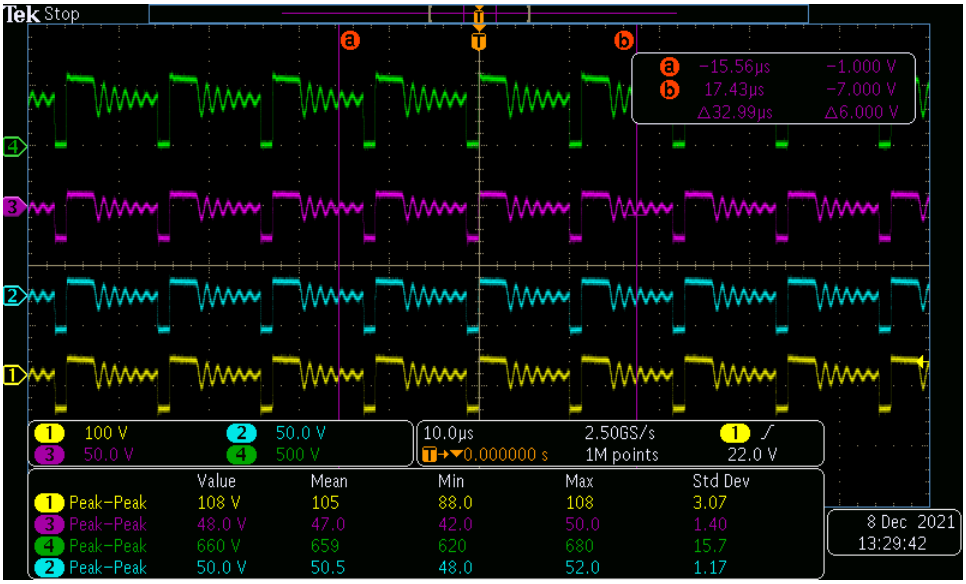


Figure 16. Specification of the B to G transformer T60. 750344929

In the B to G mode U60 will start−up first and charge C99 to 110 Vdc, then U70 will start−up. D99 blocks the current flow to C2 in order to prevent a U70 start−up failure if VBUS is connected to a heavy load. Once the converter is up and running in B to G mode, C2 is charged to higher than 110 Vdc and U60 works under no load condition.

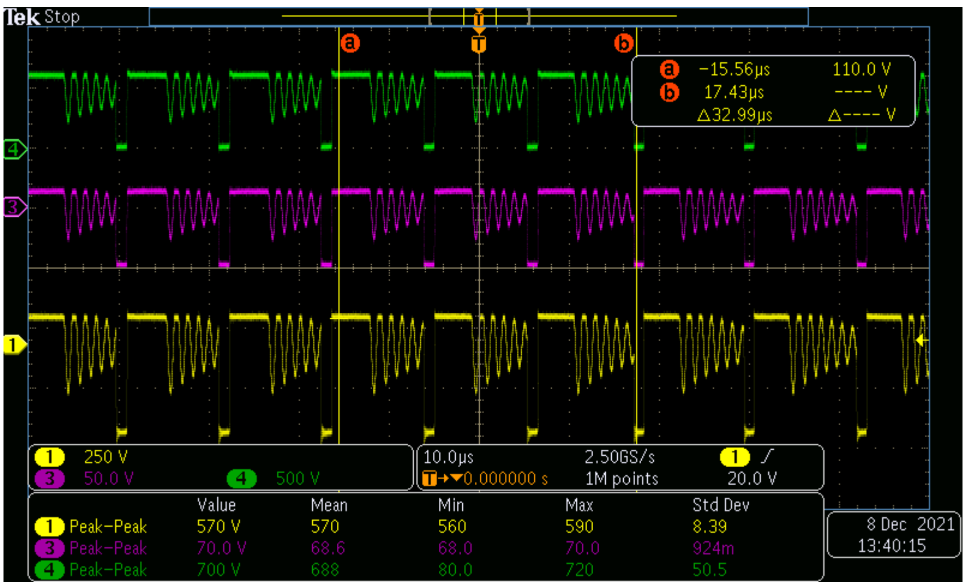
U60 is the FSL538APG which will work under VBAT = 480 Vdc (before OVP). Since the voltage requirement is not precise, the U60 feedback from Vcc is a simple circuit. The specification of the transformer T60 is shown on figure 16.

The key waveforms of U70 and U60 are shown in figures 17 and 18. We can see, the voltage stresses are acceptable.



*CH1: Pin 7−8 of T70; CH2: Pin 9−10 of T70; CH3: Pin 5−6 of T70; CH4: Vds of U70.

Figure 17. Key Waveforms on T70 at VBUS = 800 V



*CH1: Pin 13−11 of T60; CH3: Pin 7−8 of T60; CH4: Vds of U60.

Figure 18. Key Waveforms on T60 at VBAT = 480 V

Besides the above rails, the reference design also needs a +3.3V rail on both the bus side and battery side. The loads of the +3.3VBA include Vdd1 of the gate drivers, Vdd1/Vdd2 of the digital isolator U201/U200, Vdd of the comparator U160, and the LEDs. We use the buck converter U110 connected to +12V to supply the +3.3VBA rail. The loads of the +3.3VBU include Vdd2/Vdd1 of the digital isolator U201/U200, and Vcc of the ADCs U180 and U181. The load current is light, so a LDO is used for U93. While the LDO is a lower efficiency solution, it serves another purpose; it is also a dummy load for the +20V rail.

TEST RESULTS

Grid to Battery Operation

Efficiency of Grid to Battery Operation

For Grid to Battery mode, the converter works in a closed loop. We adjust the Vin for different Vo to set the switching frequency around the resonant point to get maximum efficiency. Table 3 shows the input voltage for each output voltage with Sunlord transformer. The Vin with Magsonder transformer will be 7.2% lower. Figure 19 shows the efficiency across different Vo and load current settings.

Table 3. INPUT VOLTAGE ON EACH OUTPUT VOLTAGE FOR MAXIMUM EFFICIENCY

Vo (V)	250	300	350	400	450
Vin (V)	355	427	495	566	624

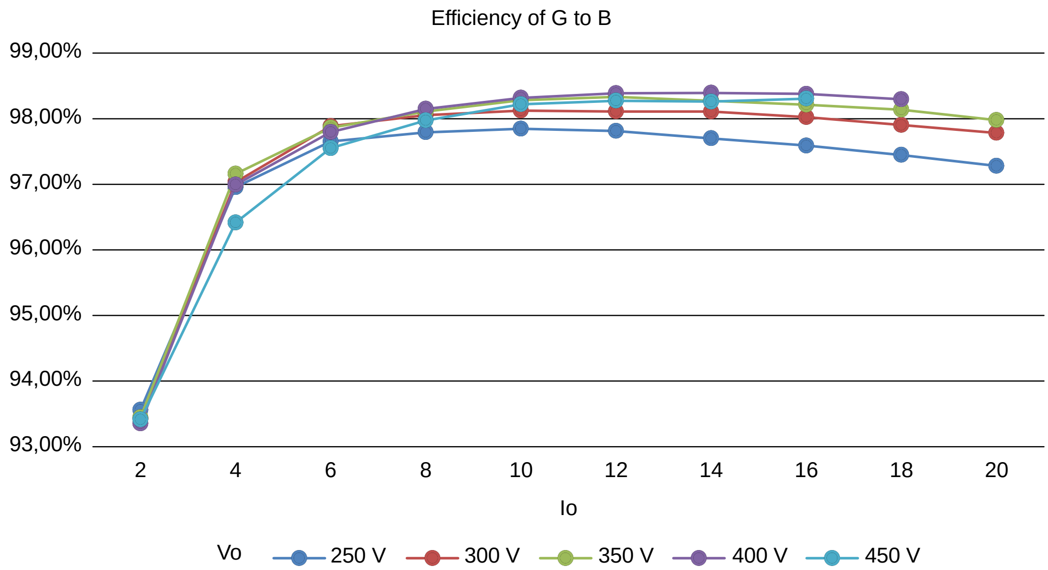
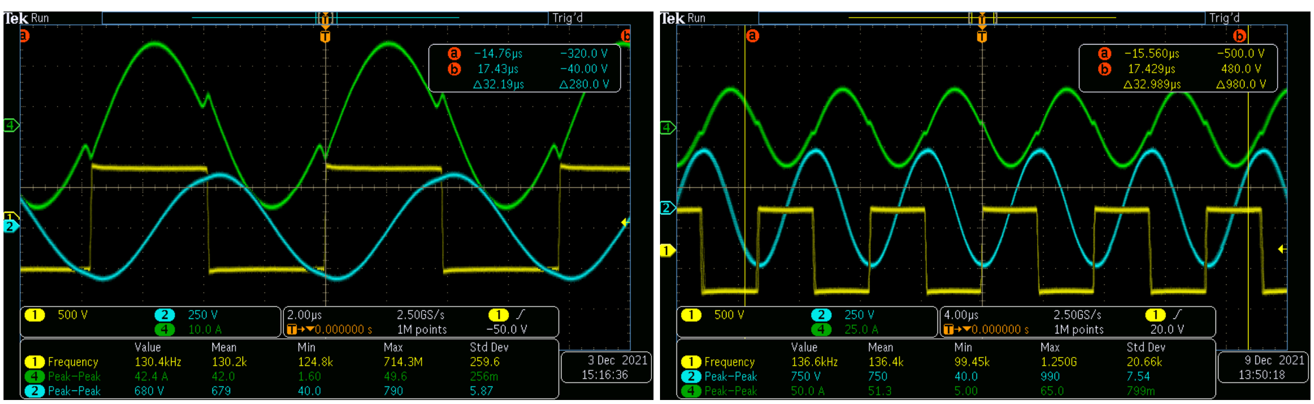


Figure 19. Efficiency for Grid to Battery Mode

Waveforms on Grid to Battery Operation

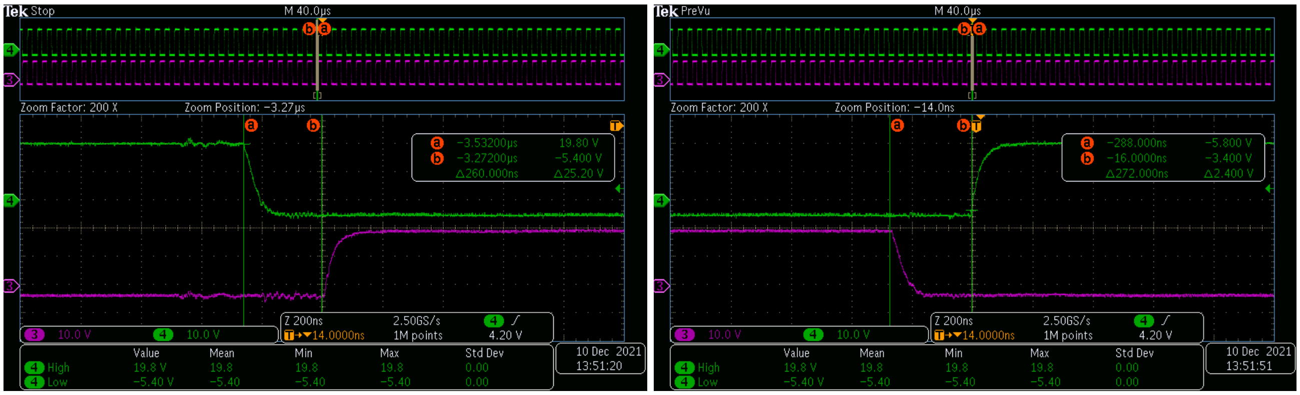
Figure 20 shows the voltage and current stresses under Vo = 450 V/16 A (Left) and Vo = 350 V/20 A (Right).



*CH1: Trans UA − Trans UB; CH2: Voltage on Resonant Capacitors; CH4: Current of Resonant tank.

Figure 20. Voltage, Current Stress at Full Load

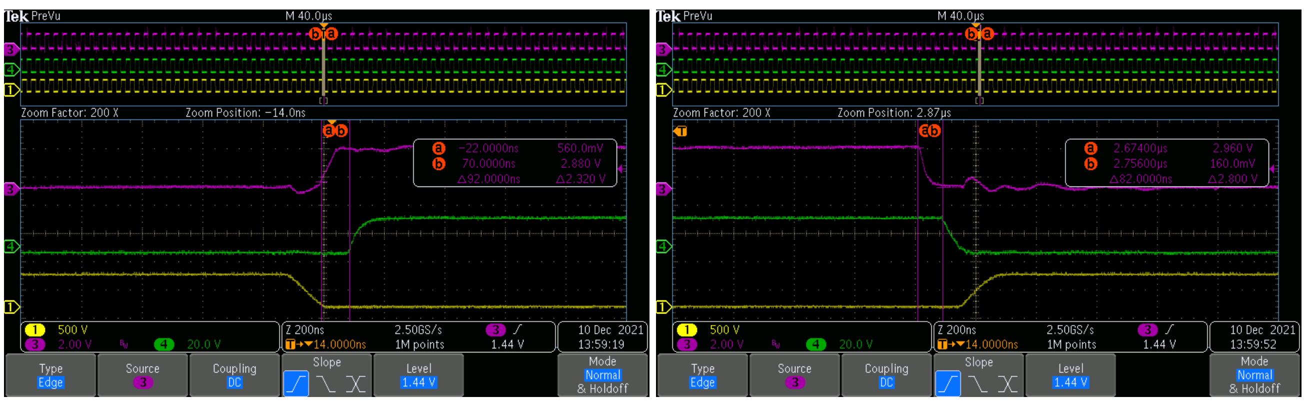
Figure 21 shows the gate drive signals of the high−side and low−side MOSFETs. We can see the driving voltage and the dead time between each signal.



*CH3: Vgs of Q50 (same with Q20); CH4: Vgs of Q30 (same with Q40).

Figure 21. Gate Drive Signal of the SiC MOSFETs

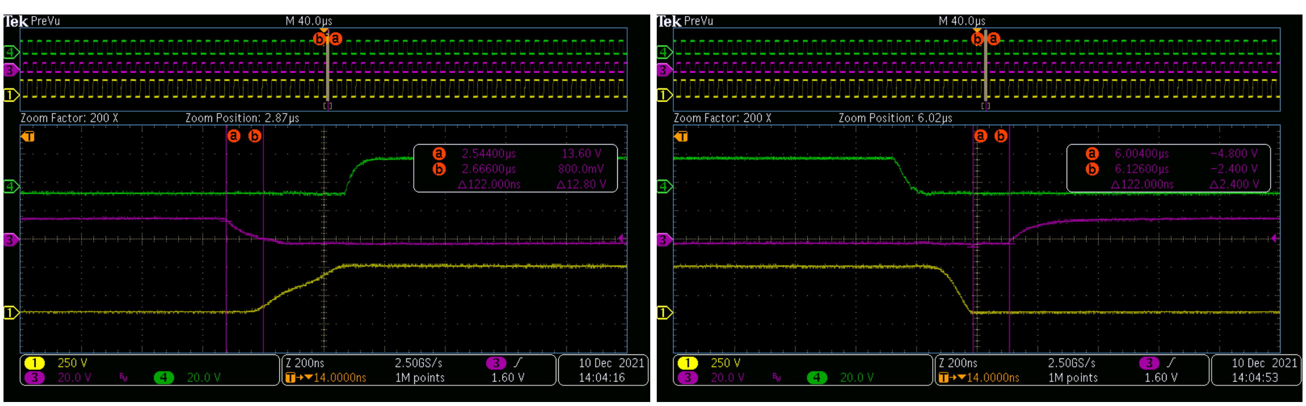
Figure 22 shows the PWM signals from the control interface to the MOSFETs. We can see the delay times on the turn−on and turn−off moment.



*CH1: Vds of Q30; CH3: Pin17 of the Control interface (LSUA); CH4: Vgs of Q30.

Figure 22. PWM Signals from the Control Interface to the MOSFETs

Figure 23 shows the gate driver waveforms of the synchronous rectifier operation. We can see the synchronous rectifier driver timing minimizes conduction losses and prevents current feedback from the battery to the transformer. This is achieved with fine control of the gate source drive voltage relative to the turn on and turn off the body diodes.



*CH1: Vds of Q150; CH3: Vgs of Q150; CH4: Vgs of Q30.

Figure 23. Gate Driver Waveforms of the Synchronous Rectifier Operation

Battery to Grid Operation

Vin and Vout for Battery to Grid Operation

In the Battery to Grid mode, the converter works as open loop. The switching frequency is approximately 142 kHz (F0). Even with Vin fixed, the output voltage Vo will have some variation under different load currents. Under a no−load condition, Vo is much higher and may trip the OVP point due to the parasitic oscillations on the Bus winding of the transformer (the design can handle this without any issues). Table 4 shows the output voltage for different input currents and voltages with the Sunlord transformer. The voltage with the Magsonder transformer will be around 7% lower.

Table 4. OUTPUT VOLTAGE ON DIFFERENT INPUT CURRENT AND VOLTAGE

Iin (A)	0	2	4	6	8	10	12	14	16	18	20
Vin = 250 V	639	363	351	349	348	347	346	344	343	342	340
Vin = 300 V	805	434	419	418	417	416	414	413	412	411	410
Vin = 350 V	805	507	488	487	486	485	483	482	481	480	479
Vin = 400 V	805	581	558	557	556	555	553	552	551	550	−
Vin = 450 V	805	657	628	627	625	624	623	621	620	−	−

Efficiency for Battery to Grid Operation

Figure 24 shows the efficiency for different V (Battery) and Iout (Battery).

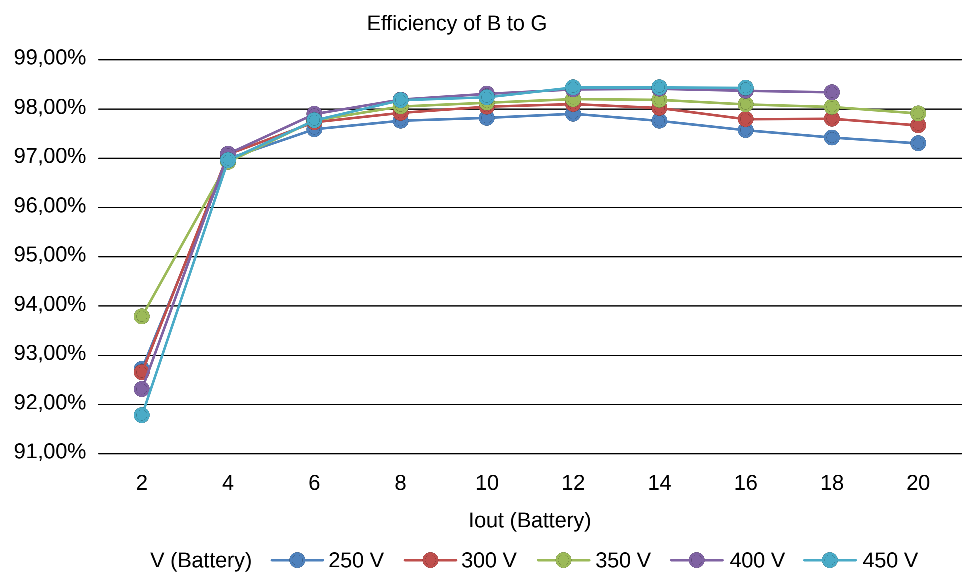
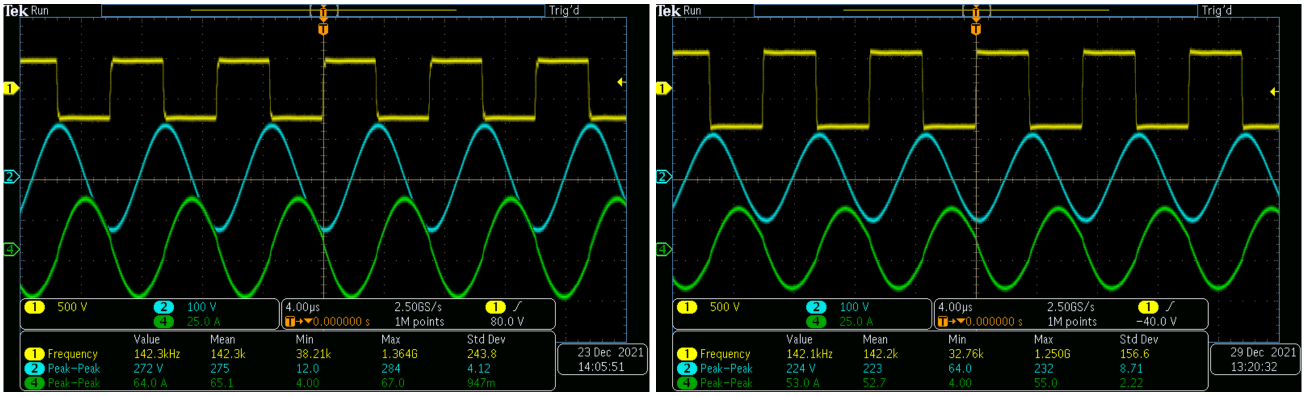


Figure 24. Efficiency for Grid to Battery Mode

Waveforms on Battery to Grid Operation

Figure 25 shows the voltage and current stresses when Vin = 350 V/20 A (Left) and Vin = 450 V/16 A (Right).



*CH1: TransAB − TransAA; CH2: Voltage on Resonant Capacitors; CH4: Current of Resonant tank.

Figure 25. Voltage, Current Stress on Full Load

DESIGN FILES

PCB Layout

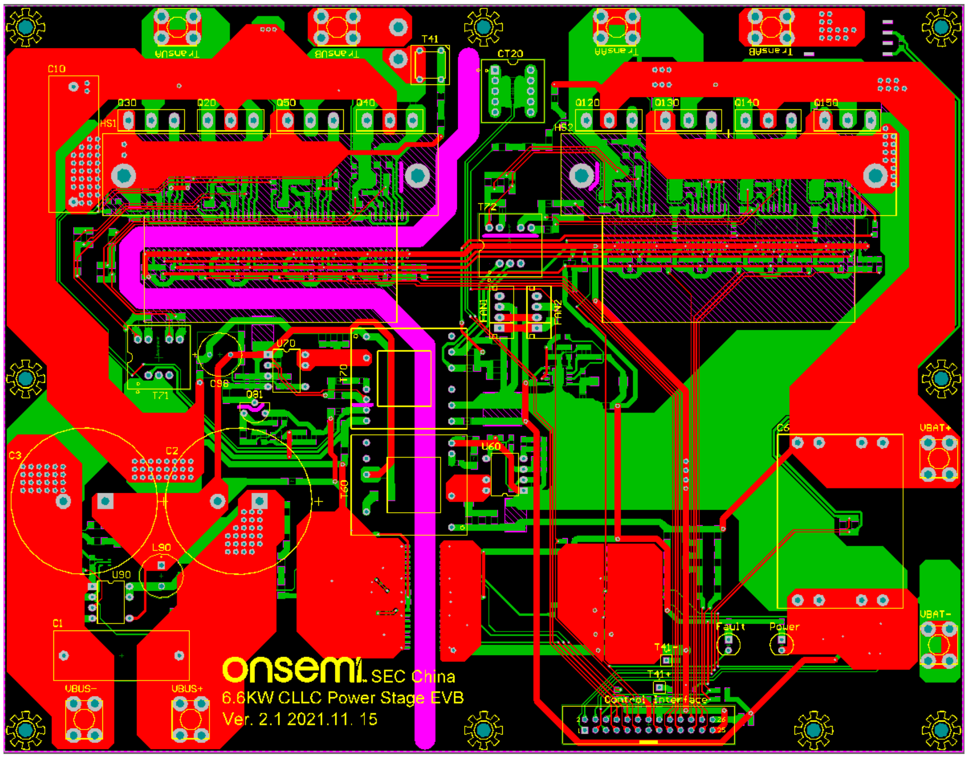


Figure 26. Top View of the Main Board, 228.6 x 177.8 mm

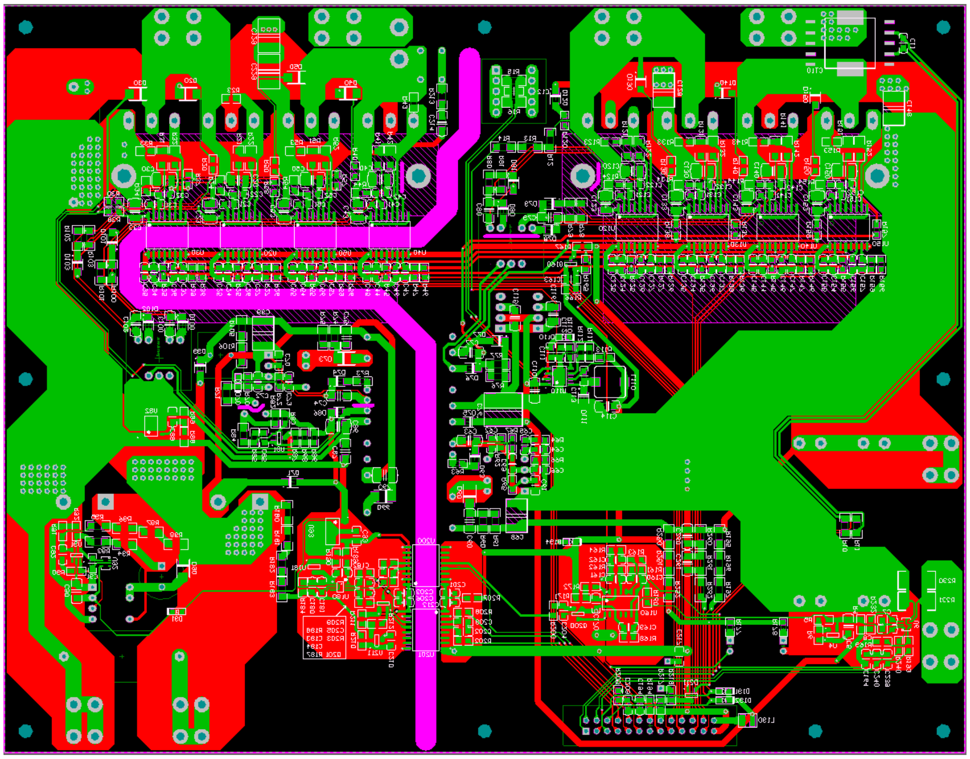


Figure 27. Bottom View of the Main Board, 228.6 x 177.8 mm

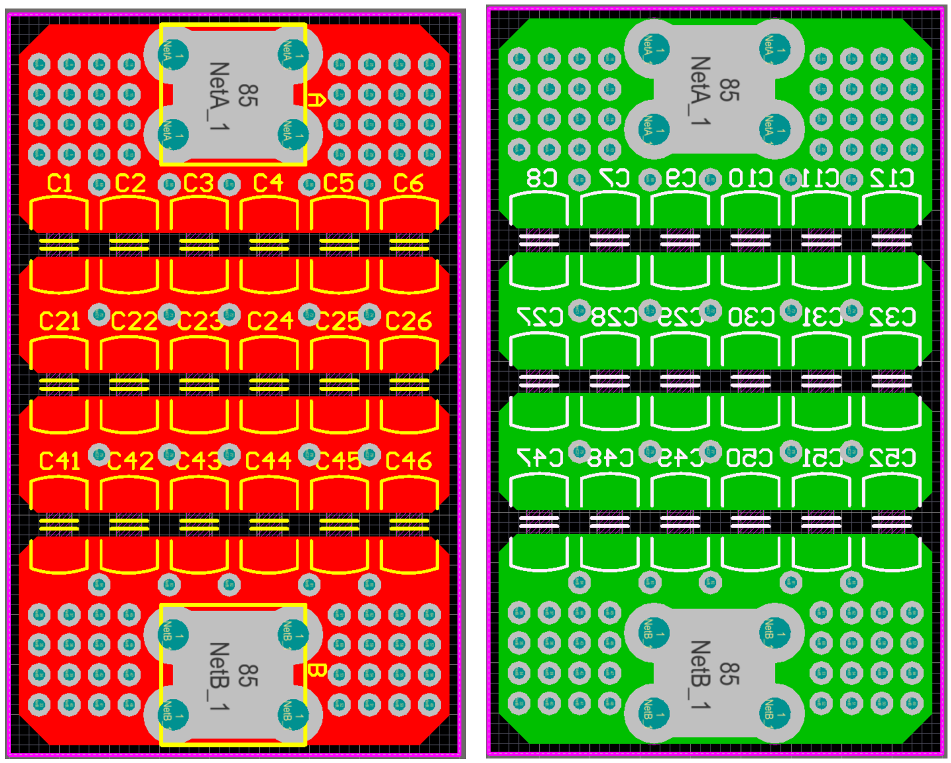


Figure 28. Top, Bottom View of the 3 Rows Resonant Capacitor Board, 47 x 28.6 mm

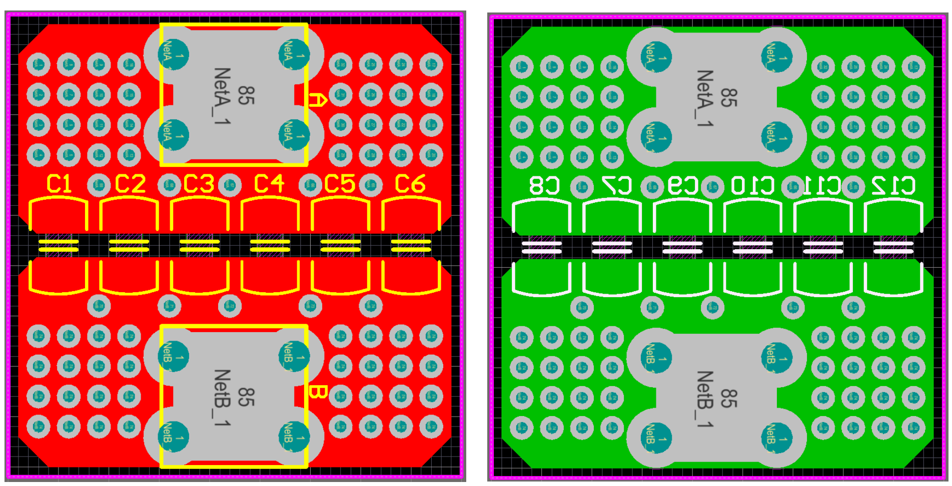


Figure 29. Top, Bottom View of the 1 Row Resonant Capacitor Board, 29.2 x 28.6 mm

Bill of Materials

Table 5. BOM OF THE MAIN BOARD

Description	Manufacturer Part Number	Manufacturer	Qty.	Designator
IC 12−Bit Low Power SAR ADC, SSop−8	NCD98010XDPT3G	**onsemi**	1	U180,
IC High Speed Quad−Channel Digital Isolator, SOIC−16W	NCID9401	**onsemi**	2	U200, U201
IC +4/−8 A Galvanic Isolated Gate Driver, SOIC−16W	NCV57000DWR2G	**onsemi**	8	U20, U30, U40, U50, U120, U130, U140, U150
IC 800 V Switcher, 100 kHz, PDIP−7	FSL538APG	**onsemi**	2	U60, U70
IC 1000 V Switcher, 50 kHz, PDIP−7	FSL4110LRN	**onsemi**	1	U90
IC Buck Switcher, 1.2 A, 2 MHz, SO8EP	NCV890100PDR2G	**onsemi**	1	U110
IC LDO 400 mA, 3.3 V, SOT−223	NCV4274CST33T3G	**onsemi**	1	U93
IC Shunt Regulator, SOT23−3L	SC431AVSNT1G	**onsemi**	4	U4, U81, U181, U211
IC Shunt Regulator, Sop−8	NCV431AIDR2G	**onsemi**	1	U82
IC LDO, 3.3 V, 50 mA, Ultra−Low Iq, SC−88A (SC70−5)	NCV8715SQ33T2G	**onsemi**	1	U92
IC Current Sense Amplifier, SC70−6	NCV210SQT2G	**onsemi**	1	U6
IC Quad, Single Supply Comparator, Sop−14	NCV2901DR2G	**onsemi**	1	U160
IC RRO OP Amplifier, SOT−23 5L	NCV2003SN2T1G	**onsemi**	1	U91
SiC MOSFET 40 mΩ 1200 V, TO−247	NVHL040N120SC1	**onsemi**	4	Q20, Q30, Q40, Q50
SiC MOSFET 20 mΩ 900 V, TO−247	NVHL020N090SC1	**onsemi**	4	Q120, Q130, Q140, Q150
MOSFET 600 V 11.5 Ω, TO92	FQN1N60CTA	**onsemi**	1	Q81
Transistor 40 V 0.6 A NPN, SOT23	SMMBT4401LT1G	**onsemi**	1	Q200
Transistor 40 V 0.6 A PNP, SOT23	SMMBT2907ALT1G	**onsemi**	2	Q160, Q201
Diode 600 V 1 A 75 nS, SOD−123FL	NRVUS1JFA	**onsemi**	6	D71, D99, D120, D130, D140, D150
Diode 1000 V 1 A, SMA	NRVA4007T3G	**onsemi**	2	D60, D73
Diode 1000 V 1.5 A 75 nS, SMA	NRVUS2MA	**onsemi**	6	D20, D30, D40, D50, D66, D90
Diode 100 V 0.8 A 150 nS, SOD−123FL	NRVHPRS1BFA	**onsemi**	2	D63, D74
Schottky Diode 2 A 150 V, SOD−123FL	NRVBS215FA	**onsemi**	6	D76, D78, D80, D86, D100, D102
Schottky Diode 1 A 20 V, SOD−123FL	NRVB120VLSFT1G	**onsemi**	1	D111
Schottky Diode 3 A 60 V, SOD−123FL	NRVBSS36FA	**onsemi**	1	D75
Schottky Diode Dual 0.2 A 30 V, SOT−23−3L	NSVBAT54SWT1G	**onsemi**	2	D211
Switching Diode 0.2 A 100 V, SOD323	BAS16H	**onsemi**	6	D70, D91, D110, D191, D192, D194
ZENER Diode 0.5 W 4.7 V, SOD123	SZMMSZ4V7T1G	**onsemi**	5	D77, D79, D81, D101, D103
LED D = 5 mm THT Green	151051VS04000	WURTH	1	Power
LED D = 5 mm THT Red	151051RS11000	WURTH	1	Fault
Chip resistor 0805 2.2 Ω−J		Any	10	R24, R34, R44, R54, R63, R73, R124, R134, R144, R154
Chip resistor 0805 4.7 Ω−J		Any	16	R25, R35, R37, R38, R45, R55, R57, R58, R125, R135, R137, R138, R145, R155, R157, R158
Chip resistor 0805 10 Ω−J		Any	4	R171, R189, R207, R232
Chip resistor 0805 100 Ω−J		Any	15	R26, R36, R46, R56, R111, R126, R136, R146, R156, R187, R188, R202, R203, R205, R208
Chip resistor 0805 300 Ω−J		Any	1	R113

Table 5. BOM OF THE MAIN BOARD (continued)

Description	Manufacturer Part Number	Manufacturer	Qty.	Designator
Chip resistor 0805 330 Ω−J		Any	2	R177, R178
Chip resistor 0805 470 Ω−J		Any	1	R190
Chip resistor 0805 1 kΩ−J		Any	12	R20, R30, R40, R50, R120, R130, R140, R150, R167, R200, R211, R219
Chip resistor 0805 1.8 kΩ−J		Any	1	R162,
Chip resistor 0805 2.2 kΩ−J		Any	14	R4, R27, R39, R47, R59, R112, R127, R139, R147, R159, R166, R172, R193, R240
Chip resistor 0805 4.7 kΩ−J		Any	6	R85, R87, R88, R89, R165, R209
Chip resistor 0805 4.75 kΩ−F		Any	2	R6, R164
Chip resistor 0805 6.65 kΩ−F		Any	1	R5
Chip resistor 0805 10 kΩ−J		Any	16	R23, R33, R43, R53, R64, R83, R110, R123, R133, R143, R153, R161, R163, R210, R212, R217
Chip resistor 0805 11.5 kΩ−F		Any	1	R168
Chip resistor 0805 12 kΩ−J		Any	1	R169
Chip resistor 0805 12.7 kΩ−F		Any	3	R91, R92, R184
Chip resistor 0805 20 kΩ−J		Any	2	R72, R82
Chip resistor 0805 27 kΩ−J		Any	1	R160
Chip resistor 0805 39 kΩ−J		Any	1	R86
Chip resistor 0805 43 kΩ−J		Any	2	R66, R67
Chip resistor 0805 56 kΩ−J		Any	1	R68
Chip resistor 0805 100 kΩ−J		Any	3	R62, R70, R90
Chip resistor 0805 220 kΩ−J		Any	1	R65
Chip resistor 1206 4.7 Ω−J		Any	16	R21, R22, R31, R32, R41, R42, R51, R52, R121, R122, R131, R132, R141, R142, R151, R152
Chip resistor 1206 100 Ω−J		Any	2	R10, R11
Chip resistor 1206 150 Ω−J		Any	2	R15, R16
Chip resistor 1206 1 kΩ−J		Any	1	R213
Chip resistor 1206 2.2 kΩ−J		Any	6	R76, R77, R78, R79, R80, R81
Chip resistor 1206 3.9 kΩ−J		Any	4	R100, R101, R102, R103
Chip resistor 1206 47 kΩ−J		Any	2	R71, R84
Chip resistor 1206 150 kΩ−J		Any	3	R12, R13, R14
Chip resistor 1206 470 kΩ−J		Any	4	R60, R61, R74, R75
Chip resistor 1206 1 MΩ−J		Any	18	R93, R94, R95, R96, R97, R98, R105, R106, R180, R181, R182, R183, R195, R196, R197, R250, R251, R252
Chip resistor 1206 3 MΩ−J		Any	3	R260, R261, R262,
Chip resistor 2512 2 mΩ−F	SMA25A2FR002T	SART	2	R230, R231
Chip resistor 2512 2 mΩ−F	ERJMS4SF2M0*	Panasonic	2	R230, R231
MLCC 0805−450V−100pFJ−NP0	CGA4C4C0G2W101J	TDK	33	C11, C12, C21, C26, C27, C31, C36, C37, C41, C46, C47, C51, C56, C57, C121, C126, C127, C131, C136, C137, C141, C146, C147, C151, C156, C157, C180, C183, C184, C202, C205, C208, C210

Table 5. BOM OF THE MAIN BOARD (continued)

Description	Manufacturer Part Number	Manufacturer	Qty.	Designator
MLCC 0805−450V−100pFJ−NP0	GCM21A5C2J101JX01	Muruta	33	C11, C12, C21, C26, C27, C31, C36, C37, C41, C46, C47, C51, C56, C57, C121, C126, C127, C131, C136, C137, C141, C146, C147, C151, C156, C157, C180, C183, C184, C202, C205, C208, C210
MLCC 0805−450V−471J−NP0	CGA4C4C0G2W471J	TDK	2	C64, C163
MLCC 0805−450V−471J−NP0	GCM21A5C2J471JX01	Muruta	2	C64, C163
MLCC 0805−100V−102J−NP0	CGA4C2C0G2A102J	TDK	10	C62, C66, C72, C73, C88, C164, C169, C204, C239, C240
MLCC 0805−50V−222J−NP0	CGA4C2C0G1H222J	TDK	1	C112
MLCC 0805−50V−223J−NP0	CGA4J2C0G1H223J125AA	TDK	3	C65, C69, C85
MLCC 0805−50V−223J−NP0	GCM21B5C1H223JA16	Muruta	3	C65, C69, C85
MLCC 0805−100V−104K−X7R	CGA4J2X7R2A104K	TDK	24	C7, C8, C24, C34, C44, C54, C61, C70, C92, C111, C113, C124, C134, C144, C154, C160, C161, C162, C170, C181, C182, C203, C212, C217
MLCC 0805−100V−104K−X7R	GCM21BR72A104KA37L	Muruta	24	C7, C8, C24, C34, C44, C54, C61, C70, C92, C111, C113, C124, C134, C144, C154, C160, C161, C162, C170, C181, C182, C203, C212, C217
MLCC 0805−50V−105K−X7R	CGA4J3X7R1H105K125AB	TDK	12	C22, C32, C42, C52, C91, C93, C122, C132, C142, C152, C201, C206
MLCC 0805−50V−105K−X7R	GCM21BR71H105KA03L	Muruta	12	C22, C32, C42, C52, C91, C93, C122, C132, C142, C152, C201, C206
MLCC 0805−25V−225K−X7R	CGA4J3X7R1E225K	TDK	8	C25, C35, C45, C55, C125, C135, C145, C155
MLCC 0805−25V−225K−X7R	GCM21BR71E225KA73L	Muruta	8	C25, C35, C45, C55, C125, C135, C145, C155
MLCC 1206−50V−475K−X7R	CGA5L3X7R1H475K	TDK	2	C100, C102
MLCC 1206−50V−475K−X7R	GCM31CC71H475KA03	Muruta	2	C100, C102
MLCC 1206−25V−106K−X7R	CGA5L1X7R1E106K	TDK	10	C5, C74, C77, C79, C80, C87, C90, C110, C114, C115
MLCC 1206−25V−106K−X7R	GCM31CC71E106KA03	Muruta	10	C5, C74, C77, C79, C80, C87, C90, C110, C114, C115
MLCC 1206−50V−104J−C0G	CGA5L2C0G1H104J160AA	TDK	1	C63
MLCC 1206−50V−104J−C0G	GCM31C5C1H104JA16	Muruta	1	C63
MLCC 1206−630V−222K−X7R	CGA5H4X7R2J222K	TDK	5	C60, C75, C214, C260, C261
MLCC 1206−630V−222K−X7R	GCJ31BR72J222KXJ1	Muruta	5	C60, C75, C214, C260, C261
MLCC 1210−25V−226K−X7R	CGA6P3X7R1E226M250AB	TDK	18	C20, C23, C30, C33, C40, C43, C50, C53, C86, C116, C120, C123, C130, C133, C140, C143, C150, C153
MLCC 1210−25V−226K−X7R	GCM32EC71E226KE36	Muruta	18	C20, C23, C30, C33, C40, C43, C50, C53, C86, C116, C120, C123, C130, C133, C140, C143, C150, C153
MLCC 1210−630V−154K−X7T	CGA6M1X7T2J154K200AC	TDK	1	C67
MLCC 1210−630V−154K−X7T	GC355DD72J154KX01	Muruta	1	C67
MLCC 2220−630V−105M−X7T	CAA572X7T2J105M	TDK	6	C68, C99, C128, C129, C148, C229
MLCC 2220−630V−105M−X7T	KC355TD7LQ105MV01	Muruta	6	C68, C99, C128, C129, C148, C229
MLCC 2220−35V−157M−X7T	CAA573X7R1E157M	TDK	1	C76

Table 5. BOM OF THE MAIN BOARD (continued)

Description	Manufacturer Part Number	Manufacturer	Qty.	Designator
THT Film Capacitor 1 μF, 1100 V	ECWFG1B105J	Panasonic	2	C1, C10
THT Film Capacitor X2 470 nF, 1000 V	890493427007CS	WURTH	2	C1, C10
Film Cap 800 V 30 μF PP	EZPV80306MTB	Panasonic	1	C6
E−Cap 450 V−680 μF−105 (35 X 57 mm)	861141486026	WURTH	2	C2, C3,
E−Cap 450 V−680 μF−105 (35 X 57 mm)	B43508A5687M062	TDK	2	C2, C3,
Current Transformer EE13/7/4	750316796	WURTH	1	CT10
Current Transformer EE13/6/6	750344930	WURTH	1	CT20
Auxiliary Power Transformer B to G PQ2620/14p	750344929	WURTH	1	T60
Auxiliary Power Transformer G to B PQ2620/14p	750344928	WURTH	1	T70
Pulse Transformer EE13/6/6/ 1:1 10−Terminal, THT	750344931	WURTH	2	T71, T72
Pulse Transformer EE8 56:1 4−Terminal, THT	750345072	WURTH	1	T41
SMD Inductor 3225−100 μH−0.12 A	NLCV32T−101K−EFD	TDK	1	L190
SMD Inductor 3225−100 μH−0.26 A	LQH3NPH101MMEL	Muruta	1	L190
SMD Inductor 3225−100 μH−0.3 A	74403042101	WURTH	1	L190
Radial Leaded Inductor 1014, 2200 μH, 0.48 A	7447480222	WURTH	1	L90
SMD Inductor 7 X 7 X 3.5 mm−22 μH−1.6 A	784778220	WURTH	1	L110
SMD Inductor 7 X 7 X 4.5 mm−22 μH−1.7 A	SPM7045VT−220M−D	TDK	1	L110
SMD Inductor 7 X 7 X 4.5 mm−22 μH−2.9 A	ETQP4M220KFM	Panasonic	1	L110
SMD Inductor 7 X 6 X 2.8 mm−22 μH−2.5 A	AMP0603H220MT	Sunlord	1	L110
Main transformer	ATWPPQ655462B202T	Sunlord	1	Outside of the board
Main transformer	PTX6R6K−17025−r	Magsonder	1	Outside of the board
Male Box Header WR−BHD, THT, Vertical, 2.54 mm, 26 pins	61202621621	WURTH	1	Control_Interface
Connector 5 mm Screw type. 200 X 300 mil	74760050	WURTH	8	VBUS+, VBUS−, VBAT+, VBAT−, TransUA, TransUB, TransAA, TransAB
Connector 2.54 mm 2 Pin	Header 4	Any	2	FAN1, FAN2
Heat Sink	80 x 60 x 20	Any	2	HS1, HS2
FAN 60 X 60 X 25 mm 12 V 0.27 A	AFB0612SH	DELTA	2	HS1, HS2

*The adjacent items in same shadow are optional from different manufacturer.

Table 6. BOM OF THE 3 ROWS RESONATE CAPACITOR BOARD

Description	Manufacturer Part Number	Manufacturer	Qty.	Designator
MLCC 1210−1000V−223J−C0G	CGA6P1C0G3A223JT0Y0N	TDK	30	C1, C2, C3, C4, C5, C6, C7, C9, C10, C11, C21, C22, C23, C24, C25, C26, C28, C29, C30, C31, C41, C42, C43, C44, C45, C46, C48, C49, C50, C51
MLCC 1210−630V−223J−C0G	GCM32E5C2J223JX03L	Muruta	30	C1, C2, C3, C4, C5, C6, C7, C9, C10, C11, C21, C22, C23, C24, C25, C26, C28, C29, C30, C31, C41, C42, C43, C44, C45, C46, C48, C49, C50, C51

*The adjacent items in same shadow are optional in different manufacturer.

Table 7. BOM OF THE 1 ROW RESONATE CAPACITOR BOARD

Description	Manufacturer Part Number	Manufacturer	Qty.	Designator
MLCC 1210−1000V−223J−C0G	CGA6P1C0G3A223JT0Y0N	TDK	12	C1, C2, C3, C4, C5, C6, C7, C8, C9, C10, C11, C12
MLCC 1210−630V−223J−C0G	GCM32E5C2J223JX03L	Muruta	12	C1, C2, C3, C4, C5, C6, C7, C8, C9, C10, C11, C12

*The adjacent items in same shadow are optional from different manufacturers.

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